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The Multisphere
Neutron-Monitoring Technique

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The Multisphere
Neutron-Monitoring Technique

by

Dale E. Hankins

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THE MULTISPHERE NEUTRON-MONITORING TECHNIQUE

by

Dale E. Hankins

ABSTRACT

This paper describes the multisphere technique for converting to dose equivalent the data obtained from the Bonner-sphere neutron detector. The responses from the various sizes of detector are illustrated with data obtained from several sources and critical assemblies. The theory and principles involved in converting these responses to dose equivalent are explained in detail.

The multisphere technique is revised to include new calculated response curves which replace the previously used extrapolations in the intermediate-energy region. The accuracy of the technique for an intermediate-energy neutron spectrum which does not follow the $1/E$ distribution is evaluated. The multisphere technique described does not require a computer analysis.

Introduction

The dose rate from neutrons with intermediate energies (cadmium-cutoff to 100-keV) has always been difficult to determine. Many instruments have been developed to measure accurately the dose rate from neutrons having fast and thermal energies. Some, such as the long counter, respond to neutrons of all energies, but the conversion of the response to a neutron dose rate is uncertain for spectra containing all neutron energies.

Intermediate-energy neutrons are always accompanied by fast- and thermal-energy neutrons. An instrument that responds only to intermediate-energy neutrons has

not been developed, although there is one that responds primarily to them.¹ There are a number of rem meters that respond to intermediate-energy neutrons,²⁻⁴ but their responses are normally high by varying amounts. Despite this drawback, these rem meters are generally accepted as the instrument with which to measure the dose rate from intermediate-energy neutrons.

The multisphere technique described in this report was developed to evaluate the dose rate from intermediate-energy neutrons in the complex leakage neutron spectrum of a reactor. The measurements made indicate that intermediate-energy neutrons sometimes contributed a large part of the total dose.⁵

The multisphere technique, described originally by Hankins,⁶ requires considerable time for collection and interpretation of data. It does, however, provide information about the neutron spectrum which is not available from other methods. This paper describes the principles on which the technique is based, revises the original report to include recently calculated efficiency curves, and evaluates the error created by assuming that a $1/E$ distribution exists in the intermediate-energy region.

The Instrument

The instrument used to collect data is commonly called the "Bonner spheres." The neutron detector, described by Bramblett, Ewing, and Bonner⁷ is a lithium-iodide crystal, 4-mm in diameter and 4-mm thick, which is more than 80% "black" for thermal neutrons. The crystal is coupled to a photomultiplier tube by means of a 1/2-in.-o.d. quartz or polystyrene light pipe that is wrapped in aluminum foil and taped to limit light loss. The system is enclosed in a hollow brass tube that gives mechanical support and acts as a light shield. The output of the photomultiplier tube is fed through a standard preamplifier and amplifier to either a scaler, a ratemeter, or a pulse-height analyzer. Circuitry and details of construction were obtained from the late Dr. T. W. Bonner of Rice Institute. The thermal-neutron detector is surrounded in succession by a series of polyethylene spheres, 2, 3, 5, 8, and 12 in. in diameter. The spheres are made in one or two pieces from standard polyethylene. A 41/64-in.-dia. hole is drilled in each sphere to a depth that permits the light pipe to be inserted so that the lithium-iodide crystal is centered in the sphere. With these detectors, gamma discrimination is obtained by biasing,

Fig. 1. Multisphere neutron-detection instrument.

which results in only a few counts per minute from a 1 R/h ^{60}Co gamma flux, or by using a pulse-height analyzer. One of the Los Alamos Scientific Laboratory multisphere detection units is shown in Fig. 1.

The energy response curves for the detector with 2-, 3-, 5-, 8-in, and 12-in. spheres were given by Bramblett et al.⁷ The energy responses in the intermediate-energy region were extrapolations because sources of monoenergetic intermediate-energy neutrons are not available. Recently, calculations of the energy responses of the detector with these spheres and several other spheres have been made^{3,8,9} (Table I). The calculated energy responses agree reasonably well with Bramblett's data in the thermal- and fast-energy regions. The calculated energy response in the intermediate-

Table I

Detector Sphere Efficiencies at 21 Neutron-Energy Levels

Energy MeV	Sphere Diameters										
	2 in.	3 in.	5 in.	8 in.	9 in.	9½ in.	10 in.	12 in.	16 in.	18 in.	20 in.
96-192	0.000008	0.0001	0.0014	0.0068		0.01019	0.0115	0.0161	0.0239	0.0274	0.0302
48-96	0.00003	0.0004	0.0049	0.0210		0.02990	0.0331	0.0439	0.0587	0.0638	0.0670
24-48	0.00012	0.0014	0.0144	0.0523		0.06969	0.0754	0.0917	0.1054	0.1057	0.1031
12-24	0.00032	0.0034	0.0293	0.0916		0.1145	0.1209	0.1351	0.1317	0.1200	0.1068
6-12	0.00095	0.0087	0.0618	0.1533	0.1541	0.1730	0.1759	0.1712	0.1277	0.1000	0.0773
3-6	0.0020	0.017	0.1076	0.2286	0.2391	0.2410	0.2388	0.2116	0.1315	0.0929	0.0656
1.4-3	0.0044	0.033	0.1651	0.2720	0.2610	0.2548	0.2412	0.1809	0.0806	0.0474	0.0282
0.9-1.4	0.0083	0.055	0.2211	0.2711	0.2359	0.2197	0.1964	0.1186	0.0332	0.0146	0.0066
0.4-0.9	0.0137	0.078	0.2502	0.2386	0.1918	0.1725	0.1478	0.0765	0.0160	0.0060	0.0023
0.1-0.4	0.0257	0.112	0.2644	0.1792	0.1303	0.1121	0.0912	0.0396	0.0062	0.0020	0.00071
keV											
17-100	0.0437	0.147	0.2493	0.1236	0.08319	0.06947	0.0546	0.0215	0.0030	0.0010	0.00035
3-17	0.0656	0.178	0.2423	0.1023	0.06693	0.05540	0.0431	0.0167	0.0023	0.00075	0.00027
0.55-3	0.0919	0.209	0.2401	0.0914	0.05090	0.04863	0.0377	0.0145	0.0020	0.00065	0.00024
eV											
100-550	0.1247	0.240	0.2354	0.0825	0.05272	0.04333	0.0335	0.0128	0.0017	0.00056	0.00022
30-100	0.1622	0.267	0.2257	0.0738	0.04688	0.03846	0.0297	0.0113	0.0015	0.00051	0.00021
10-30	0.1942	0.282	0.2136	0.0670	0.04246	0.03480	0.0269	0.0102	0.0014	0.00044	0.00020
3-10	0.2248	0.288	0.1972	0.0599	0.03784	0.03105	0.0240	0.0091	0.0012	0.00042	0.00019
1-3	0.2515	0.284	0.1776	0.0527	0.03320	0.02727	0.0211	0.0080	0.0011	0.00037	0.00019
0.4-1.0	0.2563	0.260	0.1509	0.0442	0.02812	0.02286	0.0176	0.0067	0.00088	0.00032	0.00020
0.1-0.4	0.2207	0.205	0.1141	0.0333	0.02124	0.01727	0.0133	0.0051	0.00067	0.00026	0.00020
thermal	0.1457	0.114	0.0588	0.0171	0.01093	0.00889	0.0069	0.0026	0.00033	0.00010	0.000002

Fig. 2. Relative count rate vs energy for moderating spheres.

energy region, however, is markedly higher. Figure 2 was prepared from Bramblett's data in the fast-energy region, the results of recent calibration in the thermal-energy region, and the calculated values in the intermediate-energy region (broken line).

