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COMMISSIONING OF A PROTON-RECOIL SPECTROMETER

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Abstract — Measurements of neutron fluence spectra in fields from bare and heavy-water-moderated ^{252}Cf were made with a commercially available proton-recoil spectrometer (PRS) that covers 50 keV to 4.5 MeV. Data obtained from these measurements were compared with data from Bonner sphere spectrometry, Monte Carlo simulation and the open literature. Alterations to the input data file used in unfolding recoil-proton pulse–height distributions were made. Understanding the reasons for these changes and considering the effects of some of them results in an appreciation of the significance of parameters used in the unfolding. An uncertainty of 10% is estimated for values of fluence and ambient dose equivalent for the energy region covered by this PRS.

INTRODUCTION

In order to improve evaluations and calibrations of neutron dosemeters in CANDU® power plants, a programme to create 'CANDU-like' workplace neutron fields has been set up in our Neutron Irradiation Facility (NIF). The feasibility of doing this has been theoretically demonstrated previously[1]. Creating workplace neutron fields suitable for dosemeter calibrations is a topic that is also of interest to others in the radiation protection community[2].

Characterisation of 'CANDU-like' neutron fields that we create is necessary. Methods for doing this include Bonner sphere spectrometry (BSS) and Monte Carlo simulation (MCS). A proton-recoil spectrometer (PRS) that is advertised to cover the energy range 50 keV to 4.5 MeV has recently been purchased. This system provides improved resolution over the BSS, although the latter covers a broader energy range, namely, thermal through tens of MeV. Neither system has a calibration traceable to a primary standards laboratory. However, the BSS was used in an intercomparison exercise and the limits of its accuracy can be estimated from this.

Furthermore, our national standards laboratory no longer provides monoenergetic neutron calibrations; nor do they provide calibrations in neutron fields such as heavy-water-moderated ^{252}Cf[3]. Within these constraints, it was nonetheless possible to estimate with what confidence the PRS can be used. This was done by demonstrating that there is consistency and quantitative agreement amongst results from independent methods used to determine neutron spectra and integral values of fluence rates and ambient dose equivalent rates in the energy region 50 keV to 4.5 MeV for two generally accepted neutron fields. Besides PRS, BSS and MCS, data published in the open literature for these fields were used for intercomparison.

IRRADIATION FACILITY AND SOURCE–DETECTOR GEOMETRY

The NIF is not a low-scatter facility. The inside dimensions are 7.47 m wide by 9.75 m long and 4.27 m high. ^{252}Cf, bare, or moderated by being placed at the centre of a thin spherical stainless steel shell, 30 cm in diameter, that is filled with heavy water (D_2O), was used. The emission rate or strength of the bare source was 1.1×10^8 $n.s^{-1}$ in March 1999. This value was determined by correcting the rate specified at the time of purchase for decay. The rate provided by the manufacturer[4] was 2.528×10^8 $n.s^{-1}$ ($\pm 2.6\%$ standard error) on 31 January 1996 and is traceable to a calibration at a primary standards laboratory.

Measurements were made at a source–detector centre-to-centre distance of 100 ± 1 cm. The mid-planes of the detectors and the sources were parallel to the floor and 130 ± 1 cm from the floor.

METHODS BESIDES PRS

As stated in the Introduction, three independent sources of information were used.

Bonner sphere spectrometry system (BSS)

The system consists of seven polyethylene spheres (diameters 7.6 cm to 25.4 cm). A ^3He-filled proportional counter is inserted into each sphere at the centre. Commercially available electronics are used. For a spectral measurement, nine count rates are measured, one for each of the seven spheres, one for a bare detector and one for a cadmium-covered detector. The cadmium-covered measurement is used to estimate the thermal neutron fluence.

Using the eight count rates and a set of response functions[5–7], a fifty-two energy bin neutron fluence spectrum is unfolded with the computer program STAY'SL[8]. At least two different guess spectra are used in the unfolding. Better than 5% agreement between measured count rates and count rates calculated using the unfolded spectrum is expected. The physical plausibility of the unfolded spectrum, based on information about the neutron source and shielding is considered. The thermal fluence in the unfolded spectrum should agree with the value determined from the cadmium-difference measurement.

Measured count rates are given by

$$\dot{B}_i = \sum_{j=1}^{52} Y_j^i \dot{\phi}_j \quad i = 1 \ldots 8 \qquad (1)$$

where $\dot{B}_i$ is the count rate for sphere i (counts.s^{-1}); Y_j^i is the response of sphere i to neutrons of energy in group j (counts.n^{-1}.cm^{-2}); and $\dot{\phi}_j$ is the fluence rate of neutrons in energy group j (cm^{-2}.s^{-1}).

From our participation in an intercomparison exercise[9], it was estimated, conservatively, that in the energy region 100 keV — several MeV, our ambient dose equivalents and fluences are accurate to within 30%. Thermal fluences are likely to be accurate to within 8%. It is of interest to note that fluences over the entire energy range were accurate to within 3%. There were eight other participants in the Bonner sphere category in the intercomparison. Comparisons were made relative to data from Monte Carlo simulation and to the means of data from the nine participants. One of the conclusions from that exercise was that the unfolded spectra from BSSs can have fluences that are not accurately shared amongst neighbouring energy bins.[9]

Monte Carlo simulation

The code MCNP, version 4A[10], was used to calculate fluence spectra for the neutron fields used in this work. One million histories were run in each simulation. A Watt fission energy spectrum was used to represent the spectrum emitted from bare ^{252}Cf. Details are given in Reference 1. Distance from the source to the floor was 100 cm. Detectors were not included in the simulations. However, walls, floor and ceiling were included to take room scatter into account. Uncertainties due solely to statistics for narrow energy regions are typically less than 5%. An upper limit on uncertainty for fluence and dose equivalents calculated for broad energy regions was estimated to be 20%; this value covers aspects such as accuracy of the simulation model in addition to the statistical error. Broad energy regions refer to regions that span two orders of magnitude (e.g. 10 keV–1 MeV).

Information from ISO8529 (1989)

Values of group source strength per unit logarithmic energy interval, for sources of strength 1 n.s^{-1}, are provided in Reference 11. Tables A1 and A3 of this reference contain such data for bare ^{252}Cf and D_2O-moderated ^{252}Cf, respectively. There is no room scatter in these data. Also, for the latter source, the heavy-water sphere is surrounded by cadmium so that no thermal fluence emerges; the thermal fluence accounts for 11.5% of the total[11].

