Rem-meter correction factor for measuring high energy neutrons outside concrete shielding

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Abstract Correction factors of both Rem-meters, the 10 inch diameter single-sphere Rem-meter and the standard A-B Rem-meter, were estimated for measuring high energy neutron dose equivalent outside a concrete shielding wall and the effects that the emitted neutron spectra become remarkably "harder" penetrated through a concrete shielding wall, and the energy response of the Rem-meter were taken in account. The estimated results could be applied in the measurement of neutron dose equivalent for the intermediate energy heavy ion reactions to avoid the difficulty induced by the energy response of the Rem-meters.

Keywords High energy neutron, Rem-meter, Dose equivalent, Correction factor, Shielding

1 Introduction

In heavy ion reactions, the emitted neutron energy could reach twice incident ion energy per nucleon or even more.[1,2] The error between the Rem-meter direct reading and the real neutron dose equivalent might appear due to the present of a great deal of high energy neutrons and the energy response characteristics of the instrument during measuring the neutron dose equivalent with a universal neutron Rem-meter.[3]

The Rem-meter correction factors for measuring high energy neutron on the inside of shielding wall for both Rem-meters, a 10 inch diameter single-sphere Rem-meter and a standard A-B Rem-meter, have been presented in Ref.[3] by using the energy response curves of the both Rem-meters[4,5] (Fig.1 in Ref.[3]). Outside the concrete shielding wall, however, the neutron spectra penetrated through the shielding would become "harder", namely, the lower energy neutrons are much rapidly attenuated in the shielding and the proportion of high energy neutrons in the neutron field outside a thicker shielding would be higher than that outside a thinner shielding. In this case, from the Rem-meter direct reading the neutron dose equivalent value would be underestimated more seriously.

2 Neutron spectra outside concrete shielding wall

The energy spectra of neutrons from intermediate energy heavy ion reactions are rather complicated and it is very difficult to calculate exactly the neutron spectra penetrated through a thick shielding. In order to make the problem simple and convenient, the energy of neutrons emitted from the reaction of 100 MeV/u $^{12}C+Cu$[6] were divided into 11 energy intervals. For example, the proportions of neutrons in each of the 11 energy intervals, k_i, penetrating through different thickness concrete shielding at 10 m from the neutron source (thick target) outside shielding were calculated, respectively, by the neutron attenuation theory method and taking into account the variation of neutron spectra with the shielding thickness.

Table 1 Parameters of neutron spectra calculation

Reaction:	$^{12}C+Cu$				Beam current:		3.9×10^{11} ions/s				
E_p:	100 MeV/u				Neutron yield:		1.95 n/(^{12}C-ions)[6]				
Neutron energy E_n/MeV	0~20	20~0	40~60	60~80	80~100	100~120	120~140	140~160	160~180	180~200	200~220
Half-thickness $d_{1/2}$/cm[8]	8	12	16	19	24	29	34	39	41	43	44

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The relevant parameters were shown in Table 1 and the calculated k_i value, the percent of neutron number in the i-th energy bin in total neutrons, were listed in Table 2. Fig.1 given the variation of k_i with concrete shielding thickness in different directions (only showing two set of curves in 0° ~ 15° and 15° ~ 30° directions as an example in the text).

Table 2 Neutron distribution outside the concrete shielding at 10 m from the neutron source (target)