The calculated energy response for intermediate-energy neutrons agrees better with the experimental data than do Bramblett's extrapolated energy responses. Previously one had to ignore the extrapolated energy responses and fit the experimental data to estimated energy responses.⁶ The estimated energy responses agree within a few percent of the calculated energy response to intermediate-energy neutrons.

Theory

The energy response curves of the detector with the different spheres are shown

in Fig. 2. The curves vary greatly with the neutron energy. In the thermal region, the energy response decreases as the sphere size increases, but for neutron energies > 5 MeV the energy response increases with the size of the sphere. In the energy regions between these extremes, the relative energy responses do not have a simple dependence on sphere size. The large variations in the energy response curves make it possible to use the spheres as a spectrometer.

Shown below are the relative count

Sphere Size (in.)	Relative Count Rate	
	1-MeV Neutrons	2-MeV Neutrons
2	0.35	0.2
3	2.4	1.4
5	9.6	7.1
8	11.2	11.3
12	4.7	7.5

rates, obtained from Fig. 2, for monoenergetic 1- and 2-MeV neutron sources. The count rates of the 8-in. sphere for both 1- and 2-MeV neutrons are nearly the same, but those of the other spheres vary considerably. To use the spheres as a spectrometer, data are obtained and the count rates with the various spheres are compared to the energy responses given in Fig. 2. When the relative count rates match the energy response, the neutron energy has been determined.

The large difference in the relative count rate for 1- and 2-MeV neutrons indicates that for monoenergetic neutrons this technique is capable of differentiating relatively small changes in the neutron energy.

The relative intensity of neutrons in complex neutron spectra consisting of two or more monoenergetic neutron components can be determined if the neutron energies are known. For example, if monoenergetic 1- and 2-MeV neutrons are present in about equal intensities, the relative count rates will indicate an energy of ~ 1.5 MeV, but if it is known that 1- and 2-MeV neutrons are present, the relative intensity of each energy can be determined by weighting the relative count rate for 1- and 2-MeV neutrons until the experimental count rate is obtained.

Only rarely are monoenergetic neutrons encountered in health physics monitoring. To use the sphere neutron detector with a neutron spectrum that has been partially moderated, consideration must be given to the counts caused by the lower-energy neutrons. An effective, or average, neutron energy can be obtained as described in the preceding paragraph where two monoenergetic neutron energies of 1 and 2 MeV in equal intensities cause an apparent 1.5-MeV neutron

energy. This is normally not acceptable because a spectrum which contains a large thermal-energy neutron component causes the average energy interpretation and dose rate evaluation to be low.

One of the computer techniques breaks the neutron energy region from thermal to 10 MeV into as many groups as there are spheres, which is normally five.⁶ Five equations are written using the count rate obtained with each sphere, and a 5×5 matrix is solved for the energy spectrum. Two problems arise: (1) the indicated spectrum may have negative values in one or more energy groups, and (2) when there is a large statistical inaccuracy in the data, the spectrum obtained may be unrealistic. Some computer codes have been written which prevent these negative values and include smoothing factors to give a reasonable spectrum, but we will not dwell further on the computer applications of the spheres; information about these computer programs is available elsewhere.¹⁰⁻¹⁴

Substantial counting time with each sphere is required to attain reasonable counting accuracy. To reduce the data collection time, we eliminated two of the spheres. The 5-in. sphere was eliminated because its energy response is flat over a large energy region and the procedure used depends on large variations in the response. The 12-in. sphere was eliminated because it is too heavy to handle easily and its counting rate is normally quite low, requiring long counting times for reasonable accuracy. The 2- and 3-in. spheres have similar efficiency curves, but both were retained.

The thermal neutron responses of the spheres can be eliminated by surrounding them with cadmium. Since the LiI crystal is a thermal neutron detector, count rates can

Table II

Efficiencies of Spheres for a 1/E Spectrum
Extending from 0.237 eV to Energy Indicated

Energy Increment eV	2-in. Sphere Efficiency		3-in. Sphere Efficiency		8-in. Sphere Efficiency	
	For the Energy Increment	For a 1/E Spectrum	For the Energy Increment	For a 1/E Spectrum	For the Energy Increment	For a 1/E Spectrum
0.237-0.422	8.8		8.5		1.4	
0.422-0.75	9.5		9.5		1.6	
0.750-1.33	9.9		10.3		1.8	
1.33-2.37	9.5		10.7		2.0	
2.37-4.22	9.1		10.8		2.15	
4.22-7.50	8.6		10.8		2.25	
7.50-13.3	7.9		10.7		2.4	
13.3-23.7	7.3		10.6		2.5	
23.7-42.2	6.65		10.3		2.65	
42.2-75.0	6.1		10.0		2.75	
75.0-133	5.5		9.7		2.9	
133-237	5.0		9.3		3.0	
237-422	4.5		9.0		3.15	
422-750	4.0		8.6		3.25	
<u>kev</u>						
0.75-1.33	3.6		8.2		3.4	
1.33-2.37	3.25		7.8		3.5	
2.37-4.22	2.95		7.3		3.6	
4.22-7.50	2.65		6.9		3.75	
7.50-13.3	2.3		6.4		3.9	
13.3-23.7	2.05		6.0		4.1	
23.7-42.2	1.80	5.76	5.6	8.90	4.3	2.87
42.2-75.0	1.42	5.56	5.3	8.74	4.5	2.95
75.0-133	1.28	5.38	4.9	8.57	4.9	3.03
133-237	1.03	5.19	4.2	8.39	6.2	3.16
237-422	0.77	5.02	3.75	8.21	7.5	3.34
422-750	0.54	4.85	3.1	8.01	9.7	3.58
<u>MeV</u>						
0.75-1.33	0.34	4.68	2.2	7.79	11.0	3.86
1.33-2.37	0.21	4.52	1.45	7.57	11.2	4.12
2.37-4.22	0.11	4.36	0.84	7.34	10.0	4.32
4.22-7.50	0.05	4.22	0.50	7.11	8.5	4.46
7.50-13.3	0.03	4.09	0.26	6.89	5.0	4.48

be obtained with the bare probe and with a cadmium-covered probe and the difference between the two rates can be used to determine the thermal neutron fluence. The data required to determine the total neutron dose rate by the multisphere technique consist of the count rates of the bare and cadmium-covered probes and the cadmium-covered 2-, 3-, and 8-in. spheres.

The count rates of the cadmium-covered spheres can be used to determine an average neutron energy for the region from cadmium-cutoff to the fast-neutron energies. This is similar to the techniques used in some earlier neutron monitoring procedures.¹⁵ The average neutron energy determined is not very meaningful, particularly when the fluence of intermediate-energy neutrons is high.

A more meaningful evaluation of the neutron spectrum can be obtained by dividing the spectrum into intermediate and fast components (thermal fluence is determined from the bare and cadmium-covered probes).

The fast-energy component of the neutron spectrum will consist of a weighted, or average, fast-neutron energy similar to the average of 1.5 we obtained previously from 1- and 2-MeV neutrons. The neutron spectrum in the intermediate-energy region must be known.

Usually the leakage neutron spectrum through hydrogenous shielding materials has a $1/E$ dependence in the intermediate-energy region or approximates this dependence. For the moment we will assume that the intermediate region of the spectrum has a $1/E$ dependence and will discuss later the error created when this energy dependence does not exist.