Our Monte Carlo results for the fluence spectrum for a bare ^{252}Cf source in a vacuum agree well with data from ISO8529. However, as expected, our calculations that included details of the irradiation room produced a spectrum that included a low energy component that was absent from the other spectra. These spectra are shown in Figure 1.

A thermal fluence fraction of 24% was determined from our Monte Carlo calculations for a D_2O-moderated ^{252}Cf source in our NIF. BSS measurements gave a value of 22 ± 2%. These values are about twice that from the spectrum in Reference 11. The difference is likely to be because of room scatter — our Monte Carlo calculations with a D_2O-moderated ^{252}Cf source in vacuum gave a thermal fluence fraction of 10%, consistent with the value from Reference 11. In order to compare fluence spectra, the spectrum from the literature was normalised such that the total fluence (i.e. the fluence above the cadmium cut-off, 0.5 eV) equalled the fluence from BSS (i.e. total fluence — thermal or 'sub-cadmium' fluence). The uncertainty on the BSS value is estimated to be 3%, from results of the intercomparison exercise mentioned earlier.

Consistency of results from these methods

Figure 2 shows fluence spectra for ^{252}Cf, bare and D_2O-moderated, from BSS, MCS and from Reference

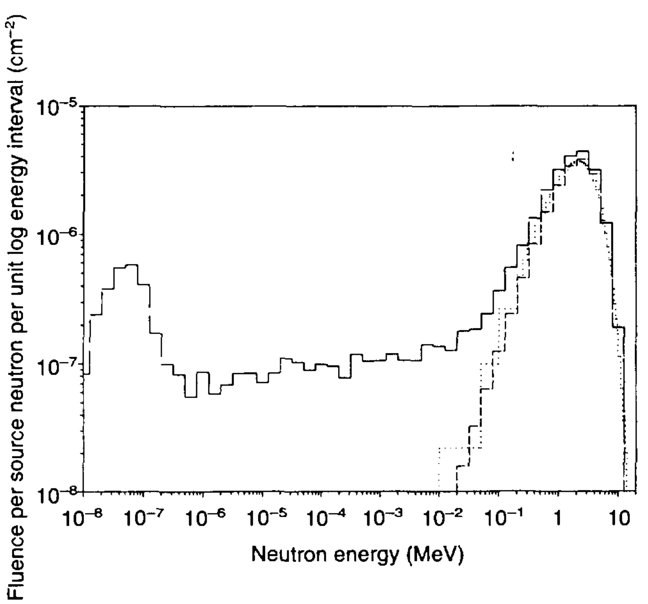

Figure 1. Comparison of bare ^{252}Cf spectra from the open literature and from our Monte Carlo simulations, in vacuum and including room scatter. (····) ISO8529. (– – –) MCS vacuum. (——) MCS.

11. The spectral shapes from the different methods are consistent with one another. In the D_2O-moderated ^{252}Cf spectrum, the dips at about 0.4 MeV and 1 MeV are due to resonances in oxygen. The peak at 2.5 MeV is due to unmoderated neutrons from ^{252}Cf. The BSS result shows these peaks and dips because they were included in guess spectra. It is not possible for this low resolution system to exhibit such fine structure without information being provided during the unfolding. Use of relatively coarse energy bins in our MCS masks some of the finer structure that is evident in the spectrum from ISO8529. The bare ^{252}Cf spectrum from Reference 11 shows less scattered component than spectra from both MCS and BSS.

Data listed in Table 1 illustrate the level of agreement amongst integral values of fluence rate and ambient dose equivalent rate for the energy range 50 keV to 4.5 MeV that is of specific interest here. Data from the three methods agree within 5%; average values are listed in the rightmost column of Table 1.

Ambient dose equivalents, H*(10), are calculated from fluence spectra using fluence-to-ambient dose equivalent conversion factors from ICRP 74[12].

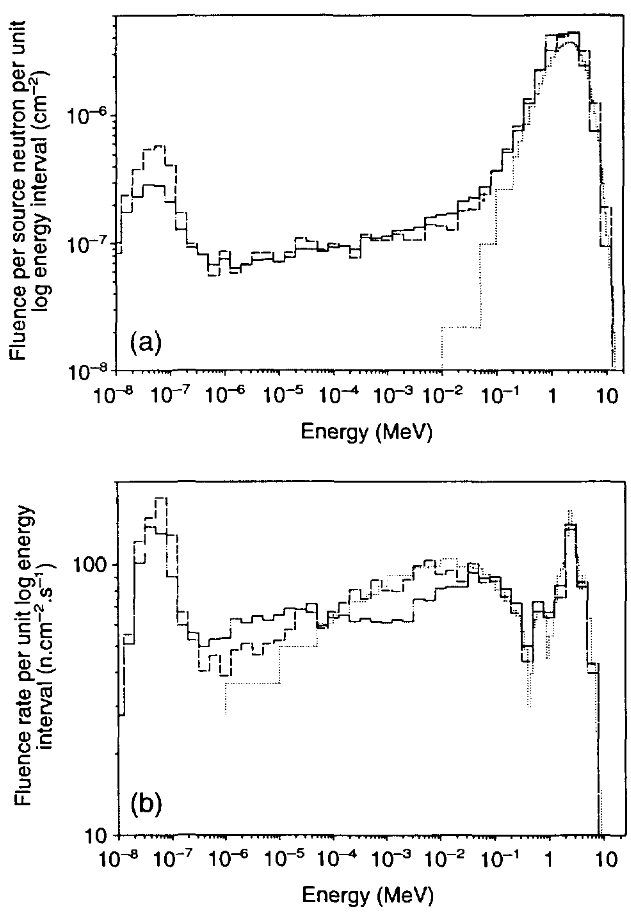

Figure 2. Comparison of spectra from the open literature, our Monte Carlo simulation and Bonner sphere spectrometry: (a) bare ^{252}Cf ; (b) D_2O-moderated ^{252}Cf. (---) MCS. (–·–) BSS. (····) ISO8529.

