PNL-SA-6603

MASTER

CONF-780612--10

MEASURING NEUTRON DOSE AND QUALITY FACTORS
WITH TISSUE EQUIVALENT PROPORTIONAL COUNTERS

June 26-30, 1978 Stockholm, Sweden
IAEA-SM-229/52

MEASURING NEUTRON DOSE AND QUALITY FACTORS WITH TISSUE EQUIVALENT PROPORTIONAL COUNTERS*

L. W. Brackenbush, G. W. R. Endres and L. G. Faust
Battelle
Pacific Northwest Laboratories
Richland, Washington 99352
U.S.A.

ABSTRACT

This paper reviews the methods used to obtain absolute neutron dose measurements and quality factor determination from the tissue equivalent proportional counter (TEPC). Exposure to nearly monoenergetic neutrons with energies from 200 keV to 7.5 MeV indicate that the absorbed dose due to fast neutrons measured by the TEPC averaged 3% higher, with a standard deviation (1σ) of 9%, than the tissue kerma calculated from neutron fluence measurements. The absorbed dose due to fast neutrons measured by the TEPC agreed within 0.6% of the calculated tissue kerma for a PuBe neutron source, whose neutron yield was determined within 2% by the United States National Bureau of Standards. Data are presented which show the TEPC measures quality factors accurately enough for health physics purposes for neutrons with energies between 200 keV and 5 MeV.

INTRODUCTION

The tissue equivalent proportional counter (TEPC), sometimes referred to as the Rossi counter, has been used for neutron dosimetry in a few laboratories for almost 20 years to measure neutron doses and quality factors. The TEPC has remained a laboratory instrument because of experimental difficulties in using the counter and unfamiliarity with the methods of analyzing the data. With the possibility of future changes in the definitions of quality factor for fast neutrons [1], the TEPC may become more widely used. This paper reviews the methods used to obtain absolute neutron dose measurements and quality factors and demonstrates that the TEPC is sufficiently accurate for many health physics applications for fast neutrons.

---

* This paper is based on work performed under U.S. Department of Energy Contract EY-76-C-06-1830.

DISCLAIMER

At Hanford the TEPC has been used for radiobiology and microdosimetry research. One program involved exposing about 150 swine to ^{226}Ra or ^{252}Cf sources in the uterine cervix to determine RBEs (relative biological effectiveness) for acute and long-term effects [2]. The purpose of this study was to provide data for the treatment of cervical cancer with neutrons. Several small tissue equivalent proportional counters were used for in-vivo measurements of the neutron dose to adjacent tissues. Tissue equivalent proportional counters have also been used for other studies including: (1) measuring the neutron doses from cardiac pacemakers and artificial heart power sources fueled by ^{238}Pu, (2) measuring the neutron dose equivalent rates involved in the fabrication of plutonium fuel elements for fast breeder reactors, and (3) measuring the effectiveness of various hydrogeneous neutron shields. The experience gained in these studies has convinced the authors that, with certain improvements, the tissue equivalent proportional counter can, and perhaps should, be used as a health physics instrument.

CONSTRUCTION OF TISSUE EQUIVALENT PROPORTIONAL COUNTERS

For ease in the analysis of data, the TEPC isusually a hollow sphere of A-150 tissue equivalent (TE) plastic filled with methane-compounded tissue equivalent gas. Details of plastic and gas composition and methods of construction can be found in ICRU Report 26 [3].

One such commercially available[1] proportional counter used in this work is shown in Figure 1. This form of a TEPC, called a Rossi Counter, has a helical grid around the central anode to maintain uniform gas multiplication along the length of the anode wire. The plastic sphere is contained in a pressure vessel with a valve for admitting tissue equivalent gas. The gas pressure is maintained at a low pressure of a few torr (a few hundred Pa) so that charged particles crossing the cavity lose very little energy. The energy deposited in the cavity is then equal to the linear energy transfer of the particle times the path length. At these low pressures the gas filled cavity has the same mass stopping power as a sphere of tissue with a diameter of about one micrometer and is said to have an "equivalent diameter" of one micrometer.

ANALYSIS OF DATA FROM TISSUE EQUIVALENT PROPORTIONAL COUNTERS

Figure 2 shows a typical pulse height spectrum derived from a Rossi-type tissue equivalent proportional counter. Curve B represents the data from a Rossi counter exposed to 1.4 MeV neutrons; curve A represents the data from ^{60}Co gamma rays; curve C is derived by multiplying the counts per channel times the channel number - this is proportional to the energy deposited or dose. Neutron and gamma induced events can be separated on the basis of event size. The minimum at point 1 has been selected as the lower limit of neutron events. This works well unless the photon exposure rate is sufficient to produce pulse pile-up, which occurs at dose rates of several rad/hr (0.01 Gy/hr).