The $1/E$ spectrum in the intermediate-energy region begins at the cadmium cutoff (about 0.3 eV) and extends uniformly to the fast-neutron energies. For a monoenergetic fast-neutron source, the $1/E$ spectrum ends abruptly at the fast-neutron energy, but for a fission spectrum it decreases gradually over the entire width of the fission spectrum. To simplify calculations, we assume that the $1/E$ spectrum extends uniformly to the average fast-neutron energy where it has an abrupt cutoff. This assumption is felt to be reasonably valid since the neutrons having energies greater than the average fast-neutron energy partially compensate for the shortage of neutrons immediately below this energy.

A $1/E$ distribution has the same number of neutrons in equal logarithmic intervals. The intermediate region was divided into many intervals of equal logarithmic size.

Table III

Count Rates of Spheres for a $1/E$ Spectrum Extending from 0.237 eV to Energy Indicated
(Normalized to a Total Count Rate of 100)

High-Energy Cutoff keV	Count Rate		
	2-in. Sphere	3-in. Sphere	8-in. Sphere
42.2	32.9	50.8	16.4
75.0	32.2	50.7	17.1
133.0	31.7	50.5	17.8
237.0	31.0	50.1	18.9
422.0	30.3	49.5	20.1
750.0	29.5	48.7	21.8
MeV			
1.33	28.7	47.7	23.6
2.37	27.9	46.7	25.4
4.22	27.2	45.8	27.0
7.50	26.7	45.0	28.2
13.30	26.5	44.6	30.0

From Fig. 2 the average energy response in each interval was determined for the 2-, 3-, and 8-in. spheres (see Table II). The energy response of each sphere to a $1/E$ neutron spectrum in the intermediate energy region is determined by averaging the response from the cadmium cutoff to the fast-neutron energy cutoff.

Fig. 3. Relative count rate of the spheres for a $1/E$ spectrum extending from 0.237 eV to energy indicated (count rate normalized to a total count rate of 100).

Table IV

Count Rates of Spheres for
Intermediate-Energy Neutrons
(Normalized to a Total Count Rate of 100)

Energy MeV	Count Rate		
	2-in. Sphere	3-in. Sphere	8-in. Sphere
0.1	32.0	50.7	17.4
0.2	31.3	50.2	18.5
0.3	30.8	49.9	19.2
0.4	30.4	49.6	20.0
0.5	30.2	49.2	20.6
0.6	29.9	49.0	21.1
0.7	29.7	48.7	21.6
0.8	29.4	48.5	22.1
0.9	29.2	48.3	22.5
1.0	29.1	48.1	22.8
1.5	28.5	47.5	24.0
2.0	28.0	47.0	25.0
3.0	27.5	46.3	26.2
4.0	27.2	46.8	26.0
5.0	27.0	47.3	25.7
10.0	26.4	44.7	29.0
14.0	26.4	44.6	30.0

We find that the data are more easily interpreted if the count rates are adjusted until the 8-in. sphere has a count rate of 1 or until the count rates can be expressed as a percent of the total count (normalized to a total count rate of 100). The latter is done by adding the count rates of the three spheres and determining each rate's percent of the total. The second method has been found most useful; Table III shows the count rates given in Table II normalized to a total count rate of 100. The information in Table III has been plotted in Fig. 3 and indicates a fairly slow change in the relative count rates as a function of the fast-neutron energy cutoff. Table IV has been prepared from Fig. 3 and gives the normalized count rate for a number of useful fast-neutron energy cutoffs.

The relative count rates of the spheres for a number of monoenergetic fast-neutron energies have been obtained from Fig. 2 and

Table V

Count Rates of Spheres for Fast Neutrons
(Normalized to a Total Count Rate of 100)

Energy MeV	Count Rate		
	2-in. Sphere	3-in. Sphere	8-in. Sphere
0.1	10.9	41.6	47.5
0.2	8.2	35.7	56.1
0.3	6.7	31.7	61.7
0.4	5.5	28.8	65.7
0.5	4.7	26.1	69.2
0.6	4.1	23.6	72.3
0.7	3.7	22.0	74.3
0.8	3.3	20.3	76.4
0.9	3.0	18.8	78.2
1.0	2.8	17.5	79.7
1.5	2.0	13.3	84.7
2.0	1.6	11.1	87.4
3.0	1.1	8.3	90.6
4.0	0.8	6.9	92.2
5.0	0.8	6.4	92.8
6.0	0.7	6.0	93.3
10.0	0.5	4.7	94.7
14.0	0.4	4.0	95.6

are given in Table V. Figure 4 has been plotted from the information given in Table V and indicates a fairly significant change in count-rate ratio as a function of neutron energy.

The cadmium-covered sphere count rates obtained from a moderated spectrum have counts from fast and intermediate energy neutrons. Unfortunately, the count rate

Fig. 4. Relative count rate of the spheres for fast neutron energies (count rate normalized to a total count rate of 100).

Fig. 5. Change in per cent of total count, 1/E spectrum to fast spectrum of 1.0 MeV.

due to the fast and intermediate components can not be determined by a simple procedure, and a relatively complex procedure must be followed.

A 1.0-MeV monoenergetic source, or a fast neutron spectrum with an average energy of 1.0 MeV, has normalized count rates for the 2-, 3-, and 8-in. spheres (Table V) of 2.8, 17.5, and 79.7, respectively; and for a 1/E spectrum in the intermediate region extending from 0.237 eV to 1.0 MeV, the normalized count rates (Table IV) are 29.1, 48.1, and 22.8, respectively. Let us assume a spectrum in which half the neutrons have fast energies of 1.0 MeV and the others have 1/E dependence. The normalized count rate is determined by weighting the count rates from fast- and intermediate-energy spectra. In this case, where half is from each spectrum, rate ratios for the 2-, 3-, and 8-in. spheres are 16.0, 32.8, and 51.2, respectively.

The same type of calculation is performed for other fractions of 1-MeV to intermediate-energy neutrons, or a graph may be prepared from which the expected normal-

ized count rates can be obtained. Figure 5 was prepared by plotting the normalized count rates for 1.0-MeV neutrons on the right side of the graph and the normalized count rate for intermediate-energy neutrons (0.237 eV to 1.0 MeV) on the left. Straight lines were then drawn to connect the points. For 50% 1.0-MeV neutrons, the normalized count rates from Fig. 5 are the same as those calculated in the preceding paragraph. These normalized count rates for the 2-, 3-, and 8-in. spheres are unique for this particular spectrum; no other combination of fast- and intermediate-energy neutrons would have this normalized count rate. Additional curves can be drawn by using the information in Table IV and V for any energy regions of particular interest to the reader (see Fig. 6).

Data from Critical Assemblies

Recently dosimetry data were obtained from the critical assemblies at the Los Alamos Scientific Laboratory during a study of blood-sodium activation. Data were obtained near the Jezebel, Flattop, and Parka assemblies. The Jezebel assembly has an unreflected ^{239}Pu core about 5 in. in diameter.^{16,17} The Flattop assembly consists of a ^{239}Pu core 4 in. in diameter surrounded by a reflector of 7 in. of normal uranium.¹⁷ The Parka assembly, a Kiwi-type reactor with enriched uranium in graphite,¹⁷ is cylindrical with a radius of about 37 in., and has a 4-in beryllium reflector surrounding the core.