PROTON-RECOIL SPECTROMETER (PRS)

The PRS has the trade-name ROSPEC (*Ro*tating *Spec*trometer)[13]. Outwardly, the system consists of a cylinder of mass about 20 kg, a lap-top computer and cables. Analysis of the measured recoil-proton pulse–height distributions can be carried out on the lap-top. Data are passed to the latter from the cylinder via cables and an RS-422 Interface.

The cylinder is 41 cm in diameter and 53 cm long; it houses four spherical proportional counters, associated preamplifiers and power supplies atop a rotating platform, and amplifiers and analog-to-digital converters below the platform. Details of the system and its development may be found elsewhere[14,15].

The detectors are of the type developed by Benjamin[16] and the unfolding of the proton-recoil pulse–height distributions is done using the algorithm SPEC4[17]. Each proportional counter can be used on its own for determining neutron spectra in a certain energy region. Each requires information on the neutron spectrum above its energy range. In the software provided, neutron spectra unfolded from the four counters are merged; individual spectra from each detector as well as a merged, composite spectrum, are provided in output files. Information on the performance of other PRSs can be found in the literature[9,18–20].

Two distinguishing features of the PRS used here are its relatively compact size and 'push-button' mode of operation. The advantages of these features are obvious. A disadvantage of the latter feature may be that the system can be employed like a 'black box' with too much reliance and without an appreciation of the physics behind it.

Unfolding neutron spectrum

Details may be found elsewhere[17,21,22]. An outline is sketched here.

It is assumed that, for each proportional counter, the pulse height or number of counts in a specified channel of the associated multichannel analyser, is proportional to the number of recoil protons of an energy corresponding to that channel. The proton-recoil pulse–height distribution that is measured is given by

$$M_i = \sum_{j=1}^{m} H_j^i \phi_j, \quad i = 1 \ldots 256 \qquad (2)$$

where M_i is the number of counts or recoil protons in channel i due to neutrons in energy groups 1 through m; ϕ_j is the neutron fluence in energy group j (cm^{-2}); and H_j^i is the response function contribution to channel i — i.e. the number of recoil protons in channel i produced by monoenergetic neutrons in energy group j.

Neutrons of energy E_n can produce, via elastic scatter with hydrogen, recoil protons of energy E_p, where $0 \leqslant E_p \leqslant E_n$. $E_{p,max} = E_n$. The neutron energy in group j exceeds or equals the proton energy in group i. The magnitude of neutron energy that can be detected depends on the stopping power of the filling gas in the counter and the dimensions of the counter.

It is of interest to note that there are typically a couple of hundred channels in a PRS, compared with the few channels (spheres) in the BSS (see Equation 1). As a consequence, the result of unfolding in PRS is of higher resolution than in BSS.

The neutron fluence above E_{max}, the maximum energy analysed, is specified. The proton-recoil distribution due to this fluence is calculated following Equation 2. These data are subtracted from the distribution measured by the counter — i.e. the contribution due to neutrons above E_{max} is subtracted. The remaining pulse–height distribution is then unfolded to give the neutron fluence spectrum. In SPEC4, slopes of response functions are used; this is said to prevent oscillations in the unfolded spectrum[17].

For the set of four counters in this PRS, the spectrum unfolded for the highest energy counter serves as input for the next-highest energy counter. Thus, it is likely that errors will be largest for the lowest energy counter because its data will rely on cumulative results from the other three counters.

In a perfect PRS, the response function for unit fluence of neutrons of energy E_n is given by

$$H(E_p) = \frac{K\sigma(E_n)}{E_n} \tag{3}$$

where K is the number of hydrogen atoms in the detector; $\sigma(E_n)$ is the cross section of hydrogen–neutron elastic scatter for neutrons of energy E_n; and $H(E_p)$ is the number of protons per MeV at energy E_p to E_p+dE_p due to neutrons of energy E_n.

In reality, the system is not perfect; for example, there are 'wall effects' — i.e. recoil protons interact with detector walls and do not deposit all their energy in the detector gas to create a measurable signal. An analytical expression developed by Snidow[23] takes account of these effects in a spherical counter. The expression for the fraction of recoil protons of energy E_p to E_p+dE_p due to neutrons of energy E_n is given by[23,17]

$$\frac{C(E_p)}{C_{tot}} = \left\{\frac{F(E_p)}{E_n} + \frac{1}{E_n}\int_{E'=E_p}^{E_n} \frac{dR}{dE_p}(E' - E_p)\, P[R(E') - R(E' - E_p)]dE'\right\} K\sigma(E_n) \tag{4}$$

where C_{tot} is the total number of recoil protons; R(E) is the range of protons of energy E; $F(E_p)$ is the fraction of protons of energy E_p that are stopped in the detector. It is obtained from integrating P(L) as follows:

$$\int_{L=R(E_p)}^{L_{max}} P(L)dL$$

where P(L) is the probability that protons will travel a distance between L and L+dL to the detector wall,

$$P(L) = \frac{3}{4a}\left[1 - \frac{L^2}{4a^2}\right] dL \tag{5}$$

where a is the radius of the detector. Equations 4 and 5 highlight the requirement for accurate proton range data.

In the energy ranges of interest here, the response function would be rectangular if the detector were perfect, as indicated by Equation 3. If one defines a correction factor, CF, as follows:

$$CF = \frac{\text{No of pulses at } E_{p,max}}{\text{No of pulses at } \frac{1}{2} E_{p,max}} \tag{6}$$

then, for a perfect system, CF = 1. Correction factors

Table 1. Comparison of fluence and ambient dose equivalent rates in energy region 50 keV–4.5 MeV from methods besides proton recoil spectrometry.

