Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 29-30, 2014

Review of Scattering Corrections for Calibration of Neutron Survey Meters

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1. Introduction

When neutron survey meters are calibrated with a radionuclide neutron source in a calibration room, the neutron survey meter responds to neutrons scattered in the walls, ground, ceiling and air of the calibration room. The calibration measurement should be corrected to what the reading would be from the source spectrum in vacuum (free-field dose equivalent, FFDE), i.e. with no contributions from neutron scattered by the air and room [1]. ISO 8529-2 (the International Organization for Standardization) recommends four different approaches to the problem of correcting for scatter effects. The first three methods, denoted as the shadow-cone method, the generalized fit method, and the semi-empirical method, usually involve an initial set of careful measurements as a function of the distance between neutron source and detector [2].

In this study, the calibration factors of the several neutron survey meters obtained by both the shadow-cone method and semi-empirical method. Generally and theoretically, the calibration factors obtained by the methods given in ISO 8529-2 have the similar values. However we found that the calibration factors obtained by two methods have the different values.

2. Methods and Results

2.1 Correction for Scattering Effects for Radionuclide Sources

A calibration factor of a neutron survey meter is obtained by dividing the calculated dose equivalent in FFDE by the survey meter's reading, corrected for scattering neutron. In the 'shadow-cone method', the accuracy of this method depends strongly upon the design of the shadow-cone and upon its position relative to the source-detector geometry. If $M_S(l)$ and $M_T(l)$ are the detector readings obtained with and without the shadow-cone placed between the source and the detector, then the following equation (1) holds,

$$[M_T(l) - M_S(l)]F_A(l) = \frac{B\,F(\theta)}{4\pi l^2}$$

where l is the distance from the centre of the source to the point of test. $M_C(l)$ and $F_A(l)$ are the measured reading corrected for all extraneous effects and appropriate air-attenuation (air outscatter) factor [2,3], and $F(\theta)$ is the anisotropy function of the radionuclide neutron source [4,5]. The schematic diagram illustrating arrangement and structure of the shadow-cone used in the present study is shown in Figure 1 [2]. It consists of two parts: a front end, 20 cm long made entirely of stainless steel; and a rear section, 30 cm long made of borated-polyethylene.

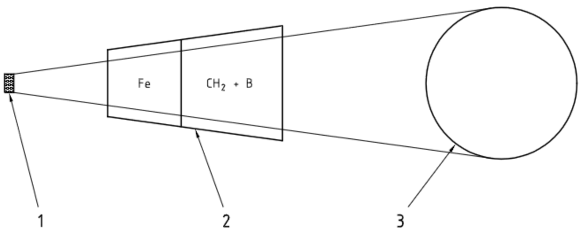

Fig. 1. Schematic diagram illustrating arrangement of neutron source (1), shadow-cone (2), and neutron survey meter (3).

The 'semi-empirical method' [5-7] is based on the assumption that the fraction of the instrument's reading due to scattered neutrons can be deduced from a deviation of the reading from the inverse-square law. The various contributions are characterized by a component independent of l due to room-return neutrons, and a component decreasing linearly with the separation distance, due to air-scattering. The instrument reading, $M_T(l)$, as a function of distance, due to the total radiation field (source neutrons plus scattered neutrons) is related to the fluence response R_ϕ by the equation (2):

$$\frac{M_T(l)}{F_1(l)\,(1+Al)} = \frac{B\,F(\theta)}{4\pi l^2}(1+Sl^2)$$

where, the room-scatter correction is give by $(1 + Sl^2)$ and the quantity S is the fractional room-scatter contribution at unit calibration distance. A is the net air-scatter effect (inscatter minus outscatter), and the total air-scatter correction is given by $(1 + Al)$ and this values are recommended by ISO [4]. $F_1(l)$ is the geometry correction factor and this contribution is negligible (≈1).

2.2 Calibration Factors of Several Neutron Survey Meters

The values of $M_S(l)$ and $M_T(l)$ in equation (1) were measured to compare the calibration factor obtained by both the 'shadow-cone method' and 'semi-empirical method The values of $M_T(l)$ in equation (2) were obtained at thirteen points ranging from 50 cm to 200 cm. A plot of the left-side of equation (2) vs l^2 should yield a straight line. From a weighted linear least-squares fit to the data, the intercept will be the fluence response, and the slope of the line will give the fractional room-scattered component *S*. Once *S* has been determined for a particular device, calibrations of similar devices may be performed by determining $M_T(l)$ at one, or a few, distances (l) to determine the fluence response.

