SLAC-PUB-8258
January 2000

Evaluation of a Microdosimetric-Based Neutron Instrument

James C. Liu

Presented at International Workshop on Neutron Field Spectrometry in Science,
Technology and Radiation Protection, 6/5/2000—6/8/2000, Pisa, Italy

Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

Work supported by Department of Energy contract DE–AC03–76SF00515.

EVALUATION OF A MICRODOSIMETRIC-BASED NEUTRON INSTRUMENT

James C. Liu

Stanford Linear Accelerator Center, MS 48, P.O. Box 4349, Stanford, CA 94309, U.S.A.

*E-mail: james@slac.stanford.edu

Abstract

The commercially available REM500 neutron survey meter is a microdosimetric instrument based on the use of a low-pressure tissue-equivalent proportional counter. The neutron spectrometry capability, as well as the dose equivalent response, of the REM500 was evaluated with five radioisotopic neutron sources (^{238}PuLi, ^{238}PuF, ^{238}PuB, ^{238}PuBe and ^{252}Cf) and the mono-energetic 14-MeV neutrons. The response (counts/mSv) and sensitivity (counts/neutron) as a function of neutron energy were determined. From the measured pulse height spectra, the frequency-mean and dose-mean lineal energy values, as well as the mean quality factors, were derived for all sources. The neutron dose equivalent determined from the dose and mean quality factor measured by the REM500 agreed well with the reference values of ICRP21 maximum dose equivalent. However, for the REM500 to measure proper lineal spectra, the low sensitivity and inaccurate measurements for high-energy neutrons are areas that may need improvements.

INTRODUCTION

The use of microdosimetric-based detectors for radiological protection measurements has been studied before (1-5). Two portable instruments based on the principle of low-pressure tissue-equivalent proportional counter are commercially available for routine health physics survey (6,7). The portable neutron survey meter REM500, commercially available from the Health Physics Instruments *, is a microdosimetric instrument. The REM500 performance as a neutron field survey meter has been tested in a nuclear power plant (7). The REM500 performance was also compared with that of HANDI (6) in an accelerator reference field (8).

Instead of the REM500's field survey function, this study emphasized on the evaluation of its neutron spectrometry capability. The performance of the REM500 meter was tested with five well-characterized radioisotopic neutron sources (^{238}PuLi, ^{238}PuF, ^{238}PuB, ^{238}PuBe and ^{252}Cf) and the mono-energetic 14-MeV neutrons. The response (counts/mSv) and sensitivity (counts/neutron) as a function of neutron energy were determined. From the microdosimetric spectra, the frequency-mean and dose-mean lineal energy values, as well as the mean quality factors, were derived. The neutron dose equivalent determined from the dose and mean quality factor measured by the REM500 was compared with the reference values of maximum dose equivalent.

---

* Health Physics Instruments, A Division of Far West Technology, 330 D South Kellogg Ave., Goleta, CA 93117

DESCRIPTION OF REM500

While the REM500 Operations and Repair Manual can be consulted for the details of the instrument, the key information of the REM500 is described here. The sensor is a Rossi type, sealed spherical tissue-equivalent proportional counter (5.97 cm ID). The wall is made of Shonka A150 tissue-equivalent plastic (0.127 cm thick, 0.144 gm cm^{-2}). The counter is filled with low-pressure, tissue-equivalent propane gas (pressure 1.77 kPa and mass 3.54 mg) to simulate a tissue volume of 2 μm [#] in diameter at unit density. The counter is enclosed inside a sealed aluminum (0.165-cm-thick) cylindrical can.

There are three main operation modes for the REM500: rate, integrate, and multichannel analyzer (MCA) modes. Rate and integrate modes are for routine field survey to measure neutron dose equivalent rates directly while the MCA mode is to measure a microdosimetric spectrum. In MCA mode a pulse height spectrum in 256 channels (i.e., events vs. energy deposition) can be collected and then downloaded to a computer through the RS232 serial link. With post-processing, the MCA mode allows the users to evaluate important quantities in microdosimetry (lineal energy spectrum, frequency-mean and dose-mean lineal energy values, quality factor, sensitivity, etc.) and is, therefore, the main operation that was studied here. The rate and integrate modes simply gather pulses (counts) into appropriate channels over a preset time period (10-60 s) and then calculate and display the dose and dose equivalent rates using its internal algorithm.

The manual mistakenly stated 1 μm.

