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Evaluation of the calibration factors of neutron dose rate meters in a ^{241}Am–Be neutron field

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Abstract Calibrations were performed for three types of neutron ambient dose equivalent rate meters, i.e., Aloka TPS-451C (Hitachi), KSAR1U.06 (Baltic Scientific Instruments), and Model 12-4 (Ludlum), using a standard field of a ^{241}Am–Be source. The measured total neutron ambient dose equivalent rates, $H^*(10)'_{\mathrm{tot}}$, were analyzed to obtain the direct neutron ambient dose equivalent rates, $H^*(10)'_{\mathrm{dir}}$, using the ISO 8529-2-recommended generalized-fit method, semiempirical fit method, and reduced-fitting method (RFM) fit methods. The calibration factor (CF), defined as the ratio between the conventional true value of the neutron ambient dose equivalent rates in a free field, $H^*(10)'_{\mathrm{FF}}$, and $H^*(10)'_{\mathrm{dir}}$, was evaluated as one of the important characteristics of the neutron meters in the present work. The fitting results show that the $H^*(10)'_{\mathrm{dir}}$ values of the meters are in good agreement within the theoretical data within 4%. The averaged CFs of the three neutron meters were evaluated as 0.99 ± 0.01, 1.00 ± 0.03, and 0.99 ± 0.08, respectively. The largest standard uncertainty of these values was determined to be approximately 18.47% ($k = 1$). The standard uncertainty of the CFs obtained using the RFM method was less than 4.23% ($k = 1$), which is the smallest uncertainty among the three methods.

Keywords Neutron meter · Calibration factor · ^{241}Am–Be source

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1 Introduction

The reading of a neutron dose equivalent rate meter in a neutron field is attributable to both neutrons that arrive directly from the source to the meter and neutrons scattered from air, concrete walls, and other objects in the calibration room. The scattered component depends on the source type, room materials and configuration, calibration distance, and also the shape and the material composition of the neutron meters [1]. However, different neutron meters could yield different readings for the same total neutron field. Thus, an appropriate calibration process is necessary before this instrument can be used for radiation protection assessment. In the calibration process, the calibration factor (CF) of the neutron meter is evaluated as one of the important characteristics. The CF is defined as the ratio between the conventional true value of the neutron ambient dose equivalent rate in a free field (denoted as $H^*(10)'_{\mathrm{FF}}$) and the direct component of the neutron ambient dose equivalent rate as measured by the neutron meter (denoted as $H^*(10)'_{\mathrm{dir}}$). $H^*(10)_{\mathrm{FF}}$ can be calculated analytically, and $H^*(10)_{\mathrm{dir}}$ can be obtained by analyzing the readings of the neutron meters.

To obtain the value of $H^*(10)'_{\mathrm{dir}}$, the scattered component must be extracted from the total neutron ambient dose equivalent rate (denoted as $H^*(10)'_{\mathrm{tot}}$). Various methods are available for this purpose, such as the well-known shadow-cone technique and the ISO 8529-2-recommended fit methods. To apply the shadow-cone technique, it is necessary that the geometry of the shadow cone should be amenable to that of the source and the neutron meter. Regarding the fit methods, three methods are recommended including the generalized-fit method (GFM), semiempirical fit method (SEM), and reduced-fitting method (RFM) [2].

In the present work, calibrations were performed for three types of neutron meters, i.e., Aloka TPS-451C (Hitachi), KSAR1U.06 (Baltic Scientific Instruments), and Model 12-4 (Ludlum), in the standard calibration field with a ^{241}Am–Be source at the Institute for Nuclear Science and Technology (Hanoi, Vietnam). The neutron meters were used to measure the values of $H^*(10)'_{\mathrm{tot}}$ at various distances from the source. Give that a suitable shadow cone for the ^{241}Am–Be source and the neutron meters is not available, the GFM, SEM, and RFM fit methods were used to obtain the values of $H^*(10)'_{\mathrm{dir}}$ for the neutron meters. The $H^*(10)'_{\mathrm{dir}}$ values of each meter obtained using the three fit methods were compared to confirm the reliability of these approaches. Once the $H^*(10)'_{\mathrm{dir}}$ values of the meters are available, the CFs can be evaluated. A comparison of the CFs of the neutron meters and the uncertainties among the three methods was also performed. The most suitable fit method for the calibration routine is discussed in this work.

2 Instruments and methods

2.1 Neutron calibration field property

A neutron calibration room was constructed with inner dimensions of $7.0 \times 7.0 \times 7.0$ m^3 [3], and a radionuclide neutron ^{241}Am–Be source of X14-type encapsulation supplied by Hopewell Designs, Inc., USA, was installed in a container at the center of the floor base. The initial source strength was determined at NIST (USA) on January 23, 2015, to have a value of 1.299×10^7 s^{-1} with the expanded uncertainty of 2.9% ($k = 2$). A detailed description of the neutron calibration room and the ^{241}Am–Be source can be found in previous works [3, 4]. The source anisotropy correction factor is 1.030, which was evaluated at a distance of 100 cm from the source and in a direction perpendicular to the cylindrical source axis using the MCNP5 simulation [4]. This anisotropy correction factor is consistent with the values of 1.027–1.030 for similar ^{241}Am–Be sources as reported by other laboratories [5, 6].

