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**Energy Spectra of the Pneumatically Positioned
Neutron Sources at LLNL's Hazards Control
Standards and Calibration Facility**

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June 15, 1987

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ENERGY SPECTRA OF THE PNEUMATICALLY POSITIONED
NEUTRON SOURCES AT LLNL'S HAZARDS CONTROL
STANDARDS AND CALIBRATION FACILITY

ABSTRACT

The Hazards Control Department of Lawrence Livermore National Laboratory maintains a Standards and Calibration Laboratory that includes three neutron sources (two ^{252}Cf and one $^{238}\text{PuBe}$) that can be positioned pneumatically for irradiations. Ten moderators exist to modify the neutron energy spectra produced by these sources. The thicknesses and materials of these moderators are: 25-cm water; 5-, 10-, 15-, and 25-cm heavy water; 20-cm aluminum; and 2-, 5-, 10-, and 15-cm polyethylene. We used a multisphere spectrometer to measure the neutron spectra at 2 m from both the PuBe source and the smaller Cf source, with the sources bare, and in all of the moderators. These data were reduced in 25 energy groups ranging from 0.25 eV to 16 MeV. Except for the 15-cm polyethylene moderator, we also made measurements using a liquid-scintillator fast-neutron spectrometer. These data were reduced in 0.1-MeV increments from 0.5 to 12.5 MeV. Spectra from the measurements and from independent calculations are presented in tabular and graphic form. Dosimetric values, calculated from both the measured and calculated spectra, are also presented.

1. INTRODUCTION

The Standards and Calibration Laboratory operated by the Hazards Control Department at Lawrence Livermore National Laboratory provides radiation standards, and facilities for calibrating and standardizing instruments. Several of the sources can be moved pneumatically from storage into a large, heavily shielded cell for exposures. This facility, and its capabilities were reviewed by Elliott.¹

There are three pneumatically positioned neutron sources. Two are ^{252}Cf spontaneous-fission sources, with different intensities, and the third is a $^{238}\text{PuBe}$ (α, n) source. The energy distribution of the neutrons from each of these sources can be modified by making the exposure with the source inside

one of a collection of spherical moderators. Thicknesses and materials of the available moderators are: 25 cm of water; 5, 10, 15, and 25 cm of heavy water; 20 cm of aluminum; and 2, 5, 10, and 15 cm of polyethylene. (Because the moderators are usually identified by their dimensions in cm, thicknesses will be given in cm throughout this report, rather than the preferred SI unit, mm.) The resulting wide range of spectra are useful for calibrating detectors in neutron fields similar to those encountered in use. A thin cadmium shield exists to enclose the 15-cm-thick heavy-water moderator during californium irradiations. This conforms to proposals by the National Bureau of Standards to use this configuration as a standard for calibrating instruments for use at nuclear power stations.

For the optimum use of these source-moderator combinations, the neutron energy spectra they produce must be well known. The spectra produced by Cf and PuBe, bare, and in each of the moderators, except 15-cm polyethylene, were calculated by H. W. Patterson in 1974 using the ANISN one-dimensional, discrete-ordinate code. In 1983, the MORSE code was used by C. T. Prevot to make Monte Carlo calculations at 1 m for bare Californium, and for that source in 15 cm of heavy water and in 15 cm of polyethylene. A similar calculation was also made at 2 m for Cf in 15 cm of polyethylene.

Modeling the experimental geometry for use in calculations is often difficult. For example, an ANISN calculation requires a spherical approximation to the geometry. A calculation also may not provide precise information about the lowest energy neutrons, and depends upon the initial spectrum assumed for the source. For these reasons, and to test our ability to make spectrum measurements, the neutron spectra produced by two of the pneumatically positioned neutron sources were determined experimentally.

2. DETECTORS

LIQUID SCINTILLATOR

Two spectrometers were required to cover the entire energy range of interest. Detailed data, taken with an organic-liquid scintillation detector, were reduced in 0.1-MeV increments from 0.5 to 12.5 MeV. The lower limit was the energy at which the signals from the detector became too small to separate the pulses produced by neutrons from those produced by gamma rays. Above 12.5 MeV, the small number of neutrons produced by the sources produced

statistical uncertainties that made the data unusable. Low light yields, and multiple scattering of neutrons in the detector limited the quality of the results between 0.5 and 2 MeV.

We conducted an extensive development project to optimize the performance of organic-liquid scintillator fast-neutron spectrometers, with an emphasis on radiation-protection measurements. A detailed description of this work is in another report.² To measure the sources at the calibration facility, we used a cylindrical cell, 51-mm diameter by 51-mm long, that was filled with the liquid scintillator NE-213 (Nuclear Enterprises, Ltd., Edinburgh, Scotland). To ensure uniform light collection over the length of the scintillator, the cell was coupled to the RCA 8850 photomultiplier tube via a 25-mm-long glass light pipe.

It was necessary to improve the electronic circuits used with the spectrometer. For example, we had to design a transistorized circuit to bias the photomultiplier tube dynodes in order to obtain linearity over the wide range of signal sizes encountered. The PSD 5010 pulse-shape discriminator (Link Systems, High Wycombe, England) that we used to separate the neutron signals from those produced by gamma rays was easy to use and had an acceptable dynamic range, but generated considerable dead time. As a result, we had to design a separate clock to combine the dead time of the PSD unit with that produced by the multichannel analyzer used to store the data.

MULTISPHERE SPECTROMETER

Most of the moderated spectra have a significant number of neutrons below 1 MeV. Because we could not measure below 0.5 MeV with the liquid scintillator, we chose a multisphere spectrometer to provide information about these low-energy neutrons. The multisphere technique was first described by Bramblett, Ewing, and Bonner.³ Among its advantages are ease of use and an energy range from 0.025 eV to 10 MeV. Disadvantages are the complicated data reduction procedures required and the limited detail obtained in the reduced data.

The detector for our multisphere system was a 13-mm-high by 13-mm-long ⁶LiI scintillator mounted on a 130-mm-long, polymethylmethacrylate light pipe. Signals produced by the interactions of thermal neutrons with the ⁶Li in the detector were recorded, for each source-moderator combination, with the

detector in seven configurations: bare, enclosed in a 0.8-mm-thick cadmium shield, or centered in one of a collection of polyethylene spheres. We used spheres that were 76, 127, 203, 254, and 305 mm (3, 5, 8, 10, and 12 in.) in diameter. Each sphere has a hole in it to allow the detector to be operated at the center of the sphere. The light pipe ensured that the remainder of the hole was filled with plastic when the detector was in position. The 76- and 127-mm spheres were enclosed in 0.8-mm-thick cadmium to decrease the sensitivity of these detector-sphere combinations to thermal neutrons. A cadmium-covered 51-mm (2-in.) moderator was available but was not used for these measurements. Modifications to adapt this system and its data reduction procedures to our needs are described elsewhere.⁴

3. DATA ACQUISITION

Because most of the exposures at the calibration facility are made at 1 m, we would have preferred to make our measurements at that distance. Unfortunately, the pulse-shape discriminator used with the liquid scintillator produced excessive dead time for count rates greater than 3000 per second, which would be exceeded for many of the source-moderator configurations at a 1-m source-to-detector separation. Thus, to have a consistent set of results, all of the spectra were measured at 2 m. Some calibration runs for the multisphere system, however, were made at 1 m. For those cases, the maximum count rates in the thermal neutron peak were about 2500 per second. The corresponding total count rate produced approximately 2% counting losses.

Count-rate considerations limited the ²⁵²Cf measurements to the smaller of the two available sources, identified by the LLNL number 400595. The ²³⁸PuBe source was number 300167. Although they differ in yield, the two californium sources are similar in physical size and encapsulation. Thus they should produce the same neutron spectrum per source neutron.

LIQUID SCINTILLATOR

Liquid scintillator measurements were made at two gain settings. Neutrons with energies from 1.5 to 20 MeV were measured at low gain while the high gain covered energies from 0.5 to 2 MeV. The gain of the system was changed by adjusting the high voltage applied to the photomultiplier tube. Because the linear signal was taken from the eighth dynode and the pulse-shape

signal from the anode, their relative gain changed as a power function of the high voltage. This required a concurrent change in the gain of the linear amplifier used with the dynode signal to ensure optimum use of the dynamic range of the pulse-shape discriminator.

Gains were calibrated using gamma rays from a number of sources. The light produced in the scintillator by these sources was determined, and correlated to light output as a function of neutron energy, during the previously mentioned development work. At the low gain setting, ^{22}Na (0.511 and 1.274 MeV) and ^{207}Bi (0.570, 1.064, and 1.770 MeV) gamma rays, and the carbon de-excitation gamma rays from a PuBe neutron source (4.43 MeV) were used. Gamma rays from ^{241}Am (0.0595 MeV), ^{22}Na and ^{137}Cs (0.662 MeV) were used at high gain.

Normally the low-gain run was made first, because it contained the majority of the data, and because it required the most time. For both gain settings, a gamma-ray calibration preceded the measurement of the neutrons from the californium source. The Cf measurement was followed, in turn, by a second gamma-ray calibration, the PuBe measurement, and a third gamma-ray calibration. Low-gain runs lasted from 2.5 to 14.5 hours, depending upon the source and the moderator. High-gain runs were shorter, lasting from 1.25 to 4 hours.

Pulse-height data were recorded by a multichannel analyzer using 512 bins, the smallest number of bins consistent with the requirements of the data reduction procedures. All the gamma-ray and neutron data were stored, first on tape, then on a disk, for later reduction. Each of the spectra were measured three times, so data taking lasted from June 1983 to March 1984.

MULTISPHERE

Data acquisition with the multisphere system was more tedious, because, before the exposure cell could be entered for each change in the detector configuration, the source had to be returned to storage. To minimize this problem, we recorded the data for both sources before changing the detector set-up.

We built a special stand to hold the ^6LiI scintillator and the detector's moderator spheres. The design assured that the center of the detector was 1 m above the floor regardless of which sphere was being used. In addition, the detector, which is quite fragile, could be retracted below

the plate upon which the spheres were placed, thus decreasing the probability of damaging the detector during changes of the spheres.

The pulse-height data produced by the detector were recorded using a multichannel analyzer configured for 256 bins. This is the minimum number of bins that could be used on this analyzer. Throughout the experiment, no changes were made in the detector high voltage, or the linear-amplifier gain and pulse shaping. A 3- μ s amplifier-pulse peaking time was used to be consistent with the decay time of the light from the scintillator. Data were transferred from the multichannel analyzer to a computer and stored on a disk. In order to obtain 1%, or better, counting statistics, the length of the runs varied from a minute to half an hour, depending on the sphere being used with the detector, and the source and its moderator. These measurements were all made during October 1985.

4. DATA REDUCTION

LIQUID SCINTILLATOR

The shape of the gamma-ray calibration data produced by the liquid scintillator depends upon the source producing it. Gamma rays with energies below 100 keV will produce total energy peaks. At higher energies, only the Compton distribution is produced, which must be identified by its upper edge. At still higher energies, pair-producing interactions can occur in the detector that can be identified by a peak produced when both of the resulting positron annihilation gamma rays escape the detector. We wrote a program to locate the appropriate feature in the data. The calculation started from a manually entered approximate value. Once the centroid of the peak, or the half-height of the edge, was found, a light value, obtained from previous calibrations, was assigned to it. After all of the gamma-ray data associated with a given neutron spectrum measurement were reduced, a least-squares fit of a straight line was made to the results. The parameters of this fit, which relate light values to channel numbers, were put into a disk file.

The neutron data-reduction program used the gamma-ray calibration results, and the relation between neutron energy and scintillator light output, to rebin the recoil-proton pulse-height spectrum into bins that were 0.1-MeV wide in neutron energy. If only recoil-proton interactions and single scattering of the neutron occurred in the detector, the negative of the slope of the

rebinned data would be related to the neutron-energy spectrum. We found the slope by taking the difference of adjoining bins and dividing by 0.1 MeV. No smoothing was used at this point.

For a real detector, multiple scattering, edge effects and interactions with the carbon in the scintillator are possible. To obtain the neutron spectrum, the slope obtained at a given point was multiplied by the related energy and by correction factors, which varied with energy, for efficiency, multiple collisions, and edge effects. Finally, the results were smoothed with a Gaussian-weighted function, the width of which varied with energy in the same way as the resolution of the detector. The resulting spectrum was put into a disk file and also printed out. The entire procedure, starting with the gamma-ray data, took about 5 minutes per data set.

Since the low- and high-gain measurements were each repeated three times to obtain the data presented in this report, there were six sets of reduced data for each source-moderator configuration. Another program was written to combine these six sets of results into a single spectrum. Having the data reduced in consistent energy units made combining the results straightforward. The program also carried out the required combination of the errors.

MULTISPHERE

The detector used for the multisphere spectrometer yielded relatively simple pulse-height data. Thermal neutron interactions with the ^6Li in the scintillator produced an alpha particle and a triton that shared the 4.78-MeV energy from the reaction. When both particles lost all of their energy in the scintillator, a peak, that fell on top of a background continuum, was produced in the pulse-height distribution. We wrote a data reduction program that searched down from the uppermost multichannel-analyzer bin until it found a peak in the pulse-height spectrum. The width of the peak was found by looking on both sides of the peak for minima in the smoothed first derivative of the data. Next, the program found the sum of the data between the minima, and a background was subtracted based on fitting a logarithmic function of pulse height to the data on either side of the peak.

The net count was normalized to the counting time and source yield. This gave net-counts per source-neutron. Other normalizations could have been used. After this value was found for all seven detector configurations, the

results were put into a disk file. A printout of gross and net counts was also made to compare with data generated by a less sophisticated peak-area calculation made by the multichannel analyzer.

The neutron spectrum was obtained from the detector counts using the program MINKY, a FORTRAN program we wrote for a Digital Equipment Company LSI-11/23 computer. Like most programs used to reduce multisphere data, MINKY starts with an assumed spectrum and modifies it until the convolution of the calculated spectrum with the assumed detector response functions agree, within some limits, to the measured counts. Our detector response functions were obtained by collapsing the 171-group data reported by Hertel and Davidson into 25 groups.⁵ Corrections for the density of the spheres were applied, based on those reported by Sanna.⁶ The final calibration was made using bare Cf, by normalizing the detector counts measured at 1 m to comparable values obtained by convoluting the response functions with a MORSE calculation of the same spectrum.

Measured detector counts (and a rebinned version of the liquid-scintillator results when they were available) were used by the program (MINKY) to calculate a first guess of the neutron spectrum. The program then randomly selected a bin and modified the value in it by a factor selected randomly between 0.98 and 1.02. Detector counts were calculated using this modified spectrum and, if the new values agreed better with the measured values than the previous guess, the revised spectrum value was retained. This process was repeated until the resulting spectrum produced detector counts that agreed, within some limits, to the measured counts. The sum of the squares of the fractional deviations of the calculated to measured counts was used as the convergence criterion. Normally, the limit chosen for this sum was 0.0003, which provided an approximately 1% worst-case agreement between measured and calculated counts. Five solutions were obtained for each set of input data and averaged to provide the final spectrum. The program printed a listing of the spectrum and put the data into a disk file.

There were four data sets for which convergence, for each of the five solutions, had not occurred after 25,000 modifications of the initial guess (i.e., 1000 guesses per energy bin, on the average). This number was set as a maximum in order to limit the time needed for data reduction. Calculated and measured counts agreed within 2% for two of these cases and within 2.5% for the other two. The worst cases were those with the 25-cm D₂O moderator.

Times required to reduce the data varied from a minimum of 20 seconds up to 17 minutes for the nonconvergent cases. A typical time was 5 minutes.

As shown in Fig. 4-1, results from repeated runs agree well. The spectra to be presented, however, depend upon a single measurement of each source-moderator configuration.

DOSIMETRIC CALCULATIONS

The energy limits of the bins and the factors needed, for these bins, to calculate the absorbed dose, the kerma, and the dose equivalent (using both NCRP and ICRP conversion factors) are given in Table 4-1. The energy values are in MeV and the conversion factors are in rads per neutron per square centimeter, or rems per neutron per square centimeter. Absorbed dose conversion factors are based on the "element 57" factors published by Auxier, Snyder, and Jones.⁷ The tissue kerma factors are based on the table in ICRU Report 26; the NCRP fluence to dose equivalent factors are from NCRP Report 38; the ICRP dose equivalent factors are from ICRU Report 20.⁸⁻¹⁰

Figure 4-1. Two multisphere measurements of californium-252 without a moderator.

Table 4-1. Multisphere energy bins and dose-conversion factors.

Bin No.	Bottom Energy (MeV)	Dose (rads/n/cm ²)	Kerma (rads/n/cm ²)	NCRP D. E. (rems/n/cm ²)	ICRP D. E. (rems/n/cm ²)
1	2.5E-8	5.29E-10	1.74E-11	1.08E-9	1.71E-9
2	4.0E-7	5.75E-10	5.68E-12	1.20E-9	1.23E-9
3	1.0E-6	5.72E-10	3.61E-12	1.24E-9	1.24E-9
4	2.5E-6	5.43E-10	2.31E-12	1.24E-9	1.22E-9
5	6.3E-6	5.15E-10	1.54E-12	1.24E-9	1.20E-9
6	1.6E-5	4.85E-10	1.15E-12	1.22E-9	1.19E-9
7	4.0E-5	4.56E-10	1.30E-12	1.20E-9	1.17E-9
8	1.0E-4	4.42E-10	2.12E-12	1.16E-9	1.13E-9
9	2.5E-4	4.37E-10	5.00E-12	1.08E-9	1.07E-9
10	6.3E-3	4.33E-10	1.22E-11	1.02E-9	1.02E-9
11	1.6E-3	4.33E-10	2.91E-11	1.01E-9	1.00E-9
12	4.0E-3	4.34E-10	7.29E-11	9.97E-10	9.87E-10
13	1.0E-2	5.00E-10	1.60E-10	1.53E-9	1.50E-9
14	2.5E-2	6.40E-10	3.68E-10	3.16E-9	3.03E-9
15	6.3E-2	8.54E-10	6.72E-10	6.69E-9	6.16E-9
16	1.6E-1	1.15E-9	9.94E-10	1.15E-8	9.80E-9
17	2.5E-1	1.45E-9	1.29E-9	1.74E-8	1.39E-8
18	4.0E-1	1.86E-9	1.64E-9	2.56E-8	1.96E-8
19	6.3E-1	2.59E-9	2.04E-9	3.29E-8	2.76E-8
20	1.0	3.26E-9	2.56E-9	3.60E-8	3.49E-8
21	1.6	3.75E-9	3.04E-9	3.51E-8	3.95E-8
22	2.5	4.56E-9	3.82E-9	3.77E-8	4.09E-8
23	4.0	5.58E-9	4.42E-9	4.22E-8	4.16E-8
24	6.3	6.34E-9	5.13E-9	4.03E-8	4.17E-8
25	1.0E+1 1.6E+1	8.05E-9	6.20E-9	5.35E-8	4.23E-8

5. SOURCE YIELDS

All of the data presented in this report are normalized to the number of source neutrons. To use the results, it is necessary to be able to determine the source yields at any time. Table 5-1 gives the calibrated source yields and the date of the calibrations. Both californium sources were calibrated by the National Bureau of Standards, and the PuBe source was calibrated locally, using a manganese sulfate bath. The californium source given the number NS-120 by the Bureau of Standards and identified in the table by the LLNL number 401099 is actually a replacement for an older source that had that LLNL number. The control panel and the computer for the pneumatic facility still refer to the larger source by that number so it is included as such in the table.

The PuBe source yield can be corrected to any date using the ^{238}Pu half life of 87.74 years. Correcting for the decay of the ^{252}Cf sources is complicated by an admixture of other californium isotopes. Data necessary to correct for the other isotopes are shown in Table 5-2. The half-lives and spontaneous fission fractions are from Lederer and Shirley, and the neutrons per fission are from Manero and Konshin.^{11,12} The assay data were provided by the group at Oak Ridge National Laboratory that made the source. The assay dates were July 19, 1973 for NS-75 (400595) and September 5, 1984 for NS-120 ("401099").

Table 5-1. Calibrated yields of the sources.

Source	Number	Yield (n/s)	Calibration date
^{252}Cf	401099 (NS-120)	4.115E9	February 7, 1985 (NBS)
^{252}Cf	400595 (NS-75)	4.315E9	November 24, 1973 (NBS)
$^{238}\text{PuBe}$	300167	1.370E8	January 14, 1981 (LLNL)

Table 5-2. Isotope assay and decay data for the californium sources.