The counter response can be checked with an internal ^{244}Cm source in the CHECK mode. With the shutter opened in the CHECK mode, the alpha particles from the ^{244}Cm source can traverse the diameter of the counter. The stopping power of these alpha particles in propane is about 108 keV/μm as compared with 91 keV/μm in tissue gas. The stopping power of protons (recoils from neutron interaction with A150 wall) is also higher in propane than in tissue gas with similar magnitudes. Therefore, the alpha peak was set by manufacturer at channel 90, equivalent to an energy deposition (ε) of 180 keV in tissue over the 2 μm diameter. The relationship between channel number I and lineal energy y (keV/μm) is then $y = \varepsilon/l = 2I/(2d/3)$, where d is counter diameter (2 μm) and l is the mean chord length (1.333 μm). Thus, channel 90 is equivalent to a lineal energy y of 135 keV/μm in tissue. The lowest detection limit is set by manufacturer at channel 5, i.e., 7.5 keV/μm. Therefore, photons may still contribute some counts into lower channels. Any event depositing more than 512 keV (i.e., 384 keV/μm) is accumulated into channel 256. This may cause errors if heavy ion recoils are present.

METHODS

The REM500 was irradiated to the neutron sources in a low-scattering environment (source and detector heights were 175 cm above ground and the source-to-detector distance was 75 cm). The average energies and the ICRP21 (9) fluence-to-maximum dose equivalent conversion factors for the sources are given in Table 1. To ensure good statistics, more than 8000 counts were accumulated in any single pulse height spectrum. The effects of dead time (60 μs) and background (~90 count per day) were negligible for these source irradiations.

The magnitude of photon dose rate of every neutron source was measured with a Victoreen 450p photon survey meter*. The photon contribution to the REM500 response was first removed by assuming source photons are similar to ^{137}Cs photons. With the resulting pulse height spectrum due to neutrons only, N(I), the absorbed dose in tissue, D (in units of Gy), can be calculated as Equation 1 below:

$$D = (C/M)\ \Sigma\ N(I)\ \varepsilon(I) \tag{1}$$

where C = unit conversion (Gy.gm/keV) = $1.6\mathrm{x}10^{-13}$,

M = mass of propane (gm) = $3.54\mathrm{x}10^{-3}$,

N(I) = number of counts in channel I (I = 6 to 256), and

$\varepsilon(I)$ = deposited energy for channel I (keV) = 180I / 90 = 2I

The summation in Equation 1 is summed over channels 6-256. From the pulse height spectrum and using the above-mentioned channel-lineal energy relationship, the normalized spectra of lineal energy, f(y), and probability density of dose, d(y), as a function of y can then be derived using Equations 2.21 and 2.25 of ICRU36 (10), respectively. The frequency-mean lineal energy, y_F, and dose-mean lineal energy, y_D, can also be calculated from the distributions of f(y) and d(y) using Equations 2.22 and 2.26 of ICRU36 (10), respectively.

---

* Victoreen Inc., Cochran Blvd, Cleveland, OH 44139

The mean quality factor, Q, is estimated using the linear equation (10):

$$Q = 0.8 + 0.14y_D \tag{2}$$

or by the following summation:

$$Q = \Sigma\, q(y)\, d(y) \tag{3}$$

where q(y) is the quality factor as a function of y. The function q(y) was chosen to approximate the ICRP26 (11) function of quality factor vs. LET by setting either y=L or y=9L/8 (5). The Q is 1 for L below 3.5 keV/μm, Q is 20 for L above 175 keV/μm, and Q is proportional to L within the interval (11). The function of q(y) is shown in Figure 1 for the cases of setting y=L and y=9L/8.

The neutron dose equivalent, H (in Sv), is then calculated using

$$H = D\, Q \tag{4}$$

RESULTS

In this section the sensitivity, microdosimetric spectra for neutron sources, the frequency-mean and dose-mean lineal energy values, quality factors, and dose equivalent response as a function of neutron energy are presented. The results are also summarized in Table 1.

Response and sensitivity

The response of the REM500 was ~30000 counts/mSv for low-energy neutrons and increases to ~70000 counts/mSv for 14-MeV neutrons, while the sensitivity (count per neutron) increases from $2x10^{-4}$ to $1.1x10^{-3}$.