2.2 Neutron meters

In the measurements, three portable neutron meters were used as shown in Fig. 1. The Aloka TPS-451C meter that is made by the Hitachi group consists of a cylindrical proportional counter with a length of 15.5 cm and a diameter of 2.5 cm and filled with 5 atm ^{3}He gas at 20 °C. The counter is covered by a cylindrical moderator of high-density polyethylene ($\rho = 0.95$ g/cm^3) with a length of 23.0 cm and a diameter of 21.0 cm. The counter has cylindrical effective dimensions of 7.0 cm in length and 2.4 cm in diameter. The Aloka TPS-451C meter can be used to measure neutrons in the energy range from 25×10^{-9} to 15 MeV with a dose equivalent rate up to 10 mSv/h. In general, the meter is not sensitive to photons [7].

The KSAR1U.06 meter that is made by Baltic Scientific Instruments (BSI) enterprise has three cylindrical ^{3}He proportional counters with a diameter of 3.2 cm and a length of 2.0 cm and is filled with 2.7 atm pressure assembled to form a neutron-sensitive detector and a photon-sensitive Geiger Muller counter. The meter allows for measurement of the ambient dose equivalent rate in the range from 0.28 to 700 µSv/h for neutrons and from 0.14 to 1400 µSv/h for photons. The KSAR1U.06 meter is produced in compliance with IAEA recommendations and requirements [8]. The outer dimensions of the meter are 30 cm × 16 cm × 13 cm [9].

The Model 12-4 meter is made by Ludlum Incorporation and consists of a cylindrical proportional counter ^{3}He with a diameter of 1.6 cm and a length of 2.5 cm surrounded by a 22.9-cm-diameter cadmium-loaded polyethylene sphere. The meter rejects photons up to 100 mSv/h and facilitates the measurement of neutrons from thermal through 7-MeV sources. It provides response up to 12 MeV with a neutron ambient dose equivalent rate up to 100 mSv/h. The meter generates an energy response for an appropriate inverse radiation protection guide curve for neutrons [10].

Aloka – TPS 451C/ Hitachi

KSAR1U.06/ Baltic Scientific Instruments

Model 12-4/ Ludlum

Fig. 1 Neutron dose equivalent rate meters

2.3 Measurements of total neutron ambient dose equivalent rates

In the experiments, the effective points of the neutron meters were placed at the reference point of the neutron field such that the central axis of the Aloka TPS-451C meter was parallel to the base floor and perpendicular to the central beamline at the effective point. The appropriate settings were applied to the other two neutron meters during the measurements. The KSAR1U.06 meter was irradiated from the front side, whereas the Model 12-4 meter was irradiated from the side with the needle analog display facing upward. Then, the values of $H^*(10)'_{\mathrm{tot}}$ were measured using each neutron meter at various distances ranging from 60 to 250 cm away from the source.

In general, the neutron meters based on the ^{3}He gas proportional counters as thermal neutron detectors can detect neutrons by the reaction $^3\mathrm{He}(n, p)^3\mathrm{H}$ ($Q =$ 0.76 MeV) and are not sensitive to photons due to the suitably applied discrimination level [11]. Therefore, the influence of photons on the $H^*(10)'_{\mathrm{tot}}$ readings is negligible. In this work, the low sensitivity to photons of the Aloka TPS-451C and Model 12-4 meters was confirmed by irradiation at the photon ambient dose equivalent rate of the ^{137}Cs OB6 Buchler standard source at 100 µSv/h. The photon sensitivity of the KSAR1U.06 meter was not confirmed because it is integrated with a photon-sensitive Geiger Muller counter. However, the influence of photons to the KSAR1U.06 meter can also be neglected due to its low contribution in the neutron standard field, which is confirmed in a previous work [12].

2.4 Fit methods

To obtain the $H^*(10)'_{\mathrm{dir}}$ for the neutron meter's total reading, the scattered component must be extracted from the $H^*(10)'_{\mathrm{tot}}$ measured by the meter. Three ISO-recommended fit methods, i.e., GFM, SEM, and RFM methods, were used with the assumption that the linearity of the neutron meter is unity. The GFM method describes $H^*(10)'_{\mathrm{tot}}$ as a function of the distance from the source as follows: [2, 13]

$$H^*(10)'_{\mathrm{tot}}(l) = \frac{k}{l^2} \times \left[\frac{1 + \delta \times \left(\frac{r_{\mathrm{d}}}{2l}\right)^2}{1 + \overline{\Sigma}(E) \times l} + A' \times l + s \times l^2\right], \tag{1}$$

where k is the characteristic constant; l is the distance from the center of the source to the device center; A' is the air in-scatter component; s is the factor that accounts for the contribution of all other in-scattered neutrons; r_{d} is the detector radius of the spherical meter or it is considered as half of the minimum dimension for a non-spherical meter; $\delta = 0.5$ is the neutron effectiveness parameter and $\overline{\Sigma}(E) = 890 \times 10^{-7}\ \mathrm{cm}^{-1}$. In Eq. (1), k, A', and s are free parameters obtained during the fitting process.