The Jezebel assembly was moved outside the kiva (the concrete building that houses the assemblies) to avoid scattered neutrons from the walls of the building. Data were obtained with the cadmium-covered 2-, 3-, and 8-in. spheres at various distances from the assembly. A 10-in. sphere,³ threshold

Fig. 6. Change in per cent of total count, $1/E$ spectrum to fast spectrum.

detectors,^{18,19} and Hurst proportional neutron counter²⁰ were also used at these locations. The count rates obtained with the 2-, 3-, and 8-in. spheres are shown in Table VI and are relative to that of the 8-in. sphere which are normalized to one.

When the Jezebel assembly is outside the kiva, the relative count rates of the 2- and 3-in. spheres increase as the distance from the assembly is increased out to about 4 m. Beyond 4 m, the relative count rates remain fairly constant. The 2- and 3-in spheres are highly sensitive to lower-energy neutrons (see Fig. 2), and the increase in their count rates indicates the presence of scattered neutrons and the moderation of the neutron spectrum by air. Placing the assembly 90 cm from the concrete wall of the kiva approximately doubles the count rate of the 2- and 3-in. spheres.

When the assembly is moved inside the kiva, the count rate for the 2-in. sphere more than doubles at 3 and 6 m, and at 9 m an increase by a factor of >3 is observed. These results indicate that small changes in the neutron spectrum at the sphere's location can be detected. Large differences in the leakage-neutron spectra from the three assemblies are shown in Table VII where variations as large as a factor of 10 in the 2-in.-sphere count rate were obtained at 3 m from the assemblies.

The presence of scattered neutrons and the moderation of the spectrum observed with the sphere detector is confirmed by the data obtained with the threshold detector system. This system uses sulfur pellets and uranium, neptunium, and plutonium foil inside a boron shield. The activity obtained with the system from the

Table VI

Relative Count Rate of Spheres Obtained
with the Jezebel Critical Assembly

Assembly Location	Distance from Assembly (meters)	Relative Count Rates		
		2-in. Sphere	3-in. Sphere	8-in. Sphere
Outside kiva	0.5	0.042	0.24	1.0
	1.0	0.052	0.25	1.0
	2.0	0.068	0.28	1.0
	2.0 ^a	0.22	0.55	1.0
	2.0 ^b	0.13	0.39	1.0
	3.0	0.077	0.31	1.0
	3.0 ^b	0.18	0.50	1.0
	4.0	0.12	0.37	1.0
	6.0	0.12	0.36	1.0
	7.7 ^c	0.18	0.50	1.0
	8.0	0.11	0.36	1.0
	9.0	0.11	0.37	1.0
	9.0 ^b	0.17	0.51	1.0
Inside kiva	3.0	0.19	0.50	1.0
	6.0	0.25	0.59	1.0
	9.0	0.37	0.83	1.0

- a. A plastic man-phantom was positioned midway between the assembly and this location.
- b. The assembly was 90 cm from the kiva wall.
- c. There was a concrete wall directly behind this position.

Table VII

Relative Count Rates of Spheres Located
3 Meters from the Critical Assemblies

Critical Assembly	Assembly Location	Relative Count Rate		
		2-in. Sphere	3-in. Sphere	8-in. Sphere
Jezebel	Outside			
	kiva	0.077	0.31	1.0
	Outside			
	90 cm from kiva wall	0.18	0.50	1.0
Flattop	Inside			
	kiva	0.19	0.50	1.0
	Inside			
Parka	kiva	0.36	0.95	1.0
	Inside			
	kiva	0.78	1.46	1.0

Table VIII

Relative Activations of Threshold-Detector
Foil with the Jezebel Assembly

Assembly Location	Distance from Assembly (meters)	Activation Relative to Sulfur			
		Pu	Np	U	S
Outside kiva	0.5	2.9	2.2	0.50	1.0
	1.0	2.9	2.2	0.48	1.0
	2.0 ^a	5.7	2.8	0.61	1.0
	2.15	3.2	2.2	0.54	1.0
	3.0	3.8	2.3	0.52	1.0
	4.0	4.4	2.6	0.58	1.0
	6.0	3.8	2.9	0.61	1.0
	7.7 ^b	5.1	3.3	0.60	1.0
	8.0	4.9	2.6	0.58	1.0
Inside kiva	3.0	4.1	2.7	0.54	1.0
	6.0	5.3	3.0	0.65	1.0
	9.0	7.0	3.3	0.67	1.0

- a. A plastic man-phantom was positioned midway between the assembly and this location.
- b. There was a concrete wall directly behind this location.

Jezebel assembly is shown on Table VIII normalized to the sulfur pellet activation. An increase in relative activation is obtained for the plutonium, neptunium, and uranium as the distance from the assembly increases. When the assembly is moved inside the kiva, a significant increase in the activity of these foils is obtained.

Table IX gives the threshold detector results obtained from the three critical assemblies at a distance of 3 m, and can be compared to the sphere data in Table VII. The plutonium, neptunium, and uranium foils used with the Flattop and Parka assemblies have much higher count rates than those obtained with the Jezebel assembly.

The leakage of neutrons from the surface of the Jezebel assembly has been calculated and is given in Table X. The rela-

Table IX

Relative Activations of Threshold-Detector Foils
Located 3 Meters from the Critical Assemblies

Critical Assembly	Assembly Location	Activation Relative to Sulfur			
		²³⁹ Pu (≥0.004 MeV)	²³⁹ Np (≥0.75 MeV)	²³⁵ U (≥1.5 MeV)	²³⁵ S (≥2.5 MeV)
Jezebel	Outside Kiva	3.8	2.3	0.52	1.0
	Outside, 90 cm from kiva wall	3.8	2.2	0.41	1.0
	Inside Kiva	4.1	2.7	0.54	1.0
	Flattop	3.3	6.2	0.79	1.0
Parks	Inside Kiva	15.2	5.5	0.88	1.0

Table X

Calculated Responses of Spheres for the Computed
Leakage Spectrum of the Jezebel Assembly

Energy (MeV)	Computed Neutron Leakage per Fission Neutron	Count		
		2-in. Sphere	3-in. Sphere	8-in. Sphere
<3	0.1251	0.00025 ^a	0.00213 ^a	0.02860 ^a
1.4 to 3.0	0.1980	0.00087	0.00653	0.05386
0.9 to 1.4	0.1118	0.00093	0.00615	0.03031
0.4 to 0.9	0.1378	0.00189	0.01075	0.03701
0.1 to 0.4	0.0759	0.00195	0.00850	0.01360
keV				
17 to 100	0.0108	0.00133	0.00159	0.00047
Total count		0.00636	0.03565	0.16471
Normalized to 8-in. sphere		0.039	0.22	1.00
Per cent of total count		3.1	17.2	79.7

a. Sphere efficiency for 3 to 6 MeV was used.

tive count rate of the spheres for the same energy regions was given previously in Table I. Multiplying the number of neutrons in each energy interval by the relative count rate for that energy interval gives the calculated count rate for the spheres (Table X). The calculated count rates of the 2-, 3-, and 8-in. spheres normalized to an 8-in.-sphere count rate of 1.0 are 0.039, 0.22, and 1.0, respectively, and compares reasonably well with the 0.042, 0.24, and 1.0 obtained experimentally at 50 cm (see Table VI).