In the present study, the calibration measurement was carried out at KAERI (Korea Atomic Energy Research Institute). The ^{252}Cf neutron source was used as a point source positioned in the centre of the neutron irradiation room [8 (L)×6(W)×6 (H) m^3], and the source-detector distances were 100-200 cm. Six neutron survey meters were used for the comparison of the calibration factors obtained by both 'shadow-cone method' and 'semi-empirical method'. Six neutron survey meters evaluated were (1) LB6411 (Berthold Technologies, GmbH & Co. KG, Germany), (2) FHT762 WENDI-2 (Thermo Scientific, USA), (3) FHT752 (Thermo Scientific, USA), (4) 12-4 (Ludlum Measurements, Inc., USA). The survey meters use different detectors and differ in construction with respect to shape, size and moderator material around the detector. 'LB6411', 'WENDI-2', and '12-4' are single-moderator based survey meters and utilize ^{3}He gas counter tube as the detector. 'FHT752' is also single-moderator-based survey meters but utilizes BF_3 counter as the detector. The calibration factors of two survey meters (LB6411-A and FHT762-A) obtained by both methods at the different calibration distances (100–200 cm) are summarized in Table 1. The calibration factors of six survey meters obtained at 100 cm distance by two methods are summarized in Table 2.

Table 1. Calibration Factors of the Neutron Survey Meters Determined by Two Methods at the Different Distances.

	LB6411-A		FHT762-B	
Distance (cm)	Shadow -cone	Semi-empirical	Shadow -cone	Semi-empirical
100	1.19	1.23	0.95	0.98
120	1.17	1.23	0.99	0.98
140	1.16	1.23	0.98	0.98
160	1.17	1.25	0.99	0.98
180	1.21	1.30	0.97	0.98
200	1.19	1.27	0.96	0.99

Table 2. Calibration Factors of Six Neutron Survey Meters Determined by Two Methods at 100 cm Distance.

Survey meter	Calibration factor		Deviation
	Shadow-cone method	Semi-empirical method	
LB6411-A	1.18	1.25	5.6%
LB6411-B	0.89	0.94	5.3%
FHT762-A	0.96	1.00	4.0%
FHT762-B	0.95	0.99	4.0%
FHT752	0.84	0.91	7.7%
12-4	1.13	1.23	8.1%

Table 1 shows that the calibration factors determined at the different distances (100–200 cm) have the similar values. The calibration factors as a function of the source-detector distance have almost the same values, and these results are in agreement with the recommendation of ISO 8529-2 [4] that the minimum calibration distance greater than twice the shadow-cone length. In Table 2, all of the calibration factors obtained by the 'semi-empirical method' are larger than that of the 'shadow-cone method'. It means that the total scatter correction (room- and air-scatter correction) of the conventional true scatter effects in the 'shadow-cone method' was underestimated by 4.0–8.1% rather than the scatter correction in the 'semi-empirical method'.

2.3 Summary of the Calculation for the Fast Neutron Spectra

The Monte Carlo code MCNPX (version 2.5.0) [8] was used to obtain the two neutron fluence spectra with- and without-shadow-cone. The dosimetric values were obtained using the fluence-to-ambient-dose-equivalent conversion coefficients [$h^*(10)$] of ICRU-57 [9]. The neutron fluence spectra and dosimetric quantities with and without the shadow-cone are shown in Figure 2.