Emission direction	Neutron energy MeV	Concrete shielding thickness/cm 100 k_i/%	200 k_i/%	300 k_i/%	400 k_i/%	500 k_i/%
0° ~ 15°	0~20	–	–	–	–	–
	20~40	0.3	–	–	–	–
	40~60	3.2	0.5	–	–	–
	60~80	14.5	4.8	1.3	0.3	–
	80~100	35.9	25.6	6.3	6.2	2.4
	100~120	25.4	29.8	28.6	19.5	12.5
	120~140	11.6	19.3	26.3	25.5	23.3
	140~160	5.7	12.3	21.7	27.3	32.5
	160~180	1.8	4.3	8.3	11.4	14.8
	180~200	0.8	1.9	4.1	6.1	8.6
	200~220	0.1	1.2	2.6	3.9	5.7
15° ~ 30°	0~20	0.1	–	–	–	–
	20~40	1.7	–	–	–	–
	40~60	10.1	2.0	0.3	–	–
	60~80	22.7	8.7	2.2	0.5	–
	80~100	27.1	22.1	12.1	5.5	2.2
	100~120	19.3	25.9	23.3	17.3	11.4
	120~140	13.7	26.1	33.5	35.3	32.9
	140~160	2.8	7.9	15.2	20.8	25.3
	160~180	1.8	4.9	9.0	13.4	17.7
	180~200	0.8	2.3	4.5	7.3	10.5
	200~220	–	–	–	–	–
30° ~ 60°	0~20	0.7	–	–	–	–
	20~40	8.3	0.6	–	–	–
	40~60	24.8	7.5	0.9	0.2	–
	60~80	27.6	16.6	4.1	1.3	0.3
	80~100	19.7	25.3	13.3	9.2	4.1
	100~120	10.8	22.9	19.7	22.4	16.4
	120~140	5.8	17.3	46.5	34.3	35.6
	140~160	2.5	9.7	15.5	32.5	43.8
	160~180	–	–	–	–	–
60° ~ 120°	0~20	11.1	0.1	–	–	–
	20~40	37.9	12.1	2.2	0.3	–
	40~60	36.5	49.2	38.3	24.4	14.1
	60~80	14.5	38.6	59.5	75.2	85.9
	80~100	–	–	–	–	–
120° ~ 180°	0~20	30.3	0.1	–	–	–
	20~40	37.7	21.8	6.2	1.5	0.4
	40~60	32.0	78.1	93.8	98.5	99.6
	60~80	–	–	–	–	–

3 Calculation of correction factor

A correction factor K was defined as Ref.[3, 7]

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

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, the real neutron dose equivalent $H(\mu\text{Sv})$ would be written as

$$H(\mu\text{Sv}) = K \cdot A(\mu\text{Sv}) \quad (2)$$

where $A(\mu\text{Sv})$ is the Rem-meter direct reading.

The calculation of the correction factor was performed by two steps. First, the variations of the neutron spectra penetrating through different thickness concrete shielding were calculated and obtained the k_i values, then the correction factors K were calculated by Eq.(1) and using the values of k_i, η_i and ε_i listed in Tables 2, 3.

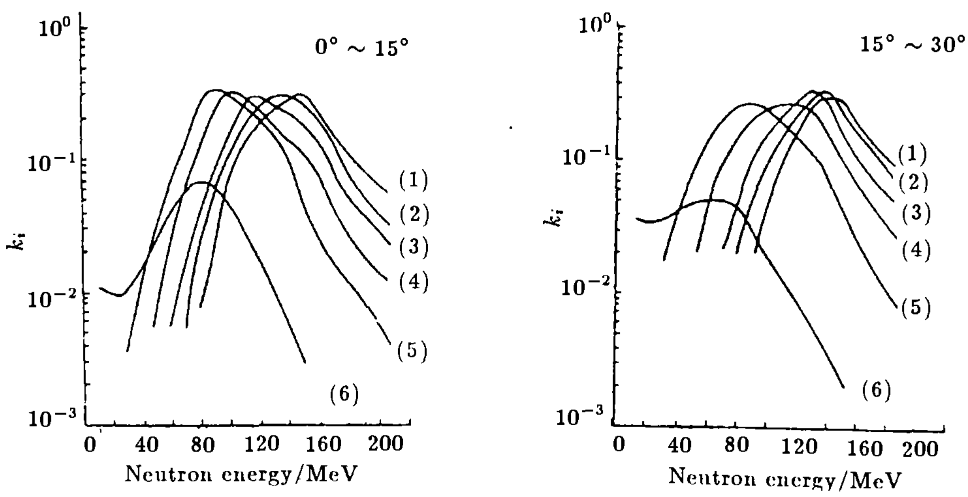

Fig.1 Neutron distributions at 10 m from the source and outside the concrete shielding with different thicknesses: 500cm (1), 400 cm (2), 300 cm (3), 200 cm (4), 100 cm (5) and without shielding (6)