Microdosimetric spectra

The photon response (count/mGy) of the REM500 to ^{137}Cs and ^{60}Co sources, shown as event spectra in Figure 2, indicated most photons deposit energy less than 15 keV/μm and the response between ^{137}Cs and ^{60}Co photons is similar.

Figure 3 shows the lineal energy spectrum, f(y) vs. y on linear scales, for PuLi neutrons with the photon components subtracted. Because of the sources' small photon/neutron fractions and the low energy deposition for photons, the use of either ^{137}Cs or ^{60}Co photon response in Figure 1 for photon component subtraction does not affect the neutron's lineal energy spectra.

Figure 4 shows the lineal energy spectra, yf(y) on a linear scale vs. y on a logarithmic scale, for five radioisotopic neutron sources (in this figure the visual area under the curve is also proportional to the event frequency). The neutron spectrometry capability of the REM500 is clearly seen: the lower the average energy of the neutron source, the harder the lineal energy spectrum. Most neutrons produced events with y between 10 and 150 keV/μm.

Figure 5 compares the dose spectra, yd(y) on a linear scale vs. y on a logarithmic scale, for five neutron sources (in this figure the visual area under the curve is proportional to the dose). Note that the doses in channel 256 are over the scale.

Figure 6 shows that the lineal energy spectrum of 14-MeV neutrons is similar to that of the PuBe, both softer than the ^{252}Cf spectrum. Figure 7 indicates that the 14-MeV neutrons produce higher doses at large y values than isotopic neutron sources, most likely due to heavy ion recoils. The significant presence of dose in channel 256 is clearly seen in the case of 14-MeV neutrons.

Frequency-mean (y_F) and dose-mean (y_D) lineal energies

The y_F and y_D values as a function of average energy of the neutron sources (see Table 1) agree with Figure F6 of ICRU36 (10). For radioisotopic neutron sources, either y_F or y_D value can be used as an index for neutron spectrum like the average energy.

The fractions of y_F and y_D contributed from channel 256, i.e., $y \geq 384$ keV/μm, are higher for high-energy neutrons. For 14-MeV neutrons the y_D fraction is as high as 24%. Note that these fractions, as well as the y_F and y_D values, were underestimated (except for PuLi and PuF) because a fixed y value of 384 keV/μm was used for all events above channel 256.

Quality factor, Q

The mean quality factors determined using Equation 2 (which gives the highest Q) and Equation 3 are shown in Figure 8 and Table 1. Note that our Q values are due to neutrons only. The Q value determined using Equation 2 is valid for radiation qualities where the fraction of dose deposited at L values above 100 keV/μm is small (10). Therefore, the Q value of 15.5 for 14-MeV neutrons has a larger error, compared to those of isotopic neutron sources. The Q values close to 10 for radioisotopic neutron sources agree with those in 10CFR835 (12).

Dose equivalent response and summary

As stated by Blanc and Terrissol (13), for neutrons between 0.2-5 MeV and a sphere size of 1-2 μm, the Q value estimated using Equation 2 should agree with the Q value for the ICRP21 maximum dose equivalent. Therefore, if the tissue dose estimation using Equation 1 is correct, the dose equivalent estimation using Q from Equation 2 should have better agreement than those using Q from Equation 3. This expectation is verified in the dose equivalent comparison shown in the last three rows of Table 1. Except for the PuLi and 14-MeV neutrons, the neutron dose equivalent measured by the REM500 (using Q from Equation 2) agrees with the ICRP21 maximum dose equivalent within 10%.

CONCLUSIONS

With a simple alpha peak check before a pulse height measurement and some spectral post-processing, the REM500 can measure neutron dose and quality factor (and thus the neutron dose equivalent) accurately. The neutron spectrometry capability of the REM500 survey meter was demonstrated. The frequency-mean (y_F) and dose-mean (y_D) lineal energies can also be used to estimate the average energy and the fluence-to-dose equivalent conversion factor for a neutron spectrum. However, for the REM500 to measure proper lineal spectra, the low sensitivity and inaccurate measurements for high-energy neutrons are areas that may need improvements. For example, at a field of 0.01 mSv/h, a measurement as long as a few hours may be needed to achieve good statistics. The measurement performance of the REM500 in SLAC neutron fields, which have pulsed and high-energy (up to a few hundred MeV) neutrons, is currently under testing and the results are to be presented in another report.

ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy under contract DE-AC-03-76SF00515. The author is grateful to the assistance from Ron Seefred.