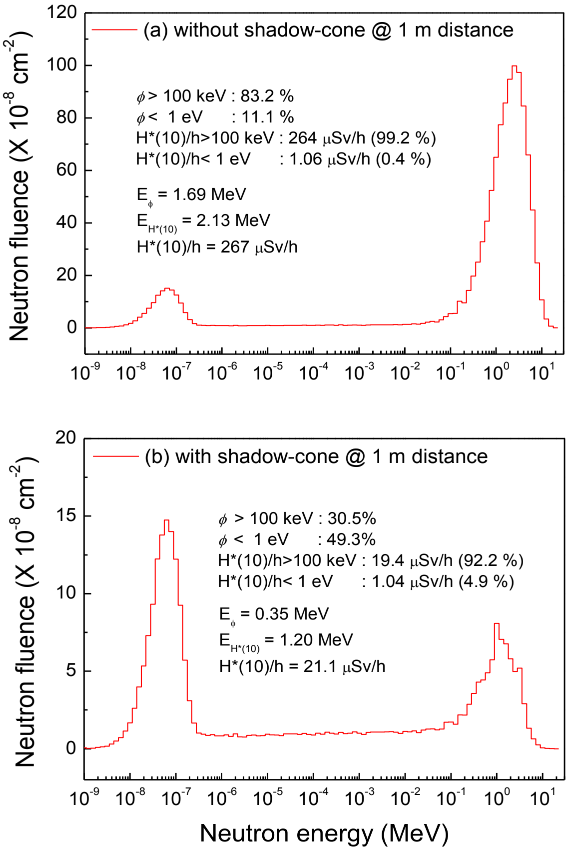

Fig. 2. Neutron fluence spectra and dosimetric quantities (a) without the shadow-cone and (b) with the shadow-cone at the 100 cm distance from the ^{252}Cf neutron source.

The spectral characteristics (percentile to total fluence rate, fluence- and dose equivalent-average energy) and ambient-dose-equivalent rates (percentile to total ambient dose equivalent rate) with the shadow-cone and without the shadow-cone neutron fields for neutron energy ranges of >100 keV and <1 eV are summarised in Figure 2(a) and Figure 2(b), respectively. As shown in Figure 2(a), the percentages of neutron-fluence to total neutron-fluence rate in different neutron energy ranges, >100 keV and <1 eV, are 83.2 % and 11.1 %, respectively. The percentages to total ambient-dose-equivalent rate [$H^*(10)/h$] for >100 keV and <1 eV are 99.2 % and 0.4 %, respectively. In Figure 2(b), the percentages of neutron fluence to total neutron-fluence-rate in different neutron energy ranges, >100 keV and <1 eV, are 30.5 % and 49.3 %, respectively, and the percentages to total ambient dose equivalent rate for >100 keV and <1 eV are 92.2 % and 4.9 %, respectively. The thermal neutron fluences (<1 eV) are owing to the moderated and scatter neutrons by wall, ceiling and ground. As shown in Figure 2, the values of total ambient-dose-equivalent rates calculated without and with the shadow-cone were 267 and 21.1 μSv/h, respectively. However, thermal neutrons (<1 eV) measured without and with the shadow-cone exhibited almost same values (1.06 and 1.04 μSv/h) of the ambient-dose-equivalent rate. It means that the scattering neutrons owing to air and room are accurately measured by the ‘shadow-cone method’. In Figure 2(b), the fast neutrons (>100 keV) still remained even though the shadow-cone was used, it means that the shadow-cone used in this study didn’t totally shadow the fast neutrons from the neutron source. This result of the ummoderated fast neutrons was different with the ISO recommends [4]; at very small separation distances between the cone and the neutron source, the reading due to inscattered neutrons is low, since the cone effectively prevents most of the neutrons produced in the forward hemisphere centred about the neutron detector axis from scattering into the neutron detector. Therefore the shadow-cone should have a negligible transmission of the direct neutrons.

2.3 Results of the Measurements and Calculations

In comparison with two calibration factor set obtained by two calibration methods, the calibration factors for the ‘shadow-cone method’ was smaller the that of the ‘semi-empirical method’. This reason of the under-response of a commercial neutron survey meter in the thermal neutron fields of the neutron survey meters in thermal or scattered neutron fields can be elucidated as a result of the S. I. Kim et al [10], most of single-moderator-based survey meters excluding tissue-equivalent proportional counter (TEPC) have a under-response in the thermal neutron field.

3. Conclusions

The calibration factors were obtained by two calibration method and the validity of the ‘shadow-cone method’ was proven by the MCNPX calculation. The total scattering correction of the conventional true scatter effects in the ‘shadow-cone method’ was under-estimated by 4.0–8.1% rather than the scatter correction in the ‘semi-empirical method’. This lower calibration factor than that of the ‘semi-empirical method’ is owing to the under-response of the neutron survey meters in the thermal neutron field. These results are elucidated from that most of single-moderator-based survey meters excluding tissue-equivalent proportional counter (TEPC) have an under-response in the thermal neutron field. It is concluded that a great care is needed while calibrating a survey meter using a shadow-cone calibration method and in interpreting the readouts.

Acknowledgement

This work was carried out as part of the National-& Intermediate-Term Project of Nuclear Energy Development (NRF - 2012M2A8A4025916) of the Ministry of Science, ICT and Future Planning, Republic of Korea.

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