Table 3 The values of ε_i and η_i

Neutron energy E_n/MeV	10 inch single-sphere Rem-meter ε_i	η_i by ICRP	η_i by H*(10)	A-B Rem-meter ε_i	η_i by H*(10)
0~20	1.00	1.00	1.00	1.00	1.00
20~40	0.39	2.00	2.00	0.32	1.46
40~60	0.22	2.22	1.40	0.22	0.78
60~80	0.13	2.24	1.00	0.19	0.76
80~100	0.09	2.52	0.70	0.16	0.78
100~120	0.07	2.67	0.60	0.16	0.78
120~140	0.06	2.78	0.60	0.15	0.78
140~160	0.04	2.89	0.60	0.15	0.81
160~180	0.03	3.00	0.60	0.14	0.81
180~200	0.03	3.11	0.60	0.13	0.83
200~220	0.03	3.33	0.60	0.13	0.85

4 Results and discussion

The calculated Rem-meter correction factors for both, the 10 inch diameter single-sphere Rem-meter and the standard A-B Rem-meter, were given in Table 4.

It may be seen from Table 4 that: (1) The correction factors are increased with the increase in concrete shielding thickness, which are minimal as shielding thickness equals to zero; (2) The correction factors are decreased with the increase in the angles between the measuring point and the incoming beam. The facts reflect that the neutron spectra become "harder" outside thicker shielding than outside thinner shielding[9], i.e., outside the shielding, the percent of higher energy neutron in total neutrons increases with increasing of shielding thickness, and that the over 60% of total neutron and nearly all neutrons with energy over 100 MeV were emitted in the sterad of 0° ~ 60° in the reaction of 100 MeV/u $^{12}C + C$.[1,3]

The percent of emitted high energy neutron in total neutrons is very high in intermediate energy heavy ion reactions, therefore, it is not suitable to take the direct reading of a Rem-meter as the neutron dose equivalent due to this fact and the energy response of the Rem-meter. In order to get more exact neutron dose equivalent value the Rem-meter direct reading must be corrected.

Table 4 Correction factor K

Concrete shielding thickness /cm	K(for 10 inch single-sphere Rem-meter)									
	0° ~ 15°		15° ~ 30°		30° ~ 60°		60° ~ 120°		120° ~ 180°	
	by									
	ICRP	H*(10)	ICRP	H*(10)	ICRP	H*(10)	ICRP	H*(10)	ICRP	H*(10)
0[3]	13.4	5.2	6.6	4.1	3.0	2.3	1.4	1.3	1.2	1.1
100	29.8	8.3	24.1	7.7	15.2	6.6	5.7	4.3	3.4	2.9
200	38.5	9.3	36.0	8.9	27.8	8.1	10.4	6.4	8.2	5.9
300	49.3	10.8	45.5	10.2	41.6	9.5	13.8	6.9	9.6	6.2
400	54.5	11.6	52.9	11.0	46.4	10.6	15.6	7.2	9.9	6.3
500	61.8	12.9	59.2	12.5	51.6	11.1	16.8	8.4	10.1	6.4

Concrete shielding thickness /cm	K (for A-B Rem-meter)				
	0° ~15°	15° ~30°	30° ~60°	60° ~120°	120° ~180°
	by H*(10)				
0[3]	3.6	2.9	1.9	1.2	1.1
100	4.9	4.5	4.1	3.0	2.2
200	5.0	4.9	4.7	5.8	3.8
300	5.2	5.1	5.0	3.8	3.6
400	5.3	5.3	5.1	3.8	3.6
500	5.5	5.4	5.2	3.9	3.6

For the 10 inch diametr single-sphere Rem-meter, the correction factors calculated by NCRP and ICRP recommendations in 1965 are greater than those by H*(10)[10], the reason causing this difference is very clear as the statement in Ref.[3].

An earlier study has pointed out that the neutron yield mainly depends on the projectile energy per nucleon and the neutron yield variation is a little as the target nuclei vary from Al to Pb[11]. Therefore, the correction factors listed in the Table 4 could be used approximately for the reactions induced by heavy ions with energy 100 MeV/u on the middle-heavy targets to obtain the real neutron dose equivalent with a Rem-meter.

The Rem-meter correction factor method is one of the effectivest methods overcoming the difficulty caused by the energy response of the Rem-meter and is a method of practical significance in the field of neutron dose measurement. It makes the high energy neutron dose equivalent measurement problem simple, convenient and practicable in the range of the intermediate energy heavy ion reactions. In this work, the correction factors for intermediate energy heavy ion reaction of 100 MeV/u ^{12}C-ion on thick Cu target were calculated only. This method could be applied to calculate the correction factors for measuring dose equivalent of neutrons known energy spectra or for other Rem-meters of known energy response.

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