Determining the Average Fast-Neutron Energy

Curves similar to those in Fig. 6 can be used with the Jezebel data (Table VI) to determine the average energy of the fast neutron and the per cent of the neutrons in the fast- and intermediate-energy regions. Since the known leakage neutron spectrum has an average energy of around 1 MeV, a series of curves were drawn for 1.5, 1.0, and 0.8 MeV (Fig. 7). For the position 50 cm from the Jezebel assembly, the count rates of the 2-, 3-, and 8-in. spheres (normalized to a total count rate of 100) are 3.3, 18.7, and 78.0, respectively. These points were plotted on the curves in Fig. 7 for the 1.5-MeV average-neutron energy.

Vertical alignment between these points does not exist. The principle involved in preparing this figure requires that vertical alignment be obtained; therefore, the average fast neutron energy of the spectrum is not 1.5 MeV. The points were then plotted on the 1.0-MeV curves where vertical alignment is very nearly obtained. The multisphere-technique interpretation of these count rates gives a spectrum that has an average fast-neutron energy of 1.0 MeV with 97% of the neutrons in the fast-neutron region and 3% in the intermediate-energy region which extends from 0.237 eV to 1.0 MeV.

The normalized count rates for the 2-, 3-, and 8-in. spheres obtained at 8 m from the Jezebel are 7.5, 24.5, and 68.0. These points have been plotted on the curves in Fig. 8, and are best aligned when plotted on the 0.8-MeV curves. Better alignment would have resulted if curves for 0.85 MeV were drawn, but to evaluate the average energy with this degree of accuracy requires more accurate experimental data than those presented here. (See Appendix-A for information on obtaining data.) The multisphere technique interpretation of these count rates gives a spectrum with an average fast-neutron energy of 0.8 MeV with 84% of the

Fig. 7. Average fast neutron energy of the Jezebel assembly leakage spectrum at 50 cm from the assembly.

neutrons in the fast-neutron energy region and 15% in the intermediate-energy region (0.237 eV to 0.8 MeV).

The count rates obtained at the other distances from the assembly have been evaluated and are presented in Table XI. As the distance from the assembly is increased, the average fast-neutron energy decreases and the per cent of neutrons in the fast part of the spectrum drops. Placing the assembly near the kiva wall or inside the kiva decreases both the average fast-neutron energy and the per cent of neutrons in the fast

part of the spectrum.

The average fast neutron energy and the per cent of neutrons in the fast part of the spectrum at 3 m from the three critical assemblies are compared in Table XII. The Flattop and Parka assemblies both have very low average-fast-neutron energies of 0.2 and 0.3 MeV, respectively, and the per cent of neutron in the fast part of the spectrum was 65 to 27%, respectively. These results are in reasonable agreement with calculated leakage-neutron spectra for the systems.²¹

Fig. 8. Average fast neutron energy of the Jezebel assembly leakage spectrum at 8 m from the assembly.

By using the method described previously, count rates have been calculated for the measured or calculated neutron spectra from several neutron sources,²²⁻²⁴ and they are compared to experimental count rates in Table XIII. The average fast-neutron energy and the per cent of neutrons in the fast part of the spectrum, obtained by using the multisphere technique, are shown in Table XIV. The calculated and observed spectra agree well. The observed spectra show, in all but one case, the effect of scattered neutrons.

The average fast-neutron energies given

in Table XIV for the PuBe and PoBe sources are 2.5 and 3.0 MeV, respectively, for the calculated count rates and 2.0 and 2.5 MeV for the observed count rates. These values are significantly lower than the 4.0- to 5.0-MeV average fast-neutron energy generally stated for these sources. Using a lower average fast-neutron energy decreases the dose rate determined by the multisphere technique, and a correction is necessary if one of these sources is used for calibration. The lower average neutron energy is caused by the shape of the spectrum and the efficiency of the 8-in. sphere which pro-

Table XI

Average Fast-Neutron Energy and Per Cent of Neutrons in Fast Part of Spectrum for the Jezebel Assembly

Assembly Location	Distance from Assembly (meters)	Ave. Fast-Neutron Energy (MeV)	Neutrons in Fast Part of Spectrum (%)
Outside kiva	0.5	1.00	97
	1.0	1.00	95
	2.0	0.90	93
	2.0 ^a	0.70	66
	2.0 ^b	0.90	79
	3.0	0.85	91
	3.0 ^b	0.75	86
	4.0	0.90	81
	6.0	0.90	80
	7.7 ^c	0.60	74
	8.0	0.80	84
	9.0	0.75	86
	9.0 ^b	0.50	77
Inside kiva	3.0	0.75	69
	6.0	0.75	61
	9.0	0.50	51

- a. A plastic man-phantom was positioned midway between the assembly and this location.
- b. The assembly was 90 cm from the kiva wall.
- c. There was a concrete wall directly behind this location

duce a lower value than would be obtained with a detector having a uniform response. This is discussed in Appendix B, and a correction factor for calibration is given in the section on dose rate determination.

Dose Rate Determination

Calculation of the neutron dose rate is based on the count rate obtained with the 8-in. sphere. The dose rate can be determined quickly by using two graphs in which the mrem/h for 1000 cpm with the 8-in. sphere is given as a function of average fast neutron energy. The graph for the fast

Table XII

Average Fast-Neutron Energy and Per Cent of Neutrons in Fast Part of Spectrum 3 Meters from Critical Assemblies

Critical Assembly	Assembly Location	Ave. Fast-Neutron Energy (MeV)	Neutrons in Fast Part of Spectrum (%)
Jezebel	Outside kiva	0.85	91
	Outside, 90 cm from kiva wall	0.75	86
	Inside kiva	0.75	69
Flattop	Inside kiva	0.20	65
Parka	Inside kiva	0.30	27

part of the spectrum is prepared by determining the relative efficiency of the 8-in. sphere for a given fast-neutron energy from Fig. 2 and the Radiation Protection Guide (RPG) for this energy from NBS Handbook 63.²⁵ The count rate from a neutron flux of 1 n/cm²/sec is calculated using the relative efficiency. This count rate is divided by the dose rate in mrem/h from 1 n/cm²/sec de-

Table XIII

Calculated and Observed Count Rates of Spheres for Several Neutron Sources (Normalized to a Total Count Rate of 100)

Neutron Source	Calculated			Observed		
	2-in. Sphere	3-in. Sphere	8-in. Sphere	2-in. Sphere	3-in. Sphere	8-in. Sphere
PuF ₄	3.3	18.7	78.0	3.2	18.5	78.3
PuBe	1.4	9.7	88.9	3.5	15.3	81.2
²⁴¹ Am	2.4	14.8	82.9	3.5	16.6	79.9
Fission spectrum	2.7	16.0	81.3	-	-	-
PoBe	1.2	8.8	90.0	1.4	9.8	88.8
Flattop critical assembly	7.1	31.3	61.6	10.0 ^a	35.6 ^a	54.4 ^a
Jezebel critical assembly	3.1	17.5	79.4	3.3 ^b	18.7 ^b	78.0 ^b

a. Count rate obtained at 3 m from assembly.

b. Count rate obtained at 50 cm from assembly.