REFERENCES

1. Braby, L.A., Ratcliffe, C.A., and Metting, N.F. *Evaluation of a Portable Microdosimetry System*. Radiat. Prot. Dosim. **9(3)**, 219-221 (1984).
2. Schmitz, Th., Smit, Th., Morstin, K., Muller, K.D., and Booz, J. *Construction and First Application of a TEPC Dose Equivalent Meter for Area Monitoring*. Radiat. Prot. Dosim. **13(1/4)**, 335-339 (1985).
3. Cowling, A.R. and Waker, A.J. *Experimental Studies of a Large Volume Tissue Equivalent Proportional Counter*. Radiat. Prot. Dosim. **13(1/4)**, 353-356 (1985).
4. Dietze, G., Menzel, H.G., and Schuhmacher, H. *Determination of Dose Equivalent with Tissue Equivalent Proportional Counters*. Radiat. Prot. Dosim. **28(1/2)**, 77-81 (1989).
5. Menzel, H.G., Lindborg, L., Schmitz, Th., Schuhmacher, H., and Walker, A.J. *Intercomparison of Dose Equivalent Meters Based on Microdosimetric Techniques: Detailed Analysis and Conclusions*. Radiat. Prot. Dosim. **29(1/2)**, 55-68 (1989).
6. Kunz, A., Arend, E., Dietz, E., Gerdung, S., Grillmaier, R.E., Lim, T., and Piher, P. *The Homburg Area Neutron Dosemeter HANDI: Characteristics and Optimization of the Operational Instrument*. Radiat. Prot. Dosim. **44(1/4)**, 213-218 (1992).
7. Pope, J. *Use of the REM500 Neutron Survey Meter at McGuire Nuclear Station*. Radiat. Prot. Management 11(3), 91-96 (1994).
8. Aroua, A., Hofert, M., and Sannikov, A.V. *On the Use of Tissue Equivalent Proportional Counters in High Energy Stray Radiation Fields*. Radiat. Prot. Dosim. **59(1)**, 49-53 (1995).
9. ICRP *Recommendations of the International Commission on Radiological Protection*, ICRP Publication 21, (Pergamon Press, Oxford) (1973).
10. ICRU *Microdosimetry*, Report 36 (Bethesda, MD:ICRU Publications) (1983).

11. ICRP *Recommendations of the International Commission on Radiological Protection*, ICRP Publication 26, Annals of the ICRP, Vol. 1, No. 3 (Pergamon Press, Oxford) (1977).
12. USDOE *Title 10, Code of Federal Regulations, Part 835 Occupational Radiation Protection,* U.S. Federal Register Vol. 63, No. 213 (1998).
13. Blanc, D. and Terrissol, M. *Microdimetry. A Tool for Radiation Research*. Radiat. Prot. Dosim. **13(1/4)**, 387-393 (1985).

Table 1. Summary of neutron source parameters, neutron dose equivalent H and fluence irradiated, the response and sensitivity of the REM500, the frequency-mean y_F and dose-mean y_D lineal energies and their corresponding fractions from channel 256, the tissue dose (calculated with Equation 1), and quality factors (Q evaluated with Equations 2 and 3) measured by the REM500, and comparison of dose equivalent between the REM500 measurement and irradiation.

Source	^{238}PuLi	^{238}PuF	^{252}Cf	^{238}PuB	^{238}PuBe	14-MeV
Ave. Energy (MeV)	0.5	1.4	2.2	2.7	4.3	14.0
h-ICRP21 (x10^{-10} Sv cm^2)	1.80	3.40	3.33	3.90	3.90	4.18
H delivered (mSv)	0.33	0.27	0.80	0.21	0.27	1.25
Fluence (cm^{-2})	1850000	806000	2400000	544000	703000	2987869
Total counts	11278	8196	25734	9643	13798	90339
Response (counts/mSv)	33870	29910	32200	45450	50330	72330
Sensi. (counts/neutron)	0.00022	0.00037	0.00039	0.00064	0.00070	0.00109
y_F (keV/μm)	54.8	48.6	40.6	37.5	32.0	35.8
y_D (keV/μm)	75.6	69.9	70.7	67.8	66.1	104.7
Ch256 Fraction y_F	0.000	0.000	0.008	0.004	0.016	0.064
Ch256 Fraction y_D	0.000	0.000	0.044	0.024	0.091	0.235
Tissue Dose (mGy)	0.039	0.025	0.066	0.023	0.028	0.204
Q (0.8+0.14 y_D)	11.4	10.6	10.7	10.3	10.1	15.5
Q-ICRP26 y=L	8.9	8.3	7.9	7.5	7.0	9.2
Q-ICRP26 y=9L/8	8.0	7.4	7.2	6.9	6.4	8.7
H(Q) / H-ICRP21	1.34	0.97	0.89	1.11	1.03	2.53
H(y=L) / H-ICRP21	1.05	0.76	0.65	0.81	0.72	1.51
H(y=9L/8) / H-ICRP21	0.94	0.68	0.59	0.74	0.65	1.42