Isotope	Half-life (Days)	Spontaneous fission fraction	Neutrons per fission	Assay for NS-75	Assay for NS-120
249	1.281E+5	5.110E-9	3.40	0.0448	-----
250	4.777E+3	7.880E-4	3.52	0.1017	0.1105
251	3.300E+5	1.000E-8	3.67	0.0308	-----
252	9.650E+2	3.092E-2	3.756	0.8226	0.8005
254	6.054E+1	9.970E-1	3.89	0.00003	0.00004

6. DATA PRESENTATION

Results of ANISN and MORSE calculations for bare Cf are compared in Fig. 6-1. A similar comparison for Cf in 15 cm of heavy water is shown in Fig. 6-2. In both cases the agreement is reasonable, so we will use the ANISN calculations, when they exist, to keep the data presentation consistent. There are no ANISN calculations (or liquid-scintillator measurements) for the 15-cm polyethylene moderator cases. However, a MORSE calculation exists for Cf in this moderator. Except for this moderator, the results for a given combination of source and moderator are presented in two tables and three graphs. Each combination is presented in a separate section.

The first table in each section of the report is identified by a number with the form n.1, where n is the number of the section. This table presents the differential neutron spectrum and contains six columns of data. The first column gives the energies of the bottoms of the bins used. Except for the data for PuBe in 15 cm of polyethylene, the second and third columns give the calculated spectra at 1 and 2 m, respectively, with the results rebinned into the multisphere bins. For californium in the 15-cm polyethylene moderator, the calculated spectra were obtained from recent MORSE calculations. No calculations exist for PuBe in this moderator. The ratios of the 1-to-2-m calculated fluences are given in column four.

Columns five and six give the spectrum measured at 2 m and its uncertainties, respectively. In every case, the measured data up to 0.63 MeV, come from the multisphere measurements. When available, the liquid-scintillator results, rebinned to multisphere energy bins, are given above that energy. Measured values for both sources in 15 cm of polyethylene depend solely on multisphere results because this moderator was obtained after the completion of the liquid-scintillator measurements. The uncertainties in the multisphere numbers are one standard deviation of the average of the five solutions found by MINKY. A more complex algorithm, that included all known sources of error, was used to calculate the uncertainties in the liquid-scintillator data.

The first figure (n.1) for each configuration of source and moderator shows the total neutron spectra measured at 2 m. It is plotted as the logarithm of fluence per source neutron versus the logarithm of neutron energy, using the multisphere energy bins. In those cases where they are

Figure 6-1. Two calculations of californium-252 without a moderator.

Figure 6-2. Two calculations of californium-252 in a 15-cm heavy-water moderator.

available, the liquid-scintillator results, rebinned into the multisphere energy groups, are used as the measured spectrum above 0.63 MeV. Except for PuBe in 15-cm polyethylene, the comparable calculated spectrum is also shown in this figure.

None of the data are shown with error estimates because that would make the graph too complicated. Uncertainties for the measured values can be obtained from table n.1. Although uncertainties were available for the MORSE calculations used for ^{252}Cf in 15-cm polyethylene, no uncertainties are shown for the calculated spectra because none are obtained from ANISN calculations.

To make comparisons easier, the same ranges of fluence ($1\text{E}-10$ to $1\text{E}-5$) and energy (0.025 eV to 16 MeV) are used for all figures n.1. No normalization, either in energy or lethargy, was made to compensate for the varying energy widths of the bins. The additional decades on the ordinate that would be needed to plot these data per MeV would obscure details. A lethargy plot would use a reasonable number of decades, but distortions would occur at 160 keV, where the relative bin width changes, and for the lowest energy bin, which is much wider than the others.

The second figures (n.2), given for every source, moderator configuration except 15-cm polyethylene, show the detailed liquid-scintillator data. This plot gives fluence per source neutron on a logarithmic scale from $1\text{E}-11$ to $1\text{E}-6$ as a function of energy on a linear scale from 0 to 13 MeV. Like the data in figures n.1, these data are not plotted per MeV, but, in this case, the energy bins have a uniform width so that the data would have the same shape plotted either way. Uncertainties in both the energy assignments and fluences are shown. Calibration uncertainties are the major contributor to the spread in the energy values. At the higher energies, the energy uncertainties become larger than the 0.1-MeV width of the bins.

Similar detailed data could also be taken using the 15-cm polyethylene moderator, if necessary, but the multisphere results are normally adequate for dosimetry purposes. Tables of the detailed fluence and dosimetric spectra can be provided for those cases where liquid-scintillator measurements were made.

A second table (n.2) is given after these figures. It presents a collection of values calculated from the differential spectrum. The first section of this table gives the total fluence values per source neutron for the calculations, at both distances, and the measured 2 m value.

A 1-to-2-m ratio is given for the values derived from the calculations, and an uncertainty is given for the total derived from data measured at 2 m.

Two values of the mean energy of the spectrum, calculated from the spectrum measured at 2 m, are given in the next section of the table. The second value excludes the lowest energy bin.

Factors to convert from source yield to absorbed dose, kerma, and NCRP and ICRP dose equivalents are given in the last section of table n.2. These values were calculated for each of the spectra in table n.1. The conversion factors used were given in Table 4-1. Average quality factors can be derived from these results.

Total fluences, average energies, and dose conversion factors for all 22 combinations of source and moderator, are shown in a set of summary tables in Section 29 of the report (Tables 29-1 through 29-6). These tables were included to simplify the choice of the proper spectrum for a given exposure.

The third figure (n.3), given for every source-moderator configuration, shows the integrals, as a function of energy, of the fluence measured at 2 m, and the absorbed dose in tissue, tissue kerma, and NCRP dose equivalent derived from that fluence. These values are all normalized to their respective total values in order to make the data presentation more uniform, and are plotted on a linear scale versus a logarithmic energy scale. Although the integrals are limited to 12.5 MeV by the liquid-scintillator results, the same energy range is used as in figure n.1 (0.025 eV to 16 MeV). Integral values below 630 keV are obtained from the multisphere data. Above 630 keV, they are derived from the liquid-scintillator data. When no scintillator results are available, the entire plot is derived from the multisphere data. Dose-equivalent values derived from the ICRP conversion factors were not plotted because they do not differ significantly from the NCRP results. Tables of these data are available.

7. ²⁵²Cf, NO MODERATOR

Of all the spectra presented in this report, this one should be the easiest to measure with a combined multisphere, liquid-scintillator system. The agreement between measurements and calculations should also be about as good as possible. Figure 7-1, the plot of the 2-m fluence per source neutron data from Table 7-1, shows that the measured data fall below the calculations at the lowest and highest energies. The lowest energy bin is measured quite

accurately by the multisphere system, so the measured data should be used for this bin. From about 10 keV to 2 MeV the measured fluence values are greater than the calculations, but there is no reason to prefer one set of data over the other. For the highest energies, the measurements rely on the liquid scintillator, and are in a region in which we have confidence in this detector. For this source-moderator combination we recommend using the measured results, and the values obtained from them.

The 1-to-2-m fluence ratios from the calculations are essentially 1 for neutrons energies up to 100 keV. Bare californium produces few neutrons below this energy so those in the spectra must have obtained these energies by scattering off the cell walls. A ratio of 1 implies the fluence is uniform from 1 to 2 m. The importance of scattering is further reflected in the fact that the ratios remain less than 4 for neutron energies up to 4 MeV.

Figure 7-2 shows the detailed spectrum measured above 500 keV by the liquid scintillator. There are some small fluctuations in these results, but they show the decreasing exponential form expected from a Maxwellian distribution. That is, above 1 MeV the spectrum is essentially a straight line in this semilogarithmic presentation.

As shown in Table 7-2, the total fluence per source neutron obtained from the calculated spectrum is less than the comparable measured value by a percentage difference of 4%. Much of the difference is in the lowest energy bin, which is difficult to calculate. An agreement within 10% would probably be reasonable. The corresponding dosimetric values do, in fact, have percentage differences below 10%. Because the dosimetric values derived from the measurements are larger than those from the calculated spectrum, and by an amount larger than the difference in the respective fluence values, the measured spectrum must have a higher average energy.

The mean energy of the spectrum measured at 2 m is 1.4 MeV. Neutrons with energies below 100 keV are not a major factor in this spectrum. The integral values in Fig. 7-3 show that the median energy for the fluence is 400 keV, and for the dosimetric values it is near 1 MeV.

Table 7-1. Differential spectra from ^{252}Cf without a moderator.

Fluence values are normalized to one source neutron

Bottom energy (MeV)	From ANISN calculations			Measured	
	1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)	
2.5E-8	7.45E-7	7.45E-7	1.00	4.39E-7	$\pm$ 0.0%
4.0E-7	2.31E-8	2.31E-8	1.00	1.29E-8	$\pm$ 5.8%
1.0E-6	5.77E-8	5.78E-8	1.00	3.68E-8	$\pm$ 2.9%
2.5E-6	3.63E-8	3.64E-8	1.00	2.19E-8	$\pm$ 7.9%
6.3E-6	3.15E-8	3.16E-8	1.00	2.55E-8	$\pm$ 8.3%
1.6E-5	3.63E-8	3.63E-8	1.00	3.47E-8	$\pm$ 6.0%
4.0E-5	2.58E-8	2.59E-8	1.00	3.22E-8	$\pm$ 5.3%
1.0E-4	4.60E-8	4.61E-8	1.00	6.04E-8	$\pm$ 2.9%
2.5E-4	2.19E-8	2.20E-8	1.00	2.88E-8	$\pm$ 2.6%
6.3E-4	5.55E-8	5.56E-8	1.00	7.20E-8	$\pm$ 5.5%
1.6E-3	1.96E-8	1.91E-8	1.03	2.27E-8	$\pm$ 7.8%
4.0E-3	4.90E-8	4.77E-8	1.03	5.46E-8	$\pm$ 10.9%
1.0E-2	4.60E-8	3.79E-8	1.21	4.31E-8	$\pm$ 5.4%
2.5E-2	7.56E-8	5.26E-8	1.44	6.97E-8	$\pm$ 8.5%
6.3E-2	2.00E-7	1.08E-7	1.85	1.82E-7	$\pm$ 4.8%
1.6E-1	1.96E-7	8.17E-8	2.40	1.24E-7	$\pm$ 4.6%
2.5E-1	3.57E-7	1.24E-7	2.87	1.70E-7	$\pm$ 7.2%
4.0E-1	5.77E-7	1.94E-7	2.97	2.51E-7	$\pm$ 3.2%
6.3E-1	9.91E-7	3.16E-7	3.13	3.72E-7	$\pm$ 1.5%
1.0	1.44E-6	4.05E-7	3.57	5.28E-7	$\pm$ 1.1%
1.6	1.69E-6	4.61E-7	3.67	5.55E-7	$\pm$ 0.7%
2.5	1.70E-6	4.56E-7	3.72	4.37E-7	$\pm$ 0.7%
4.0	9.71E-7	2.48E-7	3.92	1.96E-7	$\pm$ 0.6%
6.3	3.05E-7	7.63E-8	4.00	5.37E-8	$\pm$ 1.0%
1.0E+1	2.85E-8	7.08E-9	4.03	5.16E-9	$\pm$ 4.0%
1.6E+1

Figure 7-1. Californium-252 without a moderator.

Figure 7-2. Californium-252 without a moderator.

Figure 7-3. Californium-252 without a moderator.

Table 7-2. Values derived from the spectra for ^{252}Cf without a moderator.

<u>Total fluences per source neutron</u>				
From ANISN calculations			Measured	
1 meter	2 meters	1m/2m	2 meters	
(n/cm ²)	(n/cm ²)		(n/cm ²)	
9.73E-6	3.71E-6	2.62	3.83E-6 $\pm$ 0.6%	

<u>Average energy of the measured spectrum</u>	
Above 0.025 eV: 1.38 MeV	
Above 0.400 eV: 1.56 MeV	

<u>Source-yield to dose conversion factors</u>			
	From ANISN calculations		Measured
	1 meter	2 meters	2 meters
Absorbed dose (rads/source n)	3.16E-14	9.24E-15	9.74E-15
Tissue kerma (rads/source n)	2.52E-14	7.04E-15	7.57E-15
NCRP dose eq. (rems/source n)	2.89E-13	8.26E-14	9.12E-14
ICRP dose eq. (rems/source n)	2.89E-13	8.21E-14	9.00E-14

8. ^{252}Cf IN A 25-cm WATER MODERATOR

It was difficult to measure this heavily moderated spectrum with the multisphere system as we used it. Table 8-1 and Fig. 8-1 show there are significantly more neutrons above 0.63 MeV in the spectrum measured at 2 m than in the corresponding calculated spectrum. Since this part of the measured results depend upon the liquid scintillator (which normally gives good results), this may indicate difficulties in the calculations for a moderator this thick. The multisphere system gives an accurate value for the fluence in the lowest energy bin, and it is lower than the calculated value. Between 1 and 100 keV, measured fluence values exceed the calculations. An obviously low fluence value occurs in the measured spectrum in the bin that covers the energy from $2.5\text{E-}4$ to $6.3\text{E-}4$ MeV. This could reflect a problem in measuring this energy range with a multisphere system that does not use the 51-mm sphere, or one or more of the response functions we used may be in error.

For this source-moderator combination, the calculated 1-to-m ratios are somewhat greater than 2 at the lowest energies. This means that there are neutrons of these energies coming directly from the moderator, in addition to those scattered back by the cell walls. However, the ratios do not become 4 until the neutron energies exceed 4 MeV.

The detailed liquid-scintillator results in Fig. 8-2 clearly show the effects of the resonances in the oxygen cross section. This effect is discussed in more detail in the summary of the report (Section 29). The basic shape remains a decreasing exponential.

Considering the problems with the measured spectrum, the measured and calculated total fluence per source neutron values for 2 m agree quite well (see Table 8-2). However, the associated total dosimetric values have percentage differences as large as 30%. The sign of the differences indicates that the measured spectrum has a higher average energy.

At 2 m, the mean energy of the measured spectrum is 800 keV. The integral spectra in Fig. 8-3 show that the fluence from this heavily moderated spectrum has a median energy of 16 eV, but the median energy for the absorbed dose and dose equivalent is 1 MeV, and of the kerma is 1.5 MeV. That is, the energy distributions of the total dosimetric values for this spectrum are not significantly different from those for an unmoderated source.

Table 8-1. Differential spectra from ^{252}Cf in a 25-cm-thick water moderator.

Fluence values are normalized to one source neutron

Bottom energy (MeV)	From ANISN calculations			Measured	
	1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)	
2.5E-8	6.24E-7	2.71E-7	2.30	1.86E-7	± 0.0%
4.0E-7	6.85E-9	2.95E-9	2.32	3.52E-9	± 6.4%
1.0E-6	1.71E-8	7.37E-9	2.32	7.30E-9	± 2.7%
2.5E-6	1.09E-8	4.60E-9	2.36	5.15E-9	± 4.0%
6.3E-6	9.62E-9	3.92E-9	2.45	5.22E-9	± 5.5%
1.6E-5	1.10E-8	4.47E-9	2.46	6.07E-9	± 3.9%
4.0E-5	7.54E-9	3.04E-9	2.48	3.84E-9	± 11.2%
1.0E-4	1.34E-8	5.39E-9	2.48	7.09E-9	± 5.4%
2.5E-4	6.15E-9	2.44E-9	2.52	4.41E-10	± 27.2%
6.3E-4	1.56E-8	6.18E-9	2.52	9.66E-9	± 3.1%
1.6E-3	5.98E-9	2.21E-9	2.71	2.63E-9	± 12.0%
4.0E-3	1.50E-8	5.53E-9	2.71	8.05E-9	± 4.7%
1.0E-2	1.06E-8	3.91E-9	2.71	8.50E-9	± 3.7%
2.5E-2	1.26E-8	4.62E-9	2.73	1.22E-8	± 4.3%
6.3E-2	2.06E-8	7.54E-9	2.73	1.71E-8	± 3.2%
1.6E-1	1.13E-8	4.06E-9	2.78	9.78E-9	± 5.9%
2.5E-1	1.38E-8	4.72E-9	2.93	7.53E-9	± 6.0%
4.0E-1	2.18E-8	7.21E-9	3.03	8.39E-9	± 11.6%
6.3E-1	3.16E-8	1.01E-8	3.13	1.83E-8	± 1.5%
1.0	4.06E-8	1.17E-8	3.46	2.25E-8	± 1.1%
1.6	6.39E-8	1.75E-8	3.64	2.84E-8	± 0.8%
2.5	6.66E-8	1.81E-8	3.69	2.34E-8	± 0.8%
4.0	5.65E-8	1.45E-8	3.90	1.54E-8	± 0.8%
6.3	2.90E-8	7.25E-9	4.00	6.11E-9	± 1.5%
1.0E+1	3.34E-9	8.27E-10	4.03	7.43E-10	± 5.5%
1.6E+1

Figure 8-1. Californium-252 in a 25-cm-thick water moderator.

Figure 8-2. Californium-252 in a 25-cm-thick water moderator.

Figure 8-3. Californium-252 in a 25-cm-thick water moderator.

Table 8-2. Values derived from the spectra for ^{252}Cf in a 25-cm-thick water moderator.

Total fluences per source neutron

From ANISN calculations			Measured
1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)
1.12E-6	4.31E-7	2.61	4.23E-7 ± 0.4%

Average energy of the measured spectrum

Above 0.025 eV: 0.78 MeV
 Above 0.400 eV: 1.38 MeV

Source-yield to dose conversion factors

	From ANISN calculations		Measured
	1 meter	2 meters	2 meters
Absorbed dose (rads/source n)	1.78E-15	5.49E-16	6.56E-16
Tissue kerma (rads/source n)	1.13E-15	3.14E-16	4.29E-16
NCRP dose eq. (rems/source n)	1.29E-14	3.74E-15	5.12E-15
ICRP dose eq. (rems/source n)	1.30E-14	3.75E-15	5.10E-15

9. ^{252}Cf IN A 5-cm HEAVY-WATER MODERATOR

In the lowest energy bin, the 2-m data from Table 9-1, which are plotted in Fig. 9-1, show that the measured fluence is significantly less than that calculated. The multisphere measurement is accurate for this bin, so the measured value should be used. Measured fluences for the next four bins are also below the calculations, but there is no guarantee that the measurements are more reliable than the calculations for these bins. Measured values are above the calculations from 100 keV to 1.6 MeV, but are lower above that energy.

The 1-to-2-m ratios of the fluences values from the calculated spectra start near 1 for this configuration but increase, with increasing energy, more rapidly than they do for the bare source. This means that some of the neutrons are coming directly from the moderator rather than from scattering off the walls of the cell. However, scattering must still be the major source of the low energy neutrons since the ratios only approach 4 for neutrons with energies above 4 MeV.

Even with a moderator this thin, the effects of the resonances in the oxygen cross sections (see Section 29) are beginning to appear in the detailed, liquid-scintillator results (Fig. 9-2). Even so, the basic shape is a decreasing exponential.

For this source-moderator combination, the percentage differences of the measured and calculated total fluences per source neutron, and the dosimetric quantities derived from them, given in Table 9-2, are less than 5%. Total dosimetric values determined from the measurements are larger than those from the calculations, which implies the measured spectrum has a higher average energy.

The mean energy of the spectrum measured at 2 m is 900 keV, much the same as that when the 25-cm water moderator is used. Data given in the integral curve in Fig. 9-3 show the median energy for the measured fluence is 0.063 MeV. Absorbed dose and dose equivalents calculated from this spectrum have a median energy of 0.63 MeV, and the kerma has a median energy of 1 MeV. These energies are only one bin lower than those obtained with the unmoderated source.

Table 9-1. Differential spectra from ^{252}Cf in a 5-cm-thick heavy-water moderator.