CALIBRATION

The point of inflection at point 2 of curve C in Figure 2 is defined as the proton drop point. This corresponds to a slow proton recoil having the highest linear energy transfer or stopping power traversing the diameter of

[1] Manufactured by EG&G, Inc., Goleta, California, U.S.A.

the spherical cavity. The proton drop point is independent of the initial energy of the neutron producing the event. According to the data of Glass, et al,[4] this point occurs at about 100 keV/μ and is a very slowly varying function of tissue equivalent gas pressure. An alternate method of calibration is to use tabulated data of mass stopping powers of alpha particles passing through the cavity from a small source contained in the counter.

ABSORBED DOSE DETERMINATION

Multiplying the number of events of a given size by the energy of the event gives the absorbed energy distribution in the TE gas, which is a direct measure of absorbed dose. Following the nomenclature in ICRU-26 [3], this may be stated mathematically as

$$\frac{D}{rad} = \frac{100D}{Gy} = 1.602 \times 10^{-8} \sum_{h_1}^{h_2} \left(\frac{c\ h N(h)}{MeV}\right)\left(\frac{\rho}{gcm^{-3}}\right)^{-1}\left(\frac{V}{cm3}\right)^{-1}$$

where h is the measured pulse height expressed as channel number, N(h) is the number of pulses accumulated in channel h, h_1 and h_2 are the limits in pulse height between which the absorbed dose is to be determined, ρ is the gas density, V is the sensitive volume of the cavity, and C is the calibration relating energy to channel number, which was determined from the proton drop point as explained previously. In this paper, h_1, the lower limit of neutron dose, is arbitrarily defined as the minimum between photon and neutron induced events which occurs at an event size of about 10 keV/μ. The measured neutron dose is the energy absorbed in the TE gas cavity divided by the mass of TE inside a sphere of A-150 TE plastic with 3.2 mm (1/8-inch) thick walls; this is very nearly a measure of kerma for fast neutrons.

A series of experiments were performed in which six different tissue equivalent proportional counters were exposed to approximately monoenergetic neutrons produced by particle accelerators. The neutron fluence was measured by a precision long counter, using the methods of DePangher and Nichols [5], or by a fission counter. The neutron kerma in soft tissue was calculated using the fluence-to-kerma factors for the human body of Ritts, et al [6]. A comparison of the experimentally measured neutron absorbed doses and the kermas calculated from fluence measurements is shown in Figure 3 as a function of neutron energy. For the average of about 30 measurements, the neutron absorbed dose measured by the TEPC is about 3% higher than the tissue kerma calculated from fluence measurements with a standard deviation (1σ) of 9%. There are many sources of error; the largest and most obvious are: (1) the uncertainties associated with the long counter measurement of neutron fluence, (2) the differences between the absorbed dose in TE gas and tissue kerma, and (3) systematic uncertainty in the effective value of $\bar{W}$, the average energy required to produce an ion pair in the tissue equivalent gas. In ICRU-26 [3] it is estimated that the overall uncertainty for proportional counter measurements of absorbed dose is about 10%.

The absorbed dose was also measured by a TEPC at 1 meter from a PuBe neutron source, whose neutron yield was measured by the U.S. National Bureau of Standards within 2%. The tissue kerma was calculated using the fluence-to-kerma factors of Ritts [6] and assuming the neutron spectrum of

Anderson [7], which was measured on an almost identical PuBe neutron source. After correcting for source anisotropy, the neutron absorbed dose measured by the TEPC agreed within 0.6% of the calculated kerma. This close agreement is perhaps fortuitous, although the accuracy of the measurement should be better because many of the systematic errors are cancelled for the wide range of neutron energies from 100 keV to 13 MeV. Measurements at the U.S. National Bureau of Standards facilities with monoenergetic beams of 144 keV, 25 keV and 2 keV showed that the TEPC detected neutrons at these energies. There was not sufficient resolution to separate events from 2 keV neutrons from events induced by photons. Large fluences of thermal neutrons produced an event spectrum similar to 600 keV neutrons, probably as the result of N(n,p) reactions.