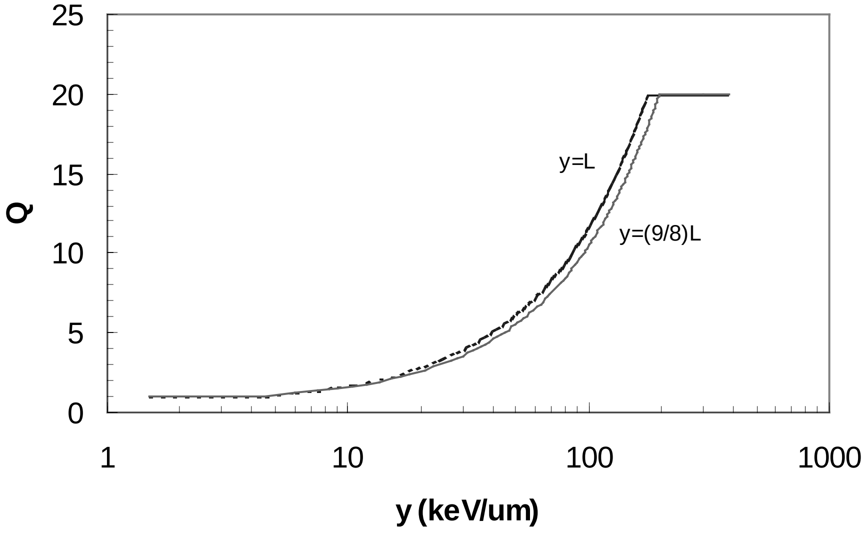

Figure 1. Function of quality factor Q vs. lineal energy y, q(y), for the cases of setting y=L and y=9L/8.

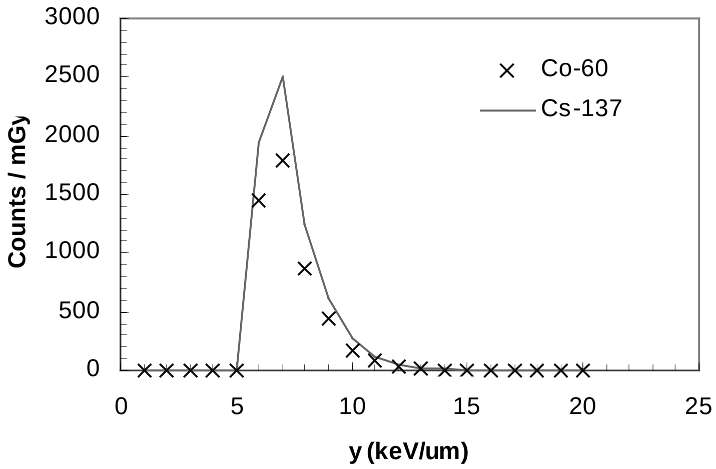

Figure 2. Photon response (count/mGy) of the REM500 to ^{137}Cs and ^{60}Co sources, which shows that most photons deposit energy less than 15 keV/μm and the response between ^{137}Cs and ^{60}Co photons is similar.