	Bonner sphere spectrometry[a]	Monte Carlo simulation[b]	ISO8529 (1989)	Average
D_2O-moderated ^{252}Cf[c]				
$\dot{\Phi}$ ($cm^{-2}.s^{-1}$)	299.5	287.0	294.2	293.6
$\dot{H}^*(10)$ ($\mu Sv.h^{-1}$)	300.8	288.6	294.3	294.6
Bare ^{252}Cf				
$\dot{\Phi}$ ($cm^{-2}.s^{-1}$)	907	895	715[d]	901
$\dot{H}^*(10)$ ($\mu Sv.h^{-1}$)	1242	1206	986[d]	1224

[a]Uncertainty estimates: ±30%.
[b]Uncertainty estimates: ±20%.
[c]Source strength: 10^8 $n.s^{-1}$.
[d]Not included in average; does not take account of room scatter.

determined from response functions calculated using Equation 4 deviate from 1; the deviation increases with increasing 'range over radius', R/a, where R is the range of the maximum energy proton produced by neutrons of energy E_n (i.e. $E_{p,max} = E_n$)[21]. Furthermore, it was found that these calculated response functions differed from measured ones[18,21]. The magnitude of the difference is obvious from values of CF. In the SPEC4 code, calculated response functions are modified by ratios of correction factors determined from measured response functions (CFE) to those determined from calculated response functions (CFS); these ratios are referred to as CFE:CFS.

Three of the four proportional counters are filled with H_2 at pressures of $\frac{3}{4}$ atm (0.076 MPa), 4 atm (0.405 MPa) and 10 atm (1.013 MPa). These detectors are 2 inches (5.08 cm) in diameter and are referred to as SP2–1, SP2–4 and SP2–10, respectively. The fourth counter is 6 inches (15.24 cm) in diameter and contains a mixture of argon (0.456 MPa) and methane (0.0507 MPa); it is referred to as SP6. The neutron energies covered by each of these spectrometers are: 50–250 keV; 150–700 keV; 400 keV–1.5 MeV; and 1.2–4.5 MeV. The upper energy values of each range (E_{max}) correspond to values of R/a of 0.56, 0.54, 0.81 and 0.9, respectively. Proton ranges in different pressures of gas mixtures are calculated as follows[21]:

$$R_{mixt}(E_p) = \left[\sum_{i=1}^{g} \frac{GP_i}{R_i\,(E_p)}\right]^{-1} \tag{7}$$

where R_{mixt} (E_p) is the range of proton of energy E_p in the gas mixture of interest; GP_i is the pressure of gas i in the counter (atm); R_i (E_p) is the range of proton of energy E_p in gas i at 1 atm and g is the number of gases in the mixture.

As stated earlier, neutron spectra from the four detector systems are merged. There are two parameters that can be considered after merging these pieces of information. The first is the 'normalising pulse–heights ratio', A. It is defined as follows[21]:

$$A = MP/CP \tag{8}$$

where MP is the measured number of protons or counts for region E_{max} to 1.05 E_{max} and CP is the number of protons or counts calculated using response functions and neutron fluence determined for this energy region.

A is a measure of how well information from a higher energy counter agrees with that from the next-highest energy counter, and is an indicator of how well the response functions and unfolding work. Values of A are printed in the output files along with the unfolded neutron spectra. A is always 1 for the SP6 detector; the neutron fluence used to evaluate CP is normalised to the value of MP in this case. The proton pulse–height distribution calculated for neutrons of energy greater than E_{max} is multiplied by A prior to subtraction from the measured pulse–height distribution and subsequent unfolding as outlined earlier[21].

The second parameter, V, is the ratio of neutron fluences obtained from two detectors having overlapping energy regions. The energy regions of overlap are: 1.2–1.5 MeV (SP2–10 and SP6 detectors); 400–700 keV (SP2–4 and SP2–10 detectors); 150–250 keV (SP2–1 and SP2–4 detectors).

Potential limitations

Information received upon purchase of the system stated that the system was checked in a ^{252}Cf field for consistency of performance with similar systems manufactured previously[24]. Agreement is within 2%. Calibration of the multichannel analyser in MeV.channel^{-1} was accomplished using monoenergetic neutrons[24]. As far as we are aware, these fields are not traceable to a primary standards laboratory and no information regarding the purity of the neutron beams is provided. Also, the pulse–height distributions measured with these monoenergetic neutrons are not used to determine values of CFE (see Equation 6).

Alterations to data used in unfolding

Proton range data, correction factors for response functions and calibration parameters are supplied via an input file to the SPEC4 code.

Proton ranges

Proton ranges supplied with the system for hydrogen and methane were the same as those listed in Appendix E of Reference 21. For hydrogen, these data agreed within 3% with data from ICRU 49[25] for energies between 100 keV and 9 MeV. At lower energies, data from Reference 25 exceeded the data supplied with the system by about 6–10%. For methane, data supplied agreed with data from Reference 25 within 5% for energies 700 keV–10 MeV; below 700 keV, data from Reference 25 exceeded the data supplied by about 10%. Range data supplied for argon agreed with data from Reference 25 within 5% for energies between 450 keV and 10 MeV and were increasingly smaller below this; at 15 keV for example, the range supplied was half that listed in Reference 25.

It is noted that for the energies measured by, and gases in, this PRS, the differences in ranges described above are not likely to be of consequence. Nevertheless, ranges supplied with the system were replaced with those from Reference 25 because the latter are believed to be more accurate.

Correction factors for response functions

The response function calculated for nominal 725 keV neutrons using the Snidow algorithm is shown in

Figure 3. CFS for this case was 1.206. A measured response function[26] is also in this figure. Experimental and calculated data are normalised at half the maximum energy. The value of CFE was estimated to be 1.6.

For selected values of R/a, values for CFS were calculated. Not unexpectedly, they agree with those listed in Reference 21 to within 3%. Monoenergetic data[26] were used to determine CFE values, where possible — the data were sparse and some of the pulse–height distributions exhibited broadened or ill-defined edges or cut-offs. Values for CFE for different pressures of hydrogen in SP2 type counters have been reported in the literature[18,21]. Figure 4 shows these data from the literature and values obtained here. The solid line on this plot is an approximate fit to the average of the published data and our data. The data were fitted in two segments, by cubics in R/a; the two discontinuities between R/a of 0.9 and 1.0 result from averaging the fits in this region. Table 2 lists R/a, CFS and CFE values that have been incorporated into the input file used for the unfolding. These values differ considerably from those used in the system as it was purchased. It is not certain why this is the case.