QUALITY FACTOR ANALYSIS

H. H. Rossi has devised a simple model to determine the absorbed dose distribution as a function of linear energy transfer, LET [8]. Since quality factors are defined in terms of LET, it is possible to determine quality factors from a single TEPC measurement. The Rossi model employs a spherical counter with neutron secondaries arising within the walls and having a constant, uniform energy loss along straight line paths which completely cross the cavity. Under these assumptions D(L), the absorbed dose distribution as a function of linear energy transfer, L, can be derived by the formula [8]

$$D(L) = \frac{k}{r^2} \left[y\, N(y) - y^2 \frac{dN}{dy} \right]_{y=L}$$

where k is a constant of proportionality; r is the radius of a sphere of tissue having the same mass stopping power as the gas cavity; y is the lineal energy, the quotient of the energy imparted to the volume divided by the mean chord length in the cavity; N(y) is the event distribution as a function of lineal energy (or pulse size); and dN/dy is the derivative of the event size distribution evaluated at the point where linear energy transfer and lineal energy are equal.

The authors have devised a computer code to perform the above calculations and compute quality factors using digital filter techniques to smooth the data and evaluate the derivative. It is not possible to distinguish between photons originating from H(n,γ)D reactions in a phantom or tissue equivalent plastic counter and photons from external sources, so all photon events are excluded in our analysis. The experimentally derived quality factors are shown as circles in Figure 4. The closed circles are the quality factors derived from TEPC measurements on the surface of a phantom; the open circles are quality factors derived from TEPC measurements in free air. The upper curve represents values from the Monte Carlo computer code calculations of Auxier, et al [9], on the central surface element of a 0.3m diameter by 0.6m high phantom in which the contribution from H(n,γ)D reactions have been eliminated. These calculations should closely match the TEPC measurements. The lower curve in Figure 4 represents the values of quality factor from ICRU Report 26 [3], which are used for health physics purposes. The data in the 2 to 4 MeV region may be suspect due to carbon contamination from vacuum pump oil on the accelerator targets producing some lower energy neutrons.

The Rossi model neglects energy loss effects from straggling and scattering, energy loss from the region due to delta rays and variations of LET along the particle track. In spite of these limitations the Rossi model seems to be sufficiently accurate to determine quality factors within one integer value, which is adequate for health physics purposes, for neutrons with energies from 200 keV to about 10 MeV.

Since photon events were excluded in the quality factor analysis, this method of analysis fails for neutron energies below about 200 keV, where $H(n,\gamma)D$ reactions within a phantom contribute significantly to the effective quality factor. Exposures at the filtered neutron beam facility at the U.S. National Bureau of Standards confirmed this. For 144 keV neutrons the TEPC gave a quality factor of 10.4 to 10.8, which is in excellent agreement with Monte Carlo computer code calculations in which photon contributions are eliminated [9] but in poor agreement with the value of 8 extrapolated from ICRU-26 [3] data. For 25 keV neutrons the recoil protons did not have sufficient energy to traverse the cavity, and the Rossi model obviously failed for a one micron equivalent diameter deposition site.

CONCLUSIONS

For health physics purposes the tissue equivalent proportional counter has been demonstrated to be sufficiently accurate for fast neutron dosimetry. Within the neutron energy range of 200 keV to about 10 MeV a single measurement with a TEPC operated at a 1 or 2 micron equivalent diameter gives both the absolute absorbed dose and the quality factor. Even if the quality factor cannot be accurately determined at other neutron energies, the absorbed neutron dose can still be measured. If the counter is operated at two or three different gains, it is possible to measure both photon and neutron induced events and absorbed doses. In the past there has been gain shift problems due to diffusion of electronegative gases from the tissue equivalent (TE) plastic walls into the TE gas. Better manufacturing techniques now make it possible to operate the counters for more than 2 months without significant gain shifts. With the introduction of suitable non-linear electronics or microprocessors, it may soon be possible to incorporate the tissue equivalent proportional counter into a practical health physics instrument for measuring both absorbed dose and quality factors for neutrons. It would also be relatively simple to change such an instrument to accommodate possible changes in the definition of neutron quality factors.

REFERENCES

[1] ROSSI, H. H., "A proposal for revision of the quality factor", To be published.

[2] SULLIVAN, M. F., et al., "The Long-Term Effects of an Intracavitary Treatment with Californium-252 on Normal Tissue", IAEA-SM-212/57.

[3] International Commission on Radiation Units and Measurements, Neutron Dosimetry for Biology and Medicine, ICRU Report 26, ICRU Publications, Washington, DC (1977).