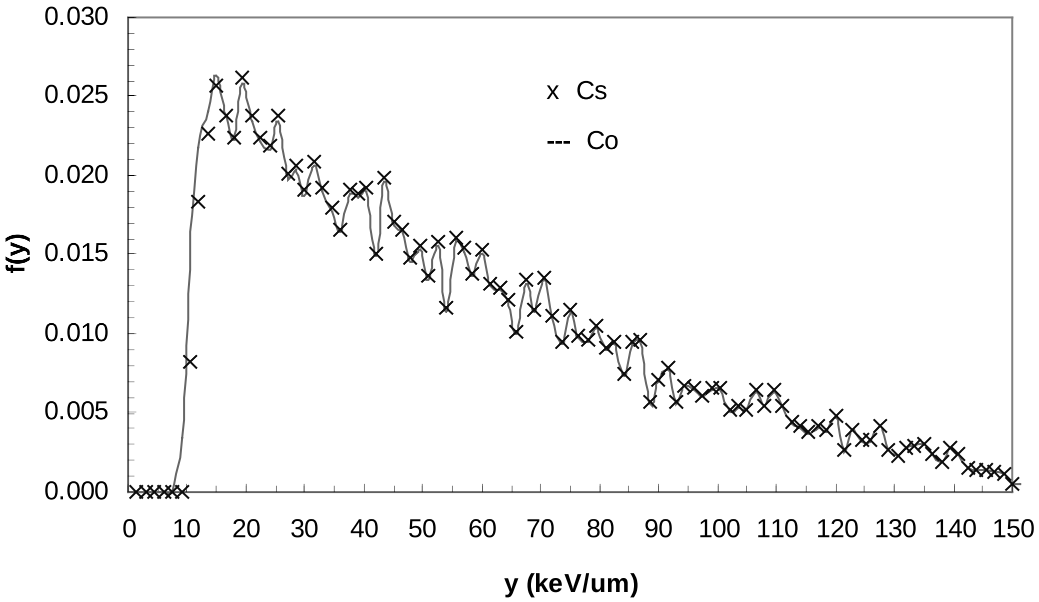

Figure 3. Lineal energy event spectrum, f(y), for PuLi neutrons with the photon components subtracted. The use of either ^{137}Cs or ^{60}Co photon response for photon component subtraction does not affect the neutron's lineal energy spectra.

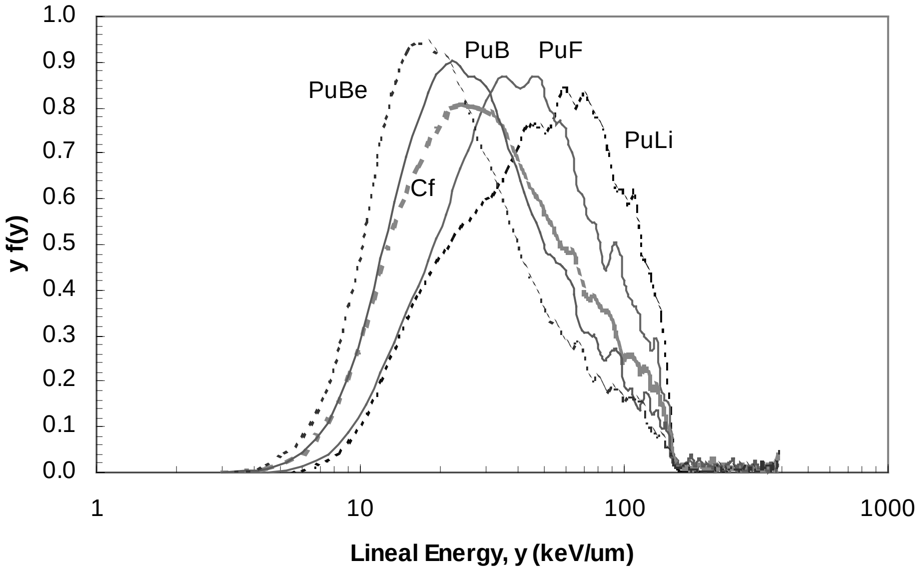

Figure 4. Lineal energy spectra, yf(y), for five radioisotopic neutron sources (the visual area under the curve is proportional to the event frequency). The lower the average energy of the neutron source, the harder the lineal energy spectrum. Most neutrons produced events with y between 10 and 150 keV/μm.