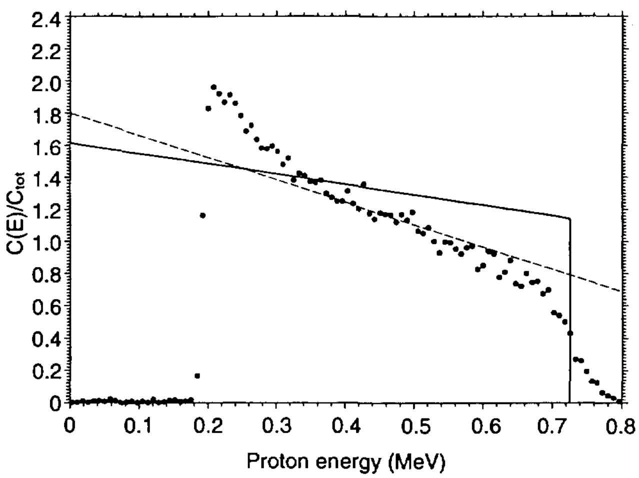

Figure 3. Response function for 725 keV neutrons in SP2–10 detector (10 atm. H_2): solid line, calculated with Snidow algorithm; symbols, measured data; dashed line, fit to measured data between 400 and 500 keV.

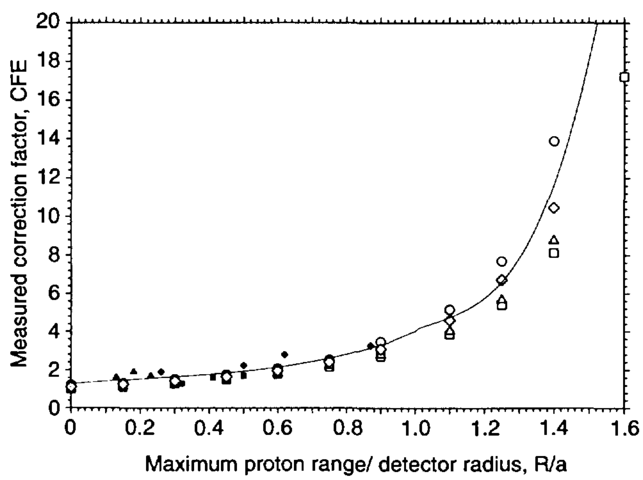

Figure 4. Correction factors as a function of 'maximum proton range/detector radius': filled symbols, from measurements in present work; open symbols, averages of data published in open literature; line, fit.

Calibration parameters

There are two calibration parameters for each detector system. These are the energy calibration or gain, G, and the effective back-bias of the multichannel analyser, EB. EB is defined as the number of channels to be added to the registered channel number to give the true channel number that is proportional to pulse height[21]. In the unfolding code, the energy scale is created as follows:

$$E = G\,(N + EB) \qquad (9)$$

where E is the energy (MeV) corresponding to the registered channel number N. A set of channel numbers is obtained from proton pulse–height distributions measured for several monoenergetic neutrons. A plot of these neutron energies against channel number should be linear with a slope of G and an intercept of G*EB.

Equation 9 may be re-written as

$$E = G(N + BB) + E_o \qquad (10)$$

where (N+BB) is the registered channel number corrected for electronic back-bias, BB; BB is determined using a calibrated pulse generator and is the channel number corresponding to zero pulse height. E_o is an offset that represents a lack of proportionality between ionisation and pulse height. For a perfect detector system, where there are no impurities in the gas filling, no electric field and wall effects, and the energy expended to produce an ion pair is constant over the energy range of interest, and proton ranges are correct, $E_o = 0$. For

Table 2. Calculated and measured correction factors (CFS and CFE) as a function of maximum proton range/detector radius, R/a.

R/a	CFS	CFE
0	1.0	1.28
0.15	1.12	1.48
0.30	1.29	1.65
0.50	1.60	1.93
0.70	2.01	2.42
0.90	2.70	3.30
1.10	3.79	4.82
1.25	5.33	6.62
1.40	7.93	11.71
1.50	10.4	18.07
1.62	17.9	30.02
1.70	30.6	41.16

hydrogen-filled counters used to measure neutrons between 10 keV and 1 MeV, E_o has been measured to be <2 keV[21,27], which is negligible for the energies being measured. Others have found somewhat different values, e.g. −7.7 keV and 15.7 keV[28]. It appears that the overall accuracy of the system depends on the accuracy with which calibration parameters are determined.

Figure 5 shows a plot of a set of three neutron energies against (N+BB) for the SP2–10 detector. The neutron energies are between 500 and 730 keV. The solid line is a linear fit to these data such that $E_o \approx 0$; BB = −13.6 channels and G = 7.85E-03 MeV.channel^{-1}.

The severity of changes or errors in G and EB have been reported elsewhere[21]. For broad neutron spectra from ^{252}Cf, bare or D_2O-moderated, Figure 6 shows the effect of a change of about 2 channels in values of EB and a change of about 3–5% in values of G. Total fluences are changed by 5–8%. Uncertainties in EB and G are estimated to be of the order of 10% and 5%, respectively. Uncertainty for EB is larger because of pulse–height distributions being measured for a few energies that cover relatively small energy ranges, and the consequent need for extrapolations from high energies to obtain a value on the intercept (see Figure 5), and the fact that G is used to calculate EB in the calibration parameters provided with the system (see Equation 9).

Ratios A and V

Table 3 lists values of A and V for measurements in bare and D_2O-moderated ^{252}Cf using two sets of calibration parameters that differ as described above. Values of A are smallest, about 0.8, for the energy span 1.5–1.575 MeV. Other values are 0.83–0.86 and 0.91–0.96. Values of V for D_2O-moderated ^{252}Cf, for both sets of calibration parameters, are about 1.03. For bare ^{252}Cf, values of V are about 1.17, 1.06 and 0.5 for highest to lowest energy counters. The very poor overlap of fluences unfolded by SP2–1 and SP2–4 over 150 – 250 keV for this case is not explained; perhaps the relatively low neutron fluence in this energy region from bare ^{252}Cf may contribute. It is interesting that the value for A in the energy region 250 – 262 keV is 0.95 for both sets of calibration parameters.