Table XIV

Calculated and Observed Average Fast-Neutron Energy and Per Cent of Neutrons in Fast Part of Spectrum for Several Neutron Sources

Neutron Source	Calculated		Observed	
	Ave. Fast-Neutron Energy (MeV)	Neutrons in Fast Part of Spectrum (%)	Ave. Fast-Neutron Energy (MeV)	Neutrons in Fast Part of Spectrum (%)
PuF ₄	1.0	97	1.0	98
PuBe	2.5	99	2.0	90
²⁴⁴ Cm	1.5	98	1.5	94
Fission spectrum	1.25	99	-	-
PoBe	3.0	99	2.5	99
Flattop critical assembly	0.35	93	0.25 ^a	90 ^a
Jezebel critical assembly	1.1	98	1.0 ^b	97 ^b

a. Using data obtained at 3 m from assembly.

b. Using data obtained at 50 cm from assembly.

terminated from the RPG curve. This is repeated for a number of neutron energies until a curve can be drawn over the desired energy range. The ordinate of the curve is adjusted until the calibration data are

Fig. 9. Millirem/h from 1000 cpm of fast-energy neutrons (based on the published counter efficiency of Bramblett).

matched. For example, a spontaneous fission neutron source is used which has at the calibration distance a dose rate of 10 mrem/h, the multisphere technique indicates an average fast-neutron energy of 1.3 MeV with 94% of the neutron in the fast part of the spectrum, and the 8-in. sphere count rate is 1070 cpm. The count rate from fast neutrons is 94% of 1070 cpm, or ~1000 cpm. The ordinate of Fig. 9 has been adjusted to give 10 mrem/h for 1000 cpm at an average fast neutron energy of 1.3 MeV.

Essentially the same procedure is followed in drawing the graph for the intermediate energy part of the spectrum, but the efficiency of an 8-in. sphere (Fig. 10) and an RPG value (Fig. 11) which apply to a $1/E$ spectrum must be used. Since the intermediate-energy neutron sources are not available for calibration, the calibration of the intermediate-energy part of the spectrum is based on the fast-neutron energy calibration. The same calibration adjustment required in the ordinate of the fast-neutron-energy graph is applied to the calculated curve for the intermediate energies, and the graph shown in Fig. 12 is obtained. At 1.3 MeV, a dose rate of ~3.9 mrem/h corresponds to 1000 cpm. In the sample calibration above,

Fig. 10. Average efficiency of an 8-in. sphere for a $1/E$ spectrum extending from 0.237 eV to energy indicated.

Fig. 11. Radiation Protection Guide for a $1/E$ spectrum extending from 0.237 eV to energy indicated.

the intermediate-energy neutrons were 6% of 1070 cpm, or ~ 65 cpm which gives a calculated intermediate-energy neutron dose rate of 0.25 mrem/h. The total fast and intermediate energy dose rate from the source is ~ 10.3 mrem/h (the thermal neutron dose rate was not included in the example).

Previously we indicated that when the calibration source is $^{239}\text{PuBe}$, $^{238}\text{PuBe}$, AmBe, PoBe, or RaBe,²⁶ a 30% correction is required. The count rate of the 8-in. sphere is increased by 30%, and the procedure described above is followed. If most of the neutron sources to be monitored are of this type it may be desirable not to apply the correction, which would cause the dose rates obtained with other sources to be slightly high (an error on the safe side), or one could use

Fig. 12. Millirem/h from 1000 cpm of intermediate-energy neutrons (based on calculated counter efficiency).

two sets of graphs (corrected and uncorrected) as needed.

The graphs given in Figs. 9 and 12 apply to any multisphere instrument having a 4×4 mm LiI crystal, and only minor adjustments to the ordinate of not greater than $\pm 50\%$ should be required. If a calibration adjustment is made to the ordinate of one graph, the same adjustment must be applied to the other.

A thermal neutron calibration of the bare detector may not be necessary if the thermal dose rate is small, as is almost always the case. A value of 2050 cpm/mrem/h (4×4 mm crystal) for the count rate of the bare detector minus the cadmium-covered detector may be used. A calibration adjustment applied to the graphs for the fast and intermediate energies (Figs. 9 and 12) is also made to this value. If the thermal

dose rate exceeds several per cent of the total dose rate, a thermal calibration should be made.

Variations from a $1/E$ Dependence in the Intermediate-Energy Region

The $1/E$ energy dependence previously assumed to exist in the intermediate-energy region is based on the known slowing down spectrum existing in hydrogenous materials. The leakage spectrum through some reactor shielding or ports may not have this $1/E$ dependence. One variation from this dependence is a leakage neutron spectrum in the intermediate-energy region which has a larger number of neutrons near the thermal region. Although a neutron spectrum having a

$1/E^2$ dependence in the intermediate region has more neutrons near the thermal region than would normally be encountered experimentally, it is used to show the changes caused in the interpretation of the spectrum by the multisphere technique.

Figure 13 shows the curves which apply for a $1/E^2$ spectrum in the intermediate energy region. Essentially the same relative count rate is found on the left side of Fig. 13 for all the curves. The relative count rates on the left side of Fig. 13 are the same as a monoenergetic intermediate-energy source with an energy slightly above the cadmium cutoff.

Let us assume that a $1/E^2$ dependence

Fig. 13. Curves for a spectrum containing a $1/E^2$ dependence in the intermediate-energy region.

Table XV

Results Obtained by Applying Curves for a $1/E$ Dependence in the Intermediate-Energy Region to Data from a $1/E^2$ Dependence

Actual Spectrum $1/E^2$ Dependence in Intermediate-Energy Region			Spectrum Interpreted Using Curves for $1/E$ Dependence in Intermediate-Energy Region		
Ave. Fast Neutron Energy (MeV)	Neutrons in Fast Part of Spectrum (%)	Relative Dose Rate (rem/h)	Ave. Fast Neutron Energy (MeV)	Neutrons in Fast Part of Spectrum (%)	Relative Dose Rate (rem/h)
0.2	90	1.0	0.25	83	1.02
	80	1.0	0.25	71	1.02
	70	1.0	0.30	55	1.00
	60	1.0	0.50	36	1.02
	50	1.0	1.25	16	1.14
	40	1.0	>10	-	-
0.75	90	1.0	0.90	84	1.04
	80	1.0	1.00	69	1.05
	70	1.0	1.50	54	1.12
	60	1.0	6.00	32	1.50
	50	1.0	>10	-	-
3.0	90	1.0	5.00	84	1.12
	80	1.0	>10	-	-

exists in the intermediate region and that the data obtained with the spheres are applied to curves drawn for a $1/E$ dependence. The interpretation of the spectrum is given in Table XV, and shows a higher average fast-neutron energy, less neutrons in the fast part of the spectrum, and essentially no change in the dose rate. When the per cent of intermediate-energy neutrons in the actual spectrum becomes large, the count rate data can no longer be analyzed with the curves drawn for a $1/E$ dependence in the intermediate-energy region. Although the dose rates shown in the last column of this table agree reasonably well with the actual dose rates, they increase rapidly when a >6.0-MeV average fast-neutron energy is indicated. If an average fast-neutron energy greater than the energy of the original neutron source is obtained with the multisphere technique, the results should be questioned.

The author has never encountered or heard of a situation similar to that described above. Although some leakage spectra are known to have more neutrons near the thermal region than near a $1/E$ dependence, the devi-

ation must be small and the effects described above have not been noticed.

Now let us consider an energy dependence in the intermediate region which is caused by partial moderation of the spectrum. This situation exists frequently; however, the relative number of neutrons of intermediate energies is small compared to those having fast energies. Figure 14 shows the curves that apply for a spectrum that has a $1/E^{0.5}$ dependence in the intermediate-energy region. This dependence causes the slopes of the curves to become flatter, and for less-moderated spectra these curves approach zero slopes.

Let us assume that a $1/E^{0.5}$ dependence exists in the intermediate-energy region and that the data obtained with spheres are applied to curves drawn for a $1/E$ dependence. The interpretation of the spectrum is given in Table XVI and shows a lower average fast-neutron energy, more neutrons in the fast part of the spectrum, and a dose rate that is reasonably accurate but becomes slightly low as the per cent of intermediate energy neutrons increases. These effects are the opposite of those found previously for the $1/E^2$ spectrum.