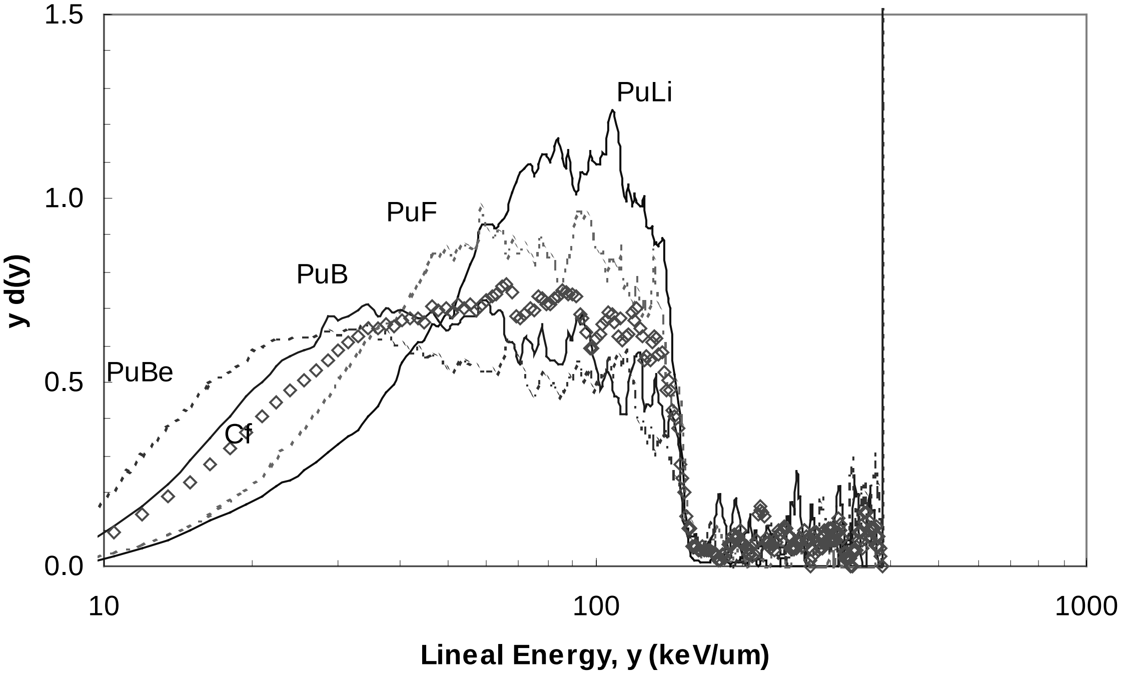

Figure 5. Comparison of the dose spectra, yd(y), for five radioisotopic neutron sources (the visual area under the curve is proportional to the dose). Note that the values in channel 256 are over the scale.

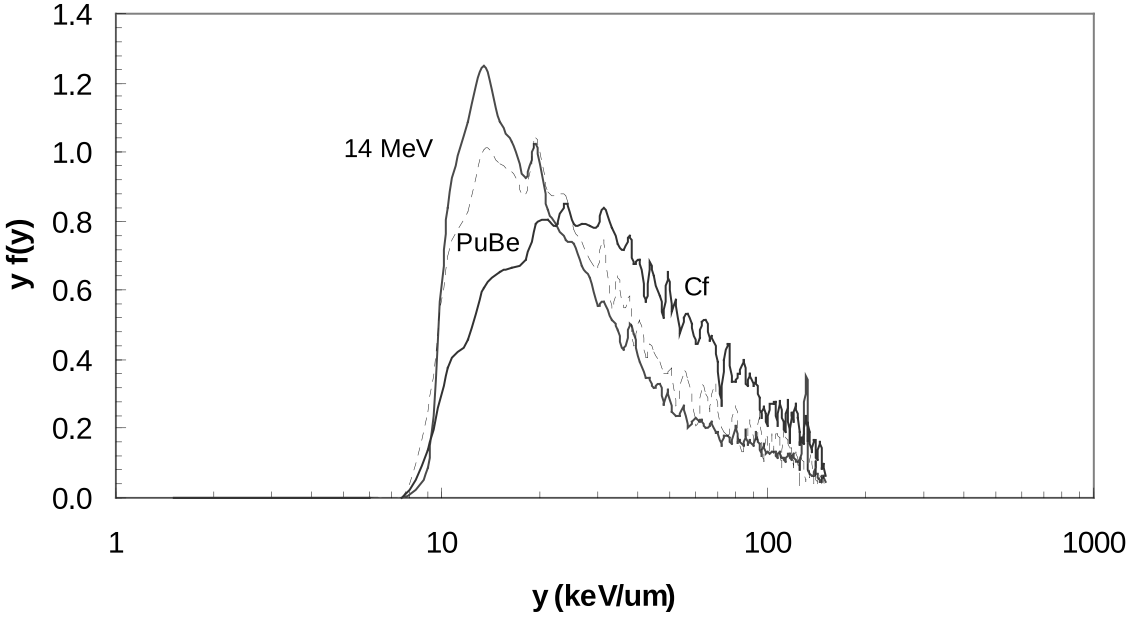

Figure 6. Lineal energy spectrum of 14-MeV neutrons is similar to that of the PuBe, both softer than the ^{252}Cf spectrum.

