Rem-meter correction factor for measuring high energy neutron dose equivalent

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Abstract The dose equivalent of neutrons from intermediate energy heavy ion reactions measured with a Rem-meter, would be underestimated because of the energy response of the instrument. The correction factors for dose equivalent of neutrons from the reactions of 41.7 MeV/u ^{12}C+Fe and 100 MeV/u ^{12}C+C measured with a 10 inch diameter single-sphere Rem-meter have been calculated. They could be applied into dose equivalent measurement for intermediate energy heavy ion reactions.

Keywords Rem-meter correction factor, Neutron dose equivalent, Intermediate energy heavy ion reaction

1 Introduction

The Rem-meter is still widely used to measure neutron dose equivalent in neutron field monitoring. However, the dose equivalent, in a strict sense, is not directly measurable with an instrument, only under certain limited conditions the Rem-meter can be used to obtain directly the reading of neutron dose equivalent. In general, these instruments are limited to energies from a few keV to about 15 MeV. The Rem-meter was priorly calibrated by using an isotope neutron source, for instance Ra-Be or Am-Be sources, with average neutron energy about 5 MeV, then the rough neutron dose equivalent in a wider energy range (E <14 MeV) could be obtained in routine dose monitoring. Therefore, Rem-meters are particularly valuable when maximum neutron energies are less than 14 MeV or when isotope neutron sources are measured.

In intermediate energy heavy ion reactions, however, the emitted neutron spectra are quite complicated. As an example, the emitted neutron energy range is from thermal energy to about 200 MeV and the neutrons of E_n >20 MeV have quite a proportion in 100 MeV/u ^{12}C+C reaction.[1] The direct readings of neutron dose equivalent measured with Rem-meter will deviate seriously from the real value due to the energy response of instruments. Therefore, the direct readings of Rem-meter must be corrected.

2 Rem-meter energy response

The energy response of Rem-meter with

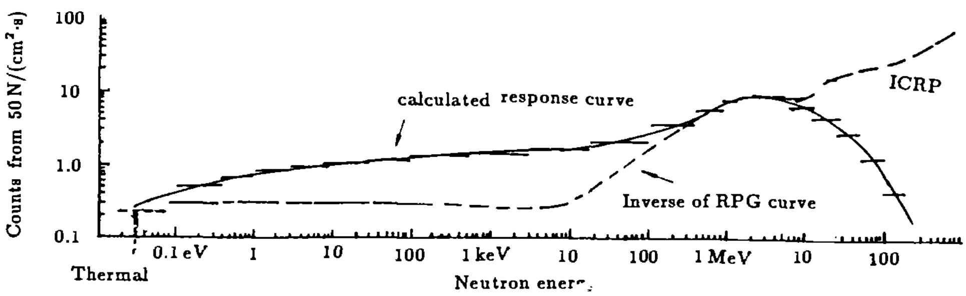

Fig.1 Calculated response of a 10 inch diameter single-sphere Rem-meter vs neutron energy

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different constructions is different. In general, the energy response curve of a Rem-meter was given only in the energy range from thermal energy to about 15 MeV. Up to now the universal commercial Rem-meter which can be applied to measure dose equivalent of neutron with energy of several hundreds MeV has not been developed.

Fig.1 shows a calculated response curve of a 10 inch diameter single-sphere Rem-meter with a wider energy range. The solid line and dashed line are the calculated response of the Rem-meter and the desired dose equivalent response based on NBS and ICRP recommendations, respectively.[2] The response of the Rem-meter is quite good for thermal neutrons (~ ±4%) and fast neutrons in the range 0.2 to 7 MeV (~ ±15%), some serious discrepancies can occur for the neutrons with higher energy. In the intermediate energy region the instrument can over-respond by as much as a factor of five. At energies above 7 MeV the instrument can considerably underestimate the neutron dose equivalent because the response of the instrument decreases rapidly.

3 Neutron spectra in the intermediate energy heavy ion reactions

The emitted neutron spectra of 100 MeV/u $^{12}C+C$ and 41.7 MeV/u $^{12}C+Fe$ had been

Table 1 Energy and angular distribution of neutrons from 100 MeV/u $^{12}C+C$ reaction[3]

