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Upgrade of the PNNL TEPC and Multisphere Spectrometer

RI Scherpelz
MM Conrady

September 2008

Pacific Northwest
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Summary

The Pacific Northwest National Laboratory (PNNL) has used two types of instruments, the tissue equivalent proportional counter (TEPC) and the multisphere spectrometer for characterizing neutron radiation fields in support of neutron dosimetry at the Hanford site. The US Department of Energy recently issued new requirements for radiation protection standards in 10 CFR 835 which affect the way that neutron dose equivalent rates are evaluated. In response to the new requirements, PNNL has upgraded the analyses used in conjunction with the TEPC and multisphere.

The analysis software for the TEPC was modified for this effort, and a new analysis code was selected for the multisphere. These new analysis techniques were implemented and tested with measurement data that had been collected in previous measurements. In order to test the effectiveness of the changes, measurements were taken in PNNL's Low Scatter Room using ^{252}Cf sources in both unmoderated and D_2O-moderated configurations that generate well-characterized neutron fields. The instruments were also used at Los Alamos National Laboratory (LANL), in their Neutron Free-in-Air calibration room, also using neutron sources that generate well-characterized neutron fields. The results of the software modifications and the measurements are documented in this report.

The TEPC measurements performed at PNNL agreed well with accepted dose equivalent rates using the traditional analysis, agreeing with the accepted value to within 13% for both unmoderated and moderated ^{252}Cf sources. When the new analysis was applied to the TEPC measurement data, the results were high compared to the new accepted value. A similar pattern was seen for TEPC measurements at LANL. Using the traditional analysis method, results for all neutron sources showed good agreement with accepted values, nearly always less than 10%. For the new method of analysis, however, the TEPC responded with higher dose equivalent rates than accepted, by as much as 25%. The reason for the overresponse is that there is very little attenuation of the neutrons by tissue, so it cannot match the effect of attenuation by 1 cm of tissue called for in the new standards. This could be corrected with a modified instrument with a thicker wall, or by analytical means that would need to be developed.

The multisphere spectrometer performed reasonably well both at PNNL and at LANL. It could produce a neutron spectrum that was similar to the accepted spectrum, and total flux values were usually within 15% of the accepted values. Dose equivalent rates were usually within 18% of the accepted values. The average energies, however, were usually lower than the accepted values. The performance of this instrument could be much better than seen in this study. If PNNL were to add some moderating spheres to its measurement set and calculate a new set of instrument response functions, performance could be improved. The multisphere could then be a more useful instrument for assessing the dose equivalent rate in the workplace.

Acronyms and Abbreviations

AmBe	Americium-Beryllium: an isotopic neutron source
Cd	cadmium
Cf	californium
CFR	Code of Federal Regulations
D_2O	Deuterium oxide
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation Units
ISO	International Organization for Standards
LANL	Los Alamos National Laboratory
LET	Linear energy transfer
LiI	Lithium iodide
LSR	Low Scatter Room
MAXED	Computer code for spectrum unfolding
MCA	Multichannel analyzer
NCRP	National Commission on Radiation Protection and Measurements
NFIA	Neutron Free-in-Air Room
PNNL	Pacific Northwest National Laboratory
Q (or QF)	Quality Factor
ROSPEC	"Rotational Spectrometer" – a neutron spectrometer
SPUNIT	Computer code for spectrum unfolding
TEPC	Tissue Equivalent Proportional Counter
TEPC 2.00R	Computer code for analysis of TEPC runs
TEPCalc	Computer code for analysis of TEPC runs

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1.0 Introduction

The Pacific Northwest National Laboratory (PNNL) has used two types of instruments, the tissue equivalent proportional counter (TEPC) and the multisphere spectrometer (also called a Bonner sphere spectrometer) for characterizing neutron radiation fields in support of neutron dosimetry at the Hanford site. The multisphere is primarily used to determine neutron flux, but it can also be used to determine neutron dose equivalent. The TEPC provides a measurement of neutron dose equivalent which is independent of neutron energy and therefore superior to most neutron survey instruments that rely on a moderator and thermal neutron detector, such as an Andersson-Braun remmeter. Both the TEPC and the multisphere collect data in standard nuclear electronics, and the data are then transferred to a computer where an analysis code manipulates the measurement data to produce the final results. The analysis codes for both instruments were written at PNNL.

The US Department of Energy recently issued new requirements for radiation protection standards in 10 CFR 835 (Code of Federal Regulations, 2007). These new requirements affect the way that neutron dose equivalent rates are evaluated. To be compliant with these requirements, dose equivalent should be evaluated using methodology that is consistent with ICRP 74 (International Commission on Radiological Protection, 1996). Since the PNNL analysis of TEPC and multisphere measurements both depend on methodologies that predate ICRP 74, it was necessary to update the analysis codes to incorporate the new methodology. For the TEPC, this required writing a new version of the original analysis code. For the multisphere, it meant choosing a new analysis code and updating the data libraries required to support it.

The changes to the analysis codes were accomplished at PNNL in FY-2008. These changes were then tested by performing measurements in the calibration rooms of both PNNL and Los Alamos National Laboratory (LANL). This testing utilized a variety of well-characterized neutron fields for the testing, and for each neutron field there were reliable accepted neutron spectra and dose equivalent rates determined by the facility operators for comparison to our measurements.

This document describes the modifications that were made to the TEPC and multisphere analysis codes and documents the measurements at PNNL and LANL.

2.0 Neutron Flux in the Low Scatter Room

For each ^{252}Cf source in the PNNL Low Scatter Room (LSR), the neutron emission rate, *B*, due to ^{252}Cf is well known, based on certifications from the National Institute of Standards and Technology. Thus the free-field neutron dose equivalent rate at distance *r* from the source can be found using equation 2-1:

$$\dot{H}_r = \frac{B}{4\pi r^2} \times \bar{h}_\Phi \tag{2-1}$$

$\dot{H}_r$ is the neutron dose equivalent rate typically reported to LSR users. The conversion factor, $\bar{h}_\Phi$, had a value of 333 pSv·cm^2·n^{-1} for unmoderated ^{252}Cf, using conversion factors from ICRP 21 (International Commission on Radiological Protection, 1973), but ISO 8529-3 (International Organization for Standard, 1998) recommends a value of 400 pSv·cm^2·n^{-1} using quality factors determined from the Q-LET relationship given in ICRP 60 (International Commission on Radiological Protection, 1990).

The use of Equation 2-1 assumes an unscattered neutron energy spectrum for ^{252}Cf with ideal irradiation conditions; any non-ideal physical irradiation condition would suggest an adjustment to this evaluation to enable a reliable comparison to a measured value. For the LSR, the adjustments most commonly made include build-in of ^{250}Cf and an anisotropy correction for source encapsulation. In addition, the effects of neutron scattering by air in the room and the structure of the room are also considered.

As an example, Table 2.1 shows the calculation of the free-field dose equivalent rate and adjustments to this value for source 318-167 (with an NSD encapsulation within the rabbit transit capsule), unmoderated, on 2/25/2008, at 100 cm from the source.

Table 2.1. Conventional assessment of dose equivalent for unmoderated ^{252}Cf source 318-167 at 100 cm on 2/25/2008

Quantity	*Value*	*Dose Equivalent Rate, mrem/h*
^{252}Cf neutron emission rate, B	2.718·10^7 n/s	
Neutron emission rate, including ^{250}Cf build-in	3.818·10^7 n/s	
Free-field neutron flux at 100 cm	304 n·cm^{-2}·s^{-1}	
Conversion factor, ICRP 21, $\bar{h}_\Phi$	333 pSv·cm^2·n^{-1}	
Free-field dose equivalent rate, including ^{250}Cf build-in, using ICRP 21 $\bar{h}_\Phi$		36.42
Anisotropy for this source	1.062	
Dose equivalent rate, with adjustments		38.68

The adjustment to emission rate for ^{250}Cf build-in was found by calculations of radioactive decay and production using the Bateman equations, and the adjustment for anisotropy was found by monte carlo radiation transport modeling.

LSR staff have also made measurements to provide estimates of air scatter and room return effects; at 100 cm the air scatter adjustment would be 1.012 and the room return 1.031. However these adjustments are dependent on the instrument response and are not routinely applied to the reported dose equivalent rate by LSR staff.

An alternate way of determining a realistic dose equivalent rate is to start with an energy-binned neutron spectrum, including the influences at the measurement location of scatter as a result of the air medium and facility structures and boundaries, and apply fluence-to-dose conversion factors. The neutron spectrum can be obtained from a study of the PNNL LSR performed by LANL (Mallett et al, 2004). In this study the LSR was carefully modeled using a monte carlo radiation transport code, and the neutron spectrum was calculated at a variety of measurement points. LANL also used two separate neutron spectrometers to make measurements at the same points, and the measurements verified the models. The current study used these spectra, rebinned to fit our multisphere binning scheme, as a second "accepted" value for the dose equivalent rate.

Table 2.2 shows the spectrum and resulting dose equivalent rate for the same source conditions as Table 2.1. The spectrum assumes that the neutron emission rate is $3.818 \cdot 10^7$ n/s, which includes the build-in of ^{250}Cf .

Table 2.2. Neutron spectrum and dose equivalent rate for unmoderated ^{252}Cf source 318-167 at 100 cm on 2/25/2008

Energy (MeV)	*Flux ($n \cdot cm^{-2} \cdot s^{-1}$)*	*ANSI-77* Dose Equivalent (mrem/h)*
2.57E-07	15.930	6.50E-02
5.48E-07	0.582	2.51E-03
1.06E-06	0.865	3.86E-03
2.25E-06	0.892	4.07E-03
4.77E-06	0.866	3.96E-03
1.01E-05	0.929	4.21E-03
2.14E-05	0.936	4.17E-03
4.52E-05	0.954	4.13E-03
9.58E-05	1.024	4.14E-03
2.03E-04	1.010	4.08E-03
4.34E-04	1.083	4.22E-03
9.13E-04	1.107	4.17E-03
1.92E-03	1.131	4.15E-03
4.07E-03	1.220	4.38E-03
8.62E-03	1.434	5.09E-03
1.83E-02	1.973	1.13E-02
3.86E-02	3.129	3.22E-02
8.18E-02	6.888	1.28E-01
1.67E-01	14.594	5.03E-01
3.37E-01	31.536	2.05E+00
6.79E-01	64.618	6.99E+00
1.39E+00	103.370	1.34E+01
2.78E+00	91.218	1.18E+01
5.54E+00	45.025	6.91E+00
1.12E+01	5.905	9.77E-01
2.04E+01	0.092	2.10E-02
Total:	398.3	42.89

**(American Nuclear Society, 1977)*

Notice that the two “accepted” values for dose equivalent rate differ from each other by about 11%: 38.68 mrem/h using the conventional LSR analysis (adjusted ideal spectrum) and 42.89 mrem/h using the LANL-developed spectrum modified by a dose factor. Note that both methods started with the same neutron emission rate, corrected for ^{250}Cf build-in, so the remaining reasons for the difference are:

- Scatted neutrons, which account for about a 31% increase in the total flux versus free field conditions.