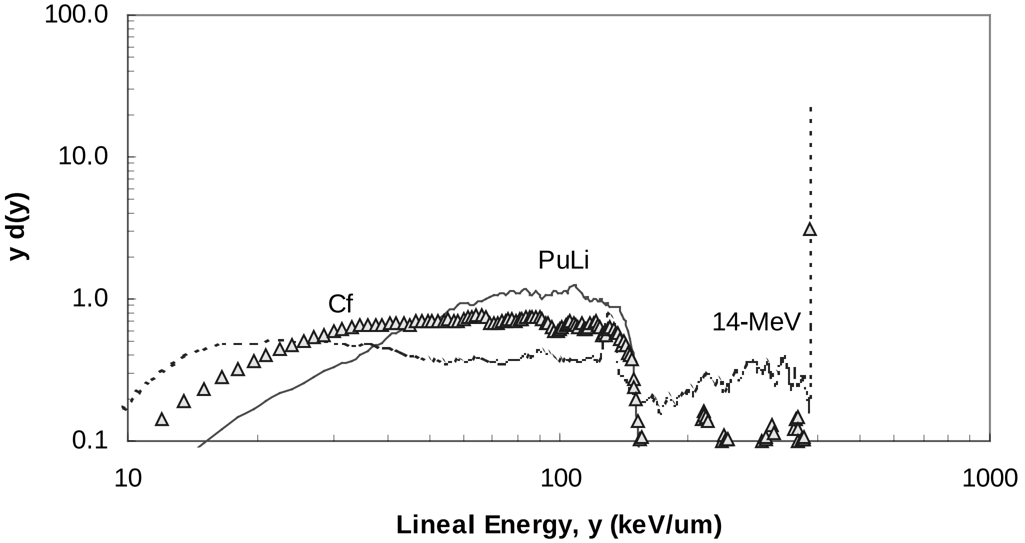

Figure 7. Comparison of dose spectra, yd(y), for three neutron sources. The 14-MeV neutrons produce higher doses at large y values than isotopic neutron sources, most likely due to heavy ion recoils.

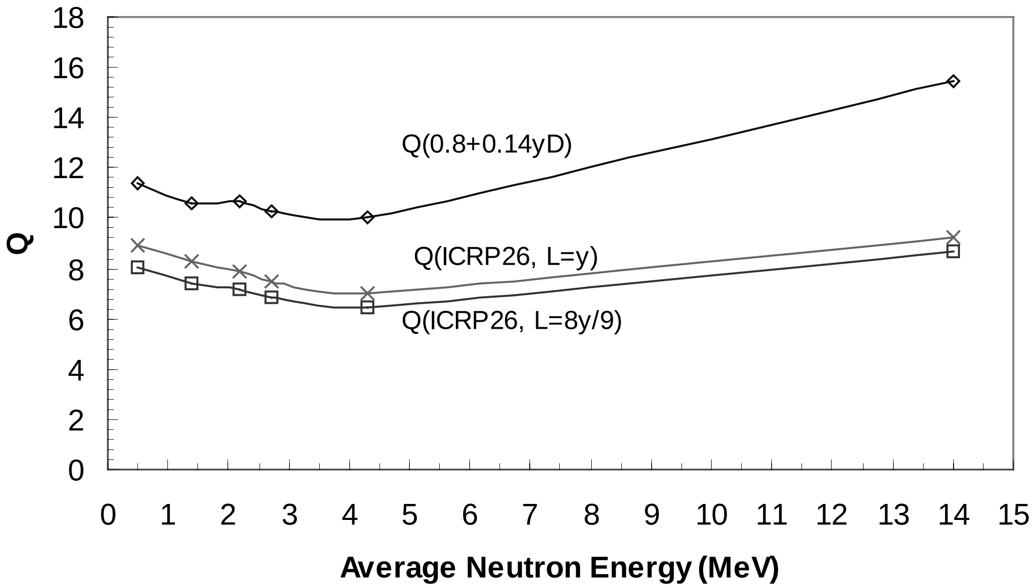

Figure 8. The mean quality factor as a function of average energy for neutron sources, determined using Equation 2 (which gives the highest Q) and Equation 3.