Fluence values are normalized to one source neutron

Bottom energy (MeV)	From ANISN calculations			Measured 2 meters (n/cm ²)
	1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	
2.5E-8	9.13E-7	8.94E-7	1.02	5.20E-7 + 0.2%
4.0E-7	3.75E-8	3.15E-8	1.19	1.63E-8 + 14.4%
1.0E-6	9.37E-8	7.88E-8	1.19	4.07E-8 + 13.2%
2.5E-6	6.71E-8	5.18E-8	1.30	2.70E-8 + 8.9%
6.3E-6	7.67E-8	4.99E-8	1.54	3.62E-8 + 11.4%
1.6E-5	9.62E-8	5.95E-8	1.62	6.07E-8 + 11.3%
4.0E-5	9.49E-8	4.92E-8	1.93	6.77E-8 + 12.4%
1.0E-4	1.72E-7	8.83E-8	1.95	1.47E-7 + 4.8%
2.5E-4	1.06E-7	4.77E-8	2.21	6.62E-8 + 7.0%
6.3E-4	2.68E-7	1.21E-7	2.22	1.66E-7 + 10.8%
1.6E-3	1.51E-7	5.59E-8	2.70	4.40E-8 + 8.5%
4.0E-3	3.78E-7	1.40E-7	2.70	1.17E-7 + 11.0%
1.0E-2	3.54E-7	1.21E-7	2.93	1.03E-7 + 10.8%
2.5E-2	5.81E-7	1.83E-7	3.17	1.56E-7 + 8.5%
6.3E-2	9.37E-7	2.92E-7	3.20	3.29E-7 + 9.8%
1.6E-1	4.64E-7	1.43E-7	3.24	1.65E-7 + 6.1%
2.5E-1	3.98E-7	1.25E-7	3.20	1.37E-7 + 9.9%
4.0E-1	5.36E-7	1.67E-7	3.22	2.03E-7 + 11.0%
6.3E-1	6.40E-7	1.98E-7	3.24	2.34E-7 + 1.5%
1.0	7.37E-7	2.09E-7	3.52	2.84E-7 + 1.1%
1.6	9.85E-7	2.69E-7	3.66	3.19E-7 + 0.8%
2.5	1.03E-6	2.76E-7	3.73	2.57E-7 + 0.7%
4.0	5.87E-7	1.50E-7	3.92	1.21E-7 + 0.6%
6.3	1.90E-7	4.75E-8	4.00	3.55E-8 + 1.0%
1.0E+1	1.79E-8	4.43E-9	4.03	3.53E-9 + 3.8%
1.6E+1

Figure 9-1. Californium-252 in a 5-cm-thick heavy-water moderator.

Figure 9-2. Californium-252 in a 5-cm-thick heavy-water moderator.

Figure 9-3. Californium-252 in a 5-cm-thick heavy-water moderator.

Table 9-2. Values derived from the spectra for ^{252}Cf in a 5-cm-thick heavy-water moderator.

Total fluences per source neutron

From ANISN calculations			Measured
1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)
9.91E-6	3.85E-6	2.57	3.66E-6 $\pm$ 1.5%

Average energy of the measured spectrum

Above 0.025 eV: 0.89 MeV
 Above 0.400 eV: 1.03 MeV

Source-yield to dose conversion factors

	From ANISN calculations		Measured
	1 meter	2 meters	2 meters
Absorbed dose (rads/source n)	2.17E-14	6.56E-15	6.66E-15
Tissue kerma (rads/source n)	1.66E-14	4.64E-15	4.89E-15
NCRP dose eq. (rems/source n)	1.92E-13	5.51E-14	5.93E-14
ICRP dose eq. (rems/source n)	1.89E-13	5.39E-14	5.78E-14

10. ^{252}Cf IN A 10-cm HEAVY-WATER MODERATOR

The fluence measured at 2 m by the multisphere system for the lowest energy bin is significantly less than the corresponding calculated value (see Table 10-1 and Fig. 10-1). Greater fluences were measured in the region from 0.63 to 2.6 MeV using the liquid scintillator. In both cases, the measurements would be expected to give reliable data, and we recommend their use.

Enough low-energy neutrons leave this moderator that the 1-to-2-m fluence ratios from the calculated spectra are becoming significantly larger than 1, even at low energies. Even in this case, however, the ratios do not approach 4 until the neutron energies are greater than 4 MeV.

Figure 10-2 displays obvious effects of the resonances in the oxygen cross section for this moderator thickness. This effect, and the energies of the most prominent resonances, are discussed in Section 29. The basic decreasing exponential shape of the spectrum remains, however.

Comparing the results in Table 10-2 shows that the percentage differences for the 2 m measurements and calculations are within 10% for the total fluences per source neutron. The corresponding absorbed dose values compare as well, but the kerma and dose equivalent values obtained from the measured spectrum are 12 to 13% larger than those from the calculated spectrum. These latter differences indicate the measured spectrum has a higher average energy than the calculations.

This moderator produced a mean energy for the spectrum measured at 2 m of 500 keV, significantly lower than that obtained with the 25-cm water moderator. The integral spectra in Fig. 10-3 show the effect that this moderator has in moving higher energy neutrons into the intermediate energy region. The median energy of the fluence is 4 keV and the median energy of the absorbed dose is 0.63 MeV, of kerma 1.5 MeV, and of dose equivalent 1 MeV.

Table 10-1. Differential spectra from ^{252}Cf in a 10-cm-thick heavy-water moderator.

Fluence values are normalized to one source neutron

Bottom energy (MeV)	From ANISN calculations			Measured	
	1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)	
2.5E-8	1.49E-6	1.17E-6	1.28	6.85E-7	± 0.3%
4.0E-7	9.16E-8	4.87E-8	1.88	3.46E-8	± 9.1%
1.0E-6	2.29E-7	1.22E-7	1.88	8.92E-8	± 7.9%
2.5E-6	1.76E-7	8.44E-8	2.09	6.53E-8	± 6.3%
6.3E-6	2.25E-7	9.10E-8	2.48	7.99E-8	± 9.5%
1.6E-5	2.75E-7	1.08E-7	2.54	1.22E-7	± 11.3%
4.0E-5	2.50E-7	8.97E-8	2.79	9.46E-8	± 9.0%
1.0E-4	4.46E-7	1.59E-7	2.80	1.76E-7	± 10.6%
2.5E-4	2.19E-7	7.52E-8	2.91	8.73E-8	± 8.7%
6.3E-4	5.54E-7	1.90E-7	2.91	2.10E-7	± 5.9%
1.6E-3	2.41E-7	7.60E-8	3.17	6.31E-8	± 12.6%
4.0E-3	6.02E-7	1.90E-7	3.17	1.62E-7	± 8.5%
1.0E-2	4.71E-7	1.44E-7	3.27	1.32E-7	± 9.0%
2.5E-2	6.43E-7	1.89E-7	3.41	2.20E-7	± 5.3%
6.3E-2	8.98E-7	2.64E-7	3.40	3.36E-7	± 7.2%
1.6E-1	3.28E-7	9.74E-8	3.36	1.43E-7	± 9.0%
2.5E-1	2.24E-7	6.94E-8	3.22	9.23E-8	± 14.0%
4.0E-1	2.93E-7	9.03E-8	3.24	1.30E-7	± 7.5%
6.3E-1	3.12E-7	9.70E-8	3.22	1.29E-7	± 1.5%
1.0	3.48E-7	1.00E-7	3.46	1.51E-7	± 1.1%
1.6	5.47E-7	1.50E-7	3.64	1.83E-7	± 0.8%
2.5	5.92E-7	1.59E-7	3.73	1.49E-7	± 0.7%
4.0	3.54E-7	9.03E-8	3.92	7.44E-8	± 0.6%
6.3	1.20E-7	2.99E-8	4.00	2.30E-8	± 0.9%
1.0E+1	1.14E-8	2.83E-9	4.03	2.38E-9	± 3.4%
1.6E+1

Figure 10-1. Californium-252 in a 10-cm-thick heavy-water moderator.

Figure 10-2. Californium-252 in a 10-cm-thick heavy-water moderator.

Figure 10-3. Californium-252 in a 10-cm-thick heavy-water moderator.

Table 10-2. Values derived from the spectra for ^{252}Cf in a 10-cm-thick heavy-water moderator.

Total fluences per source neutron

From ANISN calculations			Measured
1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)
9.94E-6	3.89E-6	2.56	3.63E-6 $\pm$ 1.4%

Average energy of the measured spectrum

Above 0.025 eV: 0.53 MeV

Above 0.400 eV: 0.66 MeV

Source-yield to dose conversion factors

	From ANISN calculations		Measured
	1 meter	2 meters	2 meters
Absorbed dose (rads/source n)	1.45E-14	4.58E-15	4.72E-15
Tissue kerma (rads/source n)	9.80E-15	2.73E-15	3.07E-15
NCRP dose eq. (rems/source n)	1.14E-13	3.31E-14	3.77E-14
ICRP dose eq. (rems/source n)	1.12E-13	3.26E-14	3.66E-14

11. ^{252}Cf IN A 15-cm HEAVY-WATER MODERATOR ENCLOSED IN CADMIUM

Table 11-1, or Fig. 11-1, show that the number of neutrons in the lowest energy bin in the calculations is much greater than the measured value. A large part of the divergence in the first bin is undoubtedly because the ANISN calculations do not include the cadmium that enclosed the moderator during the measurements. MORSE calculations, that include the cadmium, were compared with ANISN calculations in Fig. 6-2, and show significantly fewer neutrons in the first bin. Because MORSE calculations were only made at 1 m, direct comparisons with the measurements are not possible. Above the first bin, the measurements exceed the calculations from 10 keV to 2.5 MeV.

Significantly more low-energy neutrons leave this moderator, thus the 1-to-2-m ratios are considerably greater than one down to the lowest energies. The ratios remain less than 4, however, up to 4 MeV, which is the same as for the unmoderated spectrum.

Effects of the resonances in the oxygen cross section on the shape of the detailed spectrum measured with the liquid scintillator are easily seen for a moderator this thick (Fig. 11-2). For comparisons, the energies for the most prominent resonances are given in Section 29. The basic shape remains a decreasing exponential, however.

A 24% percentage difference between the measured and calculated total fluences per source neutron at 2 m is obtained from the data in Table 11-2 for this source, moderator combination. When the neutrons in the first bin are subtracted in both cases, the total fluences have a percentage difference of less than 10%. Another indication that the disagreement is due primarily to the neutrons in the lowest energy bin is that the respective calculated and measured total dosimetric values per source neutron have percentage differences from only 8 to 12%, with the values from the measured spectrum being larger. The kerma values show the largest difference.

The mean energy of the neutrons at 2 m is 0.4 MeV, almost an MeV below that for the bare source. As shown in the integral curves in Fig. 11-3, this moderator has a significant effect on the energy distribution of the fluence. Although the median energy of the measured fluence is only 250 eV, the median energy for the absorbed dose is 0.4 MeV, for kerma 1.5 MeV, and for dose equivalent 1 MeV. These latter values are not much different from those from the bare source, even for this relatively thick moderator.

Table 11-1. Differential spectra from ^{252}Cf in a 15-cm-thick heavy-water moderator.

Fluence values are normalized to one source neutron

Bottom energy (MeV)	From ANISN calculations			Measured	
	1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)	
2.5E-8	2.74E-6	1.61E-6	1.70	5.81E-7	± 0.4%
4.0E-7	1.44E-7	6.04E-8	2.38	4.48E-8	± 5.7%
1.0E-6	3.60E-7	1.51E-7	2.38	1.44E-7	± 2.2%
2.5E-6	2.70E-7	1.05E-7	2.57	1.09E-7	± 6.9%
6.3E-6	3.33E-7	1.14E-7	2.92	1.21E-7	± 6.5%
1.6E-5	3.94E-7	1.33E-7	2.96	1.32E-7	± 4.6%
4.0E-5	3.18E-7	1.02E-7	3.13	9.83E-8	± 7.6%
1.0E-4	5.61E-7	1.79E-7	3.14	1.89E-7	± 4.0%
2.5E-4	2.33E-7	7.35E-8	3.17	8.31E-8	± 2.1%
6.3E-4	5.91E-7	1.86E-7	3.17	2.12E-7	± 4.9%
1.6E-3	2.16E-7	6.48E-8	3.32	6.12E-8	± 5.5%
4.0E-3	5.39E-7	1.62E-7	3.33	1.52E-7	± 4.8%
1.0E-2	3.83E-7	1.13E-7	3.39	1.16E-7	± 5.3%
2.5E-2	4.55E-7	1.31E-7	3.49	1.82E-7	± 4.9%
6.3E-2	5.93E-7	1.71E-7	3.47	2.26E-7	± 3.5%
1.6E-1	1.79E-7	5.26E-8	3.39	7.40E-8	± 4.9%
2.5E-1	1.12E-7	3.48E-8	3.22	3.28E-8	± 7.5%
4.0E-1	1.44E-7	4.47E-8	3.23	4.77E-8	± 8.3%
6.3E-1	1.45E-7	4.58E-8	3.17	6.64E-8	± 1.5%
1.0	1.66E-7	4.86E-8	3.41	7.95E-8	± 1.0%
1.6	2.95E-7	8.11E-8	3.63	1.05E-7	± 0.8%
2.5	3.25E-7	8.74E-8	3.72	8.52E-8	± 0.7%
4.0	2.09E-7	5.33E-8	3.92	4.58E-8	± 0.6%
6.3	7.42E-8	1.85E-8	4.00	1.51E-8	± 1.0%
1.0E+1	7.19E-9	1.78E-9	4.03	1.65E-9	± 3.7%
1.6E+1

Figure 11-1. Californium-252 in a 15-cm-thick heavy-water moderator.

Figure 11-2. Californium-252 in a 15-cm-thick heavy-water moderator.

Figure 11-3. Californium-252 in a 15-cm-thick heavy-water moderator.

Table 11-2. Values derived from the spectra for ^{252}Cf in a 15-cm-thick heavy-water moderator.

Total fluences per source neutron

From ANISN calculations			Measured
1 meter	2 meters		2 meters
(n/cm ²)	(n/cm ²)	1m/2m	(n/cm ²)
9.78E-6	3.82E-6	2.56	3.00E-6 $\pm$ 0.9%

Average energy of the measured spectrum

Above 0.025 eV: 0.37 MeV
 Above 0.400 eV: 0.46 MeV

Source-yield to dose conversion factors

	From ANISN calculations		Measured
	1 meter	2 meters	2 meters
Absorbed dose (rads/source n)	1.01E-14	3.38E-15	3.12E-15
Tissue kerma (rads/source n)	5.50E-15	1.54E-15	1.73E-15
NCRP dose eq. (rems/source n)	6.67E-14	1.98E-14	2.16E-14
ICRP dose eq. (rems/source n)	6.62E-14	1.97E-14	2.13E-14

12. ^{252}Cf IN A 25-cm HEAVY-WATER MODERATOR

This is the thickest heavy-water moderator. The 2-m data from Table 12-1, which are plotted in Fig. 12-1, show that poor results were obtained with the multisphere spectrometer for this highly moderated spectrum in the energy ranges from $4\text{E-}5$ to $1\text{E-}4$ MeV, and 0.16 to 0.63 MeV. This may reflect an error in the response functions used for the multisphere system, or better results might have been obtained if the 51-mm sphere had been part of the detector system. Fluences measured with the liquid scintillator from 630 keV to 4 MeV are greater than the calculations. While we believe these values are correct, the calculated spectrum, and the values derived from it, should probably be used in this case. It is possible, however, that the calculations are inaccurate for a moderator this thick.

Above the lowest energy bin, the 1-to-2-m fluence ratios from the calculated spectra are near 3. That they are not 4 indicates that, even for this highly moderated spectrum, a significant number of the low-energy neutrons are getting to the detector by scattering off the walls of the cell. The ratios do not reach 4 until the neutron energies exceed 4 MeV.

The amount of attenuation produced by this thick moderator, and the effects of the resonances in the oxygen cross section are clearly shown in the liquid scintillator results (Fig. 12-2). This effect is also discussed in Section 29. Despite these distortions, the spectrum remains a decreasing exponential above 4 MeV.

Even with the variations between the measured and calculated spectra, the percentage difference of the total fluences per source neutron given in Table 12-2 is about 13%. The percentage differences for the related dosimetric quantities range from 2 to 11%. These are unexpectedly good. Even the agreement between the measured and calculated fluence in the lowest energy bin is quite good.

The mean neutron energy at 2 m measured for this source, moderator combination is only 120 keV, about a tenth that of the bare source. Figure 12-3 shows an integral fluence spectrum for which the median energy falls below the lowest energy bin, and the median energy for the absorbed dose is the lowest energy bin. The median energy for the kerma is 2 MeV, and for the dose equivalent is 1 MeV. Since these latter values are similar to those for the bare source, this is a clear indication of how much larger the kerma per unit fluence, and dose equivalent per unit fluence, are for higher energy neutrons.

Table 12-1. Differential spectra from ^{252}Cf in a 25-cm-thick heavy-water moderator.

Fluence values are normalized to one source neutron

Bottom energy (MeV)	From ANISN calculations			Measured	
	1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)	
2.5E-8	5.96E-6	2.62E-6	2.28	2.08E-6	+ 0.1%
4.0E-7	1.39E-7	4.91E-8	2.82	6.23E-8	+ 5.2%
1.0E-6	3.47E-7	1.23E-7	2.82	1.36E-7	+ 8.2%
2.5E-6	2.45E-7	8.29E-8	2.96	9.90E-8	+ 8.9%
6.3E-6	2.74E-7	8.48E-8	3.23	9.28E-8	+ 6.5%
1.6E-5	3.11E-7	9.59E-8	3.24	7.75E-8	+ 15.8%
4.0E-5	2.09E-7	6.30E-8	3.32	2.00E-9	+ 20.7%
1.0E-4	3.69E-7	1.11E-7	3.33	5.07E-8	+ 29.2%
2.5E-4	1.55E-7	4.53E-8	3.41	1.19E-8	+ 41.0%
6.3E-4	3.91E-7	1.15E-7	3.41	1.29E-7	+ 6.4%
1.6E-3	1.06E-7	3.05E-8	3.47	6.75E-8	+ 9.2%
4.0E-3	2.65E-7	7.63E-8	3.47	1.21E-7	+ 5.2%
1.0E-2	1.68E-7	4.79E-8	3.50	1.06E-7	+ 6.2%
2.5E-2	1.60E-7	4.51E-8	3.54	1.08E-7	+ 5.8%
6.3E-2	1.98E-7	5.62E-8	3.52	4.41E-8	+ 15.5%
1.6E-1	5.01E-8	1.48E-8	3.39	5.84E-10	+ 26.8%
2.5E-1	3.15E-8	9.84E-9	3.20	1.16E-10	+ 18.7%
4.0E-1	3.98E-8	1.25E-8	3.19	1.25E-10	+ 17.6%
6.3E-1	3.91E-8	1.25E-8	3.11	2.21E-8	+ 1.6%
1.0	4.56E-8	1.36E-8	3.34	2.69E-8	+ 1.1%
1.6	9.33E-8	2.58E-8	3.62	3.83E-8	+ 0.8%
2.5	1.09E-7	2.92E-8	3.72	3.18E-8	+ 0.7%
4.0	8.07E-8	2.06E-8	3.93	1.95E-8	+ 0.8%
6.3	3.20E-8	7.98E-9	4.01	6.91E-9	+ 1.4%
1.0E+1	3.23E-9	8.00E-10	4.04	7.91E-10	+ 5.4%
1.6E+1

Figure 12-1. Californium-252 in a 25-cm-thick heavy-water moderator.

Figure 12-2. Californium-252 in a 25-cm-thick heavy-water moderator.

Figure 12-3. Californium-252 in a 25-cm-thick heavy-water moderator.

Table 12-2. Values derived from the spectra for ^{252}Cf in a 25-cm-thick heavy-water moderator.

Total fluences per source neutron

From ANISN calculations			Measured
1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)
9.82E-6	3.79E-6	2.59	3.33E-6 $\pm$ 0.9%

Average energy of the measured spectrum

Above 0.025 eV: 0.12 MeV
 Above 0.400 eV: 0.33 MeV

Source-yield to dose conversion factors

	From ANISN calculations		Measured
	1 meter	2 meters	2 meters
Absorbed dose (rads/source n)	6.92E-15	2.45E-15	2.27E-15
Tissue kerma (rads/source n)	1.95E-15	5.53E-16	6.16E-16
NCRP dose eq. (rems/source n)	2.91E-14	9.24E-15	9.41E-15
ICRP dose eq. (rems/source n)	2.95E-14	9.40E-15	9.65E-15

13. ^{252}Cf IN A 20-cm ALUMINUM MODERATOR

Metals have considerably different effects than hydrogenous (or deuterated) materials on a neutron spectrum. In this case the calculations exceed the measured values above 250 keV (see Table 13-1 and Fig. 13-1). The opposite is true for the other spectra. Because we have confidence in the liquid-scintillator measurements used above 630 keV, we believe the measurements should be used in preference to the calculations.

The unity ratios of the 1-to-2-m fluence values in the lowest bins of the calculated spectra show that this moderator does not slow many of the source neutrons down into the lowest energy bins.

The effect of the moderator on the highest energy neutrons in the detailed spectrum obtained with the liquid scintillator (Fig. 13-2) shows as a change from the essentially exponential distribution obtained with the bare source to one noticeably concave down. There is no clear reason for the small feature between 7 and 8 MeV shown in these results.