- The dose conversion factors are slightly different, based on ICRP 21 for the conventional method and ANSI-77 for the spectral method.

- The two methods used different analyses to arrive at a dose equivalent rate. The conventional method used an adjustment for anisotropy, whereas the spectral method relied on modeling (supported by neutron spectrum measurements). The modeling may have imperfectly recreated some details of the room, or ignored some details. Any comparison of measurements will also include small variations, which can contribute to a difference.

For measurements performed in PNNL's LSR, both "accepted" values will be reported, and identified as either the "conventional accepted" or "spectrum-derived accepted" value.

2.1 Fluence to Dose Conversion Factors

Two general categories of conversion factors are addressed in this study: those developed and used in the 1970s, which have been used in early evaluations; and those developed in the 1990s, which are generally consistent with current recommendations.

Conversion Factors from the 1970s: Neutron fluence-to-dose (or flux-to-dose-rate) conversion factors that have traditionally been used for dose equivalent evaluation are drawn from three sets:

- ICRP 21 (ICRP, 1971). This early compilation of conversion factors collected data from several sources. All of them assumed a parallel beam of monoenergetic neutrons incident on a slab of water. The point in the water volume that produced the highest dose was used to derive the conversion factor.

- NCRP 38 (NCRP 1971). This compilation compiled the results of a set of calculations performed with a parallel beam of monoenergetic neutrons incident on a cylindrical tissue-equivalent phantom. Its modeling was more sophisticated than the analyses of ICRP-21, and it received wider usage.

- ANSI/ANS-6.1.1-1977 (American Nuclear Society, 1977). This standard simply provided a compilation of NCRP 38 data in a format that was easy to use for shielding calculations. The data should be entirely compatible with NCRP 38 values.

All three data sets from the 1970s should give roughly similar results.

Conversion Factors from the 1990s: Methodology in the more recent era has used dose deposition in an anthropomorphic phantom with realistic organs. ICRP 74 (ICRP, 1996) contains a compilation of $H_p(10)$, an operational quantity that is the personal dose equivalent at 10 mm depth in tissue. This represents the modern approach to the evaluation of dose equivalent.

3.0 TEPC

The tissue-equivalent proportional counter (TEPC) is used by PNNL for evaluating neutron dose and dose equivalent. The instrument collects a lineal energy spectrum created by incident photon and neutron radiation. The absorbed dose can be derived from this spectrum, and the spectrum can be analyzed to determine a quality factor. The product of absorbed dose and quality factor is dose equivalent.

In order to determine the neutron component of dose and quality factor, the analysis must discriminate between events generated by photons and those generated by neutrons. This introduces a problem, since some photons are produced by neutrons interacting in the detector, so by rejecting photon events, some of the energy deposition from incident neutrons is also rejected. In most realistic neutron fields this rejection is a minor contributor to error. Measurements performed in the PNNL Low Scatter Room (LSR) have typically shown very good agreement between measured dose equivalent and the accepted value, supporting the assumption that the effect was minor.

The current study has the goal of changing the method of quality factor determination in the TEPC to meet the new guidance of 10 CFR 835. Traditionally the quality factor, Q, is found using a relationship between LET and Q that was specified in ICRU 43 (a preliminary calculation converts the lineal energy distribution to an average LET value using a known relationship). Under the new guidance of 10 CFR 835, a relationship for converting LET to Q specified in ICRU 51 is used. The new evaluation produces values of Q about 30% higher than the old values. The new value of dose equivalent produced by a TEPC measurement is most similar to H*(2), or perhaps $H_p(2)$, since it incorporates very little tissue attenuation. (The density thickness of the TEPC wall is approximately 200 mg/cm^2.) It is therefore an overestimate of H*(10) or $H_p(10)$.

The new algorithm was tested by exposing the TEPC detectors to well-characterized neutron fields in PNNL's LSR and in LANL's calibration facility, the Central Health Physics Calibration Facility, using their Neutron Free-in-Air (NFIA) room. A variety of neutron sources with different moderators were used in the measurements.

3.1 TEPC Analysis Code Modifications

The objective of this work was to enable the TEPC analysis code to evaluate neutron dose equivalent in a way that complies with new requirements documented in the new version of 10 CFR 835.

The tissue-equivalent proportional counter (TEPC) is a detector used for determining dose equivalent due to neutrons in a radiation field. In operation, the detector is connected to a multichannel analyzer (MCA), and a pulse-height spectrum is collected. This pulse-height spectrum is transferred to a computer, where it is analyzed by a computer code. This code converts the pulse-height spectrum into an LET spectrum (LET is an acronym for linear energy transfer), which is processed in two ways. First, it is analyzed to determine the absorbed dose. Then it is analyzed to determine quality factor. The product of absorbed dose and quality factor is the dose equivalent (Brackenbush et al, 1988). The method of determining absorbed dose did not change. However, the new version of 10 CFR 835 requires that a new method for determining quality factor be adopted. Therefore, this modification to the software is intended to perform the new quality factor calculation and report a dose equivalent value that is consistent with current 10 CFR 835 requirements.

The original version of the TEPC analysis code, called "TEPC 2.00R," was written in 2000, with the software development motivated by Y2k software upgrades. This version of the software represented an upgrade to the analytical methods that had been used by PNNL since the early 1980's. The 2000 software modification did not represent any basic updates in analysis methods, other than minor changes in some algorithms to meet the standard practices of the day. This version was validated by performing TEPC measurements in PNNL's Low Scatter Room, with a ^{252}Cf neutron source producing a well-known and well-characterized radiation field.

The original method for determining quality factor, based on LET, was based on older methodology. The previous version of 10 CFR 835 referred to ICRP 21 (ICRP, 1971) for quality factor determination, but the method is better documented in Appendix A of ICRU 43 (ICRU, 1988):

Table 3.1. Relationship between quality factor and LET by the methodology of ICRU 43

L_∞ - Q Relationship	
L_∞ in water (keV/µm)	Q
3.5 (and less)	1
7	2
23	5
53	10
175 (& above)	20

TEPC 2.00R uses a fitted equation (Hartmann et al, 1981) that produces a smooth curve consistent with the values in Table 3.1:

$$QF = b\log(\frac{L}{a}) + ce^{-d(L-3.5)^f} \quad (3\text{-}1)$$

The new specification for quality factor is specified by 10 CFR 835 as coming from ICRP 60 (ICRP, 1991), but for determining Q as a function of LET, 10 CFR 835 refers to Appendix A of ICRU 51 (ICRU, 1993) . The same equations in slightly different form are given in ICRP 60, ICRP 74 and ICRU 57 as shown in Table 3.2:

Table 3.2. Determining quality factor from LET by the methodology of ICRU 51.

$$Q(L) = \begin{cases} 1 & \text{for } L < 10 \\ 0.32L - 2.2 & \text{for } 10 \le L \le 100 \\ 300 / \sqrt{L} & \text{for } L > 100 \end{cases} \qquad (3\text{-}1)$$

TEPCalc Development: The goal of this modification to the TEPC analysis code was to have the software provide dose equivalent values that use the ICRP 60 / ICRU 51 method of determining quality factor, which will meet the requirements of the new version of 10 CFR 835.

Software modifications were made to TEPC 2.00R, following a document titled "Software Design for TEPC Code Modifications" (R.I. Scherpelz and M.M. Conrady, November 3, 2007). The new version of the analysis software was given the name TEPCalc, version 3.00 (Nov. 1, 2007). The software modifications were tested, and the testing documented in "TEPCalc QA Testing," a memo from Matthew Conrady to Patrick O'Connell dated November 20, 2007. The QA document demonstrated that the new version of the software passed all tests that were designed for its acceptance testing, so it was ready to put into service.

Measurements were performed at PNNL and at LANL to further test the performance of the new code, and these measurements are documented in the next two sections.

3.2 PNNL LSR Measurements

Four TEPC detectors were used in measurements in the LSR, identified by their serial numbers:

1170
1171
1173
1174

All four detectors can be expected to respond identically. In a test performed one week after the LSR measurements, they were individually exposed in a carefully controlled radiation position in another PNNL laboratory, and a variation of only 3% was observed in their responses.

The detectors were used to measure the neutrons emitted by the ^{252}Cf source identified as 318-167 in the LSR. The source was used in the unmoderated configuration for some measurements, and in a D_2O-moderated configuration for others. Two irradiation positions were chosen: one at 100 cm from the source, on the irradiation track. The other was at 100 cm from the source, but positioned directly north of the source, toward the north wall of the room.

The results of these measurements are given in Table 3.3 to Table 3.5. In Table 3.3 the measured results are compared to the conventionally accepted values of dose equivalent rate.

Table 3.3. TEPC measurements in LSR using ICRP 21 analysis, compared to the conventional accepted value

Detector	*Source*	*Position*	*Measured* (mrem/h)*	*Quality Factor*	*Accepted*** (mrem/h)*	*Percent Difference*
1171	Bare	Track	44.6	9.6	38.7	15%
1174	Bare	Track	47.9	9.9	38.7	24%
1170	Bare	Wall	37.4	9.7	38.7	-3.4%
1173	Bare	Wall	37.6	9.7	38.7	-2.9%
1170	Moderated	Wall	10.3	9.6	9.8	4.8%
1171	Moderated	Track	12.1	9.2	9.8	23.4%

** Measured value is not corrected for the influence of neutrons scattered by air and by facility structures.*
***Accepted value is the free-field dose equivalent rate traditionally reported by PNNL LSR staff.*

In Table 3.4, the same measurements are compared to spectrum-derived accepted values.

Table 3.4. TEPC measurements in LSR using ICRP 21 analysis, compared to the spectrum-derived accepted value

Detector	*Source*	*Position*	*Measured (mrem/h)*	*Quality Factor*	*Accepted* (mrem/h)*	*Percent Difference*
1171	Bare	Track	44.62	9.6	42.9	4.0%
1174	Bare	Track	47.86	9.9	42.9	11.6%
1170	Bare	Wall	37.38	9.7	42.9	-12.8%
1173	Bare	Wall	37.56	9.7	42.9	-12.4%
1170	Moderated	Wall	10.31	9.6	11.4	-9.9%
1171	Moderated	Track	12.14	9.2	11.4	6.1%

** Accepted value is derived from a spectrum calculated by MCNP, using ANSI- 77 conversion factors*

Table 3.5 presents the data for these measurements using the new TEPC algorithm, which uses ICRP 60 quality factors and is meant to be consistent with the new version of 10 CFR 835.