[4] GLASS, W.A., SAMSKY, D.N., Radiation Research 32 (1967) 138.

[5] NICHOLS, L. L., DePANGHER, J., A precision long counter for measuring fast neutron flux density, USAEC Report BNWL-260, Battelle-Northwest, Richland, WA (1966).

[6] RITTS, J. J., SOLOMITO, M., STEVENS, P. N., "Calculation of neutron fluence to kerma factors for the human body", Nuclear Applications and Technology 7 (1969) 89.

[7] ANDERSON, M. E., BOND, W. H., Nuclear Physics 43 (1963) 330.

[8] ROSSI, H. H., "Microscopic energy distribution in irradiated matter", Radiation Dosimetry 1 (ATTIX, F. W., ROESCH, W. C., Eds), Academic Press, New York (1968) 70.

[9] AUXIER, J. A., SNYDER, W. S., JONES, T. D., "Neutron interactions and penetrations into tissue", Radiation Dosimetry 1 (ATTIX, F. W., ROESCH, W. C., Eds.), Academic Press, New York (1968) 275.

LIST OF FIGURES

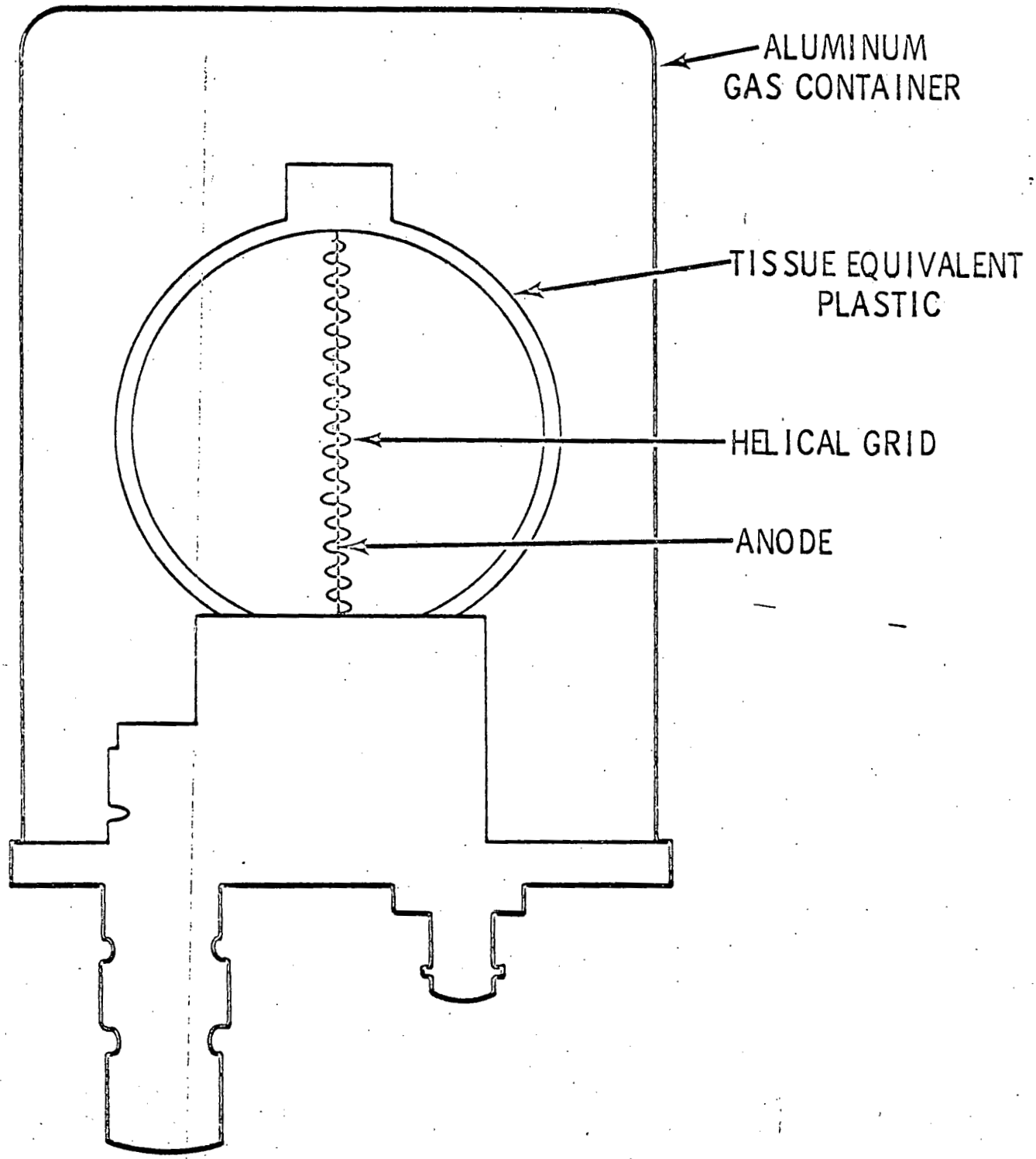

FIGURE 1. Cross-Sectional View of a Tissue Equivalent Proportional Counter

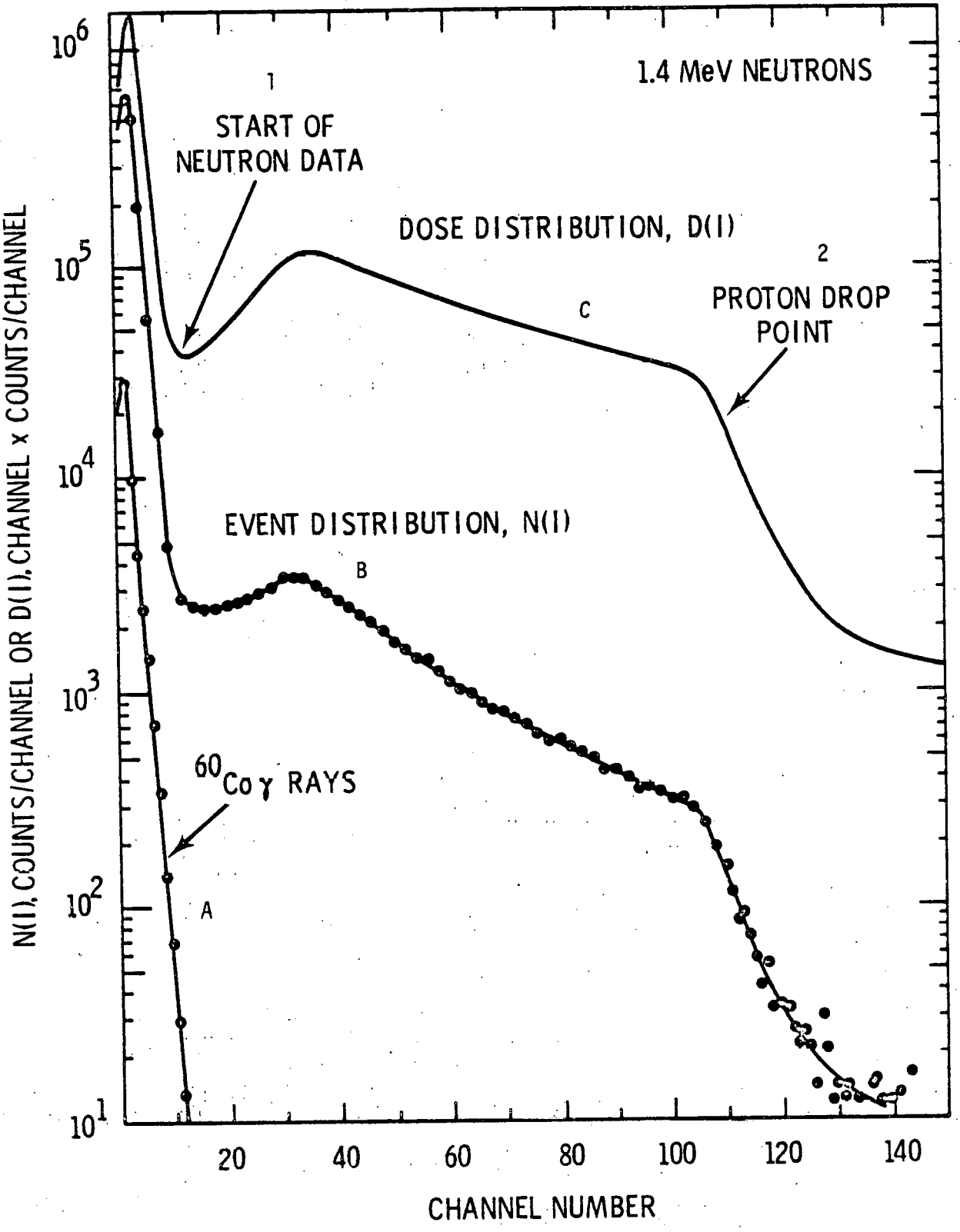

FIGURE 2. Pulse Height Spectra from a Tissue Equivalent Proportional Counter Exposed to 1.4 MeV Protons