The accuracy of the dose rate determined by the multisphere technique is not significantly affected by variations in the spectrum in the intermediate-energy region, with two exceptions. (1) When the per cent of fast neutrons is very small in a partially moderated spectrum (a situation which can not normally exist) the dose rate can be underestimated by as much as ~23%. (2) For an intermediate-energy spectrum with a large number of neutrons near the thermal region, the dose rate can be overestimated by as much as 50%, but an indicated average fast neutron energy higher than the energy of the

Fig. 14. Curves for a spectrum containing a $1/E^{0.5}$ dependence in the intermediate-energy region.

original source of neutrons would indicate that an error is present.

The average fast-neutron energy determined by the multisphere technique is subject to error when a spectrum that deviates greatly from a $1/E$ dependence exists in the intermediate-energy region, and average energies higher or lower than the actual could be obtained. The per cent of neutrons in the fast-energy part of the spectrum also

is subject to error, becoming either larger or smaller than the actual per cent. These two effects compensate, and the calculated dose rate has the good accuracy discussed above.

The dose rate determined by the multisphere technique may be in error if a complex spectrum exists in the fast-neutron energy region. We have assumed that the fast-neutron part of the spectrum is simple and

Table XVI

Results Obtained by Applying Curves for a
1/E Dependence in the Intermediate-Energy
Region to Data from a $1/E^{0.5}$ Spectrum

Actual Spectrum $1/E^{0.5}$ Dependence in Intermediate-Energy Region			Spectrum Interpreted Using Curves for 1/E Dependence in Intermediate-Energy Region		
Ave. Fast Neutron Energy (MeV)	Neutrons in Fast Part of Spectrum (%)	Relative Dose Rate (rem/h)	Ave. Fast Neutron Energy (MeV)	Neutrons in Fast Part of Spectrum (%)	Relative Dose Rate (rem/h)
3.0	90	1.0	2.5	98	0.97
	80	1.0	2.0	94	0.92
	70	1.0	1.5	93	0.88
	60	1.0	1.5	88	0.88
	50	1.0	1.25	87	0.87
	40	1.0	1.0	84	0.81
	30	1.0	0.8	83	0.81
	20	1.0	0.7	81	0.82
	10	1.0	0.6	79	0.80
0.75	0	1.0	0.5	76	0.78
	90	1.0	0.7	96	0.98
	80	1.0	0.6	93	0.94
	70	1.0	0.6	89	0.96
	60	1.0	0.5	86	0.95
	50	1.0	0.4	86	0.94
	40	1.0	0.35	79	0.91
	30	1.0	0.3	80	0.94
	20	1.0	0.25	77	0.92
0.2	10	1.0	0.2	73	0.91
	0	1.0	0.5	74	0.87
	90	1.0	0.2	96	1.03
	80	1.0	0.15	95	0.96
	70	1.0	0.15	90	1.00
	60	1.0	0.15	85	1.02
	50	1.0	0.1	85	0.96
	40	1.0	<0.1	-	-

can be reasonably well represented by an "average" energy. Where this assumption is not valid, an error in the dose rate could be made (see the discussion of PuBe sources in the section on dose-rate determinations and Appendix B).

When only the 2-, 3-, and 8-in. spheres are used, a slight loss of accuracy in determining the average fast-neutron energy may occur. The response curves for the 2- and 3-in. spheres in the fast-neutron-energy

regions are essentially straight lines with decreasing efficiency as the neutron energy increases. A wide spectrum centered at 1 MeV would result in the same count rate from these spheres as would a 1-MeV monoenergetic source. However, the shape of the 8-in.-sphere response curve causes a lower count rate to be obtained from the wide spectrum (see Fig. 2). The spectrum interpreted by the multisphere technique would indicate a slightly lower average fast-neutron energy.

Table XVII

Neutron Dose Rates Obtained with Various Detectors

Critical Assembly	Distance from Assembly (meters)	Dose for 20 min of Assembly Operation			
		Threshold Detector Units (hectoergs/gm)	Hurst Proportional Counter (rad)	Multisphere Technique (rem)	10-in. Sphere (rem)
Hydro	5.9 ^a	4.8	6.0	96	107
	6.0	4.8	4.8	73	86
	8.7	2.2	2.5	39	46
	12.3	1.3	1.5	20	24
	16.2	0.69	0.83	12	14
	19.8	0.49	0.58	7.2	8.6
	19.8 ^b	0.63	0.66	9.3	12
Jezebel, outside kiva	50	460	460	6300	>3500
	1	130	130	1700	1700
	2	35	37	450	450
	3	18	17	210	220
	4	11	9.8	110	130
	6	4.9	4.6	56	61
	7.7 ^b	3.3	3.6	41	50
	8	2.8	2.7	33	35
	9	2.2	2.1	27	29
	2 ^c	6.4	5.8	131	160
	inside				
	3	19	20	182	220
	kiva				
	6	6.3	6.2	65	78
	9	2.9	3.0	27	38
outside kiva, 90 cm from wall	2	45	45	490	520
	3	20	20	200	220
	9	2.6	2.7	31	38
Flattop	110	33	29	480	500
	3	4.9	4.3	55	71
	6.1	1.6	1.5	19	29
Parka	3 ^a	6.1	7.4	81	150
	3 ^d	4.2	5.8	58	110

a. Elevated ~2 m to height of core.

b. About 30 cm from concrete wall.

c. A man-phantom was positioned between the assembly and this location.

d. Slant range.

A wide spectrum center at 2 MeV would also cause a low count rate for the 8-in. sphere, resulting in an interpreted spectrum having a slightly higher average-neutron energy. Fortunately, this effect is small and results in an 8-in.-sphere count rate only a few per cent lower than that of a monoenergetic source. For neutrons with energies less than about 0.6 MeV and greater than

4.0 MeV, this effect is no longer observed. Only those fast neutron spectra which are wide and have an average energy in the 1- to 2-MeV region are affected.

Comparison with Dose Rates Obtained
with Other Neutron Detectors

The dose rates that were obtained in a recent study with the Hurst proportional

neutron counter, the threshold detector units (TDU), the 10-in. rem-responding sphere, and the multisphere technique are given in Table XVII. The Hurst instrument and TDU dose rates are the first-collision absorbed dose and kerma, respectively, and the multisphere and the 10-in. sphere rates are the dose equivalent. The thermal neutron dose rate is not included in the data for the Hurst instrument and threshold detector units, but only the Parka assembly had dose rates from thermal neutrons that were >1% of the total dose rate and for this assembly were 5.7%.

The leakage spectra of the four critical assemblies listed in Table XVII are significantly different and vary from a near-fission spectrum to a highly moderated fission spectrum.²¹ The leakage spectrum of the Jezebel assembly has little moderation and is very close to a fission spectrum. The Hydro assembly has two components, a partially moderated fission spectrum and a small thermal and intermediate-energy component from an exponential column located above the assembly. The Flattop assembly has a low energy, fast-neutron leakage spectrum with essentially no thermal and intermediate energy component. The Parka assembly has a highly moderated leakage spectrum with a large component of thermal and intermediate energy neutrons.