While the measured and calculated total fluences per source neutron at 2 m shown in Table 13-2 agree with a percentage difference of 7%, the related dosimetric values have percentage differences from 14 to 16%. Unlike the other cases, the dosimetric values obtained from the measured spectrum are smaller than those from the calculation. This is consistent with the difference in the spectra, because the greatest contribution to the total dosimetric values is obtained from the higher bins.

There is a considerable decrease in the average energy of the energy distribution at 2 m, from 1.4 MeV for the bare source to 0.7 MeV when the source is in this moderator. Movement of neutrons from higher energies into the 1 keV to 1 MeV region by this moderator is also reflected in the integral spectra shown in Fig. 13-3. The median energy of the fluence is 0.16 MeV, and of the absorbed dose, kerma, and dose equivalent 0.63 MeV. These values are significantly lower for this moderator than for most of the other moderators, which signifies a considerable decrease in the most energetic neutrons.

Table 13-1. Differential spectra from ^{252}Cf in a 20-cm-thick aluminum moderator.

Fluence values are normalized to one source neutron

Bottom energy (MeV)	From ANISN calculations			Measured		
	1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)		
2.5E-8	8.37E-7	8.40E-7	1.00	4.83E-7	±	0.1%
4.0E-7	2.70E-8	2.71E-8	1.00	1.44E-8	±	8.9%
1.0E-6	6.76E-8	6.78E-8	1.00	3.97E-8	±	8.3%
2.5E-6	4.26E-8	4.28E-8	1.00	2.63E-8	±	8.0%
6.3E-6	3.73E-8	3.74E-8	1.00	3.16E-8	±	12.1%
1.6E-5	4.31E-8	4.32E-8	1.00	4.60E-8	±	7.9%
4.0E-5	3.11E-8	3.11E-8	1.00	5.58E-8	±	11.2%
1.0E-4	5.55E-8	5.55E-8	1.00	1.09E-7	±	12.9%
2.5E-4	2.79E-8	2.71E-8	1.03	5.51E-8	±	8.4%
6.3E-4	7.07E-8	6.85E-8	1.03	1.29E-7	±	9.8%
1.6E-3	3.77E-8	2.72E-8	1.39	3.73E-8	±	11.5%
4.0E-3	9.43E-8	6.81E-8	1.39	9.06E-8	±	7.1%
1.0E-2	1.50E-7	7.06E-8	2.13	8.25E-8	±	12.5%
2.5E-2	3.35E-7	1.26E-7	2.66	1.28E-7	±	10.6%
6.3E-2	6.02E-7	2.20E-7	2.73	3.82E-7	±	11.7%
1.6E-1	3.99E-7	1.37E-7	2.91	2.44E-7	±	2.0%
2.5E-1	6.06E-7	1.91E-7	3.18	1.72E-7	±	6.7%
4.0E-1	1.02E-6	3.07E-7	3.32	2.86E-7	±	13.0%
6.3E-1	1.47E-6	4.29E-7	3.42	3.96E-7	±	1.5%
1.0	1.52E-6	4.09E-7	3.73	3.70E-7	±	1.1%
1.6	1.15E-6	3.04E-7	3.77	2.38E-7	±	0.7%
2.5	7.72E-7	2.06E-7	3.75	1.32E-7	±	0.7%
4.0	3.88E-7	9.85E-8	3.94	5.01E-8	±	0.7%
6.3	1.11E-7	2.77E-8	4.01	1.24E-8	±	1.3%
1.0E+1	9.66E-9	2.39E-9	4.03	1.26E-9	±	5.2%
1.6E+1

Figure 13-1. Californium-252 in a 20-cm-thick aluminum moderator.

Figure 13-2. Californium-252 in a 20-cm-thick aluminum moderator.

Figure 13-3. Californium-252 in a 20-cm-thick aluminum moderator.

Table 13-2. Values derived from the spectra for ^{252}Cf in a 20-cm-thick aluminum moderator.

Total fluences per source neutron

From ANISN calculations			Measured
1 meter	2 meters	1m/2m	2 meters
(n/cm ²)	(n/cm ²)		(n/cm ²)
9.90E-6	3.86E-6	2.56	3.61E-6 $\pm$ 1.8%

Average energy of the measured spectrum

Above 0.025 eV: 0.66 MeV
 Above 0.400 eV: 0.77 MeV

Source-yield to dose conversion factors

	From ANISN calculations		Measured
	1 meter	2 meters	2 meters
Absorbed dose (rads/source n)	2.43E-14	7.26E-15	6.15E-15
Tissue kerma (rads/source n)	1.91E-14	5.34E-15	4.55E-15
NCRP dose eq. (rems/source n)	2.42E-13	6.89E-14	5.98E-14
ICRP dose eq. (rems/source n)	2.31E-13	6.53E-14	5.58E-14

This thin moderator does not have much effect on the differential neutron spectrum. Figure 14-1, a plot of the 2-m fluence data from Table 14-1, shows good agreement between the measurements and calculations. Although either set of data could be used, we recommend using the measured spectrum, and the values derived from it.

One-meter to 2-m fluence ratios from the calculations are greater than 1, even in the lowest energy bins, which shows that, despite being thin, this moderator has a definite effect on the spectrum. In fact, these ratios are greater than those obtained with a 5-cm-thick heavy-water moderator. This reflects the fact that hydrogen is more effective than deuterium at slowing down neutrons, provided the moderator is not so thick that a significant number of the low-energy neutrons are captured by the hydrogen. This is discussed further in Section 29. Even so, the ratios do not reach 4 until the neutron energies exceed 4 MeV.

Dips in the detailed spectrum obtained with the liquid scintillator (Fig. 14-2) can, in a general way, be correlated with the resonances in the carbon cross section. This effect is also discussed, and the relevant energies given, in Section 29.

As shown in Table 14-2, this moderator lowers the average energy of the californium spectrum to 1.31 MeV. Measured and calculated total fluence per source neutron at two meters have a percentage difference of only 3%. The related dosimetric values have a maximum percentage difference of 7%.

The integral spectra in Fig. 14-3 show that this moderator results in a neutron spectrum for which the median energy of the fluence is 0.4 MeV, of the absorbed dose and kerma 1.5 MeV, and of the dose equivalent 1 MeV. These are the same as the energies obtained for the bare source, although the average energy of the spectrum measured at 2 m is 1.11 MeV as opposed to 1.38 MeV for the bare source.

Table 14-1. Differential spectra from ^{252}Cf in a 2-cm-thick polyethylene moderator.

Fluence values are normalized to one source neutron

Bottom energy (MeV)	From ANISN calculations			Measured	
	1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)	
2.5E-8	1.09E-6	9.13E-7	1.19	5.60E-7	+ 0.0%
4.0E-7	5.01E-8	3.22E-8	1.55	1.92E-8	+ 9.2%
1.0E-6	1.25E-7	8.06E-8	1.55	5.29E-8	+ 6.3%
2.5E-6	8.36E-8	5.17E-8	1.62	3.69E-8	+ 3.9%
6.3E-6	8.35E-8	4.73E-8	1.77	4.61E-8	+ 7.9%
1.6E-5	9.81E-8	5.48E-8	1.79	6.58E-8	+ 5.1%
4.0E-5	7.69E-8	4.06E-8	1.90	5.44E-8	+ 4.7%
1.0E-4	1.38E-7	7.24E-8	1.91	9.92E-8	+ 7.0%
2.5E-4	7.44E-8	3.63E-8	2.05	5.70E-8	+ 7.3%
6.3E-4	1.88E-7	9.17E-8	2.05	1.22E-7	+ 4.5%
1.6E-3	7.48E-8	3.34E-8	2.24	4.41E-8	+ 7.8%
4.0E-3	1.87E-7	8.36E-8	2.24	8.90E-8	+ 6.3%
1.0E-2	1.52E-7	6.46E-8	2.36	6.66E-8	+ 9.2%
2.5E-2	2.17E-7	8.66E-8	2.51	8.25E-8	+ 10.6%
6.3E-2	4.05E-7	1.55E-7	2.62	1.90E-7	+ 9.2%
1.6E-1	2.71E-7	9.64E-8	2.81	8.96E-8	+ 11.4%
2.5E-1	3.71E-7	1.22E-7	3.03	1.26E-7	+ 6.2%
4.0E-1	5.57E-7	1.80E-7	3.09	2.02E-7	+ 4.9%
6.3E-1	8.27E-7	2.60E-7	3.18	3.17E-7	+ 1.5%
1.0	1.12E-6	3.12E-7	3.57	4.07E-7	+ 1.1%
1.6	1.29E-6	3.51E-7	3.67	4.06E-7	+ 0.7%
2.5	1.26E-6	3.40E-7	3.72	3.19E-7	+ 0.7%
4.0	7.43E-7	1.89E-7	3.92	1.52E-7	+ 0.6%
6.3	2.46E-7	6.16E-8	4.00	4.41E-8	+ 1.0%
1.0E+1	2.35E-8	5.84E-9	4.03	4.47E-9	+ 3.7%
1.6E+1

Figure 14-1. Californium-252 in a 2-cm-thick polyethylene moderator.

Figure 14-2. Californium-252 in a 2-cm-thick polyethylene moderator.

Figure 14-3. Californium-252 in a 2-cm-thick polyethylene moderator.

Table 14-2. Values derived from the spectra for ^{252}Cf in a 2-cm-thick polyethylene moderator.

Total fluences per source neutron

From ANISN calculations			Measured
1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)
9.75E-6	3.76E-6	2.59	3.65E-6 $\pm$ 0.8%

Average energy of the measured spectrum

Above 0.025 eV: 1.11 MeV
Above 0.400 eV: 1.31 MeV

Source-yield to dose conversion factors

	From ANISN calculations		Measured
	1 meter	2 meters	2 meters
Absorbed dose (rads/source n)	2.59E-14	7.68E-15	7.81E-15
Tissue kerma (rads/source n)	2.01E-14	5.61E-15	5.84E-15
NCRP dose eq. (rems/source n)	2.33E-13	6.67E-14	7.12E-14
ICRP dose eq. (rems/source n)	2.31E-13	6.58E-14	6.99E-14

15. ^{252}Cf IN A 5-cm POLYETHYLENE MODERATOR

Good agreement between the measured and calculated spectra at 2 m for this source, moderator combination is apparent in Fig. 15-1; a plot of the 2-m fluence data from Table 15-1. For the calculations, the peak in the spectrum above 100 keV is at a higher energy. Below 0.1 MeV the agreement is better than the precision of either set of data would predict.

Although they are below 4 until the neutron energies exceed 4 MeV, the 1-to-2-m ratios obtained from the calculated spectra are generally above 2. This indicates some of the low-energy neutrons come directly from the moderated source rather than from room scatter.

Above 1 MeV this spectrum is basically a decreasing exponential. Dips caused by resonances in the carbon cross section can be seen in the detailed data in Fig. 15-2. The effects of resonances in the cross sections of the materials in the moderator on the transmitted spectrum are discussed further in Section 29.

Total fluence per source neutron, the related dosimetric values obtained from the measurements of this spectrum, and the comparable values from the calculated spectrum have percentage differences of 2 to 7%. These data are given in Table 15-2. The dosimetric values obtained from the calculated spectrum are smaller than those from the measurements, which implies that the measured spectrum has a higher average energy than the calculations.

The average energy of the spectrum measured at 2 m is 0.83 MeV, which is considerably below the average energy obtained with the 2-cm polyethylene moderator. At 2 m, the integral spectra (Fig. 15-3) show that the median energy of the fluence is 0.025 MeV, that of absorbed dose and dose equivalent 1 MeV, and that of kerma 1.5 MeV. While the energy given for the median fluence is significantly lower than that for the bare spectrum, the median energies for the dosimetric values are not much different. The value for the kerma is, in fact, just a bit higher than that for the bare source.

Table 15-1. Differential spectra from ^{252}Cf in a 5-cm-thick polyethylene moderator.

Fluence values are normalized to one source neutron

Bottom energy (MeV)	From ANISN calculations			Measured	
	1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)	
2.5E-8	2.01E-6	1.19E-6	1.69	8.72E-7	+ 0.2%
4.0E-7	7.67E-8	3.59E-8	2.13	2.82E-8	+ 2.2%
1.0E-6	1.92E-7	8.98E-8	2.13	7.17E-8	+ 4.6%
2.5E-6	1.26E-7	5.72E-8	2.20	4.77E-8	+ 6.6%
6.3E-6	1.20E-7	5.13E-8	2.35	5.04E-8	+ 5.2%
1.6E-5	1.39E-7	5.89E-8	2.36	6.10E-8	+ 5.4%
4.0E-5	9.96E-8	4.14E-8	2.41	4.99E-8	+ 3.1%
1.0E-4	1.77E-7	7.35E-8	2.41	8.55E-8	+ 1.2%
2.5E-4	8.52E-8	3.43E-8	2.48	3.89E-8	+ 4.8%
6.3E-4	2.15E-7	8.69E-8	2.48	1.07E-7	+ 3.8%
1.6E-3	7.41E-8	2.90E-8	2.55	2.93E-8	+ 2.7%
4.0E-3	1.85E-7	7.25E-8	2.55	7.67E-8	+ 4.8%
1.0E-2	1.41E-7	5.37E-8	2.62	6.09E-8	+ 3.6%
2.5E-2	1.85E-7	6.81E-8	2.71	9.69E-8	+ 5.9%
6.3E-2	3.23E-7	1.17E-7	2.77	1.55E-7	+ 1.9%
1.6E-1	1.97E-7	6.79E-8	2.90	8.43E-8	+ 3.5%
2.5E-1	2.53E-7	8.24E-8	3.07	8.29E-8	+ 2.0%
4.0E-1	3.72E-7	1.19E-7	3.13	1.18E-7	+ 4.3%
6.3E-1	5.27E-7	1.65E-7	3.19	2.03E-7	+ 1.5%
1.0	6.91E-7	1.93E-7	3.57	2.54E-7	+ 1.1%
1.6	7.99E-7	2.18E-7	3.67	2.54E-7	+ 0.7%
2.5	7.77E-7	2.10E-7	3.71	2.00E-7	+ 0.7%
4.0	4.90E-7	1.25E-7	3.91	1.03E-7	+ 0.6%
6.3	1.77E-7	4.43E-8	4.00	3.15E-8	+ 0.9%
1.0E+1	1.75E-8	4.35E-9	4.03	3.37E-9	+ 3.4%
1.6E+1

Figure 15-1. Californium-252 in a 5-cm-thick polyethylene moderator.

Figure 15-2. Californium-252 in a 5-cm-thick polyethylene moderator.

Figure 15-3. Californium-252 in a 5-cm-thick polyethylene moderator.

Table 15-2. Values derived from the spectra for ^{252}Cf in a 5-cm-thick polyethylene moderator.

Total fluences per source neutron

From ANISN calculations			Measured
1 meter	2 meters		2 meters
(n/cm ²)	(n/cm ²)	1m/2m	(n/cm ²)
8.45E-6	3.29E-6	2.57	3.17E-6 $\pm$ 0.4%

Average energy of the measured spectrum

Above 0.025 eV: 0.83 MeV

Above 0.400 eV: 1.14 MeV

Source-yield to dose conversion factors

	From ANISN calculations		Measured
	1 meter	2 meters	2 meters
Absorbed dose (rads/source n)	1.77E-14	5.37E-15	5.45E-15
Tissue kerma (rads/source n)	1.29E-14	3.62E-15	3.80E-15
NCRP dose eq. (rems/source n)	1.52E-13	4.36E-14	4.67E-14
ICRP dose eq. (rems/source n)	1.50E-13	4.30E-14	4.58E-14

As shown in Fig. 16-1, which is a plot of the 2-m fluence data from Table 16-1, there are some significant differences between measurements and calculations. The calculated values fall below the measurements from 0.01 to 1 MeV, and above the measurements above 1 MeV.

Effects of the resonances in the carbon cross section show clearly in the liquid scintillator results (Fig. 16-2), but the shape remains a decreasing exponential. Further discussion of the resonances is given in Section 29.

The number of neutrons coming directly from this source, moderator combination at low energies is significant, but most of the neutrons are still arriving at the detector after scattering off the walls of the cell. Only for neutron energies above 4 MeV do the calculated 1-to-2-m fluence ratios become 4.

Even with this relatively thick moderator, the measured total fluence and dosimetric values per source neutron, and the corresponding numbers calculated at 2 m have percentage differences of 2 to 8% (see Table 16-2). The signs of the differences indicate the measured spectrum has a higher average energy than the calculations. This does not appear entirely consistent with the data from Table 16-1.

The average energy of the measured spectrum is 680 keV which is not much below the 800 keV obtained with the 5-cm polyethylene moderator. That implies that, although the number of neutrons is being decreased, the distribution is not being changed significantly by the thicker moderator. This equilibrium effect is discussed further in Section 29. On the other hand, the median energy of the integral of the spectrum measured at 2 m (Fig. 16-3) is 0.1 keV, which is considerably below the median energy obtained with the thinner polyethylene moderators. The median energies of the dosimetric values are unchanged, however, 1 MeV for absorbed dose and dose equivalent, and 1.5 MeV for kerma.

Table 16-1. Differential spectra from ^{252}Cf in a 10-cm-thick polyethylene moderator.

Fluence values are normalized to one source neutron

Bottom energy (MeV)	From ANISN calculations			Measured	
	1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)	
2.5E-8	1.64E-6	8.09E-7	2.02	6.93E-7	+ 0.3%
4.0E-7	4.04E-8	1.75E-8	2.31	1.46E-8	+ 6.1%
1.0E-6	1.01E-7	4.37E-8	2.31	3.73E-8	+ 3.0%
2.5E-6	6.49E-8	2.75E-8	2.36	2.52E-8	+ 3.9%
6.3E-6	5.93E-8	2.39E-8	2.48	2.64E-8	+ 3.2%
1.6E-5	6.77E-8	2.72E-8	2.49	3.01E-8	+ 2.6%
4.0E-5	4.62E-8	1.85E-8	2.50	2.43E-8	+ 8.7%
1.0E-4	8.19E-8	3.27E-8	2.50	4.19E-8	+ 6.7%
2.5E-4	3.75E-8	1.48E-8	2.54	2.05E-8	+ 6.5%
6.3E-4	9.47E-8	3.74E-8	2.54	5.15E-8	+ 4.3%
1.6E-3	3.14E-8	1.21E-8	2.58	1.48E-8	+ 4.1%
4.0E-3	7.85E-8	3.04E-8	2.58	3.77E-8	+ 3.8%
1.0E-2	6.00E-8	2.26E-8	2.66	3.12E-8	+ 2.8%
2.5E-2	7.95E-8	2.88E-8	2.76	4.75E-8	+ 2.1%
6.3E-2	1.34E-7	4.81E-8	2.79	7.20E-8	+ 4.5%
1.6E-1	7.77E-8	2.69E-8	2.88	3.53E-8	+ 4.8%
2.5E-1	9.92E-8	3.25E-8	3.05	3.36E-8	+ 5.4%
4.0E-1	1.46E-7	4.69E-8	3.11	4.88E-8	+ 3.3%
6.3E-1	2.05E-7	6.47E-8	3.17	8.47E-8	+ 1.5%
1.0	2.71E-7	7.64E-8	3.55	1.04E-7	+ 1.1%
1.6	3.24E-7	8.87E-8	3.65	1.05E-7	+ 0.7%
2.5	3.23E-7	8.76E-8	3.68	8.42E-8	+ 0.7%
4.0	2.36E-7	6.04E-8	3.91	5.04E-8	+ 0.6%
6.3	9.88E-8	2.47E-8	4.00	1.71E-8	+ 0.9%
1.0E+1	1.04E-8	2.59E-9	4.03	1.97E-9	+ 3.4%
1.6E+1

Figure 16-1. Californium-252 in a 10-cm-thick polyethylene moderator.

Figure 16-2. Californium-252 in a 10-cm-thick polyethylene moderator.

Figure 16-3. Californium-252 in a 10-cm-thick polyethylene moderator.

Table 16-2. Values derived from the spectra for ^{252}Cf in a 10-cm-thick polyethylene moderator.