Table 3.5. TEPC measurements in LSR using ICRP 60 analysis

Detector	*Source*	*Position*	*Measured (mrem/h)*	*Quality Factor*	*Accepted* (mrem/h)*	*Percent Difference*
1171	Bare	Track	64.36	13.9	52.0	23.8%
1174	Bare	Track	69.25	14.3	52.0	33.2%
1170	Bare	Wall	54.29	14.1	52.0	4.4%
1173	Bare	Wall	54.25	14.0	52.0	4.3%
1170	Moderated	Wall	14.87	13.8	14.1	5.5%
1171	Moderated	Track	17.14	13.0	14.1	21.6%

** Accepted value is derived from a spectrum calculated by MCNP, using ICRP 74 conversion factors*

The results of this set of measurements were a bit different than we expected. During many years of experience with measuring neutron fields in the LSR, we have come to expect that the TEPCs can usually match the accepted values for the unmoderated ^{252}Cf source to within about 7%. However, in these measurements, two of these values were much higher than 7%.

For the unmoderated source, the ICRP 60 analysis gave much larger values than the accepted value for the two detectors located on the irradiation track, but close values for the position near the LSR wall. For the D_2O-moderated source, there was not good agreement between the two detectors.

It is notable that for all measurements, the dose values measured at the wall were lower than the doses measured on the irradiation track.

3.3 Measurements at LANL

Two TEPC detectors, 1170 and 1174, that had been used in the LSR measurements were used at the LANL calibration room in Building 214 of area TA-36. The irradiation room was called the Neutron Free-in-Air (NFIA) room. Two types of neutron sources, ^{252}Cf and AmBe, were used with a variety of moderating configurations to produce the neutron fields. Both sources were used in an unmoderated configuration. The ^{252}Cf source was also used with a 30-cm diameter D_2O moderator, and with polyethylene moderating shells with thicknesses of 1-, 2-, 3-, 4-. 5- and 6-inches.

LANL evaluated the neutron spectrum for each source configuration at each measurement position using radiation transport modeling of the NFIA, and performed neutron spectrum measurements with a ROSPEC[1] detector and a multisphere spectrometer to verify the modeling. LANL converted the spectra to dose equivalent rate using NCRP 38 conversion factors to find a dose equivalent rate and ICRP 74 conversion factors for $H_p(10)$.

Table 3.6 and Table 3.7 present the results of the TEPC measurements in LANL's NFIA room. Table 3.6 presents the measurements using the older ICRP 21 methodology for analyzing the TEPC measurements, compared to the LANL NCRP 38 accepted values. Table 3.7 presents the TEPC measurements analyzed with the ICRP 60 methodology, compared to the $H_p(10)$ accepted values.

[1] Bubble Technology Industries, PO Box 100, Hwy. 17, Chalk River, Ontario, Canada K0J 1J0

Table 3.6. TEPC measurements in LANL NFIA, using ICRP 21 methodology

Source	*Moderator*	*Distance (cm)*	*Average Energy (MeV)*	*Measured (mrem/h)*	*Accepted* (mrem/h)*	*Percent Difference*
^{252}Cf	Unmoderated	100	2.24	110.6	112.8	-2.0%
^{252}Cf	Unmoderated	200	1.81	30.5	32.49	-6.0%
^{252}Cf	D_2O	100	0.60	25.4	27.48	-7.4%
^{252}Cf	D_2O	200	0.46	7.18	8.185	-12.3%
^{252}Cf	1-in polyethylene	100	1.61	73.4	78.96	-7.1%
^{252}Cf	1-in polyethylene	200	1.27	22.5	22.84	-1.7%
^{252}Cf	2-in polyethylene	100	1.31	49.6	51.22	-3.2%
^{252}Cf	2-in polyethylene	200	1.02	13.7	14.86	-7.6%
^{252}Cf	3-in polyethylene	100	1.20	32.6	32.92	-1.1%
^{252}Cf	3-in polyethylene	200	0.93	9.40	9.553	-1.6%
^{252}Cf	4-in polyethylene	200	0.92	5.67	6.121	-7.4%
^{252}Cf	5-in polyethylene	200	0.95	3.74	3.953	-5.3%
^{252}Cf	6-in polyethylene	200	1.01	2.46	2.564	-4.2%
AmBe	Unmoderated	100	4.23	25.60	25.83	-0.9%
AmBe	Unmoderated	200	3.52	7.17	7.270	-1.4%

**Accepted value is based on NCRP 38 dose conversion factors*

Table 3.7. TEPC measurements in LANL NFIA, using ICRP 60 methodology

Source	*Moderator*	*Distance (cm)*	*Average Energy (MeV)*	*Measured (mrem/h)*	*Accepted* (mrem/h)*	*Percent Difference*
^{252}Cf	Unmoderated	100	2.24	160.2	130.6	22.6%
^{252}Cf	Unmoderated	200	1.81	44.5	37.91	17.3%
^{252}Cf	D_2O	100	0.60	36.1	31.73	13.9%
^{252}Cf	D_2O	200	0.46	10.2	9.486	7.6%
^{252}Cf	1-in polyethylene	100	1.61	105.8	91.79	15.3%
^{252}Cf	1-in polyethylene	200	1.27	32.6	26.69	22.0%
^{252}Cf	2-in polyethylene	100	1.31	71.4	57.13	25.0%
^{252}Cf	2-in polyethylene	200	1.02	19.7	17.31	14.1%
^{252}Cf	3-in polyethylene	100	1.20	46.2	37.86	22.0%
^{252}Cf	3-in polyethylene	200	0.93	13.5	11.06	21.8%
^{252}Cf	4-in polyethylene	200	0.92	8.0	7.062	13.8%
^{252}Cf	5-in polyethylene	200	0.95	5.20	4.527	14.8%
^{252}Cf	6-in polyethylene	200	1.01	3.29	2.919	12.7%
AmBe	Unmoderated	100	4.23	33.55	27.78	20.8%
AmBe	Unmoderated	200	3.52	9.42	7.906	19.1%

**Accepted value is $H_p(10)$, using ICRP 74 dose conversion factors*

The data in Table 3.6 show that for all cases, the dose equivalent rate measured by the TEPCs agreed very well with the accepted value for the radiation field, using the original (ICRP 21) method of analysis. This agreement was true for all neutron sources, which means that the measurement technique is reliable for all neutron energy distributions tested.

However, the data in Table 3.7 show that using the newer analysis technique (ICRP 60) results in measured dose equivalent rates somewhat higher than the accepted value for all sources, ranging up to 25% higher than the accepted value. This high response is related to the effect of neutron attenuation by tissue: the TEPC has very little attenuation of neutrons, but the accepted quantity, $H_p(10)$, assumes 1 cm of tissue attenuating the neutrons.

4.0 Multisphere

The multisphere spectrometer used at PNNL consists of a LiI detector used in the following seven configurations:

- Bare detector
- Detector covered by a layer of Cd
- Detector at center of a 3-in polyethylene sphere, with a Cd covering on the sphere
- Detector at center of a 5-in polyethylene sphere, with a Cd covering on the sphere
- Detector at center of a 8-in polyethylene sphere
- Detector at center of a 10-in polyethylene sphere
- Detector at center of a 12-in polyethylene sphere

The detector responds primarily to thermal neutrons, so covering the detector with Cd (an absorber of thermal neutrons) or polyethylene (a moderator to increase the number of thermal neutrons reaching the detector) will have a significant effect on the count rate. For measuring a neutron spectrum, a count rate is collected for each of the seven configurations, and the seven count rates are used as input for an analysis code, called an "unfolding" code. This code unfolds the neutron spectrum from the measured count rates using response functions that are appropriate for the specific detector and moderator or absorber.

The output of the unfolding code is an energy-binned flux spectrum. Sometimes the unfolding code will also multiply the flux by fluence-to-dose conversion factors to produce a neutron dose.

4.1 Multisphere Analysis Modifications

Traditionally, PNNL has used an unfolding code called SPUNIT (Brackenbush and Scherpelz, 1984). SPUNIT was written by PNNL in the 1980's and is specifically intended to be used with the detector configurations that PNNL employs. It produces a 26-bin neutron flux spectrum and uses ANSI-77 (American Nuclear Society, 1977) conversion factors to report a dose value. It has a built-in response function, developed by Sanna (1973), in the 26-bin format.

In order to make our multisphere measurements compliant with the new 10 CFR 835 requirements, PNNL decided to adopt a new unfolding code rather than modify SPUNIT. The code MAXED (Reginatto and Goldhagen, 1998) is widely used in the nuclear community, is well-documented, and has a large base of user experience. The few-channel version of this code, MXD_FC33.exe, is appropriate for analyzing a multisphere measurement to produce a neutron spectrum. A post-processing Excel spreadsheet was developed to convert the flux to dose. This combination was chosen as the most efficient choice to perform quality assurance documentation. We tested several published response functions, and found that a modified version of the Sanna response function performed best for our configuration.

Multisphere unfolding typically uses a "starting spectrum" – a rough first guess at a spectral shape. Several different starting spectra were developed, usually adapted from a measurement in a similar spectrum. We found that a spectrum called "LSRStart" based on a measurement in the

LSR with an unmoderated ^{252}Cf source gave the best performance for unfolding, so it was used for most cases.

The new method of analysis was tested with irradiations in PNNL's LSR and in LANL's NFIA. Measurements were made with both unmoderated- and D_2O-moderated ^{252}Cf in the LSR, and with a variety of ^{252}Cf configurations and an unmoderated AmBe source at LANL. The next sections document these measurements.

4.2 Measurements in PNNL LSR

The multisphere spectrometer was used in the Low Scatter Room to measure neutron fields generated by two sources: an unmoderated ^{252}Cf source and a ^{252}Cf source moderated by a 30-cm diameter sphere of D_2O.

4.2.1 Unmoderated ^{252}Cf Source

Two measurements were considered:

- August 7, 2001: using source 318-016, $2.22 \cdot 10^6$ n/s
- November 15, 2006, with source 318-167, $4.97 \cdot 10^7$ n/s.

These measurements had been performed with PNNL's multisphere set, and the measured count rates were analyzed with MAXED and the standard response function and appropriate starting spectrum. The accepted values were derived from the spectrum calculated by MCNP in the LANL study, rebinned for our 26-bin scheme, along with ANSI-77 dose conversion factors.

The results are shown in Table 4.1. Figure 4.1 presents the spectrum for this measurement and compares it to the accepted spectrum, derived from the LANL study. Table 4.2 and Figure 4.2 present the results of the measurement for source 318-167.