The ratios of the dose equivalent determined by the multisphere technique and the 10-in. sphere to the dose rate obtained with the threshold detector units are shown in Table XVIII. The multisphere technique

gave rem/hectoerg/gm ratios which averaged ~12 except for that of the Hydro assembly which average ~17. The 10-in. sphere ratio varies from 11 to 25 with the larger ratios applying to the heavily moderated spectra. The ratios are reasonably constant for a given assembly. The high ratio of the 10-in. sphere for the Parka assembly is caused in part by the inherent overresponse of this type of instrument to spectra containing a large intermediate-energy component.

Summary

Small changes in a neutron spectrum can be detected by corresponding changes in the relative counting rates obtained with the various-size spheres. For monoenergetic fast-neutron spectra, the energy of the neutrons can be determined by comparing the count rates of the sphere detectors with the count rates obtained as a function of energy from the curves given in Fig. 2.

The multisphere technique described in this report divides the spectrum into thermal, intermediate, and fast components. The assumption is made that a 1/E spectrum exists in the intermediate region and that the energy spectrum of the fast neutrons can be accurately given as a monoenergetic source. Calculations in this report indicate that when the intermediate spectrum does not have a 1/E dependence, the average fast energy and per cent of neutrons in the fast and intermediate parts of the spectrum may be in error but the dose rates determined by the multisphere technique remain reasonably accurate.

Table XVIII

Ratio of Dose Equivalent to Fast Neutron Dose Rate
Determined with the Threshold Detector Unit System

Critical Assembly	Distance from Assembly (meters)	Multisphere Technique (rem/hectoergs/gm)	10-in. Sphere (rem/hectoergs/gm)
Hydro	5.9 ^a	15	18
	6.0	20	22
	8.7	18	21
	12.3	16	18
	16.2	17	20
	19.8	15	18
	19.8 ^b	15	19
Jezebel	50	14	
outside	1	13	13
kiva	2	13	13
	3	11	12
	4	10	11
	6	11	12
	7.7 ^b	12	15
	8	12	12
	9	12	13
	2 ^c	20	25
inside	3	10	12
kiva	6	10	12
	9	9	13
outside	2	11	12
against	3	10	11
kiva	9	12	14
Flattop	1.1	15	15
	3	11	15
	6.1	12	18
Parka	3 ^a	13	24
	3 ^d	14	25

a. Elevated ~2 m to height of core.

b. About 30 cm from concrete wall.

c. A man-phantom was positioned between the assembly and this location.

d. Slant range.

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APPENDIX A

Obtaining Data

If an accurate interpretation of the neutron spectrum is to be obtained, it is important that the count rates obtained with the spheres be as accurate as possible. Some of the problems that have been encountered in the past with the sphere detectors are gamma sensitivity, gain or threshold changes, and damage to the crystal. Furthermore, the neutron fluences are frequently quite low and for some neutron sources (such as accelerators) the fluence may vary.

The problems associated with the instrument can be largely eliminated by the use of a pulse-height analyzer. At the Los Alamos Scientific Laboratory, most data are obtained with a Technical Measurement Corporation 100-channel analyzer. The analyzer allows crystal damage from moisture or radiation²⁷ to be immediately noticed, the gain of the instrument does not have to remain constant, and an instrument threshold is not necessary because the count rate is obtained by using a given number of channels (based on percent) on either side of the neutron peak. The threshold built into the analyzer can be used to avoid some of the gamma noise and thereby reduce analyzer dead time. If an analyzer is used, it is apparent when intense gamma-ray activity is causing pileup in the crystal and counts from gamma rays are occurring in the channels where the neutron counts are being recorded. It is possible, in many cases, to correct the neutron count rate by subtracting the gamma-ray component. To ensure that the gain remains constant, a pulser can be used if an analyzer is not available.

When the neutron fluence is low, the time required to obtain the count rates must

be extended. To improve the accuracy of the data, count rates are obtained with each sphere in series, repeating the series at least three times. The errors in count rates caused by gain and threshold changes become apparent and can be largely eliminated when this counting technique is employed. When the fluence is changing, or possibly could change, the count rate of a secondary neutron monitor should be used as a normalizing factor. If this must be done, the above counting sequence is recommended.

When the multisphere instrument is used, the natural background (about 1 cpm for the 8-in. sphere) is ignored. If there is a significant room background, it must be determined and subtracted from the count rate obtained with the neutron source being studied. The background count rates can also be used to determine the spectrum of the scattered neutrons in the room. In spite of the desirability for accuracy in the count rates described above, useful information can be obtained from data with poor counting accuracy. This is especially true where a series of data are taken at different points around a source of neutrons, or at increasing distances from the source, and an inconsistent count rate can be readily detected and eliminated. The spectra obtained by using count rates having a total count of <100 usually compare well with those obtained using more accurate count rates.

If the data are to be converted to a dose rate, a calibration procedure must be established to ensure that the detector retains a constant sensitivity to neutrons. Usually only the 8-in. sphere is used in this secondary calibration.

APPENDIX B

Calibration of the Multisphere Instrument

The multisphere instrument can be calibrated with almost any source of neutrons. The dose rate calculations are based on the count rate obtained with the 8-in. sphere, and, since the efficiency of the 8-in. sphere is much higher for fast neutrons than for thermal neutrons, a fast-neutron calibration is desired. Ideally, the source should be a monoenergetic fast-neutron source, but $^{239}\text{PuBe}$ neutron sources are most frequently used for calibration because of their availability and convenience. Table XIV shows that the average fast neutron energy determined with the multisphere instrument for $^{239}\text{PuBe}$ sources is only ~ 2.0 MeV which is considerably lower than the accepted average energy of 4 to 5 MeV. To prevent an error in the dose rate determined by the multisphere technique, an $\sim 30\%$ increase must be applied to the count rate of the 8-in. sphere during calibration or an average fast-neutron energy of about 4.8 MeV must be assumed. Generally, the 30% correction to the 8-in. sphere count rate is applied. This correction applies to all $^{239}\text{PuBe}$, $^{238}\text{PuBe}$, PoBe , AmBe , and RaBe sources.²⁶ No correction is applied to spontaneous fissioning neutron sources and other neutron sources with average fast-neutron energies around or below 1.0 MeV, which makes these sources preferable to those that require a correction factor. (See additional discussion in section on dose rate determination.)

When a calibration is performed with the detector and source 30 cm apart and

about 1 m above a concrete floor in a large room, the contribution to the total dose rate from scattered neutrons is only $\sim 2\%$. The neutron dose rate for the calibration is calculated using inverse square calculations. Most source strengths are known to within ± 4 to 5% which limits the accuracy of a calibration performed with these sources to slightly above these values.

The first calibration with a new multisphere instrument or a different source should include the count rates of the 2-, 3-, and 8-in. spheres. The average fast-neutron energy and the per cent of neutrons in the fast part of the spectrum is obtained from Fig. 6 and should agree reasonably well with the results given in Table XIV. For subsequent calibrations only the 8-in. sphere is used, and the average fast-neutron energy and per cent of neutrons in the fast part of the spectrum are assumed to remain constant.

The counting time required to calibrate a multisphere instrument depends on the source strength. Adequate time should be taken to obtain good counting statistics.

A multisphere instrument which has a 4×4 mm crystal should have 80 ± 20 cpm/mrem/h and the instrument with the 4×8 mm crystal, 180 ± 30 cpm/mrem/h. The gamma-ray sensitivity must be determined if a pulse-height analyzer is not used to obtain data. Poor resolution of the neutron peak ($>20\%$ full width at half maximum) is an indication of moisture leakage into the crystal or damage from other causes, and the crystal should be replaced.