Total fluences per source neutron

From ANISN calculations			Measured
1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)
4.41E-6	1.71E-6	2.58	1.73E-6 + 0.4%

Average energy of the measured spectrum

Above 0.025 eV: 0.68 MeV
Above 0.400 eV: 1.13 MeV

Source-yield to dose conversion factors

	From ANISN calculations		Measured
	1 meter	2 meters	2 meters
Absorbed dose (rads/source n)	8.04E-15	2.47E-15	2.55E-15
Tissue kerma (rads/source n)	5.56E-15	1.55E-15	1.65E-15
NCRP dose eq. (rems/source n)	6.48E-14	1.87E-14	2.03E-14
ICRP dose eq. (rems/source n)	6.44E-14	1.85E-14	2.00E-14

This moderator was constructed after the measurements of the other configurations with the liquid-scintillator neutron spectrometer were complete, so there are no liquid scintillator results for this source, moderator combination, and thus, no Fig. 17-2. Reasonable agreement was obtained between the liquid-scintillator and multisphere results for the other configurations, so the multisphere measurements are probably sufficient. It would always be possible to make the liquid-scintillator measurements should they become necessary.

In this case, the calculated spectra were obtained using the MORSE Monte Carlo code rather than the ANISN discrete ordinate code. Table 17-1 and Fig. 17-1 show that there are a number of differences between the measured and calculated spectra at 2 m. The lowest energy bin is considerably different, but the measured value is preferred. Above 1 MeV the measurements and calculations agree as well as could be expected.

Ratios of the 1-to-2-m calculated fluences are almost 3 at the lowest energies. This thick moderator obviously moves many of the source neutrons down to these low energies. The ratios do not become 4 below 4 MeV, even for this moderator.

The measured and calculated values of total kerma per source neutron given in Table 17-2 have a percentage difference of 6%, as do comparable dose equivalent values. The values of total fluence per source neutron, however, have a 43% percentage difference, and that of the related absorbed dose values is 16%. Even when the lowest energy bin is excluded, the total fluence values still have a 19% percentage difference.

This source-moderator combination produced a measured mean energy at 2 m of 700 keV, which is essentially the same as that obtained with the 10-cm polyethylene moderator. The integral spectrum, shown in Fig. 17-3, indicates a median energy for the measured fluence of 6.3 eV. Median energies for the absorbed dose and dose equivalent are 1 MeV, and for the kerma 1.5 MeV. These latter values are not significantly different from those obtained with the bare source.

Table 17-1. Differential spectra from ^{252}Cf in a 15-cm-thick polyethylene moderator.

Fluence values are normalized to one source neutron

Bottom energy (MeV)	From MORSE calculations			Measured 2 meters (n/cm ²)		
	1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m			
2.5E-8	1.67E-7	1.48E-7	1.13	3.49E-7	±	0.0%
4.0E-7	1.35E-8	5.06E-9	2.67	6.36E-9	±	3.3%
1.0E-6	3.38E-8	1.27E-8	2.67	1.43E-8	±	3.4%
2.5E-6	2.35E-8	8.00E-9	2.94	9.84E-9	±	5.2%
6.3E-6	2.56E-8	7.03E-9	3.64	1.04E-8	±	6.8%
1.6E-5	2.74E-8	7.80E-9	3.52	1.23E-8	±	6.1%
4.0E-5	1.30E-8	4.60E-9	2.82	8.72E-9	±	2.2%
1.0E-4	2.36E-8	8.38E-9	2.82	1.66E-8	±	2.9%
2.5E-4	1.54E-8	5.45E-9	2.83	5.79E-9	±	15.7%
6.3E-4	3.90E-8	1.38E-8	2.83	2.00E-8	±	5.9%
1.6E-3	1.04E-8	3.27E-9	3.19	5.61E-9	±	5.1%
4.0E-3	2.61E-8	8.17E-9	3.19	1.57E-8	±	10.6%
1.0E-2	2.24E-8	7.53E-9	2.97	1.40E-8	±	3.8%
2.5E-2	3.39E-8	1.22E-8	2.78	2.17E-8	±	3.0%
6.3E-2	5.95E-8	2.23E-8	2.67	3.39E-8	±	4.7%
1.6E-1	3.54E-8	1.39E-8	2.56	1.99E-8	±	5.2%
2.5E-1	4.12E-8	1.59E-8	2.59	1.79E-8	±	8.3%
4.0E-1	6.02E-8	2.28E-8	2.64	2.33E-8	±	7.1%
6.3E-1	9.78E-8	3.86E-8	2.53	3.05E-8	±	5.8%
1.0	1.22E-7	3.72E-8	3.29	3.77E-8	±	5.6%
1.6	1.35E-7	3.87E-8	3.48	3.80E-8	±	4.3%
2.5	1.30E-7	3.59E-8	3.61	3.69E-8	±	4.6%
4.0	8.41E-8	2.23E-8	3.77	2.37E-8	±	5.9%
6.3	3.64E-8	9.25E-9	3.93	1.15E-8	±	3.1%
1.0E+1	4.44E-9	1.11E-9	3.99	1.27E-9	±	33.2%
1.6E+1

Figure 17-1. Californium-252 in a 15-cm-thick polyethylene moderator.

Figure 17-3. Californium-252 in a 15-cm-thick polyethylene moderator.

Table 17-2. Values derived from the spectra for ^{252}Cf in a 15-cm-thick polyethylene moderator.

<u>Total fluences per source neutron</u>				
From MORSE calculations			Measured	
1 meter	2 meters	1m/2m	2 meters	
(n/cm ²)	(n/cm ²)		(n/cm ²)	
1.28E-6	5.10E-7	2.51	7.85E-7	± 0.7%

<u>Average energy of the measured spectrum</u>	
Above 0.025 eV:	0.68 MeV
Above 0.400 eV:	1.22 MeV

<u>Source-yield to dose conversion factors</u>				
	From MORSE calculations		Measured	
	1 meter	2 meters	2 meters	
Absorbed dose (rads/source n)	2.99E-15	9.54E-16	1.12E-15	
Tissue kerma (rads/source n)	2.25E-15	6.78E-16	7.09E-16	
NCRP dose eq. (rems/source n)	2.62E-14	8.18E-15	8.60E-15	
ICRP dose eq. (rems/source n)	2.59E-14	7.98E-15	8.43E-15	

18. $^{238}\text{PuBe}$, NO MODERATOR

Variations between measured and calculated fluence values show clearly in Fig. 18-1. In the lowest energy bin of the calculations, there are 75% more neutrons than were measured. Because of the wide range of PuBe spectra available in the literature, an inappropriate input spectrum may have been used for the calculations. Over 60% of the neutrons in this spectrum were measured by the liquid scintillator, and the multisphere system provides a precise value for the lowest energy bin. Therefore, we have confidence in the measurements, and recommend using them and the dosimetric values obtained from them.

A PuBe source produces few neutrons with energies below 0.5 MeV. This is the reason why the 1-to-2-m ratios of the calculated fluences are so near unity from 0.025 eV to 160 keV. All of these neutrons result from scattering off of the cell walls. Even for this relatively energetic spectrum, scattering is significant, as shown by the divergence of the fluence ratios from 4 below 4 MeV.

The liquid-scintillator results (Fig. 18-2) show how many of the details in this spectrum are lost when the data are presented in the bin structure used with the multisphere spectrometer. As discussed in our earlier report on the liquid-scintillator system, these detailed results agree quite well with a calculated PuBe spectrum.²

Table 18-2 shows that the percentage difference between the measured value of the total fluence per source neutron and the comparable value obtained from the calculations at 2 m is only 6%. However, the corresponding dosimetric values have percentage differences of 9 to 12%.

The average energy of the spectrum measured at 2 m is 2.7 MeV, but the median energy is near 1 MeV (see the integral plot in Fig. 18-3). For both the absorbed dose and kerma, the median energy is 3.5 MeV; for dose equivalent it is 3 MeV. Obviously, the higher energy neutrons produce a major contribution to the dosimetric values.

Table 18-1. Differential spectra from $^{238}\text{PuBe}$ without a moderator.

Fluence values are normalized to one source neutron

Bottom energy (MeV)	From ANISN calculations			Measured	
	1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)	
2.5E-8	6.29E-7	6.30E-7	1.00	3.59E-7	$\pm$ 0.7%
4.0E-7	1.89E-8	1.89E-8	1.00	1.81E-8	$\pm$ 3.2%
1.0E-6	4.73E-8	4.74E-8	1.00	4.52E-8	$\pm$ 2.5%
2.5E-6	2.97E-8	2.97E-8	1.00	3.03E-8	$\pm$ 2.8%
6.3E-6	2.56E-8	2.56E-8	1.00	3.03E-8	$\pm$ 3.6%
1.6E-5	2.94E-8	2.94E-8	1.00	3.58E-8	$\pm$ 3.6%
4.0E-5	2.08E-8	2.08E-8	1.00	2.62E-8	$\pm$ 1.5%
1.0E-4	3.69E-8	3.70E-8	1.00	4.62E-8	$\pm$ 3.0%
2.5E-4	1.74E-8	1.74E-8	1.00	2.22E-8	$\pm$ 2.5%
6.3E-4	4.40E-8	4.41E-8	1.00	5.61E-8	$\pm$ 4.4%
1.6E-3	1.47E-8	1.48E-8	1.00	1.61E-8	$\pm$ 4.6%
4.0E-3	3.69E-8	3.70E-8	1.00	3.93E-8	$\pm$ 2.3%
1.0E-2	2.73E-8	2.73E-8	1.00	3.24E-8	$\pm$ 4.2%
2.5E-2	3.44E-8	3.45E-8	1.00	5.03E-8	$\pm$ 3.3%
6.3E-2	5.96E-8	5.89E-8	1.01	9.95E-8	$\pm$ 3.0%
1.6E-1	6.12E-8	4.00E-8	1.53	7.32E-8	$\pm$ 3.5%
2.5E-1	1.90E-7	7.46E-8	2.55	1.56E-7	$\pm$ 3.0%
4.0E-1	2.92E-7	1.12E-7	2.60	2.25E-7	$\pm$ 1.6%
6.3E-1	4.63E-7	1.68E-7	2.75	2.14E-7	$\pm$ 1.5%
1.0	8.16E-7	2.46E-7	3.32	2.29E-7	$\pm$ 1.1%
1.6	1.09E-6	3.16E-7	3.43	2.93E-7	$\pm$ 0.8%
2.5	1.71E-6	4.82E-7	3.54	5.60E-7	$\pm$ 0.6%
4.0	2.19E-6	5.66E-7	3.87	6.00E-7	$\pm$ 0.5%
6.3	1.54E-6	3.87E-7	3.99	3.72E-7	$\pm$ 0.5%
1.0E+1	4.89E-8	1.21E-8	4.03	6.03E-8	$\pm$ 0.9%
1.6E+1

Figure 18-1. Plutonium-238 beryllium without a moderator.

Figure 18-2. Plutonium-238 beryllium without a moderator.

Figure 18-3. Plutonium-238 beryllium without a moderator.

Table 18-2. Values derived from the spectra for $^{238}\text{PuBe}$ without a moderator.

Total fluences per source neutron

From ANISN calculations			Measured
1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)
9.47E-6	3.48E-6	2.72	3.69E-6 $\pm$ 0.3%

Average energy of the measured spectrum

Above 0.025 eV: 2.71 MeV
Above 0.400 eV: 3.00 MeV

Source-yield to dose conversion factors

	From ANISN calculations		Measured
	1 meter	2 meters	2 meters
Absorbed dose (rads/source n)	3.96E-14	1.13E-14	1.24E-14
Tissue kerma (rads/source n)	3.16E-14	8.74E-15	9.75E-15
NCRP dose eq. (rems/source n)	3.19E-13	9.03E-14	1.02E-13
ICRP dose eq. (rems/source n)	3.22E-13	9.09E-14	1.00E-13

The 2-m fluence data given in Table 19-1, and plotted in Fig. 19-1, show that the measured spectrum for this source-moderator combination is generally greater than the corresponding calculations. A moderator this thick produces a spectrum that is both hard to measure and hard to calculate. That part of the spectrum measured by the liquid scintillator contributes less than 40% of the total measured fluence, but the calculations differ so much from the measurements above 0.1 MeV that we recommend using the measured values. It is hard to estimate the quality of the multisphere results, but they do not have the same problems for this source in this moderator as was experienced with the ²⁵²Cf source.

Even at the lowest energies, the ratios of the calculated fluences at 1 m to those at 2 m are greater than 2. While they are much smaller than the values that would be expected from geometric considerations (i.e., 4), they are also significantly larger than the unity ratio that would result from a uniform field of neutrons coming from room scattering. Obviously the moderator is slowing down a significant number of the neutrons produced by the source.

The spectrum above 0.5 MeV, shown in detail in Fig. 19-2, includes details caused by the resonances in the oxygen cross section as well as the features inherent in the PuBe spectrum. Effects of resonances in the cross section of the materials in the moderators is discussed further in Section 29. This detailed spectrum does not provide any clues about the source of the disagreement between the measurements and calculations.

Even with the large apparent difference between the measurements and the calculations, there is only a 10% percentage difference in the calculated and measured values of the total fluence per source neutron, given in Table 19-2. The difference isn't larger because the calculated fluence in the lowest energy bin exceeds the measured value by 44%. Above 1 MeV, the differences in the fluences result in percentage differences of 33 to 42% for the total dosimetric values deduced from the calculations and measurements.

The average energy of the measured spectrum is 1.6 MeV, just over half that of the unmoderated PuBe source. This lower average energy is reflected in the integral spectra for 2 m shown in Fig. 19-3, which show median energies of 25 keV for the fluence, 2.5 MeV for absorbed dose and dose equivalent, and 3 MeV for kerma.

Table 19-1. Differential spectra from $^{238}\text{PuBe}$ in a 25-cm-thick water moderator.

Fluence values are normalized to one source neutron

Bottom energy (MeV)	From ANISN calculations			Measured	
	1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)	
2.5E-8	7.97E-7	3.67E-7	2.17	2.55E-7	+ 0.2%
4.0E-7	1.11E-8	5.15E-9	2.15	8.77E-9	+ 4.6%
1.0E-6	2.76E-8	1.29E-8	2.15	1.93E-8	+ 3.2%
2.5E-6	1.77E-8	8.10E-9	2.19	1.30E-8	+ 2.2%
6.3E-6	1.62E-8	7.04E-9	2.30	1.15E-8	+ 6.5%
1.6E-5	1.85E-8	8.03E-9	2.30	1.10E-8	+ 9.1%
4.0E-5	1.26E-8	5.47E-9	2.31	7.45E-9	+ 5.1%
1.0E-4	2.25E-8	9.70E-9	2.31	1.33E-8	+ 5.6%
2.5E-4	1.05E-8	4.45E-9	2.35	5.98E-9	+ 7.1%
6.3E-4	2.65E-8	1.13E-8	2.35	1.54E-8	+ 3.8%
1.6E-3	8.98E-9	3.72E-9	2.42	4.48E-9	+ 7.3%
4.0E-3	2.25E-8	9.29E-9	2.42	1.12E-8	+ 3.2%
1.0E-2	1.70E-8	6.86E-9	2.47	9.31E-9	+ 9.7%
2.5E-2	2.21E-8	8.64E-9	2.56	1.44E-8	+ 5.1%
6.3E-2	3.73E-8	1.44E-8	2.59	2.09E-8	+ 4.7%
1.6E-1	2.13E-8	7.98E-9	2.67	1.27E-8	+ 4.9%
2.5E-1	2.60E-8	9.21E-9	2.82	1.99E-8	+ 6.0%
4.0E-1	4.04E-8	1.39E-8	2.90	2.87E-8	+ 3.7%
6.3E-1	5.75E-8	1.92E-8	3.00	3.24E-8	1.6%
1.0	7.54E-8	2.25E-8	3.35	4.20E-8	+ 1.1%
1.6	1.18E-7	3.34E-8	3.53	5.68E-8	+ 0.8%
2.5	1.48E-7	4.12E-8	3.59	6.35E-8	+ 0.7%
4.0	1.82E-7	4.72E-8	3.86	6.42E-8	+ 0.7%
6.3	1.56E-7	3.90E-8	4.00	4.59E-8	+ 0.8%
1.0E+1	5.02E-9	1.25E-9	4.04	7.51E-9	+ 1.4%
1.6E+1

Figure 19-1. Plutonium-238 beryllium in a 25-cm-thick water moderator.

Figure 19-2. Plutonium-238 beryllium in a 25-cm-thick water moderator.

Figure 19-3. Plutonium-238 beryllium in a 25-cm-thick water moderator.

Table 19-2. Values derived from the spectra for $^{238}\text{PuBe}$ in a 25-cm-thick water moderator.

Total fluences per source neutron

From ANISN calculations			Measured
1 meter	2 meters	1m/2m	2 meters
(n/cm ²)	(n/cm ²)		(n/cm ²)
1.90E-6	7.17E-7	2.65	7.95E-7 $\pm$ 0.4%

Average energy of the measured spectrum

Above 0.025 eV: 1.55 MeV
 Above 0.400 eV: 2.29 MeV

Source-yield to dose conversion factors

	From ANISN calculations		Measured
	1 meter	2 meters	2 meters
Absorbed dose (rads/source n)	4.27E-15	1.26E-15	1.76E-15
Tissue kerma (rads/source n)	3.05E-15	8.37E-16	1.27E-15
NCRP dose eq. (rems/source n)	3.18E-14	9.06E-15	1.38E-14
ICRP dose eq. (rems/source n)	3.21E-14	9.09E-15	1.37E-14

The 2-m data from Table 20-1, which are plotted in Fig. 20-1 show reasonable, but not exceptional, agreement between the measurements and the calculations. We recommend using the measured data, and the values derived from it.

Because the 1-to-2-m ratios of the calculated fluences are greater than one at all energies, some of the low-energy neutrons reaching the detector must come directly from the moderator. Even so, it is only for neutrons with energies above 4 MeV that the ratios approach 4. Most of the neutrons observed at the lowest energies are getting to the detector after scattering from the walls of the cell.

As shown in Fig. 20-2, effects from the resonances in the oxygen cross section are just barely evident in the detailed spectrum obtained with the liquid scintillator. Otherwise the spectrum looks much like that from the bare source. The energies of the principal resonances in the oxygen cross section are given in Section 29.

In Table 20-2, the total fluence per source neutron measured at 2 m for this source, moderator combination matches the corresponding value obtained from the calculations almost exactly. However, the percentage differences for the dosimetric values calculated from the measured spectrum are 10 to 13% larger than the corresponding values determined from the calculated spectrum. That implies that the measured spectrum is harder.

The mean energy of the spectrum measured at 2 m is 1.9 MeV, which is significantly below that obtained for the source without a moderator. Figure 20-3 shows integral versions of the measured spectrum. These spectra have median energies of 250 keV for the fluence, 3 MeV for the absorbed dose and kerma, and 2.5 MeV for the dose equivalent.

Table 20-1. Differential spectra from $^{238}\text{PuBe}$ in a 5-cm-thick heavy-water moderator.

Fluence values are normalized to one source neutron

Bottom energy (MeV)	From ANISN calculations			Measured	
	1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)	
2.5E-8	7.91E-7	7.79E-7	1.02	4.50E-7	+ 0.1%
4.0E-7	3.02E-8	2.64E-8	1.14	1.52E-8	+ 8.0%
1.0E-6	7.54E-8	6.59E-8	1.14	3.97E-8	+ 12.8%
2.5E-6	5.26E-8	4.28E-8	1.23	2.90E-8	+ 16.2%
6.3E-6	5.74E-8	4.03E-8	1.43	4.03E-8	+ 14.8%
1.6E-5	7.12E-8	4.77E-8	1.49	5.81E-8	+ 6.7%
4.0E-5	6.77E-8	3.83E-8	1.77	5.33E-8	+ 6.0%
1.0E-4	1.22E-7	6.86E-8	1.78	9.91E-8	+ 7.4%
2.5E-4	7.36E-8	3.64E-8	2.03	5.27E-8	+ 14.0%
6.3E-4	1.86E-7	9.20E-8	2.03	1.43E-7	+ 6.8%
1.6E-3	1.03E-7	4.10E-8	2.51	3.55E-8	+ 10.3%
4.0E-3	2.57E-7	1.02E-7	2.51	9.83E-8	+ 6.5%
1.0E-2	2.40E-7	8.71E-8	2.75	7.48E-8	+ 2.9%
2.5E-2	3.92E-7	1.30E-7	3.01	1.11E-7	+ 8.1%
6.3E-2	6.38E-7	2.10E-7	3.03	2.22E-7	+ 3.8%
1.6E-1	3.24E-7	1.06E-7	3.07	1.02E-7	+ 6.3%
2.5E-1	2.94E-7	9.72E-8	3.03	1.45E-7	+ 10.2%
4.0E-1	3.91E-7	1.30E-7	3.02	2.01E-7	+ 9.4%
6.3E-1	4.59E-7	1.52E-7	3.01	1.77E-7	+ 1.5%
1.0	5.61E-7	1.69E-7	3.32	1.82E-7	+ 1.1%
1.6	7.98E-7	2.32E-7	3.44	2.56E-7	+ 0.8%
2.5	1.27E-6	3.56E-7	3.58	4.05E-7	+ 0.7%
4.0	1.46E-6	3.77E-7	3.87	4.05E-7	+ 0.5%
6.3	9.83E-7	2.46E-7	4.00	2.50E-7	+ 0.6%
1.0E+1	2.96E-8	7.34E-9	4.03	3.89E-8	+ 1.1%
1.6E+1

Figure 20-1. Plutonium-238 beryllium in a 5-cm-thick heavy-water moderator.