Table 4.1. Multisphere measurement at 100 cm from source 318-016, 8/7/01

	Measured	*Value*	*Accepted Value*	*Percent Difference*
Total Flux	23	n/cm^{2}s	23	-2.5%
ANSI-77 Dose Equivalent Rate (vs spectrum-derived accepted)	2.4	mrem/h	2.5	-3.7%
ICRU 57, Hp(10)	2.9	mrem/h	3.0	-4.1%
Average Energy	1.424	MeV	1.938	

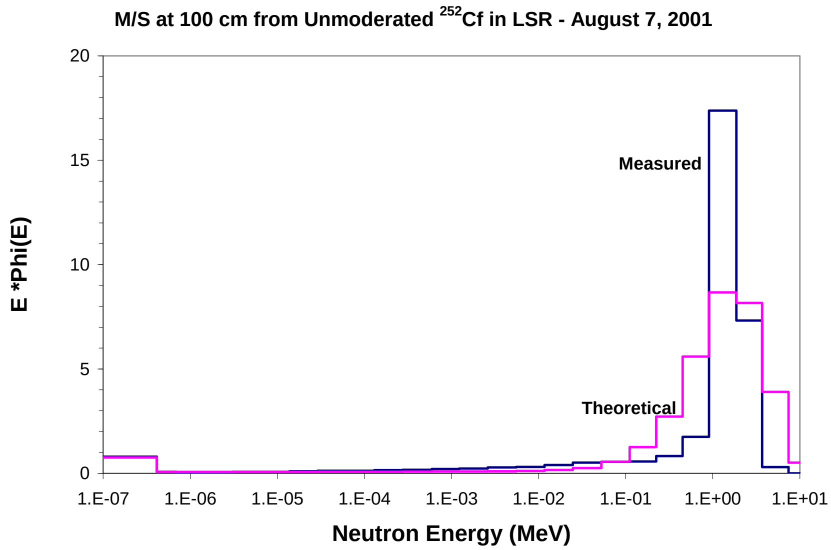

Figure 4.1. Unfolded spectrum for Source 318-106

Table 4.2. Multisphere measurement at 100 cm from source 318-167, 11/15/06

	Measured Value	*Accepted Value*	*Percent Difference*
Total Flux	517 n/cm^{2}s	519	-0.3%
ANSI-77 Dose Equivalent Rate (vs spectrum-derived accepted)	54.2 mrem/h	55.9	-2.9%
ICRU 57, Hp(10)	65.9 mrem/h	68.2	-3.3%
Average Energy	1.629 MeV	1.938	

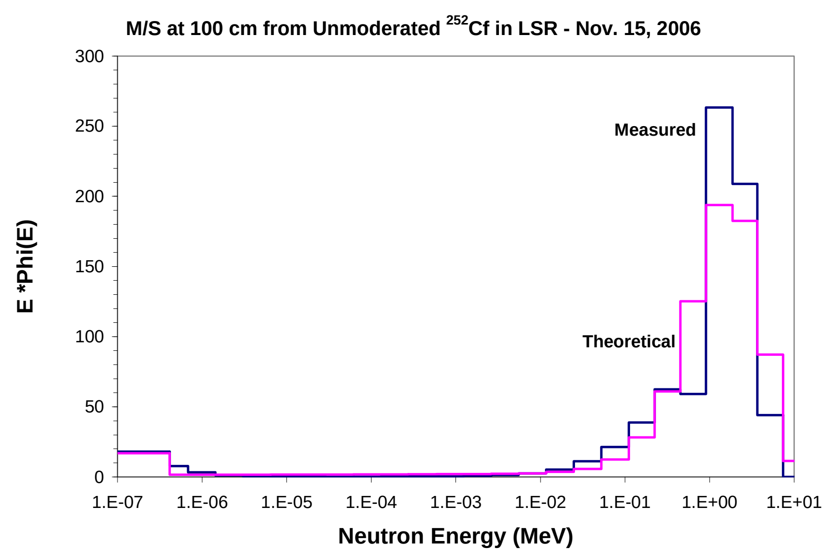

Figure 4.2. Unfolded spectrum for Source 318-106

Both measurement runs have very good agreement with accepted values for the total quantities. The graphs of the spectra look pretty similar, except that the fission peak in the theoretical spectrum is broader and shorter than the measured. The thermal flux agrees pretty well.

4.2.2 D_2O-Moderated ^{252}Cf Source

These runs were done on February 22, 2008, with source 318-167. The source strength was $3.83E \cdot 10^7$ n/s. The following measurements were done:

- 100 cm from the source, toward the north wall ("wall 100")
- 100 cm from the source, on the irradiation track ("track 100")
- 200 cm from the source, on the irradiation track
- 300 cm from the source, on the irradiation track

The irradiation track at the source runs towards the west from the source. The "wall" position is on a line at 90° from the track, directly north of the source, towards the thick north wall of the room.

The results of the multisphere measurements exposed to neutrons from the D_2O-moderated ^{252}Cf source in the LSR are presented in Table 4.3 through Table 4.6. The unfolded spectra for the two measurements at 100 cm are presented in Figure 4.3 and Figure 4.4.

Table 4.3. Multisphere measurement at 100 cm from the D_2O-moderated ^{252}Cf source, positioned toward the north wall

	Measured Value	*Accepted Value*	*Percent Difference*
Total Flux	369 n/cm^{2}s	333	10.7%
ANSI-77 Dose Equivalent Rate (vs spectrum-derived accepted)	12.4 mrem/h	11.4	8.6%
ICRU 57, Hp(10)	16.0 mrem/h	14.1	13.4%
Average Energy	0.581 MeV	0.572	

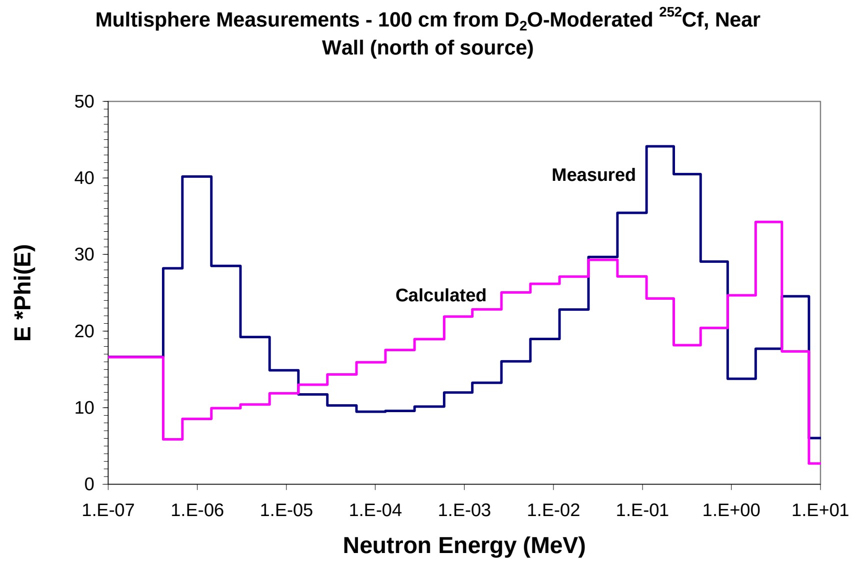

Figure 4.3. Neutron spectrum at 100 cm from the D_2O-moderated ^{252}Cf source, positioned toward the north wall

Table 4.4. Multisphere measurement at 100 cm from the D_2O-moderated ^{252}Cf source, positioned on the irradiation track

	Measured Value	*Accepted Value*	*Percent Difference*
Total Flux	384 n/cm^2s	333	15.2%
ANSI-77 Dose Equivalent Rate (vs spectrum-derived accepted)	13.0 mrem/h	11.4	14.1%
ICRU 57, Hp(10)	16.6 mrem/h	14.1	17.8%
Average Energy	0.398 MeV	0.572	

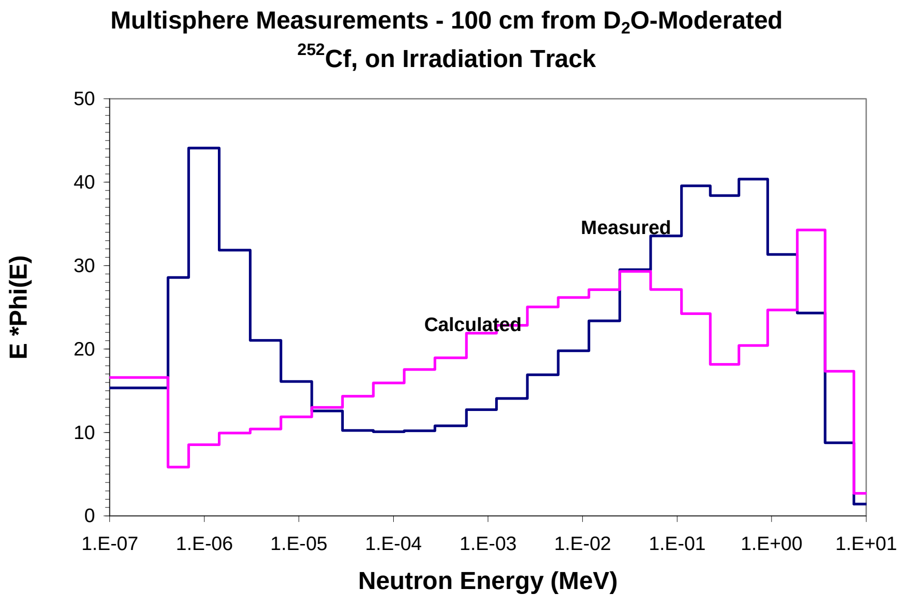

Figure 4.4. Neutron spectrum at 100 cm from the D_2O-moderated ^{252}Cf source, positioned toward the north wall

Table 4.5. Multisphere measurement at 200 cm from the D_2O-moderated ^{252}Cf source, positioned on the irradiation track

	Measured Value	*Accepted Value*	*Percent Difference*
Total Flux	139 n/cm^{2}s	120	15.9%
ANSI-77 Dose Equivalent Rate (vs spectrum-derived accepted)	3.6 mrem/h	3.4	7.8%
ICRU 57, Hp(10)	4.5 mrem/h	4.2	9.0%
Average Energy	0.314 MeV	0.432	

Table 4.6. Multisphere measurement at 300 cm from the D_2O-moderated ^{252}Cf source, positioned on the irradiation track

	Measured Value	*Accepted Value*	*Percent Difference*
Total Flux	93 n/cm^{2}s	94	-0.2%
ANSI-77 Dose Equivalent Rate (vs spectrum-derived accepted)	2.0 mrem/h	N/A	N/A
ICRU 57, Hp(10)	2.6 mrem/h	N/A	N/A
Average Energy	0.314 MeV	N/A	N/A

Note that MCNP calculations had not been made for the 300 cm position on the irradiation track, so the values in Table 4.6 that depended on these calculations were marked as "N/A."

