CALIBRATION AND APPLICATION OF THE MULTISPHERE TECHNIQUE IN NEUTRON SPECTROMETRY AND DOSIMETRY

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During production of radionuclides with the cyclotron of the Eindhoven University of Technology high fluxes of energetic neutrons are generated. For reasons of practical radiation protection we paid attention to neutron detection techniques for dosimetry purposes. Since the biological effect of neutron exposure strongly depends on energy, the detection method must submit information on the neutron energy spectrum.

MULTISPHERE TECHNIQUE

The detection method is known as the multisphere technique (1). A neutron detector is placed in the centre of a sphere of moderating material. In our case the detector is a cylindrical ^{6}LiI(Eu) scintillation crystal (4 mm high, 8 mm diameter) which is optically coupled to a photomultiplier (RCA 6199) by a perspex light pipe (170 mm long, 20 mm diameter). Mainly thermal neutrons are detected in the crystal via the $^6Li(n,\alpha)t$ reaction (Q = 4.8 MeV). The thermal cross section for this reaction is about 1000 barn and decreases strongly with increasing neutron energies ($\sigma \simeq 1/\sqrt{E}$). So fast neutrons must be moderated to increase their detection probability.
Measurements were carried out with the bare crystal and with 15 polyethylene (ρ = 940 kg/m^3) spheres with different diameters ranging from 0.05-0.45 m (2-18 inch). Suppression of γ-rays with energies upto 4 MeV is achieved with pulse height discrimination.
The relation between the measured count rate T_i of detector i with detector cross section σ_i and the spectral distribution of the neutron flux density ϕ_E is:

$$T_i = \int_0^\infty \sigma_i(E)\ \phi_E(E)\ dE \qquad i = 1, \ldots.. 16 \qquad (1)$$

Relative detector cross sections (also called detector efficiencies) for the different sphere diameters are given by Nachtigall (2). To check these theoretical curves, calibration measurements were carried out for 9 different neutron energies chosen logarithmically equidistant in the energy range from 100 keV to 4 MeV. The mono-energetic neutrons were produced with a Van de Graaff accelerator.
Theoretically the product $T_i r^2$ of the detector count rate T_i and the distance r from the point source equals a constant K_i (inverse square law: $T_i = K_i/r^2$) which is charateristic for a specific source-detector combination. In practice scattered neutrons contribute to the count rate. This contribution varies with distance. The expression for the count rate T_i is:

$$T_i(r) = K_i/r^2 + S_i(r) \qquad i = 1, \ldots.. 16 \qquad (2)$$

To simplify the problem we only used measurements for r > 0.5 m. For smaller distances correction factors must be introduced in equation (2). It was experimentally shown that the contribution to the count rate by scattered neutrons by good approximation can be described with S(r) = a+b/r.

UNFOLDING PROGRAM

To unfold the neutron energy spectrum from measurements with the 16 detectors, the SAND-II unfolding program (3) was used. This program was developed for measurements with activation detectors. The program applies a non-linear adjustment to the input spectrum at each iteration step. Using the analogy between activity and count rate on one hand and cross section and efficiency on the other the SAND-II program is applicable in our case (5). The set of equations (1) is approximated by

$$T_i = \sum_j \sigma_{ij}\,\phi_j \qquad i = 1, \ldots\ldots 16 \quad j = 1, \ldots\ldots 620 \qquad (3)$$

in which ϕ_j is the flux density in $m^{-2}s^{-1}$. The values of σ_{ij} were experimentally determined for the energy range of 100 keV - 4 MeV and were partially derived from the relative values given by Nachtigall for the non-measured energy ranges.

RESULTS

For testing purposes, the multisphere method in combination with the SAND-II unfolding program was applied to known neutron energy spectra. A 11 GBq Am-Be source and a 20 GBq ^{252}Cf source were used. The measurements took place in a concrete hall (dimensions 14 × 18 × 10 m). The detector was placed in the centre of that hall and the source could be moved over a horizontal rail at the same height. The count rates were measured at 10 different distances varying from 0.5 m to 3.5 m. For each detector and both sources the scattering parameters a and b as well as the K-value were determined with a least squares method. The resulting K-values were used as input values in the spectrum calculations. The result of the SAND-II unfolding method of the measurements with the bare Am-Be source, this means corrected for the contribution of neutron scattering, is shown in fig. 1 (curve K). A known Am-Be spectrum (5) was used as input spectrum. The same has been done for the bare Cf-source (4). When determining actual neutron spectra inclusive scattering, the measured count rates for the Am-Be source at several distances from the source were used as input values. With respect to the input spectrum a thermal Maxwell energy distribution was assumed; for intermediate energies (0.5 eV - 100 keV) proportionally to $E^{-0.7}$ proved to give the best results. The unfolded actual spectra at 1 m and 3 m distance from the Am-Be source are also shown in fig. 1. It is quite obvious that fast neutrons obey the inverse square law. For energies below 100 keV the occurrence of scattered neutrons is clear. In addition the calculated integral flux density ϕ_{tot} and the mean energy are given in the table.