Figure 20-2. Plutonium-238 beryllium in a 5-cm-thick heavy-water moderator.

Figure 20-3. Plutonium-238 beryllium in a 5-cm-thick heavy-water moderator.

Table 20-2. Values derived from the spectra for $^{238}\text{PuBr}$ 5-cm-thick heavy-water moderator.

Total fluences per source neutron

From ANISN calculations			Measured
1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)
9.73E-6	3.68E-6	2.64	3.68E-6 $\pm$ 0.9%

Average energy of the measured spectrum

Above 0.025 eV: 1.91 MeV

Above 0.400 eV: 2.18 MeV

Source-yield to dose conversion factors

	From ANISN calculations		Measured
	1 meter	2 meters	2 meters
Absorbed dose (rads/source n)	2.98E-14	8.67E-15	9.56E-15
Tissue kerma (rads/source n)	2.34E-14	6.46E-15	7.31E-15
NCRP dose eq. (rems/source n)	2.42E-13	6.87E-14	7.80E-14
ICRP dose eq. (rems/source n)	2.41E-13	6.84E-14	7.68E-14

21. $^{238}\text{PuBe}$ IN A 10-cm HEAVY-WATER MODERATOR

Figure 21-1 (or Table 21-1) shows that the measured and calculated 2-m data agree only approximately. There are significantly more neutrons in the measured spectrum in the energy range from 100 keV to 6 MeV, and significantly less from 0.025 to 6 eV. We have good confidence in the measured data above 1 MeV, since it was obtained with the liquid scintillator, so we recommend using it and the values derived from it.

Although the 1-to-2-m ratios of the calculated fluences are considerably less than four below 4 MeV, they remain near 2 down to the lowest energies. Many of the low-energy neutrons must be coming from the source rather than just scattering from the cell walls.

The resonances in the oxygen cross sections produce a significant effect on the detailed fluence spectrum measured with the liquid scintillator (Fig. 21-2). However, they are still difficult to separate from the details in the PuBe spectrum. This effect is discussed further in Section 29.

For this combination of source and moderator, Table 21-2 shows that the total fluence per source neutron obtained from the measurements has a percentage difference of only 4% from that from the calculated spectrum. On the average, the measured spectrum is harder than the calculations, which shows in the relatively poor agreement in the total dosimetric values derived from the measured and calculated spectra (percentage differences from 12 to 18%).

This source-moderator combination produces an average energy of 1.3 MeV for the spectrum measured at 2 m. The median energy of the measured fluence is 25 keV, of the absorbed dose and dose equivalent 2.5 MeV, and of the kerma 3 MeV. These values can be obtained from the integral versions of the measurements that are shown in Fig. 21-3.

Table 21-1. Differential spectra from $^{238}\text{PuBe}$ in a 10-cm-thick heavy-water moderator.

Fluence values are normalized to one source neutron

Bottom energy (MeV)	From ANISN calculations			Measured	
	1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)	
2.5E-8	1.27E-6	1.03E-6	1.24	5.95E-7	+ 0.1%
4.0E-7	7.29E-8	4.11E-8	1.77	2.79E-8	+ 4.3%
1.0E-6	1.82E-7	1.03E-7	1.77	8.36E-8	+ 2.8%
2.5E-6	1.39E-7	7.05E-8	1.97	6.02E-8	+ 3.6%
6.3E-6	1.74E-7	7.44E-8	2.34	7.07E-8	+ 7.7%
1.6E-5	2.13E-7	8.84E-8	2.40	9.32E-8	+ 7.9%
4.0E-5	1.92E-7	7.24E-8	2.66	8.28E-8	+ 3.8%
1.0E-4	3.43E-7	1.29E-7	2.66	1.37E-7	+ 3.0%
2.5E-4	1.69E-7	6.11E-8	2.77	6.76E-8	+ 10.3%
6.3E-4	4.28E-7	1.55E-7	2.77	1.82E-7	+ 7.1%
1.6E-3	1.88E-7	6.17E-8	3.04	5.04E-8	+ 3.9%
4.0E-3	4.70E-7	1.54E-7	3.04	1.20E-7	+ 9.7%
1.0E-2	3.74E-7	1.18E-7	3.16	1.04E-7	+ 7.7%
2.5E-2	5.19E-7	1.57E-7	3.30	1.52E-7	+ 7.4%
6.3E-2	7.41E-7	2.26E-7	3.29	2.47E-7	+ 4.0%
1.6E-1	2.87E-7	8.88E-8	3.23	1.02E-7	+ 6.2%
2.5E-1	2.09E-7	6.77E-8	3.08	1.08E-7	+ 5.1%
4.0E-1	2.70E-7	8.81E-8	3.06	1.60E-7	+ 4.9%
6.3E-1	2.88E-7	9.58E-8	3.01	1.22E-7	+ 1.6%
1.0	3.32E-7	1.01E-7	3.27	1.30E-7	+ 1.1%
1.6	5.40E-7	1.57E-7	3.45	1.93E-7	+ 0.8%
2.5	8.60E-7	2.39E-7	3.60	2.76E-7	+ 0.6%
4.0	9.56E-7	2.47E-7	3.88	2.71E-7	+ 0.5%
6.3	6.29E-7	1.57E-7	4.00	1.67E-7	+ 0.5%
1.0E+1	1.83E-8	4.53E-9	4.03	2.52E-8	+ 1.0%
1.6E+1

Figure 21-1. Plutonium-238 beryllium in a 10-cm-thick heavy-water moderator.

Figure 21-2. Plutonium-238 beryllium in a 10-cm-thick heavy-water moderator.

Figure 21-3. Plutonium-238 beryllium in a 10-cm-thick heavy-water moderator.

Table 21-2. Values derived from the spectra for $^{238}\text{PuBe}$ in a 10-cm-thick heavy-water moderator.

Total fluences per source neutron

From ANISN calculations			Measured
1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)
9.86E-6	3.79E-6	2.61	3.63E-6 $\pm$ 0.8%

Average energy of the measured spectrum

Above 0.025 eV: 1.33 MeV
Above 0.400 eV: 1.59 MeV

Source-yield to dose conversion factors

	From ANISN calculations		Measured
	1 meter	2 meters	2 meters
Absorbed dose (rads/source n)	2.14E-14	6.41E-15	7.20E-15
Tissue kerma (rads/source n)	1.58E-14	4.35E-15	5.20E-15
NCRP dose eq. (rems/source n)	1.65E-13	4.73E-14	5.66E-14
ICRP dose eq. (rems/source n)	1.65E-13	4.71E-14	5.56E-14

Figure 22-1 is a plot of the 2-m fluence data from Table 22-1. It shows that, excluding the lowest energy bin, the measurements and calculations of this spectrum agree quite well up to 250 keV. This moderator obviously has a large effect on the spectrum. The poor agreement in the first bin is easily explained; the moderator was enclosed in cadmium for the measurements but not for the calculations. Above 250 keV the calculated fluences are significantly below the measured values. We have good confidence in the measured values above 500 keV, because they were obtained with the liquid scintillator, and in the lowest energy bin value that was derived from the multisphere system. Thus, we believe the measured spectrum, and values derived from it, should be used.

Like the other spectra presented in this report, the 1-to-2-m ratios of the calculated fluences is not 4, the value expected from R^2 considerations, until the neutron energy is above 4 MeV. Omitting the lowest energy bin, the smallest the ratio is 2.3. A significant number of the low energy neutrons must reach the detector directly.

The liquid-scintillator results, shown in Fig. 22-2, clearly show the effects of the resonances in the cross section of the oxygen in the heavy water. This effect is discussed in more detail in Section 29.

From the data in Table 22-2, the percentage difference between the total fluences per source neutron from the measurements and the 2-m calculations is 17%. Corresponding percentage differences for the total dosimetric values range from 8 to 22%.

Overall the measured spectrum has an average energy of 1 MeV. Figure 22-3 shows integral spectra derived from the measurements. They have median energies of 1.6 keV for the fluence, 2 MeV for the absorbed dose and dose equivalent 2 MeV, and 3 MeV for the kerma. Median energies for the dosimetric values remain high because most of the contribution to their values comes from the more energetic neutrons.

Table 22-1. Differential spectra from $^{238}\text{PuBe}$ in a 15-cm-thick heavy-water moderator.

Fluence values are normalized to one source neutron

Bottom energy (MeV)	From ANISN calculations			Measured	
	1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)	
2.5E-8	2.35E-6	1.44E-6	1.63	5.33E-7	± 0.2%
4.0E-7	1.21E-7	5.33E-8	2.27	4.31E-8	± 10.1%
1.0E-6	3.03E-7	1.33E-7	2.27	1.23E-7	± 2.1%
2.5E-6	2.27E-7	9.21E-8	2.46	8.52E-8	± 8.3%
6.3E-6	2.78E-7	9.87E-8	2.82	1.01E-7	± 5.8%
1.6E-5	3.30E-7	1.15E-7	2.86	1.19E-7	± 5.4%
4.0E-5	2.69E-7	8.85E-8	3.03	8.21E-8	± 10.1%
1.0E-4	4.74E-7	1.56E-7	3.04	1.63E-7	± 5.9%
2.5E-4	2.01E-7	6.56E-8	3.07	6.92E-8	± 6.3%
6.3E-4	5.09E-7	1.66E-7	3.07	1.95E-7	± 6.9%
1.6E-3	1.89E-7	5.86E-8	3.23	6.48E-8	± 9.9%
4.0E-3	4.72E-7	1.46E-7	3.23	1.43E-7	± 2.2%
1.0E-2	3.45E-7	1.05E-7	3.29	1.22E-7	± 3.2%
2.5E-2	4.28E-7	1.26E-7	3.40	1.72E-7	± 2.4%
6.3E-2	5.74E-7	1.70E-7	3.37	1.99E-7	± 4.7%
1.6E-1	1.89E-7	5.79E-8	3.27	6.25E-8	± 11.3%
2.5E-1	1.27E-7	4.14E-8	3.08	4.11E-8	± 11.2%
4.0E-1	1.65E-7	5.39E-8	3.07	8.21E-8	± 8.2%
6.3E-1	1.69E-7	5.67E-8	2.99	8.07E-8	± 1.6%
1.0	1.92E-7	5.95E-8	3.23	8.95E-8	± 1.1%
1.6	3.46E-7	1.00E-7	3.45	1.38E-7	± 0.8%
2.5	5.44E-7	1.51E-7	3.61	1.84E-7	± 0.6%
4.0	6.02E-7	1.55E-7	3.88	1.79E-7	± 0.5%
6.3	3.93E-7	9.84E-8	4.00	1.10E-7	± 0.5%
1.0E+1	1.12E-8	2.78E-9	4.03	1.53E-8	± 1.0%
1.6E+1

Figure 22-1. Plutonium-238 beryllium in a 15-cm-thick heavy-water moderator.

Figure 22-2. Plutonium-238 beryllium in a 15-cm-thick heavy-water moderator.

Figure 22-3. Plutonium-238 beryllium in a 15-cm-thick heavy-water moderator.

Table 22-2. Values derived from the spectra for $^{238}\text{PuBe}$ in a 15-cm-thick heavy-water moderator.

Total fluences per source neutron

From ANISN calculations			Measured
1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)
9.81E-6	3.79E-6	2.59	3.20E-6 $\pm$ 0.9%

Average energy of the measured spectrum

Above 0.025 eV: 1.00 MeV

Above 0.400 eV: 1.19 MeV

Source-yield to dose conversion factors

	From ANISN calculations		Measured
	1 meter	2 meters	2 meters
Absorbed dose (rads/source n)	1.53E-14	4.75E-15	5.15E-15
Tissue kerma (rads/source n)	1.00E-14	2.78E-15	3.46E-15
NCRP dose eq. (rems/source n)	1.08E-13	3.13E-14	3.81E-14
ICRP dose eq. (rems/source n)	1.08E-13	3.12E-14	3.77E-14

23. $^{238}\text{PuBe}$ IN A 25-cm HEAVY-WATER MODERATOR

It is obvious from Fig. 23-1 (or Table 23-1) that the measured spectrum for this source, moderator combination agrees poorly with the calculated spectrum. That is probably not surprising given the large effect that a moderator this thick will have on the energy of the neutrons. Most of the problem is in the measurements between 0.25 to 0.63 MeV. This problem may reflect an error in one or more of the response functions used for the multispheres, or it might have been alleviated by including a 51-mm moderator sphere in the measurements.

In the region above 500 keV, which is measured with the liquid scintillator, the measured spectrum has considerably more neutrons per energy bin than the calculations. We normally recommend using the measured values, but the problems at lower energies prevent that. We do not, however, have complete confidence in the calculations for this spectrum.

The ratios of the 1-to-2-m calculated fluence values are near 3 in the lowest energy bins. Obviously a large percentage of the neutrons with these energies reach the detector directly from the moderator rather than from scattering from the cell walls. The fluence ratios do not approach 4, however, until the neutrons have energies of at least 4 MeV, which is common to all of these spectra.

Figure 23-2 shows the liquid scintillator results for this case. The intensity of this spectrum is considerably below that from the bare source, showing the large amount of attenuation produced by this thick moderator. Even so, this spectrum still retains most of the features of the bare source. The effects of the resonances in the oxygen cross sections are obvious. See Section 29 for more discussion of this effect.

Despite the large differences in the differential spectra, the measured and calculated total fluences per source neutron at 2 m given in Table 23-2 have a percentage difference of only 8%. As might be expected, the poor agreement of the spectra at the higher energies makes the percentage differences for the total dosimetric values derived from the spectra larger, 9% for absorbed dose, 30% for kerma, and 22% for dose equivalent. The latter both depend heavily on the more energetic neutrons so we believe the measured values are the better choice for these total quantities.

The mean energy of the spectrum measured at 2 m is only 440 keV, and the median energy falls below 0.025 eV. Other median energies determined from the integral version of the measured spectra, shown in Fig. 23-3, are 160 keV for the absorbed dose, 3 MeV for kerma, and 2 MeV for dose equivalent. The high median energies for kerma and dose equivalent are consistent with the argument that the measured values are appropriate for these parameters.

Table 23-1. Differential spectra from $^{238}\text{PuBe}$ in a 25-cm-thick heavy-water moderator.

Fluence values are normalized to one source neutron

Bottom energy (MeV)	From ANISN calculations			Measured		
	1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)		
2.5E-8	5.37E-6	2.41E-6	2.22	1.94E-6	±	0.0%
4.0E-7	1.30E-7	4.78E-8	2.72	5.82E-8	±	9.7%
1.0E-6	3.25E-7	1.20E-7	2.72	1.37E-7	±	4.6%
2.5E-6	2.31E-7	8.09E-8	2.85	9.08E-8	±	4.8%
6.3E-6	2.60E-7	8.28E-8	3.13	8.75E-8	±	4.4%
1.6E-5	2.97E-7	9.42E-8	3.15	8.17E-8	±	7.5%
4.0E-5	2.04E-7	6.33E-8	3.23	1.43E-8	±	62.4%
1.0E-4	3.61E-7	1.12E-7	3.23	9.08E-8	±	4.4%
2.5E-4	1.58E-7	4.75E-8	3.32	2.49E-8	±	31.7%
6.3E-4	3.99E-7	1.20E-7	3.32	1.22E-7	±	5.9%
1.6E-3	1.16E-7	3.41E-8	3.39	5.66E-8	±	7.0%
4.0E-3	2.89E-7	8.54E-8	3.39	1.02E-7	±	4.5%
1.0E-2	1.89E-7	5.55E-8	3.41	9.49E-8	±	2.9%
2.5E-2	1.95E-7	5.64E-8	3.46	1.11E-7	±	4.7%
6.3E-2	2.49E-7	7.28E-8	3.41	8.90E-8	±	1.5%
1.6E-1	7.10E-8	2.18E-8	3.26	1.55E-8	±	16.5%
2.5E-1	4.92E-8	1.60E-8	3.08	1.12E-9	±	41.5%
4.0E-1	6.21E-8	2.05E-8	3.03	2.07E-9	±	46.2%
6.3E-1	6.54E-8	2.20E-8	2.97	3.59E-8	±	1.6%
1.0	7.43E-8	2.32E-8	3.21	4.11E-8	±	1.1%
1.6	1.44E-7	4.15E-8	3.47	6.81E-8	±	0.9%
2.5	2.23E-7	6.18E-8	3.61	8.78E-8	±	0.7%
4.0	2.60E-7	6.69E-8	3.89	8.71E-8	±	0.6%
6.3	1.71E-7	4.28E-8	4.00	5.47E-8	±	0.7%
1.0E+1	4.76E-9	1.18E-9	4.04	7.58E-9	±	1.5%
1.6E+1

Figure 23-1. Plutonium-238 beryllium in a 25-cm-thick heavy-water moderator.

Figure 23-2. Plutonium-238 beryllium in a 25-cm-thick heavy-water moderator.

Figure 23-3. Plutonium-238 beryllium in a 25-cm-thick heavy-water moderator.

Table 23-2. Values derived from the spectra for $^{238}\text{PuBe}$ in a 25-cm-thick heavy-water moderator.

<u>Total fluences per source neutron</u>				
From ANISN calculations			Measured	
1 meter	2 meters		2 meters	
(n/cm ²)	(n/cm ²)	1m/2m	(n/cm ²)	
9.89E-6	3.80E-6	2.60	3.50E-6	± 0.6%

<u>Average energy of the measured spectrum</u>	
Above 0.025 eV:	0.44 MeV
Above 0.400 eV:	0.98 MeV

<u>Source-yield to dose conversion factors</u>			
	From ANISN calculations		Measured
	1 meter	2 meters	2 meters
Absorbed dose (rads/source n)	9.42E-15	3.15E-15	3.44E-15
Tissue kerma (rads/source n)	4.31E-15	1.20E-15	1.62E-15
NCRP dose eq. (rems/source n)	5.14E-14	1.54E-14	1.91E-14
ICRP dose eq. (rems/source n)	5.18E-14	1.56E-14	1.94E-14

24. $^{238}\text{PuBe}$ IN A 20-cm ALUMINUM MODERATOR

Figure 24-1, which is a plot of the 2-m fluence data from Table 24-1, shows relatively poor agreement between the calculated and measured differential spectra. The measured fluences fall below the calculations at the lowest and highest energies, and well above the calculations in the intermediate region. However, there is no strong reason to prefer one set of results over the other.

Another interesting aspect of this moderator is that, for energies up to 1.6 keV, the ratios of the 1-to-2-m fluence values from the calculated spectra are 1. This implies that this moderator moves few of the source neutrons into these energy bins, that those neutrons come instead from scattering off the cell walls, and produce a spatially homogeneous field. The ratios remain less than 4 below 4 MeV, which is typical of all of the source, moderator combinations.

Compared with any of the other detailed spectra (figures n.2), Fig. 24-2 shows that this moderator produces a larger effect on the shape of the high energy portion of the neutron spectrum than any of the other moderators. Many neutrons above 2.5 MeV are moved down to the range from 100 keV to 2.5 MeV. Not many of the source neutrons have their energy lowered as far as 1 keV, however.

The percentage difference, calculated from the values in Table 24-2, of the total fluence per source neutron values from the 2-m measurements and from the corresponding calculations is 4%. Percentage differences for the total dosimetric values are within 10 to 11%. Unlike the case for all of the other moderators, the calculated values in this case are greater than the those deduced from the measurements. We recommend that measured values be used, particularly for kerma and dose equivalent.

The average energy of the spectrum measured at 2 m is 1.2 MeV. As can be deduced from the integral spectra shown in Fig. 24-3, median energies are 250 keV for the fluence, 1 MeV for the absorbed dose and dose equivalent, and 1.5 MeV for the kerma.

Table 24-1. Differential spectra from $^{238}\text{PuBe}$ in a 20-cm-thick aluminum moderator.