Emission angle/(°)	0~15		15~30		30~60		60~120		120~180		
Distribution of neutrons	A(1)	B(2) %	A(1)	B(2) %	A(1)	B(2) %	A(1)	B(2) %	A(1)	B(2) %	ΣB(2) %
0~20 MeV	1.1×10	1.22	1.2×10	3.92	1.1×10	13.15	4.5	14.70	2.8	4.57	37.56
20~40 MeV	1.0×10	1.11	1.1×10	3.59	7.0	8.37	8.5×10^{-1}	2.78	2.1×10^{-1}	0.34	16.19
40~60 MeV	2.2×10	2.44	1.5×10	4.90	5.0	5.98	2.0×10^{-1}	0.65	3.9×10^{-2}	0.06	14.03
60~80 MeV	5.0×10	5.56	1.7×10	5.56	2.8	3.35	4.0×10^{-2}	0.13	1.1×10^{-2}	0.02	14.62
80~100 MeV	5.8×10	6.44	9.5	3.10	9.5×10^{-1}	1.14	9.0×10^{-3}	0.03	–	–	10.72
100~120 MeV	2.5×10	2.78	4.0	1.31	3.0×10^{-1}	0.36	–	-	–	–	4.45
120~140 MeV	8.0	0.89	2.0	0.65	1.0×10^{-1}	0.12	–	–	–	–	1.66
140~160 MeV	3.0	0.33	4.0×10^{-1}	0.13	3.1×10^{-2}	0.04	–	–	–	–	0.50
160~180 MeV	9.0×10^{-1}	0.10	1.8×10^{-1}	0.06	1.0×10^{-2}	0.01	–	–	–	–	0.17
180~200 MeV	3.5×10^{-1}	0.05	9.0×10^{-2}	0.03	–	–	–	–	–	–	0.08
200~220 MeV	2.0×10^{-1}	0.02	–	–	–	–	–	–	–	–	0.02
Σ B(2),%		20.94		23.25		32.52		18.29		5.00	100

Table 2 Energy and angular distribution of neutrons from 41.7 MeV/u $^{12}C+Fe$ reaction[4]

Emission angle/(°)	0~10		10~30		30~60		60~80		80~110		
Distribution of neutrons	A(1)	B(2) %	A(1)	B(2) %	A(1)	B(2) %	A(1)	B(2) %	A(1)	B(2) %	ΣB(2) %
0~10 MeV	3.8×10^2	3.82	1.5×10^2	11.79	7.7×10	18.66	4.0×10	9.69	2.5×10	8.53	52.49
10~20 MeV	4.2×10^2	4.23	9.7×10	7.63	2.6×10	6.29	7.0	1.69	4.3	1.47	21.32
20~30 MeV	3.5×10^2	3.52	6.0×10	4.72	1.1×10	2.67	2.7	0.65	1.9	0.65	12.21
30~40 MeV	3.0×10^2	3.02	3.8×10	2.99	5.0	1.21	1.6	0.39	1.1	0.38	7.98
40~50 MeV	8.0×10	0.80	1.8×10	1.42	2.8	0.26	7.5×10^{-1}	0.18	2.8×10^{-1}	0.09	2.75
50~60 MeV	2.0×10	0.20	8.5	0.67	1.4	0.34	5.6×10^{-1}	0.13	1.8×10^{-1}	0.06	1.41
60~70 MeV	1.2×10	0.12	4.2	0.33	9.0×10^{-1}	0.22	1.4×10^{-1}	0.03	6.8×10^{-2}	0.02	0.73
70~80 MeV	4.2	0.04	3.2	0.25	8.0×10^{-1}	0.19	1.8×10^{-1}	0.04	4.5×10^{-2}	0.02	0.55
80~90 MeV	2.2	0.02	1.8	0.14	9.5×10^{-2}	0.02	7.1×10^{-2}	0.02	2.2×10^{-2}	0.01	0.21
90~100 MeV	2.2	0.02	1.4	0.11	2.5×10^{-1}	0.06	7.1×10^{-2}	0.02	2.2×10^{-2}	0.01	0.22
100~110 MeV	3.0	0.03	1.9×10^{-1}	0.01	6.2×10^{-2}	0.02	7.1×10^{-2}	0.02	–	–	0.08
110~120 MeV	7.8×10^{-1}	0.01	3.0×10^{-1}	0.02	–	–	–	–	–	–	0.03
120~130 MeV	7.8×10^{-1}	0.01	1.9×10^{-1}	0.01	–	–	–	–	–	–	0.02
Σ B(2),%		15.85		30.10		29.94		12.88		11.24	100

(1) $A=d^2\sigma/d\Omega/dE(\times10^{-27}cm^2\cdot sr^{-1}\cdot MeV^{-1})$;

(2) B is the percentage of neutron numbers in the i-th energy interval in total emitted neutron numbers

reported by Gabriel *et al.*[3] and Bertini *et al.*[4] respectively and whose data are given in Table 1 and Table 2. The emitted neutron energy can reach about twice incident energy per nucleon in the forward direction and the mean energy of neutrons is slightly lower than incident ion energy per nucleon. The neutrons of $E_n > 20$ MeV account for about 60% of emitted total neutron for the reaction of 100 MeV/u ^{12}C+C and about 30% for the other one.

In this calculation, the neutrons with energies less than several hundreds keV have been neglected.