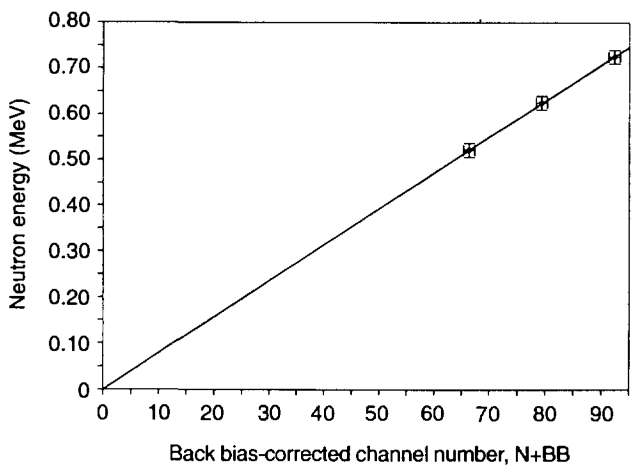

Figure 5. Data from measurements with monoenergetic neutrons and SP2–10 detector: symbols, from measurements; line, fit to measured data. See text and Equation 10 for explanation of (N+BB).

COMPARISON OF DATA FROM PRS AND OTHER METHODS

Figures 7 and 8 show fluence spectra from PRS, BSS, MCS and ISO8529[11], for bare and D_2O-moderated ^{252}Cf fields. Spectral shapes from the different methods are consistent with one another. Largest discrepancies in fluence are of the order of 25% in a few energy bins. Table 4 lists ratios of fluences and ambient dose equivalents for the energy region 50 keV to 4.5 MeV, for the two neutron fields and two sets of calibration para-

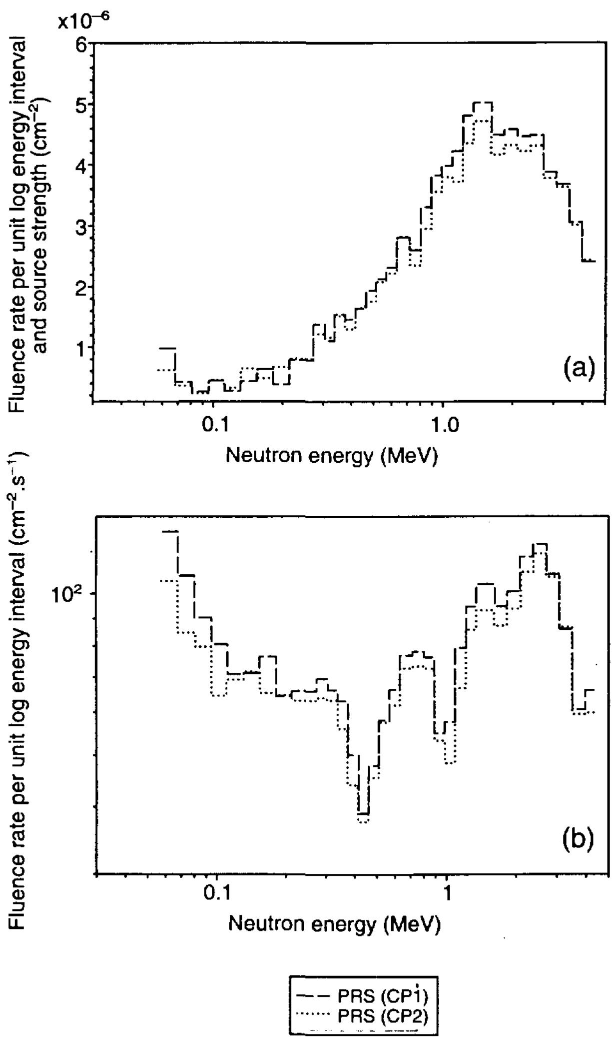

Figure 6. Effect of changes of 5–10% in calibration parameters, CP, on fluence spectra measured with PRS: (a) bare ^{252}Cf spectrum; (b) D_2O-moderated ^{252}Cf spectrum.

meters. The ratios are results from PRS compared with the average of results from the other three methods. Uncertainties in these ratios are 5%, based on 5% uncertainties in both numerator and denominator. Data for each neutron field are consistent to within 10%.

DISCUSSION

The PRS picks up positions of peaks and valleys in the D_2O-moderated ^{252}Cf spectrum accurately. An estimate of the fluence spectrum above 4.5 MeV is required. This information can be provided from measurements made with the BSS. Also, it is expected that for moderated fission-neutron fields, the contribution of fluence above 4 MeV is small.

Reports on evaluations and calibrations of PRS systems like the one discussed here have been published elsewhere previously(29,30). In these studies, fields at primary standards laboratories were used — broad-energy neutron fields in the first case(29) and monoenergetic fields in the second(30). The possibilities of 'an error in the scale of the measured spectrum' and 'systematic bias in output … probably related to calibration factors' were mentioned in the first article. These comments are consistent with the uncertainties that we suggest are associated with the calibration parameters supplied with the system. Also, one of the conclusions in this article was that data below 100 keV were less reliable. In the second report, it was found that the energies were reproduced well and that fluences were consistently high by about 5%, on average, for six energies between 100 keV and 4 MeV.

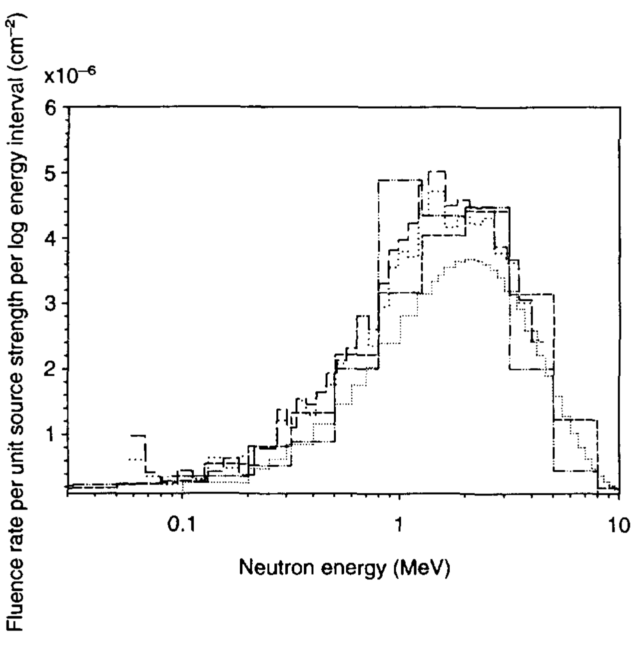

Figure 7. Comparison of bare ^{252}Cf spectra from PRS, MCS, BSS and the open literature. (····) PRS(CP2). (– – –) PRS(CP1). (----) MCS. (......) ISO8529. (—·—·—) BSS.