Fluence values normalized to one source neutron

Bottom energy (MeV)	From ANISN calculations			Measured	
	1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)	
2.5E-8	7.61E-7	7.64E-7	1.00	4.70E-7	+ 0.1%
4.0E-7	2.43E-8	2.43E-8	1.00	1.41E-8	+ 8.3%
1.0E-6	6.09E-8	6.07E-8	1.00	3.49E-8	+ 7.5%
2.5E-6	3.84E-8	3.83E-8	1.00	2.46E-8	+ 6.7%
6.3E-6	3.36E-8	3.34E-8	1.01	3.04E-8	+ 8.7%
1.6E-5	3.87E-8	3.85E-8	1.00	5.03E-8	+ 7.8%
4.0E-5	2.75E-8	2.75E-8	1.00	4.86E-8	+ 5.7%
1.0E-4	4.90E-8	4.90E-8	1.00	9.66E-8	+ 10.8%
2.5E-4	2.41E-8	2.37E-8	1.02	4.48E-8	+ 5.7%
6.3E-4	6.09E-8	5.99E-8	1.02	1.22E-7	+ 4.0%
1.6E-3	2.79E-8	2.24E-8	1.24	3.32E-8	+ 6.2%
4.0E-3	6.96E-8	5.61E-8	1.24	8.19E-8	+ 9.5%
1.0E-2	9.85E-8	5.34E-8	1.84	6.47E-8	+ 4.4%
2.5E-2	2.09E-7	8.89E-8	2.35	1.04E-7	+ 7.1%
6.3E-2	4.04E-7	1.63E-7	2.49	2.82E-7	+ 4.0%
1.6E-1	2.96E-7	1.08E-7	2.75	1.75E-7	+ 9.6%
2.5E-1	4.73E-7	1.54E-7	3.07	1.87E-7	+ 12.5%
4.0E-1	8.07E-7	2.51E-7	3.22	2.59E-7	+ 10.3%
6.3E-1	1.25E-6	3.74E-7	3.35	3.14E-7	+ 1.5%
1.0	1.36E-6	3.72E-7	3.67	3.14E-7	+ 1.1%
1.6	1.02E-6	2.78E-7	3.66	2.74E-7	+ 0.7%
2.5	9.56E-7	2.64E-7	3.63	2.52E-7	+ 0.7%
4.0	9.36E-7	2.41E-7	3.89	1.78E-7	+ 0.6%
6.3	5.62E-7	1.41E-7	4.00	8.82E-8	+ 0.8%
1.0E+1	1.57E-8	3.88E-9	4.03	1.28E-8	+ 1.6%
1.6E+1

Figure 24-1. Plutonium-238 beryllium in a 20-cm-thick aluminum moderator.

Figure 24-2. Plutonium-238 beryllium in a 20-cm-thick aluminum moderator.

Figure 24-3. Plutonium-238 beryllium in a 20-cm-thick aluminum moderator.

Table 24-2. Values derived from the spectra for $^{238}\text{PuBe}$ in a 20-cm-thick aluminum moderator.

<u>Total fluences per source neutron</u>				
From ANISN calculations			Measured	
1 meter	2 meters		2 meters	
(n/cm ²)	(n/cm ²)	1m/2m	(n/cm ²)	
9.61E-6	3.69E-6	2.61	3.56E-6	± 1.3%

<u>Average energy of the measured spectrum</u>	
Above 0.025 eV:	1.16 MeV
Above 0.400 eV:	1.33 MeV

<u>Source-yield to dose conversion factors</u>				
	From ANISN calculations		Measured	
	1 meter	2 meters	2 meters	
Absorbed dose (rads/source n)	2.85E-14	8.35E-15	7.48E-15	
Tissue kerma (rads/source n)	2.25E-14	6.27E-15	5.65E-15	
NCRP dose eq. (rems/source n)	2.63E-13	7.47E-14	6.79E-14	
ICRP dose eq. (rems/source n)	2.55E-13	7.20E-14	6.51E-14	

25. $^{238}\text{PuBe}$ IN A 2-cm POLYETHYLENE MODERATOR

As might be expected for such a thin moderator, the measured and calculated spectra at 2 m agree about as well as those from the bare source (see Table 25-1 and Fig. 25-1). For the most part, measured fluence per bin values agree well with the calculations. The major differences occur for the lowest energy bin, where the calculations exceed the measurements, and between 250 keV and 1 MeV, where the measurements exceed the calculations. We can measure the lowest energy bin quite well, but, as discussed in Section 29, between 100 and 500 keV there can be major problems with the multisphere measurements (for example see Fig. 23-1). Nonetheless, we recommend using the measured values and the quantities derived from them.

Because the 1-to-2-m ratios of the calculated fluences below 1 keV are greater than 1, it is apparent that even this thin moderator moves a significant number of higher energy neutrons to these low energies. The bare source has almost no neutrons below 100 keV. A large part of the neutrons reaching the detector are scattered off the walls of the cell, however, since the ratios are below 4 for neutron energies below 6.3 MeV.

Figure 25-2 is the spectrum measured with the liquid scintillator. It is not much different from that obtained with the bare source. A careful comparison is needed to show the decrease in the fluence that occurs above 2.5 MeV in this case. v

The total fluence per source neutron values given in Table 25-2 agree with a percentage difference of 1%, but the 9 to 11% differences for the corresponding dosimetric values are much the same as those obtained with the bare source.

The mean energy of the spectrum measured at 2 m for this source, moderator combination is 2.3 MeV. Corresponding median energies are 63 keV for the fluence, 3.5 MeV for the absorbed dose and kerma, and 3 MeV for dose equivalent. These latter values can be obtained from the integral spectra shown in Fig. 25-3.

Table 25-1. Differential spectra from $^{238}\text{PuBe}$ in a 2-cm-thick polyethylene moderator.

Fluence values are normalized to one source neutron.

Bottom energy (MeV)	From ANISN calculations			Measured	
	1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)	
2.5E-8	8.42E-7	7.49E-7	1.12	4.45E-7	+ 0.1%
4.0E-7	3.45E-8	2.49E-8	1.38	2.47E-8	+ 2.7%
1.0E-6	8.62E-8	6.23E-8	1.38	6.51E-8	+ 1.4%
2.5E-6	5.68E-8	3.97E-8	1.43	4.35E-8	+ 2.0%
6.3E-6	5.50E-8	3.56E-8	1.54	4.37E-8	+ 3.1%
1.6E-5	6.43E-8	4.12E-8	1.56	5.02E-8	+ 2.3%
4.0E-5	4.95E-8	3.00E-8	1.65	3.75E-8	+ 2.8%
1.0E-4	8.86E-8	5.35E-8	1.66	6.41E-8	+ 3.6%
2.5E-4	4.68E-8	2.63E-8	1.78	3.03E-8	+ 3.0%
6.3E-4	1.18E-7	6.65E-8	1.78	7.24E-8	+ 1.7%
1.6E-3	4.60E-8	2.37E-8	1.94	2.00E-8	+ 1.3%
4.0E-3	1.15E-7	5.93E-8	1.94	4.82E-8	+ 3.3%
1.0E-2	9.28E-8	4.54E-8	2.05	3.99E-8	+ 3.4%
2.5E-2	1.31E-7	6.01E-8	2.18	6.07E-8	+ 4.5%
6.3E-2	2.42E-7	1.06E-7	2.28	1.08E-7	+ 2.8%
1.6E-1	1.62E-7	6.50E-8	2.49	7.55E-8	+ 3.5%
2.5E-1	2.33E-7	8.38E-8	2.78	1.38E-7	+ 2.2%
4.0E-1	3.45E-7	1.22E-7	2.82	2.09E-7	+ 1.5%
6.3E-1	5.05E-7	1.74E-7	2.91	1.95E-7	+ 1.5%
1.0	7.63E-7	2.26E-7	3.37	2.27E-7	+ 1.1%
1.6	9.72E-7	2.81E-7	3.46	2.91E-7	+ 0.8%
2.5	1.44E-6	4.04E-7	3.56	4.65E-7	+ 0.6%
4.0	1.76E-6	4.54E-7	3.87	4.85E-7	+ 0.5%
6.3	1.26E-6	3.15E-7	3.99	3.04E-7	+ 0.5%
1.0E+1	3.96E-8	9.81E-9	4.03	5.01E-8	+ 1.0%
1.6E+1

Figure 25-1. Plutonium-238 beryllium in a 2-cm-thick polyethylene moderator.

Figure 25-2. Plutonium-238 beryllium in a 2-cm-thick polyethylene moderator.

Figure 25-3. Plutonium-238 beryllium in a 2-cm-thick polyethylene moderator.

Table 25-2. Values derived from the spectra for $^{238}\text{PuBe}$ in a 2-cm-thick polyethylene moderator.

Total fluences per source neutron

From ANISN calculations			Measured
1 meter	2 meters	1m/2m	2 meters
(n/cm ²)	(n/cm ²)		(n/cm ²)
9.54E-6	3.56E-6	2.68	3.59E-6 $\pm$ 0.3%

Average energy of the measured spectrum

Above 0.025 eV: 2.33 MeV

Above 0.400 eV: 2.66 MeV

Source-yield to dose conversion factors

	From ANISN calculations		Measured
	1 meter	2 meters	2 meters
Absorbed dose (rads/source n)	3.44E-14	9.89E-15	1.08E-14
Tissue kerma (rads/source n)	2.72E-14	7.51E-15	8.36E-15
NCRP dose eq. (rems/source n)	2.79E-13	7.92E-14	8.85E-14
ICRP dose eq. (rems/source n)	2.80E-13	7.92E-14	8.75E-14

Figure 26-1, a plot of the 2-m differential fluence data in Table 26-1, shows good agreement between the spectrum measured at 2 m and the corresponding calculations. However, the measured spectrum falls above the calculations for energies above 250 keV. We have confidence in the measurements in this region, because they were taken in detail with the liquid scintillator. Thus, we recommend using the measured spectrum, and the dosimetric values obtained from it.

Above the lowest energy bin, the 1-to-2-m fluence ratios obtained from the calculations are 2 or greater. This means that a significant number of the neutrons from the source are being slowed down by the moderator into this energy region, but, because the ratios are still considerably below 4, many of the neutrons at low energy must come from scattering off of the walls of the exposure cell. Such scattering remains important for neutrons below 4 MeV.

This moderator is thick enough that effects of the resonances in the carbon cross section are beginning to show in the liquid scintillator results shown in Fig. 26-2. This is discussed further in Section 29. Most of the fluctuations in these data, however, reflect those in the spectrum produced by the bare source. This figure also shows that most of the attenuation produced by the moderator occurs above 2 MeV.

The agreement between the measured and calculated spectra is reflected in 1.2% difference between the total fluences per source neutron given in Table 26-2. The percentage difference for the total dosimetric values calculated from the spectra is not as good. They range from 9% for absorbed dose to 12% for kerma, with the values obtained from the measured spectrum all larger than those from the calculated spectrum.

The mean energy of the spectrum measured at 2 m, 1.9 MeV, is about 2/3 that of the bare source. A moderator this thin can have a significant effect because of the efficiency of hydrogen for slowing down neutrons (see Section 29). As shown in Section 20, it took twice as much heavy water to produce as large an effect. The integral fluence and dosimetric spectra shown in Fig. 26-3 show a median energy for the fluence of 250 keV, 3 MeV for absorbed dose, 3.5 MeV for kerma, and 2.5 MeV for dose equivalent. These medians for the dosimetric quantities are not much different than those from the bare source, which illustrates the limited effect that low energy neutrons have on the total doses produced by a given neutron spectrum.

Table 26-1. Differential spectra from $^{238}\text{PuBe}$ in a 5-cm-thick polyethylene moderator.

Fluence values are normalized to one source neutron

Bottom energy (MeV)	From ANISN calculations			Measured	
	1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)	
2.5E-8	1.52E-6	9.84E-7	1.55	7.07E-7	+ 0.1%
4.0E-7	5.73E-8	2.99E-8	1.91	1.99E-8	+ 5.0%
1.0E-6	1.43E-7	7.48E-8	1.91	6.43E-8	+ 2.4%
2.5E-6	9.38E-8	4.76E-8	1.97	4.13E-8	+ 1.6%
6.3E-6	8.96E-8	4.25E-8	2.11	4.31E-8	+ 4.1%
1.6E-5	1.03E-7	4.89E-8	2.12	5.35E-8	+ 4.2%
4.0E-5	7.50E-8	3.46E-8	2.17	4.65E-8	+ 3.3%
1.0E-4	1.34E-7	6.14E-8	2.17	8.13E-8	+ 6.7%
2.5E-4	6.50E-8	2.90E-8	2.24	4.81E-8	+ 9.9%
6.3E-4	1.65E-7	7.33E-8	2.24	9.94E-8	+ 4.4%
1.6E-3	5.76E-8	2.48E-8	2.33	3.24E-8	+ 7.4%
4.0E-3	1.44E-7	6.19E-8	2.33	6.62E-8	+ 3.1%
1.0E-2	1.10E-7	4.61E-8	2.39	4.60E-8	+ 6.6%
2.5E-2	1.46E-7	5.88E-8	2.48	5.83E-8	+ 7.1%
6.3E-2	2.56E-7	1.01E-7	2.55	8.37E-8	+ 8.9%
1.6E-1	1.56E-7	5.84E-8	2.68	3.86E-8	+ 13.3%
2.5E-1	2.01E-7	7.01E-8	2.87	7.45E-8	+ 11.0%
4.0E-1	2.96E-7	1.02E-7	2.91	1.42E-7	+ 4.1%
6.3E-1	4.22E-7	1.41E-7	2.99	1.58E-7	+ 1.5%
1.0	5.90E-7	1.73E-7	3.40	1.94E-7	+ 1.1%
1.6	7.41E-7	2.13E-7	3.48	2.41E-7	+ 0.8%
2.5	1.03E-6	2.89E-7	3.56	3.37E-7	+ 0.6%
4.0	1.24E-6	3.20E-7	3.86	3.49E-7	+ 0.5%
6.3	9.15E-7	2.29E-7	3.99	2.22E-7	+ 0.6%
1.0E+1	2.87E-8	7.12E-9	4.03	3.77E-8	+ 1.0%
1.6E+1

Figure 26-1. Plutonium-238 beryllium in a 5-cm-thick polyethylene moderator.

Figure 26-2. Plutonium-238 beryllium in a 5-cm-thick polyethylene moderator.

Figure 26-3. Plutonium-238 beryllium in a 5-cm-thick polyethylene moderator.

Table 26-2. Values derived from the spectra for $^{238}\text{PuBe}$ in a 5-cm-thick polyethylene moderator.

Total fluences per source neutron

From ANISN calculations			Measured
1 meter	2 meters		2 meters
(n/cm ²)	(n/cm ²)	1m/2m	(n/cm ²)
8.78E-6	3.32E-6	2.64	3.28E-6 $\pm$ 0.6%

Average energy of the measured spectrum

Above 0.025 eV: 1.88 MeV
 Above 0.400 eV: 2.40 MeV

Source-yield to dose conversion factors

	From ANISN calculations		Measured
	1 meter	2 meters	2 meters
Absorbed dose (rads/source n)	2.62E-14	7.62E-15	8.34E-15
Tissue kerma (rads/source n)	2.01E-14	5.55E-15	6.23E-15
NCRP dose eq. (rems/source n)	2.09E-13	5.96E-14	6.67E-14
ICRP dose eq. (rems/source n)	2.10E-13	5.95E-14	6.62E-14

27. ²³⁸PuBe IN A 10-cm POLYETHYLENE MODERATOR

This is the thickest polyethylene moderator for which we have a calculated spectrum for the PuBe source. Figure 27-1, the plot of the 2-m fluence data given in Table 27-1, shows that, for most of the bins above 160 keV, the measurements are significantly larger than the calculations. The measured value for the lowest energy bin is lower than the calculation, which is generally the case. Data obtained with the liquid scintillator provide the high energy portion of the measured spectrum. We have confidence in these measurements, thus we recommend using the measured spectrum and values derived from it.

Ratios of the fluences calculated at 1 m to those calculated at 2 m are greater than 2 for all energies above the lowest energy bin. They are not much different from the values obtained for the 5-cm polyethylene moderator, however, which illustrates the effect of the absorption of the lowest energy neutrons by hydrogen. This equilibrium effect is discussed further in Section 29. Neutrons scattered back to the detector from the walls of the cell remain important for neutron energies below 4 MeV above which the 1-to-2-m ratios finally become 4.

The resonances in the carbon cross section produce extra details in the spectrum. These are shown in Fig. 27-2, which displays the results obtained with the liquid scintillator, and are also considered in Section 29. Even this much polyethylene does not, however, obscure the peaks in the spectrum obtained from the bare source.

Total fluence per source neutron values at 2 m from the measurements and the calculations given in Table 27-2 have a percentage difference of only 2%. Dosimetric values calculated from the same spectrum differ by 13% for the absorbed dose to 18% for the dose equivalent. This variation would be expected because of the large difference between the measurements and calculations for the higher neutron energies.

This source, moderator combination results in a neutron spectrum, as measured at 2 m, that has a mean energy of 1.6 MeV and a median energy of 63 keV. Figure 27-3 shows the integral fluence and dosimetric spectra obtained from the spectrum measured at 2 m. The median energies deduced from the integral spectra for the dosimetric values are 2.5 MeV for absorbed dose and dose equivalent and 3 MeV for kerma. These are essentially the same as those obtained with the bare source.

Table 27-1. Differential spectra from $^{238}\text{PuBe}$ in a 10-cm-thick polyethylene moderator.

Fluence values are normalized to one source neutron

Bottom energy (MeV)	From ANISN calculations			Measured	
	1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)	
2.5E-8	1.52E-6	8.15E-7	1.87	6.32E-7	± 0.2%
4.0E-7	4.17E-8	1.96E-8	2.12	2.17E-8	± 3.5%
1.0E-6	1.04E-7	4.91E-8	2.12	5.12E-8	± 4.2%
2.5E-6	6.71E-8	3.10E-8	2.17	3.47E-8	± 5.9%
6.3E-6	6.19E-8	2.71E-8	2.29	3.15E-8	± 6.0%
1.6E-5	7.08E-8	3.09E-8	2.29	3.34E-8	± 3.9%
4.0E-5	4.92E-8	2.13E-8	2.31	2.21E-8	± 7.0%
1.0E-4	8.74E-8	3.78E-8	2.31	3.74E-8	± 4.2%
2.5E-4	4.07E-8	1.73E-8	2.35	1.85E-8	± 5.0%
6.3E-4	1.03E-7	4.38E-8	2.35	4.57E-8	± 2.9%
1.6E-3	3.46E-8	1.44E-8	2.41	1.34E-8	± 5.8%
4.0E-3	8.66E-8	3.60E-8	2.41	3.24E-8	± 3.8%
1.0E-2	6.69E-8	2.66E-8	2.51	2.85E-8	± 4.4%
2.5E-2	8.96E-8	3.37E-8	2.66	4.23E-8	± 4.1%
6.3E-2	1.52E-7	5.70E-8	2.66	6.22E-8	± 2.9%
1.6E-1	8.82E-8	3.25E-8	2.71	3.77E-8	± 6.3%
2.5E-1	1.12E-7	3.86E-8	2.89	6.15E-8	± 2.0%
4.0E-1	1.64E-7	5.60E-8	2.93	8.67E-8	± 2.2%
6.3E-1	2.33E-7	7.76E-8	3.01	9.56E-8	± 1.5%
1.0	3.17E-7	9.29E-8	3.41	1.22E-7	± 1.1%
1.6	4.04E-7	1.16E-7	3.50	1.46E-7	± 0.8%
2.5	5.36E-7	1.50E-7	3.56	1.79E-7	± 0.6%
4.0	6.56E-7	1.70E-7	3.86	1.87E-7	± 0.5%
6.3	5.17E-7	1.29E-7	4.00	1.23E-7	± 0.5%
1.0E+1	1.63E-8	4.04E-9	4.03	2.13E-8	± 0.9%
1.6E+1

Figure 27-1. Plutonium-238 beryllium in a 10-cm-thick polyethylene moderator.

Figure 27-2. Plutonium-238 beryllium in a 10-cm-thick polyethylene moderator.

Figure 27-3. Plutonium-238 beryllium in a 10-cm-thick polyethylene moderator.

Table 27-2. Values derived from the spectra for $^{238}\text{PuBe}$ in a 10-cm-thick polyethylene moderator.