4.3 Measurements in LANL NFIA

Multisphere measurements were made March 17-20, 2008 in LANL's TA-36 Building 214 calibration facility. This is a low scatter room with a track extending out from a ^{252}Cf source and another track extending out from an AmBe source. Measurements were made in the following configurations:

^{252}Cf, Unmoderated	100, 150, 200, 250 cm
^{252}Cf D_2O-moderated	100, 200 cm
^{252}Cf, 1"-thick poly moderator	200 cm
^{252}Cf, 3"-thick poly moderator	100, 200 cm
^{252}Cf, 5"-thick poly moderator	200 cm
^{252}Cf, 6"-thick poly moderator	200 cm
AmBe, Unmoderated	100, 200 cm

For all cases, the multisphere count rates were unfolded using MAXED, the Sanna response functions, and the LSRstart starting spectrum (performance was improved for unfolding in all cases with this spectrum). Accepted values (or "calculated" or "theoretical") were based on MCNP calculations performed by LANL.

4.3.1 Unmoderated ^{252}Cf Source

In Table 4.7, the multisphere measurements performed with neutrons from the unmoderated ^{252}Cf source are presented. All quantities were converted to units of "per n/s." Graphs of the spectra at 100 cm and 250 cm are presented in Figure 4.5 and Figure 4.6. For the graphs of the spectra, however, spectra are presented with as-measured quantities, and not on a per unit basis.

Table 4.7. Summary of multisphere measurements for LANL's unmoderated ^{252}Cf source

	Measured Value	*Accepted Value*	*Percent Difference*
~~100 cm~~~~~~~~~~~~~~~~~~~~~~			
Total Flux	788 n/cm^{2}s	1034	-23.8%
ANSI-77 Dose Equivalent Rate	79 mrem/h	113	-30.0%
ICRP 74, $H_p(10)$	92 mrem/h	126	-27.1%
Average Energy	1.583 MeV	2.243	
~~150 cm~~~~~~~~~~~~~~~~~~~~~~			
Total Flux	443 n/cm^{2}s	529	-16.3%
ANSI-77 Dose Equivalent Rate	43 mrem/h	54	-20.3%
ICRP 74, $H_p(10)$	50 mrem/h	59	-14.2%
Average Energy	1.294 MeV	2.029	
~~200 cm~~~~~~~~~~~~~~~~~~~~~~			
Total Flux	309 n/cm^{2}s	349	-11.4%
ANSI-77 Dose Equivalent Rate	27 mrem/h	33	-16.2%
ICRP 74, $H_p(10)$	32 mrem/h	35	-7.6%
Average Energy	1.152 MeV	1.814	
~~250 cm~~~~~~~~~~~~~~~~~~~~~~			
Total Flux	241 n/cm^{2}s	264	-8.5%
ANSI-77 Dose Equivalent Rate	20 mrem/h	23	-13.2%
ICRP 74, $H_p(10)$	23 mrem/h	24	-1.3%
Average Energy	0.939 MeV	1.619	

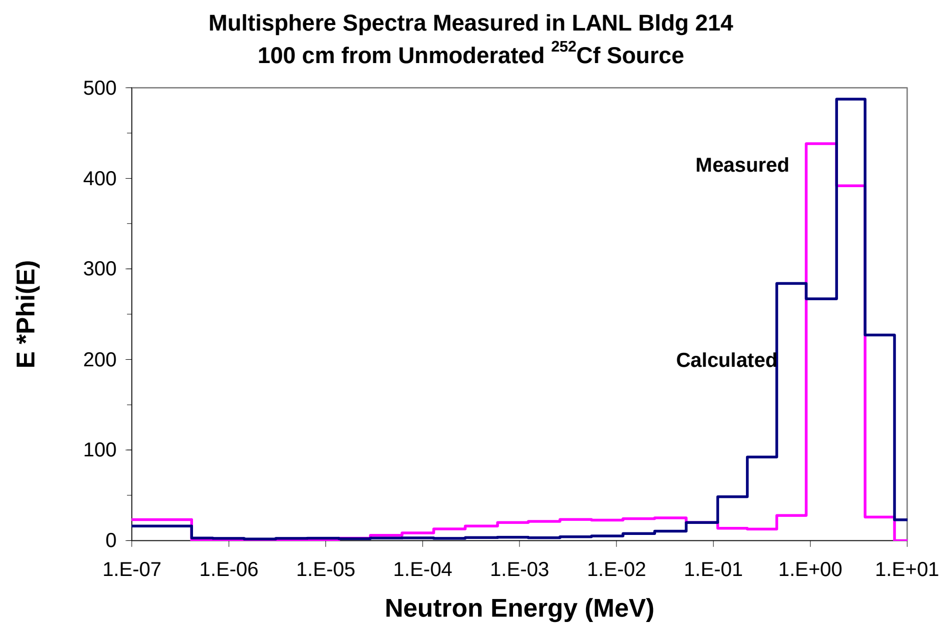

Figure 4.5. Multisphere spectra for unmoderated ^{252}Cf, 100 cm from source; LANL NFIA

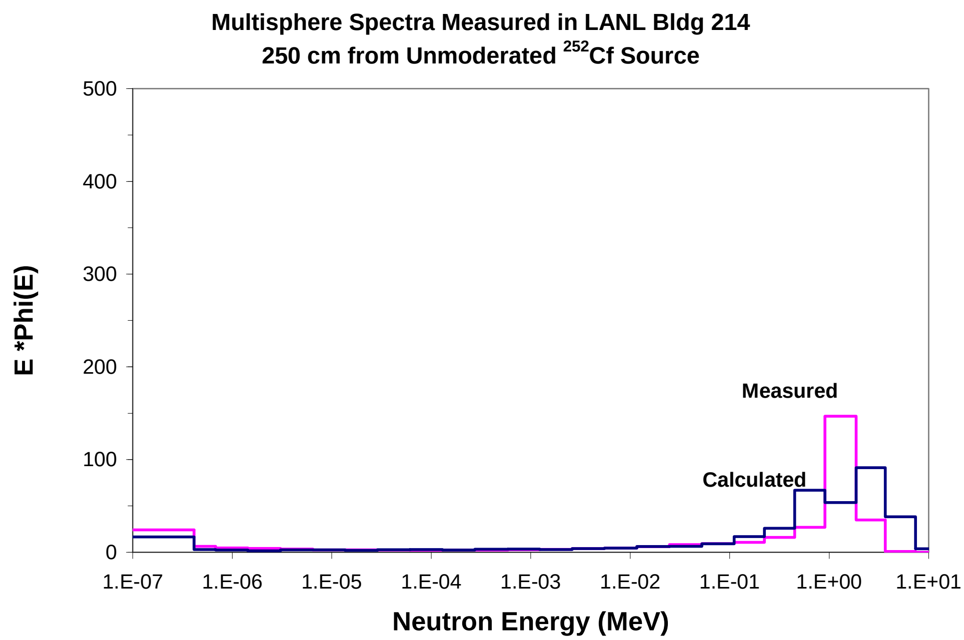

Figure 4.6. Multisphere spectra for unmoderated ^{252}Cf, 250 cm from source; LANL NFIA

4.3.2 D_2O-Moderated ^{252}Cf Source

Measurements were made at two distances from the D_2O-moderated source. Table 4.8 presents the data for these measurements; Figure 4.7 and Figure 4.8 present the unfolded spectra.

Table 4.8. Summary of multisphere measurements for LANL's D_2O-moderated ^{252}Cf source

	Measured Value	*Accepted Value*	*Percent Difference*
~~~~~~~~~~~~~~~~~~~~100 cm~~~~~~~~~~~~~~~~~~~~~~			
Total Flux	747 n/cm^{2}s	873	-14.4%
ANSI-77 Dose Equivalent Rate	26.7 mrem/h	27.5	-2.8%
ICRP 74, $H_p(10)$	32.2 mrem/h	30.4	6.0%
Average Energy	0.337 MeV	0.599	
~~~~~~~~~~~~~~~~~~~~200 cm~~~~~~~~~~~~~~~~~~~~~~			
Total Flux	310 n/cm^{2}s	316	-1.9%
ANSI-77 Dose Equivalent Rate	8.20 mrem/h	8.19	0.2%
ICRP 74, $H_p(10)$	9.95 mrem/h	8.59	15.9%
Average Energy	0.240 MeV	0.456	

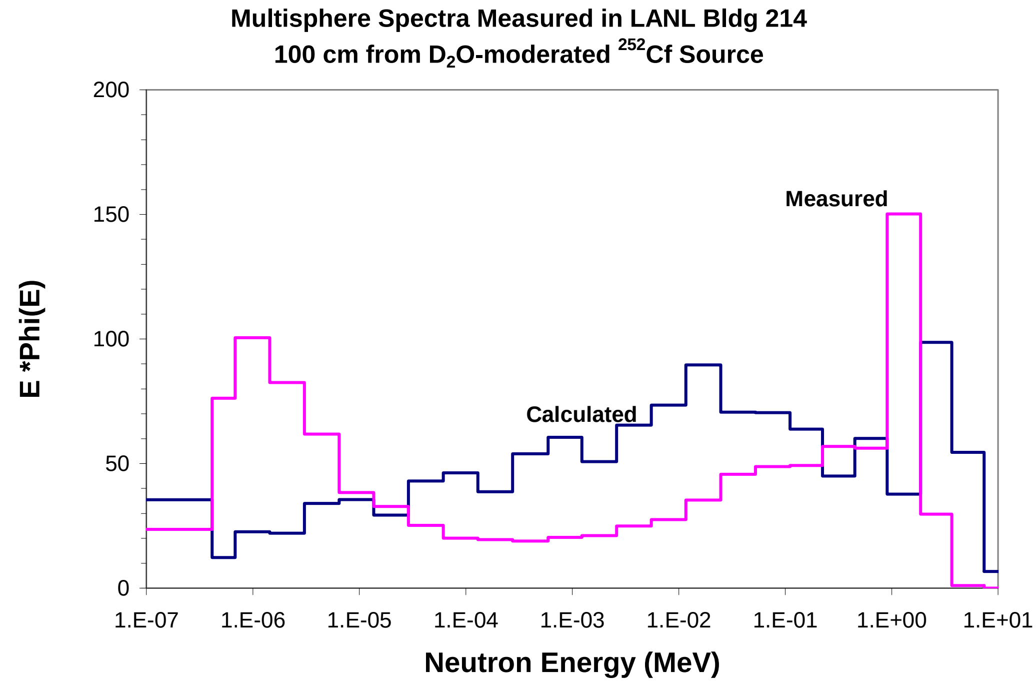

Figure 4.7. Multisphere spectra for D2O-moderated ^{252}Cf, 100 cm from source; LANL NFIA