4 Correction factors

The direct reading of the Rem-meter will seriously deviate from real neutron dose equivalent in a complicated neutron field as mentioned earlier. In order to solve this problem let us define a correction factor K as follows

$$K = (\sum_{i=1}^{n} k_i \cdot \eta_i)/(\sum_{i=1}^{n} k_i \cdot \varepsilon_i)$$

where n is number of neutron energy bins; k_i is percent of neutron in the i-th energy bin to total neutron; η_i is relative dose equivalent response of the i-th energy bin to 5 MeV neutron; ε_i is Rem-meter relative response of the i-th energy bin to 5 MeV neutron. Then if the direct reading of the Rem-meter is A (μ Sv), the real neutron dose equivalent H (μ Sv) would be

$$H(\mu\text{Sv}) = K \cdot A(\mu\text{Sv}).$$

Table 3 Correction factors for the 100 MeV/u ^{12}C+C reaction

Energy interval of emitted neutrons MeV	ε_i	η_i	k_i/% 0° ~ 15°	15° ~ 30°	30° ~ 60°	60° ~ 120°	120° ~ 180°
0~20	1.00	1.00	5.83	11.86	40.45	80.37	91.51
20~40	0.39	2.00	5.31	15.45	25.74	15.18	6.86
40~60	0.22	2.22	11.67	21.08	18.39	3.57	1.27
60~80	0.13	2.24	26.52	23.89	10.30	0.72	0.36
80~100	0.09	2.56	30.77	13.35	3.49	0.16	–
100~120	0.07	2.67	13.26	5.62	1.10	–	–
120~140	0.06	2.78	4.24	2.81	0.37	–	–
140~160	0.04	2.89	1.59	0.56	0.12	–	–
160~180	0.03	3.00	0.48	0.25	0.04	–	–
180~200	0.03	3.11	0.22	0.13	—	–	–
200~220	0.03	3.33	0.11	–	–	–	–
Correction factor K			13.38	6.55	3.04	1.39	1.15

Table 4 Correction factors for the 41.7 MeV/u ^{12}C+Fe reaction

Energy interval of emitted neutrons MeV	ε_i	η_i	k_i/% 0° ~ 10°	10° ~ 30°	30° ~ 60°	60° ~ 80°	80° ~ 110°
0~10	1.00	1.00	24.12	39.19	62.31	75.27	75.95
10~20	0.78	1.33	26.66	25.34	21.04	13.17	13.06
20~30	0.56	1.78	22.22	15.67	8.90	5.08	5.77
30~40	0.44	2.00	19.05	9.93	4.05	3.01	3.34
40~50	0.33	2.12	5.08	4.70	0.86	1.42	0.85
50~60	0.22	2.22	1.27	2.22	1.13	1.05	0.56
60~70	0.17	2.23	0.76	1.09	0.73	0.26	0.21
70~80	0.13	2.24	0.27	0.84	0.65	0.35	0.14
80~90	0.11	2.33	0.14	0.47	0.08	0.13	0.06
90~100	0.09	2.56	0.14	0.37	0.20	0.13	0.06
100~110	0.08	2.60	0.19	0.05	0.05	0.13	–
110~120	0.07	2.67	0.05	0.08	–	–	–
120~130	0.06	2.78	0.05	0.05	–	–	–
Correction factor K			2.28	1.90	1.42	1.28	1.25

The neutron energies were divided into 11 and 13 energy intervals for reaction of 100 MeV/u ^{12}C+C and 41.7 MeV/u ^{12}C+Fe, respectively in the calculation of correction factors. The response of Rem-meter to 5 MeV neutron and dose equivalent response at 5 MeV were both normalized to 1.0. The values of k_i, ε_i, η_i and calculated correction factors were listed in Table 3 and Table 4.

It should be pointed out that different correction factors would be employed when measurement was performed in different directions. This is due to the difference of neutron energy compositions in different emitted directions and the fact that high energy neutrons were mainly distributed in the forward directions of the target.

5 Results and discussion

One can see from the calculated results that correction is necessary for neutrons dose equivalent measured with the Rem-meter in intermediate energy heavy ion reactions, particularly in the reactions induced by incident ion with higher energy per nucleon and measured in the forward direction. As an example, the real dose equivalent value in the forward direction would be 13.38 and 2.28 times the size of the direct reading values from the instruments for the reactions of 100 MeV/u $^{12}C+C$ and 41.7 MeV/u $^{12}C+Fe$, respectively. The correction factors decrease with the increase in angle to incoming beam direction and approach 1.0 in the backward direction because there are few high energy neutrons.

Present experimental data indicate that the energy and angular distributions of neutrons from heavy ion reactions depend mainly on the incident ion energy per nucleon and nearly regardless of the target nuclei.[5~7] Therefore the correction factors in Table 4 and Table 3 can be employed approximately to the reactions of 50 MeV/u $^{12}C+Cu$ and 100 MeV/u $^{12}C+Cu$.

This calculation was completed only based on that the energy spectra of emitted neutrons are nearly unchanged in the case of without shielding. But, the neutron energy spectrum penetrating through the concrete shielding wall would become "harder". Therefore the dose equivalent value would be underestimated more seriously when measurement was performed outside shielding wall. For this case it would be necessary to calculate other set of correction factors if the neutron spectrum was known.

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