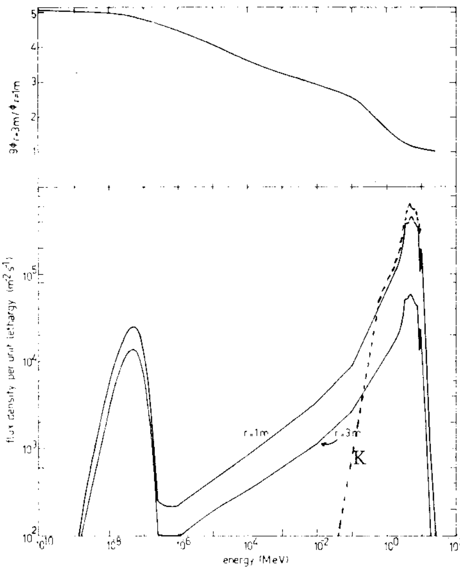

Fig. 1. The flux density per unit lethargy as a function of the energy for the ^{241}Am-Be source. The measurements were performed at 1 m and at 3 m. The spectrum for the bare source is given (curve K) and the uppermost curve gives the ratio of the flux density at 3 m multiplied by a factor 9 to that of 1 m.

FLUENCE TO DOSE EQUIVALENT CONVERSION FACTORS

For dosimetry purposes the effective energy E_{eff} is a more important quantity than the mean energy $\bar{E}$ because the neutron fluence to dose equivalent conversion factor can be strongly energy dependent. The neutron fluence to maximum dose equivalent conversion factors $\hat{h}(E)$ are defined by the ICRP (6). When the neutron energy distribution is known, the values for $\hat{h}(\bar{E}_{eff})$ can be calculated for that specific source with the relation:

$$\hat{h}(E_{eff}) = [\sum_i \hat{h}_i(E)\ \phi_i(E)]/\phi_{tot} \qquad (4)$$

in which $\phi_i(E)$ is the flux density in the energy range i between the energies E_i and E_{i+1} and ϕ_{tot} is the integral flux density. The values of E_{eff}, corresponding with $\hat{h}(E_{eff})$ can be derived from the defined ICRP curve (6). Values for $\bar{E}_{eff}$ and $\hat{h}(E_{eff})$ were calculated for the bare Am-Be source and the bare Cf source (see Table). Our values for $\hat{h}(E_{eff})$ are in agreement with literature: we found 3.7 10^{-14} Sv.m^2 for Am-Be and 3.0 10^{-14} Sv.m^2 for Cf; respective literature values are 3.62 10^{-14} (7) and 3.39 10^{-14} (8). The quantities E_{eff} and $\hat{h}(E_{eff})$ are also calculated for the actual Am-Be spectra at 1 m and 3 m distance from the source. As is shown in the table the reduction in $\hat{h}(E_{eff})$ when changing from 1 to 3 m distance is more than follows from the decrease in $\bar{E}$. This is due to the fact that the relative contribution of low energetic scattered neutrons, increases with distance.

Table. Some results of the spectrum analysis and some derived dosimetric quantities. K in column II means that K-values were used as starting values for unfolding and T stands for use of count rates.
N.B. 1 Sv.m^2 = 36 10^{11} mrem.h^{-1}.$n^{-1}cm^{-2}s^{-1}$.

Source	Remarks	ϕ_{tot} [$10^6 m^{-2}s^{-1}$]	$\bar{E}$ [MeV]	$\hbar(\bar{E})$ [10^{-14}Sv.m^2]	E_{eff} [MeV]	$\hbar(E_{eff})$ [10^{-14}Sv.m^2]
^{241}Am-Be	K	0.642	4.26	4.1	1.86	3.7
^{241}Am-Be	T(1 m)	0.727	3.98	4.1	1.45	3.5
^{241}Am-Be	T(3 m)	0.125	2.90	4.0	0.77	2.7
^{252}Cf	K	2.35	1.97	3.8	0.89	3.0
^{123}I	T(A)	1780	0.56	2.2	0.10	0.56
^{123}I	T(B_1)	28.0	0.69	2.5	0.11	0.62
^{123}I	T(B_2)	4.30	1.21	3.4	0.14	0.76
^{123}I	T(C)	4.31	0.074	0.44	0.022	0.17

The detection system was applied in practical radiation protection measurements during the production of the radionuclide ^{123}I. Results under 4 different conditions are presented in the table. The difference between condition B_1 and B_2 is shielding with a 0.2 m paraffin layer. The detailed description of measurement positions is given elsewhere in this proceedings (9).

FINAL REMARK

In practical circumstances when significant neutron scattering occurs, application of the fluence to dose equivalent conversion factor at mean energy results in a considerable over-estimation of the maximum dose equivalent.

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