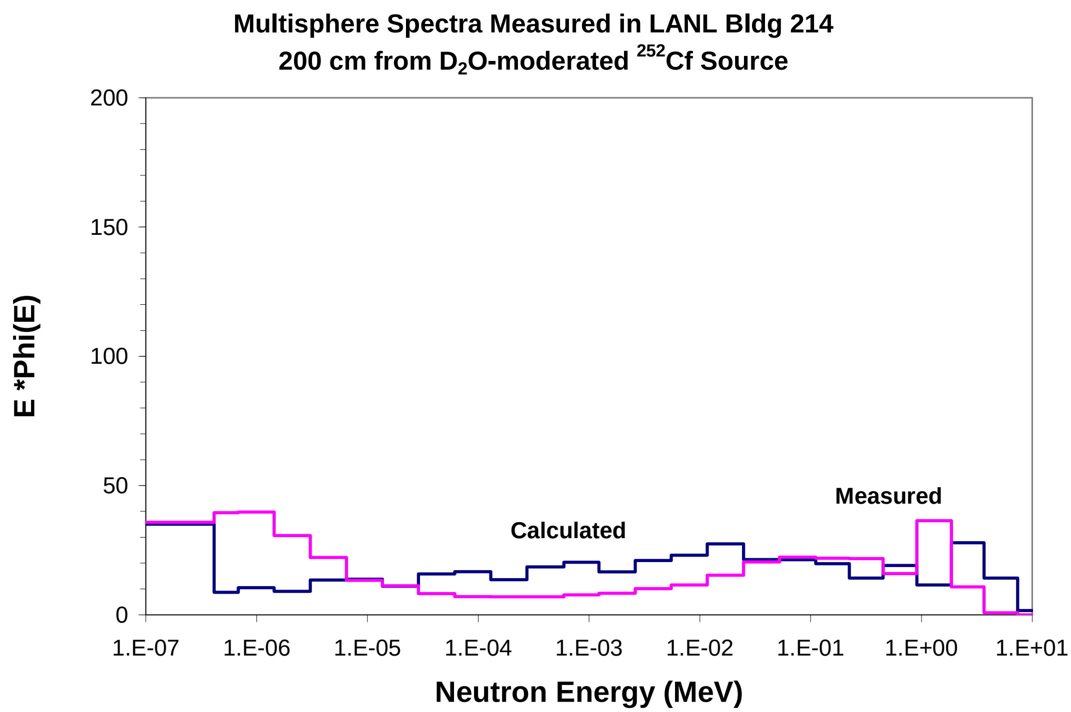

Figure 4.8. Multisphere spectra for D_2O-moderated ^{252}Cf, 200 cm from source; LANL NFIA

4.3.3 1-in Polyethylene-Moderated ^{252}Cf Source

Measurements were made at 200 cm from the ^{252}Cf source moderated by 1-in polyethylene. Table 4.9 presents the data for these measurements; Figure 4.9 presents the unfolded spectra.

Table 4.9. Multisphere measurement for LANL's ^{252}Cf source moderated by 1-in thick polyethylene

	Measured Value	*Accepted Value*	*Percent Difference*
Total Flux	338 n/cm^2s	345	-2.1%
ANSI-77 Dose Equivalent Rate	20.5 mrem/h	22.8	-10.2%
ICRP 74, $H_p(10)$	25.2 mrem/h	25.4	-0.9%
Average Energy	0.718 MeV	1.266	

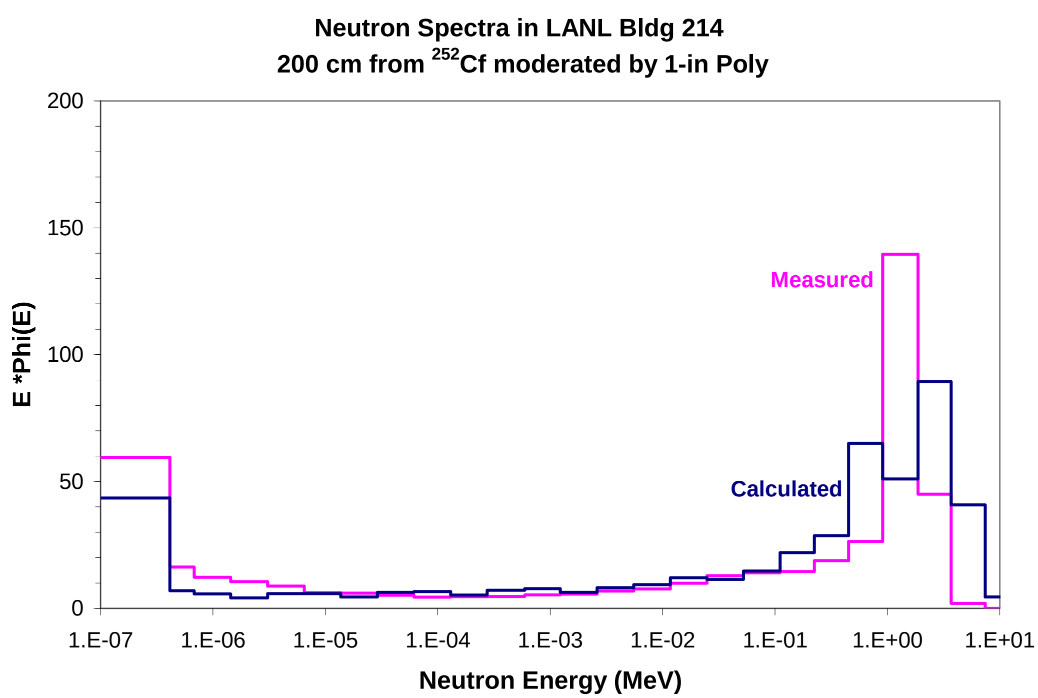

Figure 4.9. Multisphere spectra for ^{252}Cf moderated by 1-in thick polyethylene, 200 cm from source; LANL NFIA

4.3.4 3-in Polyethylene-Moderated ^{252}Cf Source

For the ^{252}Cf source moderated by a 3-in thick polyethylene sphere, measurements were made at 100 cm and at 200 cm from the source. Table 4.10 presents the data for the two measurements. Figure 4.10 and Figure 4.11 present the unfolded spectra.

Table 4.10. Multisphere measurements for LANL's ^{252}Cf source moderated by 3-in thick polyethylene

	Measured Value	*Accepted Value*	*Percent Difference*
~~*100 cm*~~~~~~~~~~~~~~~~~~~~~~			
Total Flux	593 n/cm^{2}s	580	2.2%
ANSI-77 Dose Equivalent Rate	27.6 mrem/h	32.9	-16.3%
ICRP 74, $H_p(10)$	33.5 mrem/h	37.9	-11.6%
Average Energy	0.624 MeV	1.201	
~~*200 cm*~~~~~~~~~~~~~~~~~~~~~~			
Total Flux	226 n/cm^{2}s	205	10.1%
ANSI-77 Dose Equivalent Rate	8.7 mrem/h	9.6	-9.1%
ICRP 74, $H_p(10)$	10.7 mrem/h	10.5	1.4%
Average Energy	0.469 MeV	0.927	

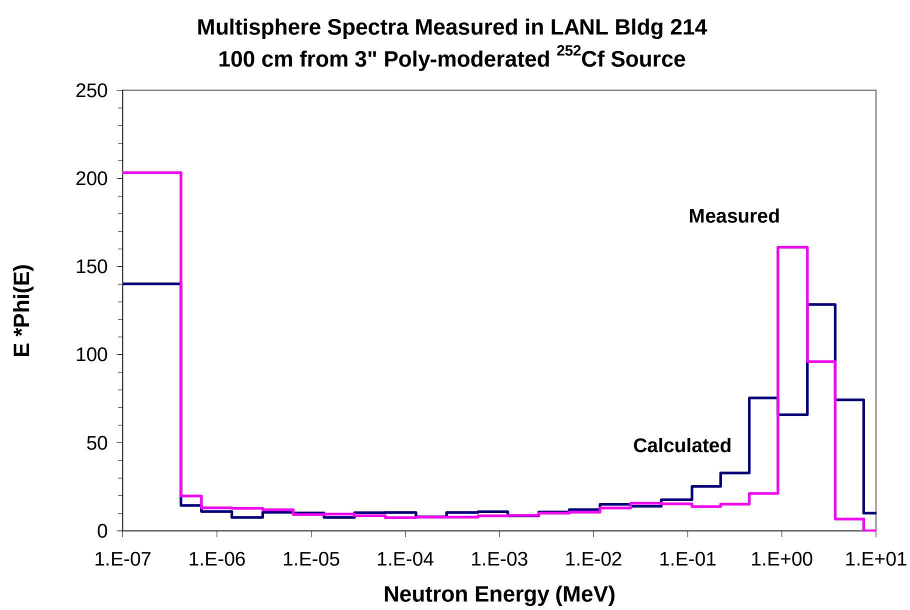

Figure 4.10. Multisphere spectra for ^{252}Cf moderated by 3-in thick polyethylene, 100 cm from source; LANL NFIA

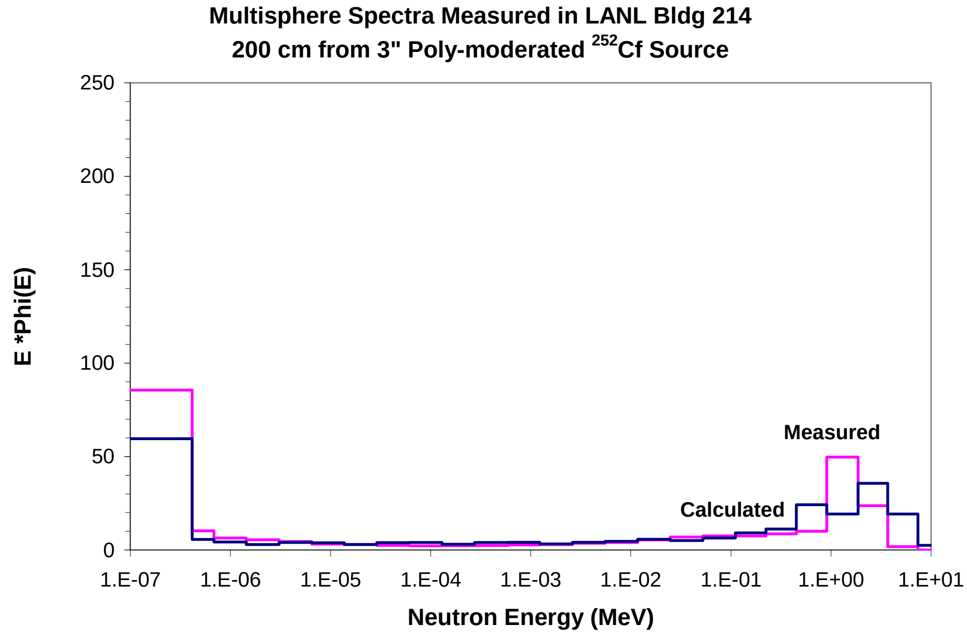

Figure 4.11. Multisphere spectra for ^{252}Cf moderated by 3-in thick polyethylene, 200 cm from source; LANL NFIA

4.3.5 5-in Polyethylene-Moderated ^{252}Cf Source

Measurements were made at 200 cm from the ^{252}Cf source moderated by 5-in polyethylene. Table 4.11 presents the data for these measurements; Figure 4.12 presents the unfolded spectra.