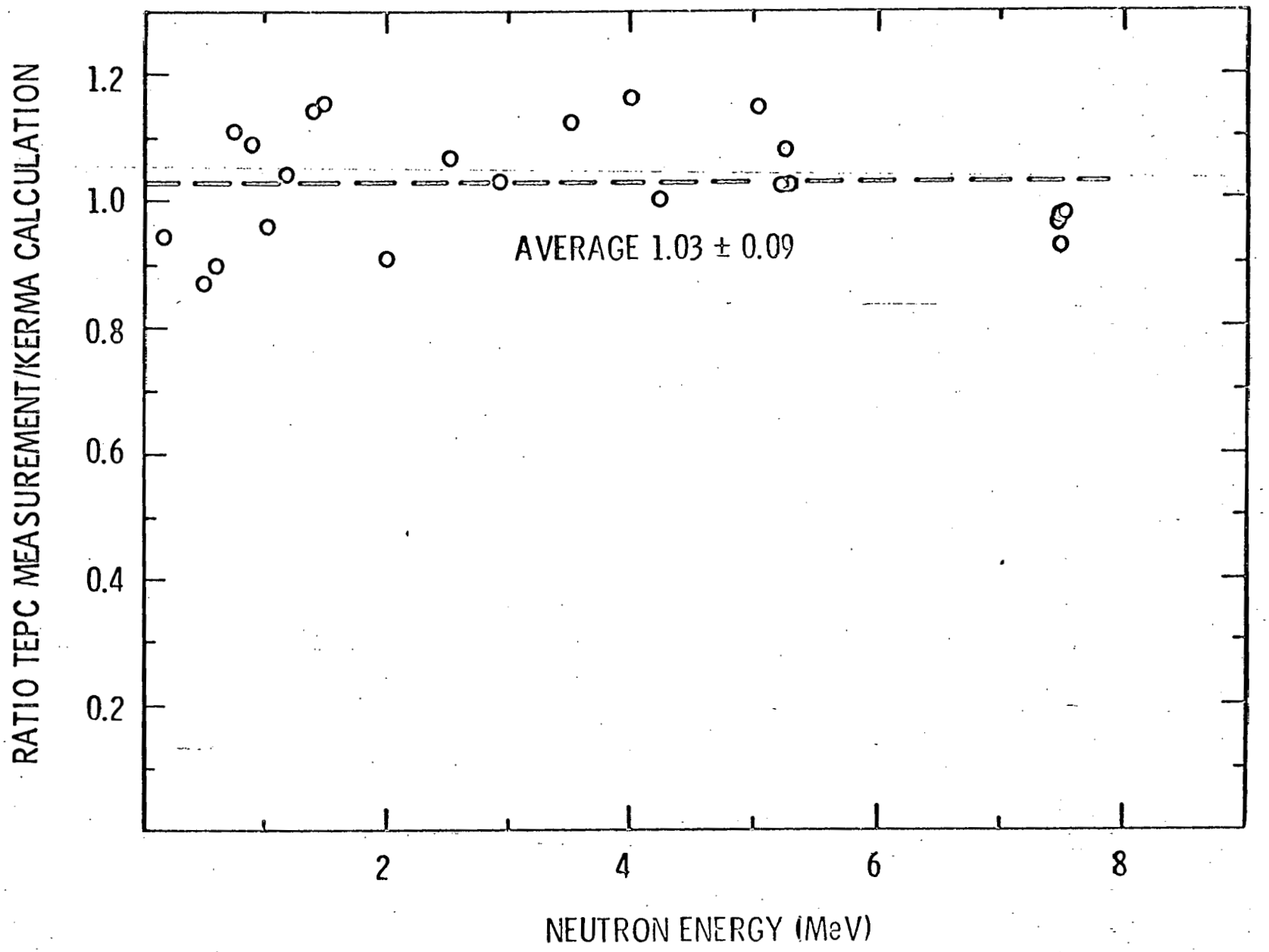

FIGURE 3. Comparison of Absorbed Dose Measured by TEPC and Kerma Calculated from Fluence Measurements for Nearly Monoenergetic Neutrons

FIGURE 4. Quality Factors from Tissue Equivalent Proportional Counter Measurements of Nearly Monoenergetic Neutrons