Total fluences per source neutron

From ANISN calculations			Measured
1 meter (n/cm ²)	2 meters (n/cm ²)	1m/2m	2 meters (n/cm ²)
5.62E-6	2.13E-6	2.64	2.17E-6 $\pm$ 0.3%

Average energy of the measured spectrum

Above 0.025 eV: 1.59 MeV
 Above 0.400 eV: 2.24 MeV

Source-yield to dose conversion factors

	From ANISN calculations		Measured
	1 meter	2 meters	2 meters
Absorbed dose (rads/source n)	1.46E-14	4.30E-15	4.89E-15
Tissue kerma (rads/source n)	1.09E-14	3.01E-15	3.56E-15
NCRP dose eq. (rems/source n)	1.14E-13	3.26E-14	3.88E-14
ICRP dose eq. (rems/source n)	1.14E-13	3.25E-14	3.84E-14

28. ²³⁸PuBe IN A 15-cm POLYETHYLENE MODERATOR

There is a limited amount of data for this source-moderator configuration because this moderator was constructed after the completion of both the ANISN calculations and the measurements with the liquid-scintillator neutron spectrometer. As a result, there is no Fig. 28-2. To date, no MORSE calculations have been made for this configuration either. Because the agreement between the liquid-scintillator and multisphere results obtained for the other configurations was reasonable, multisphere measurements are probably sufficient. It would always be possible to make the liquid-scintillator measurements, and calculations, should they become necessary.

Without calculations, no comparisons can be made, and, without liquid scintillator measurements, we must depend entirely on the multisphere results. The data shown in Fig. 28-1, or Table 28-1, look reasonable, without any major discontinuities. Obviously, the measured results have to be used in this case. Unfortunately, this also means that there are no 1-m data. Using the 1-to-2-m ratios calculated for this source in the 10-cm polyethylene moderator (Section 27) might give a reasonable estimate for 1 m.

The mean energy determined from the multisphere measurements, and given in Table 28-2, is 1.3 MeV, which seems reasonable. The median energies for the integral spectra shown in Fig. 28-3 are 10 keV for fluence, and about 1.5 MeV for the dosimetric quantities. The lack of the detailed, liquid scintillator data makes finding the median energy for the dosimetric quantities more difficult.

Table 28-1. Differential spectra from $^{238}\text{PuBe}$ in a 15-cm-thick polyethylene moderator.

Fluence values are normalized to one source neutron

Bottom energy (MeV)	Measured 2 meters (n/cm ²)
2.5E-8	3.88E-7 ± 0.2%
4.0E-7	1.49E-8 ± 9.0%
1.0E-6	3.46E-8 ± 4.3%
2.5E-6	2.20E-8 ± 7.4%
6.3E-6	1.76E-8 ± 6.8%
1.6E-5	1.80E-8 ± 4.0%
4.0E-5	1.31E-8 ± 5.3%
1.0E-4	2.33E-8 ± 4.8%
2.5E-4	1.04E-8 ± 6.9%
6.3E-4	2.77E-8 ± 4.3%
1.6E-3	7.99E-9 ± 8.2%
4.0E-3	1.91E-8 ± 4.5%
1.0E-2	1.64E-8 ± 8.9%
2.5E-2	2.59E-8 ± 3.3%
6.3E-2	3.18E-8 ± 9.9%
1.6E-1	1.57E-8 ± 2.3%
2.5E-1	2.69E-8 ± 8.6%
4.0E-1	3.80E-8 ± 4.4%
6.3E-1	5.36E-8 ± 3.5%
1.0	7.70E-8 ± 5.0%
1.6	1.13E-7 ± 6.1%
2.5	1.29E-7 ± 7.7%
4.0	8.93E-8 ± 4.9%
6.3	4.17E-8 ± 4.5%
1.0E+1	3.10E-9 ± 10.3%
1.6E+1

Figure 28-1. Plutonium-238 beryllium in a 15-cm-thick polyethylene moderator.

Figure 28-3. Plutonium-238 beryllium in a 15-cm-thick polyethylene moderator.

Table 28-2. Values derived from the spectrum for $^{238}\text{PuBe}$ in a 15-cm-thick polyethylene moderator.

Total fluence per source neutron

Measured
2 meters
(n/cm²)

1.26E-6 $\pm$ 1.2%

Average energy of the measured spectrum

Above 0.025 eV: 1.33 MeV
Above 0.400 eV: 1.92 MeV

Source-yield to dose conversion factors

	Measured 2 meters
Absorbed dose (rads/source n)	2.68E-15
Tissue kerma (rads/source n)	1.93E-15
NCRP dose eq. (rems/source n)	2.16E-14
ICRP dose eq. (rems/source n)	2.18E-14

29. SUMMARY

In this section we summarize the integral values obtained from the calculated and measured spectra that were given in table n.2 of each of the previous sections. We will also discuss some aspects of the data that are common to most, if not all of the data sets. Tables 29-1 through 29-6 summarize the total fluences, average energies, and factors to convert source yield to dosimetric quantities. A reference is included to the section of the report in which the data are discussed in detail. As in the previous sections of the report, we have normalized to one source neutron so that the results can continue to be applied as the sources decay.

Table 29-1. Summary of total fluences.

Source	Report section	Moderator	Total n/cm ² per source neutron		
			Calculated 1 meter	Calculated 2 meters	Measured 2 meters
²⁵² Cf	7	none	9.73E-6	3.71E-6	3.83E-6
	8	25cm H ₂ O	1.12E-6	4.31E-7	4.23E-7
	9	5cm D ₂ O	9.91E-6	3.85E-6	3.66E-6
	10	10cm D ₂ O	9.94E-6	3.89E-6	3.63E-6
	11	15cm D ₂ O	9.78E-6	3.82E-6	3.00E-6
	12	25cm D ₂ O	9.82E-6	3.79E-6	3.33E-6
	13	20cm Al	9.90E-6	3.86E-6	3.61E-6
	14	2cm CH ₂	9.75E-6	3.76E-6	3.65E-6
	15	5cm CH ₂	8.45E-6	3.29E-6	3.17E-6
	16	10cm CH ₂	4.41E-6	1.71E-6	1.73E-6
	17	15cm CH ₂	1.28E-6	5.10E-7	7.85E-7
²³⁸ PuBe	18	none	9.47E-6	3.48E-6	3.69E-6
	19	25cm H ₂ O	1.90E-6	7.17E-7	7.95E-7
	20	5cm D ₂ O	9.73E-6	3.68E-6	3.68E-6
	21	10cm D ₂ O	9.86E-6	3.79E-6	3.63E-6
	22	15cm D ₂ O	9.81E-6	3.79E-6	3.20E-6
	23	25cm D ₂ O	9.89E-6	3.80E-6	3.50E-6
	24	20cm Al	9.61E-6	3.69E-6	3.56E-6
	25	2cm CH ₂	9.54E-6	3.56E-6	3.59E-6
	26	5cm CH ₂	8.78E-6	3.32E-6	3.28E-6
	27	10cm CH ₂	5.62E-6	2.13E-6	2.17E-6
	28	15cm CH ₂	-----	-----	1.26E-6

Table 29-2. Summary of the average energies of the spectra measured at 2 m.

Source	Report section	Moderator	Average energies (MeV)	
			Above 0.025 eV	Above 0.4 eV
^{252}Cf	7	none	1.38	1.56
	8	25cm H_2O	0.78	1.38
	9	5cm D_2O	0.89	1.03
	10	10cm D_2O	0.53	0.66
	11	15cm D_2O	0.37	0.46
	12	25cm D_2O	0.12	0.33
	13	20cm Al	0.66	0.77
	14	2cm CH_2	1.11	1.31
	15	5cm CH_2	0.83	1.14
	16	10cm CH_2	0.68	1.13
	17	15cm CH_2	0.68	1.22
$^{238}\text{PuBe}$	18	none	2.71	3.00
	19	25cm H_2O	1.55	2.29
	20	5cm D_2O	1.91	2.18
	21	10cm D_2O	1.33	1.59
	22	15cm D_2O	1.00	1.19
	23	25cm D_2O	0.44	0.98
	24	20cm Al	1.16	1.33
	25	2cm CH_2	2.33	2.66
	26	5cm CH_2	1.88	2.40
	27	10cm CH_2	1.59	2.24
	28	15cm CH_2	1.33	1.92

Table 29-3. Summary of factors to convert from source yield to absorbed dose in tissue.

Source	Report section	Moderator	Average rads/source neutron		
			From calculations 1 meter	2 meters	Measured 2 meters
^{252}Cf	7	none	3.16E-14	9.24E-15	9.74E-15
	8	25cm H_2O	1.78E-15	5.49E-16	6.56E-16
	9	5cm D_2O	2.17E-14	6.56E-15	6.66E-15
	10	10cm D_2O	1.45E-14	4.58E-15	4.72E-15
	11	15cm D_2O	1.01E-14	3.38E-15	3.12E-15
	12	25cm D_2O	6.82E-15	2.45E-15	2.27E-15
	13	20cm Al	2.43E-14	7.26E-15	6.15E-15
	14	2cm CH_2	2.59E-14	7.68E-15	7.81E-15
	15	5cm CH_2	1.77E-14	5.37E-15	5.45E-15
	16	10cm CH_2	8.04E-15	2.47E-15	2.55E-15
	17	15cm CH_2	2.99E-15	9.54E-16	1.12E-15
$^{238}\text{PuBe}$	18	none	3.96E-14	1.13E-14	1.24E-14
	19	25cm H_2O	4.27E-15	1.26E-15	1.76E-15
	20	5cm D_2O	2.98E-14	8.67E-15	9.56E-15
	21	10cm D_2O	2.14E-14	6.41E-15	7.20E-15
	22	15cm D_2O	1.53E-14	4.75E-15	5.15E-15
	23	25cm D_2O	9.42E-15	3.15E-15	3.44E-15
	24	20cm Al	2.85E-14	8.35E-15	7.48E-15
	25	2cm CH_2	3.44E-14	9.89E-15	1.08E-14
	26	5cm CH_2	2.62E-14	7.62E-15	8.34E-15
	27	10cm CH_2	1.46E-14	4.30E-15	4.89E-15
	28	15cm CH_2	-----	-----	2.68E-15

Table 29-4. Summary of factors to convert from source-yield to tissue kerma.

Source	Report section	Moderator	Average rads/source neutron		Measured 2 meters
			From calculations 1 meter	2 meters	
^{252}Cf	7	none	2.52E-14	7.04E-15	7.57E-15
	8	25cm H ₂ O	1.13E-15	3.14E-16	4.29E-16
	9	5cm D ₂ O	1.66E-14	4.64E-15	4.89E-15
	10	10cm D ₂ O	9.80E-15	2.73E-15	3.07E-15
	11	15cm D ₂ O	5.50E-15	1.54E-15	1.73E-15
	12	25cm D ₂ O	1.95E-15	5.53E-16	6.16E-16
	13	20cm Al	1.91E-14	5.34E-15	4.55E-15
	14	2cm CH ₂	2.01E-14	5.61E-15	5.84E-15
	15	5cm CH ₂	1.29E-14	3.62E-15	3.80E-15
	16	10cm CH ₂	5.56E-15	1.55E-15	1.65E-15
	17	15cm CH ₂	2.25E-15	6.78E-16	7.09E-16
$^{238}\text{PuBe}$	18	none	3.16E-14	8.74E-15	9.75E-15
	19	25cm H ₂ O	3.05E-15	8.37E-16	1.27E-15
	20	5cm D ₂ O	2.34E-14	6.46E-15	7.31E-15
	21	10cm D ₂ O	1.58E-14	4.35E-15	5.20E-15
	22	15cm D ₂ O	1.00E-14	2.78E-15	3.46E-15
	23	25cm D ₂ O	4.31E-15	1.20E-15	1.62E-15
	24	20cm Al	2.25E-14	6.27E-15	5.65E-15
	25	2cm CH ₂	2.72E-14	7.51E-15	8.36E-15
	26	5cm CH ₂	2.01E-14	5.55E-15	6.23E-15
	27	10cm CH ₂	1.09E-14	3.01E-15	3.56E-15
	28	15cm CH ₂	-----	-----	1.93E-15

Table 29-5. Summary of factors to convert from source-yield to dose equivalent, based on NCRP conversion factors.

Source	Report section	Moderator	Average rems/source neutron		
			From calculations 1 meter	2 meters	Measured 2 meters
^{252}Cf	7	none	2.89E-13	8.26E-14	9.12E-14
	8	25cm H_2O	1.29E-14	3.74E-15	5.12E-15
	9	5cm D_2O	1.92E-13	5.51E-14	5.93E-14
	10	10cm D_2O	1.14E-13	3.31E-14	3.77E-14
	11	15cm D_2O	6.67E-14	1.98E-14	2.16E-14
	12	25cm D_2O	2.91E-14	9.24E-15	9.41E-15
	13	20cm Al	2.42E-13	6.89E-14	5.98E-14
	14	2cm CH_2	2.33E-13	6.67E-14	7.12E-14
	15	5cm CH_2	1.52E-13	4.36E-14	4.67E-14
	16	10cm CH_2	6.48E-14	1.87E-14	2.03E-14
	17	15cm CH_2	2.62E-14	8.18E-15	8.60E-15
$^{238}\text{PuBe}$	18	none	3.19E-13	9.03E-14	1.02E-13
	19	25cm H_2O	3.18E-14	9.06E-15	1.38E-14
	20	5cm D_2O	2.42E-13	6.87E-14	7.80E-14
	21	10cm D_2O	1.65E-13	4.73E-14	5.66E-14
	22	15cm D_2O	1.08E-13	3.13E-14	3.81E-14
	23	25cm D_2O	5.14E-14	1.54E-14	1.91E-14
	24	20cm Al	2.63E-13	7.47E-14	6.79E-14
	25	2cm CH_2	2.79E-13	7.92E-14	8.85E-14
	26	5cm CH_2	2.09E-13	5.96E-14	6.67E-14
	27	10cm CH_2	1.14E-13	3.26E-14	3.88E-14
	28	15cm CH_2	-----	-----	2.16E-14

Table 29-6. Summary of factors to convert from source-yield to dose equivalent, based on ICRP conversion factors.

Source	Report section	Moderator	Average rems/source neutron		
			From calculations	Measured	Measured
			1 meter	2 meters	2 meters
^{252}Cf	7	none	2.89E-13	8.21E-14	9.00E-14
	8	25cm H ₂ O	1.30E-14	3.75E-15	5.10E-15
	9	5cm D ₂ O	1.89E-13	5.39E-14	5.78E-14
	10	10cm D ₂ O	1.12E-13	3.26E-14	3.66E-14
	11	15cm D ₂ O	6.62E-14	1.97E-14	2.13E-14
	12	25cm D ₂ O	2.95E-14	9.40E-15	9.65E-15
	13	20cm Al	2.31E-13	6.53E-14	5.58E-14
	14	2cm CH ₂	2.31E-13	6.58E-14	6.99E-14
	15	5cm CH ₂	1.50E-13	4.30E-14	4.58E-14
	16	10cm CH ₂	6.44E-14	1.85E-14	2.00E-14
	17	15cm CH ₂	2.59E-14	7.98E-15	8.43E-15
$^{238}\text{PuBe}$	18	none	3.22E-13	9.09E-14	1.00E-13
	19	25cm H ₂ O	3.21E-14	9.09E-15	1.37E-14
	20	5cm D ₂ O	2.41E-13	6.84E-14	7.68E-14
	21	10cm D ₂ O	1.65E-13	4.71E-14	5.56E-14
	22	15cm D ₂ O	1.08E-13	3.12E-14	3.77E-14
	23	25cm D ₂ O	5.18E-14	1.56E-14	1.94E-14
	24	20cm Al	2.55E-13	7.20E-14	6.51E-14
	25	2cm CH ₂	2.80E-13	7.92E-14	8.75E-14
	26	5cm CH ₂	2.10E-13	5.95E-14	6.62E-14
	27	10cm CH ₂	1.14E-13	3.25E-14	3.84E-14
	28	15cm CH ₂	-----	-----	2.18E-14

It is obvious from these tables that, except for the cases involving the aluminum moderator, the dosimetric values from the measured spectra are larger than the corresponding values from the 2-m calculations. This implies that the measured spectra have higher average energies. Except for the thickest water and heavy-water moderators, we believe that the experimental values should be used, when possible. This conclusion is based on the uncertainties involved. The calculated differential spectra probably have uncertainties on the order of 10%, so the integral values derived from them probably have uncertainties of several percent. Above 0.5 MeV, where the liquid scintillator was used for the measurements, the measured differential fluences have uncertainties of a few percent. Below that energy, except for the 0.025 to 0.4 eV bin, the uncertainties in the fluences are often greater than 10%, because a multisphere system was used. However, the neutrons measured by the liquid scintillator contribute the most to the integrated dosimetric values.

For most of the cases, the agreement between the multisphere results and the ANISN calculations is good. In some cases it is extremely good. We originally thought that many of the fluctuations in the multisphere data resulted from the statistical variations created by the data reduction procedures. Often, however, the fluctuations in the multisphere data were matched by similar variations in the calculated spectra. Since the spectra obtained in repeated runs (as shown in Fig. 4-1) show similar fluctuations for both runs, these fluctuations may indeed be part of the spectra. However, some of the fluctuations in the calculated spectra could result from the rebinning necessary for these comparisons.

The worst agreement between measurement and calculations occurs with ²⁵²Cf and the 25-cm heavy-water moderator (see Section 12). In this case, the multisphere data are obviously too low in several bins. This problem is less severe for the PuBe results that are given in Section 23. The response functions for the detector configurations used are quite flat in this region. Better results might have been obtained if a 51-mm sphere had been included in the detector set, because the response function it produces changes relatively rapidly in this energy region. However, these difficulties in reproducing the spectra might also result from one or more incorrect response functions for the detectors that were used.

There is some uncertainty about the PuBe spectrum used as the starting point for the calculations. The neutron spectrum from such sources depends on

how the source is made, the form of the plutonium and beryllium, how they are mixed, and the encapsulation. It is not clear that the spectrum used for the calculations was appropriate.

Ratios of the fluences calculated for 1 and 2 m are included in each section for which calculations were available. These values can be used to approximate a 1-m value from the measured results. Variations of these ratios from the expected R^2 value of 4 give an indication of the large number of neutrons that are scattered back to the detector by the walls of the cell. At low energies, the fluence from the unmoderated sources is the same at both distances. This implies that all of the low energy neutrons in the spectra come from room return, and that this part of the field is quite uniform throughout the room. The more the initial spectrum is moderated, the larger the low-energy fluence ratios become. However, even a heavily moderated spectrum, such as ^{252}Cf in 25 cm of D_2O , yields ratios less than 4 at energies up to at least 4 MeV.

In many cases, resonances in the neutron cross sections of the constituents of the moderators produce dips or bumps in the spectra of the transmitted neutrons. Such features are caused by interactions with the oxygen in the water or heavy water moderators, and with the carbon in the polyethylene moderators. These features normally cannot be seen using the limited resolution available from the multisphere system. They will also not be evident when the liquid scintillator data are rebinned to the bins used with the multispheres. However, when the liquid scintillator data are presented in a form consistent with the resolution of that detector, many of the effects of the cross sections can be seen. Such data are presented in the Fig. n.2 given in each section of this report.

Oxygen has prominent resonances at 1, 1.32, 2.34, 4.12, 4.33, 4.83, 5.12, and 5.63 MeV. The cross section decreases at 2.34 MeV, which results in increased transmission for neutrons of this energy. This feature is noticeable to some extent in all of the spectra measured with the liquid scintillator for the sources in water or heavy-water moderators. A similar effect is usually found for neutrons coming through concrete shields.

Carbon also has many resonances, most of which are too narrow to produce effects that can be seen with the limited resolution of the liquid scintillator. Resonances near 2, 4.3, 6.3, and 7.8 MeV often produce dips in the measured spectrum. A more complicated feature in the cross section near

3 MeV produces a dip below that energy and a rise above it. These details show in the spectra given in the figures n.2 for the cases using the polyethylene moderators.

One further point that will be discussed is the different effects of hydrogen and deuterium for moderating a spectrum. On the average, a neutron will lose half of its energy in a collision with a hydrogen nucleus, but only 44% in a collision with deuterium. Thus, fewer collisions with hydrogen are required to provide a given amount of energy loss. In this respect, hydrogen is better than deuterium for slowing down neutrons. There is an additional consideration, however. At low energies, hydrogen may capture the neutron and become deuterium. Thus, low energy neutrons are constantly captured as they traverse an hydrogenous material. At some moderator thickness, an equilibrium condition occurs so that increasing the thickness has little effect on the shape of the transmitted spectrum. In fact, the average energy of the exit spectrum may increase for thick hydrogenous absorbers. This is seen in some of the data presented in this report. Conversely, a deuterated moderator will continue to increase the number of low energy neutrons in the spectrum as the thickness of the moderator increases.

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