Table 4.11. Multisphere measurement for LANL's ^{252}Cf source moderated by 5-in thick polyethylene

	Measured Value	*Accepted Value*	*Percent Difference*
Total Flux	98 n/cm^{2}s	89	10.5%
ANSI-77 Dose Equivalent Rate	3.5 mrem/h	4.0	-11.6%
ICRP 74, $H_p(10)$	4.3 mrem/h	4.3	-0.6%
Average Energy	0.407 MeV	0.947	

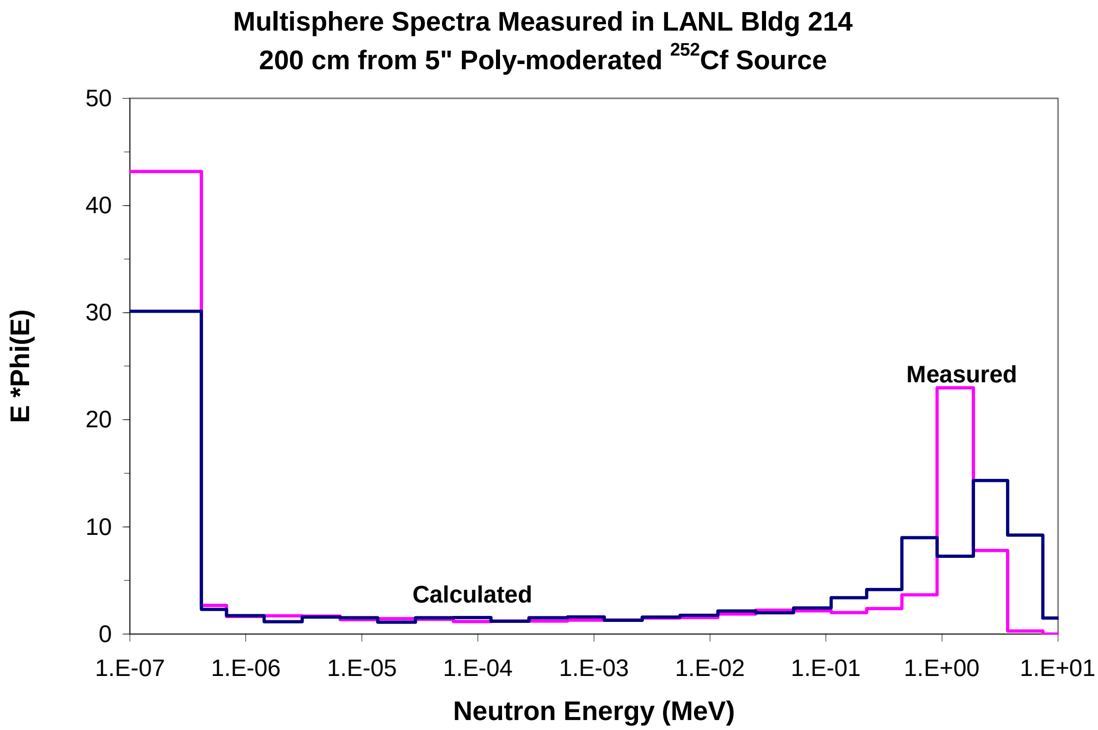

Figure 4.12. Multisphere spectra for ^{252}Cf moderated by 5-in thick polyethylene, 200 cm from source; LANL NFIA

4.3.6 6-in Polyethylene-Moderated ^{252}Cf Source

Measurements were made at 200 cm from the ^{252}Cf source moderated by 6-in polyethylene. Table 4.12 presents the data for these measurements; Figure 4.13 presents the unfolded spectra.

Table 4.12. Multisphere measurement for LANL's ^{252}Cf source moderated by 6-in thick polyethylene

	Measured Value	*Accepted Value*	*Percent Difference*
Total Flux	62 n/cm^{2}s	57	10.4%
ANSI-77 Dose Equivalent Rate	2.21 mrem/h	2.6	-13.6%
ICRP 74, $H_p(10)$	2.70 mrem/h	2.8	-2.8%
Average Energy	0.439 MeV	1.006	

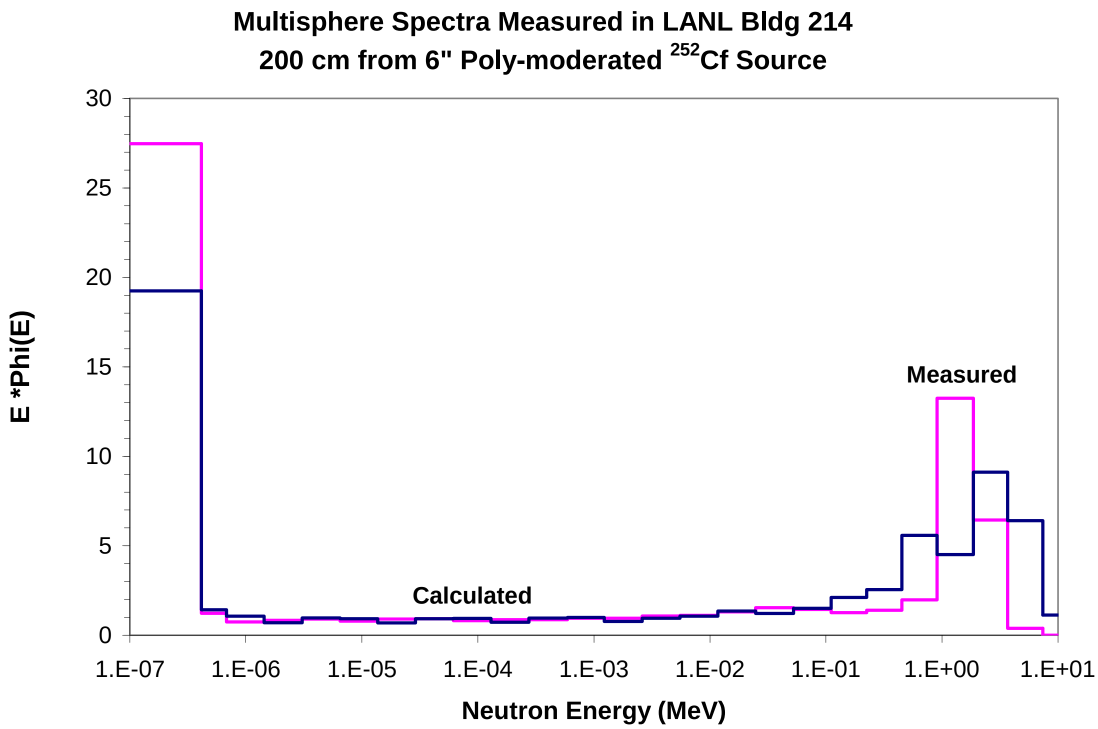

Figure 4.13. Multisphere spectra for ^{252}Cf moderated by 6-in thick polyethylene, 200 cm from source; LANL NFIA

4.3.7 Unmoderated AmBe Source

For the unmoderated AmBe source, measurements were made at 100 cm and at 200 cm from the source. Table 4.13 presents the data for the two measurements. Figure 4.14 and Figure 4.15 present the unfolded spectra.

Table 4.13. Multisphere measurements for LANL's AmBe source, unmoderated

	Measured Value	*Accepted Value*	*Percent Difference*
~~~~~~~~~~~~~~~~~~~100 cm~~~~~~~~~~~~~~~~~~~~~			
Total Flux	192 n/cm^{2}s	210	-8.6%
ANSI-77 Dose Equivalent Rate	21.5 mrem/h	25.8	-16.6%
ICRP 74, $H_p(10)$	24.6 mrem/h	28.2	-12.7%
Average Energy	2.729 MeV	4.230	
~~~~~~~~~~~~~~~~~~~200 cm~~~~~~~~~~~~~~~~~~~~~			
Total Flux	65 n/cm^{2}s	67	-3.0%
ANSI-77 Dose Equivalent Rate	6.3 mrem/h	7.3	-13.0%
ICRP 74, $H_p(10)$	7.4 mrem/h	7.6	-3.9%
Average Energy	2.121 MeV	3.516	

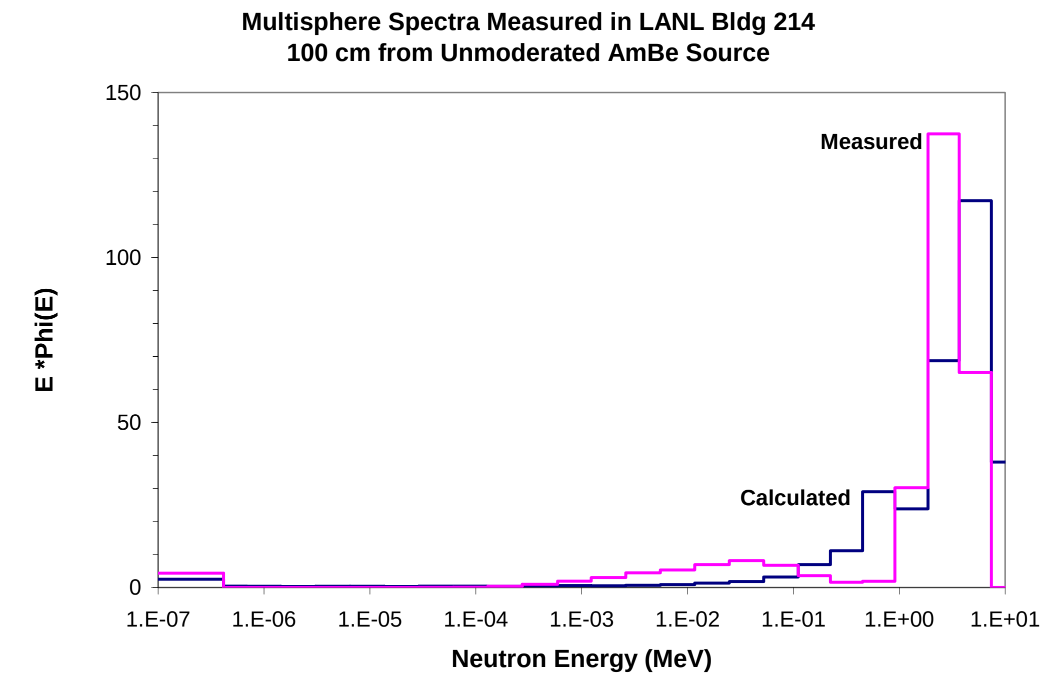

Figure 4.14. Multisphere spectra for unmoderated AmBe, 100 cm from source; LANL NFIA