The PRS is faster to use than our BSS; obtaining neutron spectra from the latter involves using several guess spectra and justifying that the unfolded neutron spectrum is credible. In addition, the PRS is easier to transport. Most advantageous perhaps is that the PRS can allocate fluence to energy bins more accurately; this was noted earlier to be a problem with the BSS.

For accurate spectrometry using this PRS, calibrations with monoenergetic neutrons that are well-characterised should be performed; values for CFE, G and EB should agree with those provided with the system.

Response functions more accurate than those calculated using the Snidow algorithm may be obtained with the SPHERE code(31,32). The latter takes account of effects of distortions in the electric field in the detectors. It would be of interest to consider incorporating such potentially more accurate response functions into the unfolding carried out with this PRS and possibly eliminate the need to adjust the response functions by ratios of correction factors, CFE:CFS.

CONCLUSION

Neutron fluence spectra from bare and D_2O-moderated ^{252}Cf sources, determined using a 'push-button' style PRS, BSS and MCS, and obtained from the open literature, were found to be consistent with one another. In the energy region covered by the PRS, namely, 50 keV–4.5 MeV, integral values of fluence and ambient dose equivalent rates were found to agree within 10%, with averages of data from the other three sources of information. For values of fluence and ambient dose equivalent rates determined with the PRS in this energy region, an uncertainty of 10% was estimated, and uncertainties of 20–30% were estimated for energy regions *smaller than this.*

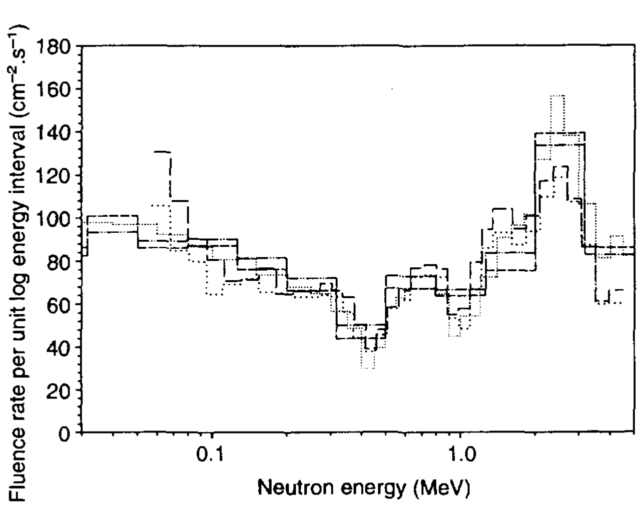

Figure 8. Comparison of D_2O-moderated ^{252}Cf spectra from PRS, MCS, BSS and the open literature. Key as Figure 7.

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Table 3. Ratios of proton-recoil counts and unfolded neutron fluences (A and V) in overlapping energy regions of successive detectors, for two neutron fields and two sets of calibration parameters.

Detector		SP6	SP2-10	SP2-4	SP2-1
Calibration parameters, CP*	G1; G2 (MeV.chnl^{-1})	0.0213; 0.022	7.85×10^{-3}; 8.1×10^{-3}	3.5×10^{-3}; 3.48×10^{-3}	1.36×10^{-3}; 1.3×10^{-3}
	EB1; EB2 (chnls)	−17.5; −20.1	−13.6; −14.9	−12.0; −13.9	−15.7; 18.0
Ratios	G1/G2, EB1/EB2	0.97, 0.87	0.97, 0.91	1.01, 0.86	1.05, 0.87

Detectors in ratio	Overlap energy region (MeV)	A		Overlap energy region (MeV)	V	
		Bare ^{252}Cf CP1; CP2	D_2O-mod. ^{252}Cf CP1; CP2		Bare ^{252}Cf CP1; CP2	D_2O-mod. ^{252}Cf CP1; CP2
SP2-10:SP6	1.5–1.575	0.76; 0.85	0.78; 0.86	1.2–1.5	1.15; 1.19	1.01; 1.01
SP2-4:SP2-10	0.7–0.735	0.84; 0.86	0.83; 0.86	0.4–0.7	1.03; 1.10	1.02; 1.02
SP2-1:SP2-4	0.25–0.2625	0.96; 0.94	0.95; 0.91	0.15–0.25	0.39; 0.57	1.05; 1.02

*EB, G are defined in text; suffixes 1 and 2 denote different sets of calibration parameters.

Table 4. Ratios of fluence and ambient dose equivalents from PRS to average values from other methods listed in Table 1.

Field	^{252}Cf		D_2O-mod. ^{252}Cf	
Calibration parameters for PRS*	CP1	CP2	CP1	CP2
Ratio of fluences	1.09	1.04	0.96	0.89
Ratio of ambient dose equivalents	1.08	1.03	0.98	0.91

*See Table 3 for values of calibration parameters in sets CP1 and CP2.

REFERENCES

1. Nunes, J. C., Cross, W. G. and Waker, A. J. *Feasibility of Creating 'CANDU®-Like' Workplace Neutron Fields in an Existing Irradiation Facility.* Radiat. Prot. Dosim. **72**(1), 11–20 (1997).
2. McDonald, J. C., Alberts, W. G., Bartlett, D. T., Chartier, J.-L., Eisenhauer, C. M., Schraube, H., Schwartz, R. B. and Thomas, D. J. *Current Status of an ISO Document on Reference Radiations: Characteristics and Methods of Production of Simulated Practical Neutron Fields.* Radiat. Prot. Dosim. **70**(1–4), 323–325 (1997).
3. Schwartz, R. B. and Eisenhauer, C. M. *The Design and Construction of a D_2O-Moderated ^{252}Cf Source for Calibrating Neutron Personnel Dosimeters Used at Nuclear Power Reactors* (National Bureau of Standards, Washington, DC 20034) Report NUREG/CR — 1204 (January 1980).
4. Frontier Technology Corporation, 1641 Burnett Drive, Xenia, OH 45385, USA.
5. Thomas, D. J., Alevra, A., Hunt, J. B. and Schraube, H. *Experimental Determination of the Response of Four Bonner Sphere Sets to Thermal Neutrons.* Radiat. Prot. Dosim. **54**, 25–31 (1994).
6. Thomas, D. J. Private communication (1993).
7. Thomas, D. J. *Use of the Program ANISN to Calculate Response Functions for a Bonner Sphere Set with a ^{3}He Detector* (Teddington, UK: National Physical Laboratory) NPL Report RSA(EXT) 31 (March 1992).