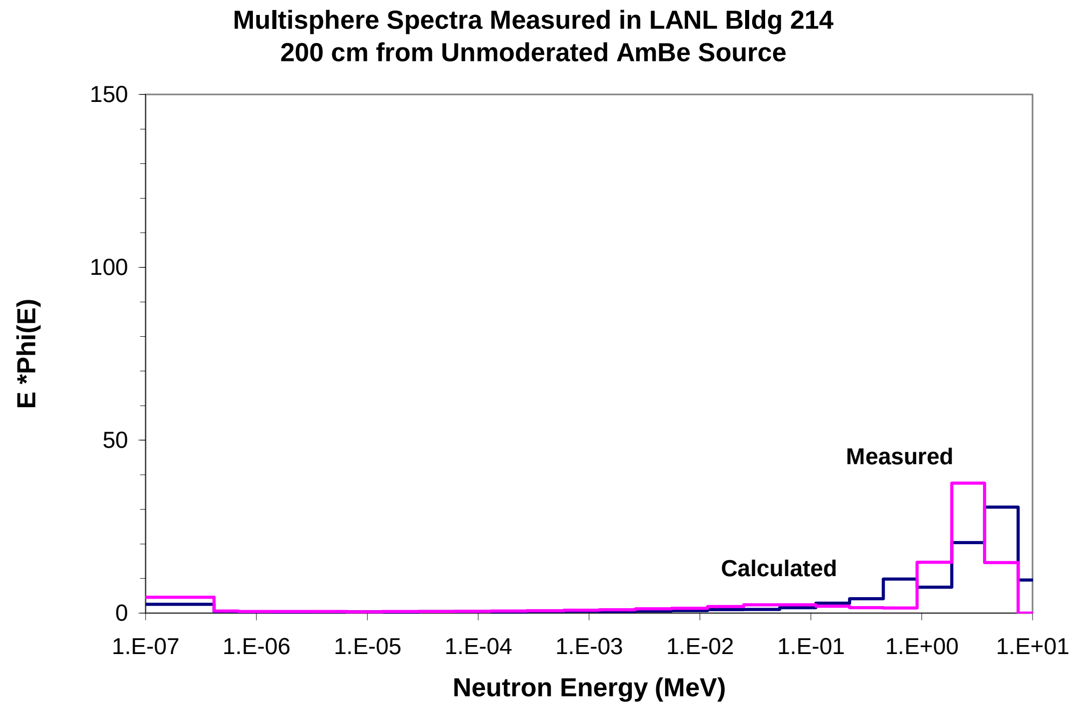

Figure 4.15. Multisphere spectra for unmoderated AmBe, 200 cm from source; LANL NFIA

4.4 Discussion of Multisphere Measurements

Unmoderated ^{252}Cf: Unfolding of the unmoderated spectra for all cases results in spectra that look reasonable. The measured spectrum shape is pretty similar to the calculated spectrum, with the fission peak higher and not as broad in the measured spectrum compared to the calculated. The spectra had similar nearly-zero values in the intermediate energy region; for the thermal energy bin, calculated and measured fluxes were within 6% of each other.

Total flux values for PNNL were within 3%, accepted vs measured, as were most dose equivalent rate comparisons. Measured average energies are lower than accepted values, which seems to be typical of all PNNL multisphere unfolding.

It is surprising that the agreement between measured and accepted values in LANL's NFIA was not better: the measurement was 24% lower than the theoretical at 100 cm. But agreement improved as the distance increased: by 250 cm the measurement was only 8.5% lower than theoretical. This is different than the experience at PNNL, where measured and calculated fluxes for unmoderated ^{252}Cf were very good: no more than 2.3% difference. While dose equivalent rates measured at PNNL agreed very well with theoretical values, they were lower than theoretical values for all cases at LANL. It is surprising that the spectrometer had different performance at PNNL than at LANL for the same neutron energy distribution.

D_2O-Moderated ^{252}Cf: Unfolding here is not quite as good as experienced with unmoderated ^{252}Cf – it is a more difficult assessment problem, both from the standpoint of measurements and modeling. For multispheres, the most difficult part to unfold is the "intermediate" region, above thermal but below approximately 10 keV. In this region the response functions are fairly flat, there are no peaks, and the unfolding process can produce a wide variety of flux shapes from minor variations in the unfolding parameters. Measured average energies were lower than theoretical, as observed for all neutron spectra.

For total flux, the measured values were about 15% higher than accepted for 100 and 200 cm in PNNL's LSR, but 15% lower than accepted for LANL's NFIA at 100cm. However, for 300 cm in the LSR and 200 cm in the NFIA, agreements between measured and accepted values were very good, well under 1%. This is part of a general trend that measured-vs-accepted comparisons seem better at larger distances from the source.

For dose equivalent rates in the LSR, measured values were typically 9-18% higher than accepted. It is hard to explain why the accepted value is closer to the "wall" measurement than the "track" measurement – the opposite would be expected, since the MCNP calculations were made on the track, not the wall.

Dose equivalent rates measured at LANL were very close to the theoretical values, presenting a much different case than at PNNL. For the ANSI-77 methodology, measured and accepted values agreed within a few percent. For ICRP 74 values, the measured values were 6 – 16% higher than the accepted values.

Polyethylene-Moderated ^{252}*Cf:* Four different configurations were tested at LANL, with thicknesses of polyethylene moderator of 1-in, 3-in, 5-in and 6-in. For the determination of total flux, the agreement between measurement and accepted value was good: less than 2% for the 1-in and 3-in moderators, and about 10% for the others. For ANSI-77 dose equivalent, the measured values were lower than the accepted, usually by 10-15%. For all four configurations, where the dose location was at 200 cm, agreement of $H_p(10)$ was very good, less than 3%. Only one configuration had a 100 cm measurement in addition to the 200 cm one; for this the $H_p(10)$ measurement was 12% lower than the accepted value. Again this showed the trend that agreement between measured and theoretical values improved with distance from the source.

Unmoderated AmBe: Measurements were made at 100 cm and 200 cm from the AmBe source, and the 200 cm measurement had a better agreement than the 100 cm. Flux showed only a 3% difference at 200 cm, where it was 8.6% lower at 100 cm. The measured ANSI-77 dose equivalent rate was 13% lower than accepted at 200 cm and 17% lower at 100 cm. Measured $H_p(10)$ was 4% lower than accepted at 200 cm and 13% lower at 100 cm.

5.0 Conclusions

PNNL has completed the modifications to the analysis software and data files for the TEPC and multisphere spectrometer, and these methods are now compliant with the new requirements found in 10 CFR 835. The neutron measurements in the PNNL LSR and the LANL NFIA provided a better understanding of the performance of these instruments. This study also pointed to several other areas of interest.

5.1 Assessment of Neutron Flux in PNNL LSR

PNNL is working on its own model of the neutron radiation fields in the LSR, which would be an update to the LANL study. The first objective is to develop a more accurate method of accounting for anisotropy in the unmoderated ^{252}Cf sources. The updated model will be useful to anyone characterizing neutron instruments in the LSR.

5.2 TEPC

The TEPC detectors have been used to provide reliable estimates of neutron dose equivalent, but the new methodology prescribed by 10 CFR 835 presents a difficulty for using this instrument. The new methodology should provide an estimate of equivalent dose, and $H_p(10)$ or $H^*(10)$ would be acceptable approximations of equivalent dose. Both of these quantities, however, specify that the dose evaluation should account for attenuation of the incident neutron field by a depth of tissue of 10 mm. The TEPC, however, has a very thin wall of tissue-equivalent plastic in its spherical detector and incorporates very little neutron attenuation. Therefore the TEPC will usually overestimate $H_p(10)$, as shown in Table 3.5 and Table 3.7. There have been attempts to use TEPCs with a thick plastic wall to simulate attenuation by tissue, but these results have been only partially successful.

The best approach to improving the TEPC analysis is to develop an analytical method to account for neutron interactions influencing dose at 1 cm tissue depth. An algorithm could be developed relating lineal energy to tissue attenuation, and develop a factor that could be multiplied by the final dose equivalent rate to bring the value closer to $H_p(10)$. Until that time, it must be accepted that our evaluation gives a dose equivalent rate that is up to 25% higher than accepted values.

5.3 Multisphere Unfolding

For the tests at both PNNL and LANL, it was disappointing that the measurements did not give values closer to the theoretical values than was observed. Measurements performed by LANL staff gave spectra that were nearly identical to the theoretical values. The shape of our measured spectra were similar to, but not identical to, the spectra derived from modeling. Measured average energies were always lower than theoretical values, which is a result of the method of spectrum unfolding. Total flux values and dose equivalent values were usually 10% or even 20% different than theoretical.

This does not mean that the PNNL multisphere spectrometer cannot be used – it can be relied on to provide values that are within 20% of measured values, no matter what the irradiating energy, which is good performance for a neutron instrument. However, it could perform much better.

There are two areas to investigate for improving our multisphere capabilities: additional spheres in the measurement set, and new response functions:

> Additional Spheres: Adding some additional spheres, such as 2”, 3” or 5” diameter spheres, all without cadmium covers, would provide additional power to the measurement.
>
> Response Functions: PNNL has investigated two response function sets: a 26-group set calculated by Sanna in the 1960’s, and a 26-group set calculated by University of Texas in the 1980’s. In our comparisons, the Sanna set provides better results, so we have used it. However, it was calculated using very general assumptions. PNNL’s multisphere set has a unique design for the detector and sphere, and it does not match the original calculation assumptions well. A new set could be calculated using MCNP, making a very realistic model of the counting configuration used in the PNNL system. Using it in the unfolding would probably improve our results.

A multisphere set that produced more reliable unfolded spectra would be very useful for assessing neutron radiation fields. With additional modifications to the configuration and analyses, it could be an important instrument for measuring dose equivalent rates at Hanford facilities.

Another potentially useful instrument for assessing neutron fields at Hanford is the ROSPEC spectrometer. This instrument has been used successfully by LANL and other laboratories for the types of neutron field characterizations that PNNL performs.

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