8. Perey, F. G. *Least-Squares Unfolding: The Program STAY'SL* (Oak Ridge, Tennessee, USA) Oak Ridge National Laboratory Report ORNL/TM-60602, ENDF-254 (1977).
9. Thomas, D. J., Chartier, J.-L., Klein, H., Naismith, O. F., Posny, F. and Taylor, G. C. *Results of a Large-Scale Neutron Spectrometry and Dosimetry Comparison Exercise at the Cadarache Moderator Assembly.* Radiat. Prot. Dosim. **70**(1–4), 313–322 (1997).
10. Briesmeister, J. F. (Ed.) *MCNP — A General Monte Carlo Code for N-Particle Transport. Version 4A* (Los Alamos, New Mexico, USA: Los Alamos National Laboratory) Report LA-12625 (Copyright data: 1988 code released in 1993).
11. The International Organization for Standardization (ISO). *Neutron Reference Radiations for Calibrating Neutron-Measuring Devices Used for Radiation Protection Purposes and for Determining Their Response as a Function of Neutron Energy* (Switzerland: International Organization for Standardization) ISO 8529 (1989).
12. ICRP. *Conversion Coefficients for Use in Radiological Protection against External Radiation* (Oxford: Pergamon Press) Table A.42, Publication 74 (1996) and Siebert, B. R. L. and Schuhmacher, H. *Quality Factors, Ambient and Personal Dose Equivalent for Neutrons, Based on the New ICRU Stopping Power Data for Protons and Alpha Particles.* Radiat. Prot. Dosim. **58**, 177–183 (1995).
13. Bubble Technology Industries. Hw 17, Chalk River, Ontario, Canada.
14. Ing, H., Cross, W. G. and Bunge, P. J. *Spectrometers for Radiation Protection at Chalk River Nuclear Laboratories.* Radiat. Prot. Dosim. **10**(1–4), 137–145 (1985).
15. Ing, H., Clifford, T., McLean, T., Webb, W., Cousins, T. and Dhermain, J. *ROSPEC — A Simple Reliable High Resolution Neutron Spectrometer.* Radiat. Prot. Dosim. **70**(1–4), 273–278 (1997).
16. Benjamin, P. W., Kemshall, C. D. and Redfearn, J. *A High Resolution Spherical Proportional Counter.* Nucl. Instrum. Methods **59**, 77–85 (1968).
17. Benjamin, P. W., Kemshall, C. D. and Brickstock, A. *The Analysis of Recoil Proton Spectra* (Aldermaston, UK: Atomic Weapons Research Establishment) AWRE Report No. 0–9/68 (1968).
18. Birch, R., Peaple, L. H. J. and Delafield, H. J. *Measurement of Neutron Spectra with Hydrogen Proportional Counters, Part I: Spectrometry System and Calibration* (Harwell, UK: AERE) Report AERE-R11397 (October 1984).
19. Posny, F., Chartier, J.-L. and Buxerolle, M. *Neutron Spectrometry System for Radiation Protection: Measurements at Work-places and in Calibration Fields.* Radiat. Prot. Dosim. **44**(1/4), 239–242 (1992).
20. Tagziria, H. and Thomas, D. J. *A High Resolution Neutron Spectrometry System for the 50 to 1500 keV Energy Region* (Teddington, UK: National Physical Laboratory) Report CIRM 21 (November 1998).
21. Kemshall, C. D. *The Use of Spherical Proportional Counters for Neutron Spectrum Measurements* (Aldermaston, UK: Atomic Weapons Research Establishment) AWRE Report No. 031/73 (1973).
22. Cross, W. G. and Ing, H. *Neutron Spectroscopy.* In: The Dosimetry of Ionizing Radiation, Eds K. Kase, B. E. Bjärngard and F. H. Attix, Ch. 2 (New York: Academic Press) pp 91–167 (1987).
23. Snidow, N. L. and Warren, H. D. *Wall Effect Corrections in Proportional Counter Spectrometers.* Nucl. Instrum. Methods **51**, 109–116 (1967).
24. *Manual for ROSPEC II.* Bubble Technology Industries, Hw 17, Chalk River, Ontario, Canada.
25. ICRU. *Stopping Powers and Ranges for Protons and Alpha Particles* (Bethesda, Maryland, USA: International Commission on Radiation Units and Measurements) Report 49 (1993).
26. Bubble Technology Industries. Private communication.
27. Allen, W. D. and Ferguson, A. T. G. *The Measurement of Fast Neutron Flux over the Neutron Energy Range 0.03 MeV to 3.0 MeV.* Proc. Phys. Soc. (London) **70A**, 639–653 (1957).
28. Brearley, I. R., Bore, A., Evans, N. and Scott, M. C. *Some Aspects of the Use of Proton Recoil Proportional Counters for Neutron Spectrometry.* Nucl. Instrum. Methods **192**, 439–446 (1982).
29. Schwartz, R. B. and Eisenhauer, C. M. *Test of a Neutron Spectrometer in NIST Standard Fields.* Radiat. Prot. Dosim. **55**(2), 99–105 (1994).
30. Rosenstock, W., Köble, T., Kruziniski, G. and Jaunich, G. *Calibration of a Neutron Spectrometer in the Energy Range 144 keV to 14.8 MeV with ISO Energies.* Radiat. Prot. Dosim. **70**(1–4), 299–303 (1997).
31. Weise, K., Weyreuch, M. and Knauf, K. *Neutron Response of a Spherical Proton Recoil Proportional Counter.* Nucl. Instrum. Methods Phys. Res.A **309**, 287–293 (1991).
32. Knauf, K., Weyrauch, M., Simon, F. and Kaldune, N. *SPHERE — A Program Package for Calculating the Neutron Response of Spherical Proton Recoil Proportional Counters.* (Braunschweig, Germany: Physikalisch-Techische Budesanstalt) Report PTB-6-42-98-1 (December 1998).