The SEM method proposed by Eisenhauer et al. [14, 15] was summarized in ISO 8529-2:2001 [2]. The SEM is based on the assumption that the air-scattered component decreases linearly with distance from the source while the room-scattered component is independent of the distance. Therefore, the $H^*(10)'_{\mathrm{tot}}$ can be fitted as a function of the distance from the source center (l) and the detector radius (r_{d}) as follows:

$$H^*(10)'_{\mathrm{tot}}(l) = \frac{k}{l^2} \times \left[1 + \delta \times \left(\frac{r_{\mathrm{d}}}{2l}\right)^2\right] \times (1 + A \times l) \times (1 + R \times l^2), \tag{2}$$

where A is the net air-scatter effect (in-scatter minus out-scatter) which may appear to be similar to the A' factor in Eq. (1); R is the room-scattered component which is similar to the factor s in Eq. (1). The other parameters such as δ, r_D, and k have the same meanings as those in Eq. (1). In the SEM method, k, A, and R are free parameters obtained via a fitting process. It is indicated in Ref. [15] that the SEM is well applied in small- and intermediate-size rooms. It is therefore suggested that the SEM will be useful for the neutron calibration room in this work.

The RFM method is applicable if the measured distance l is greater than or equal to approximately 1.5 times the largest dimension of the meter [16]. Given that in the present work the measurements were taken at distances greater than 60 cm, the RFM method is applicable. Based on this assumption, it is considered that the neutron ambient dose equivalent rate due to the room-scattered component, denoted as R_{sct}, is dominant at most calibration points and is constant in the space of the calibration room. Thus, the $H^*(10)'_{\mathrm{tot}}$ can be rewritten as [2]:

$$H^*(10)'_{\mathrm{tot}}(l) = \frac{k}{l^2} + R_{\mathrm{sct}}. \tag{3}$$

In Eq. (3), the term k/l^2 is an important factor which determines the corresponding direct component $H^*(10)'_{\mathrm{dir}}$ rate at the distance l from the source.

3 Results and discussion

3.1 Conventional true value of $H^*(10)'_{\mathrm{FF}}$

The values of $H^*(10)'_{\mathrm{FF}}(l)$ at the distance l can be theoretically determined by Eq. (4) [2]:

$$H^*(10)'_{\mathrm{FF}}(l) = \frac{B \times F_1(\theta)}{4\pi l^2} \times h_\phi, \tag{4}$$

where B is the neutron source strength; $F_1(\theta)$ is the source anisotropy correction factor which is 1.030 at 1.0 m as reported in a previous work [4]. For the purpose of this work, $H^*(10)'_{\mathrm{FF}}$ at 1.0 m is considered as the conventional true value to determine the CFs of the neutron meters.

3.2 Neutron ambient dose equivalent rates measured by neutron meters

The results of measurements of $H^*(10)'_{\mathrm{tot}}$ using the neutron meters Aloka TPS-451C (Hitachi), KSAR1U.06 (BSI), and Model 12-4 (Ludlum) in the distance range from 60 to 250 cm are shown in Fig. 2. All values of the $H^*(10)'_{\mathrm{tot}}$ were normalized to the same time point. In the measurements, the statistical deviation of the $H^*(10)_{\mathrm{tot}}$ measured using the Aloka TPS-451C meter and KSAR1U.06 meter is estimated within 5%. The value for the Model 12-4 meter is estimated within 10% given that it uses a needle analog display. It is evident from Fig. 2 that the readings of KSAR1U.06 show a higher response than that of the others. This is ascribed to the intrinsic response of the KSAR1U.06 meter.

3.3 Fitting parameters

The $H^*(10)'_{\mathrm{tot}}$ measured by the three neutron meters in the distance range from 60 to 250 cm was fitted according to Eqs. (1)–(3) with the application of the instrumental weighting method in the Levenberg–Marquardt iteration algorithm, in which the weighting factors were set as $1/\sqrt{R_{\mathrm{d}}}$, where R_{d} is the $H^*(10)'_{\mathrm{tot}}$ measured by the neutron meters. As a result of the fitting process, the free parameters corresponding to each of methods are obtained (i.e., k, A' and s in GFM; k, A and R in SEM; k and R_{sct} in RFM) as shown in Table 1. From Table 1, it is evident that the deviations of k obtained from the fit methods are less than 20%, which could contribute to the uncertainty budgets of the CFs.

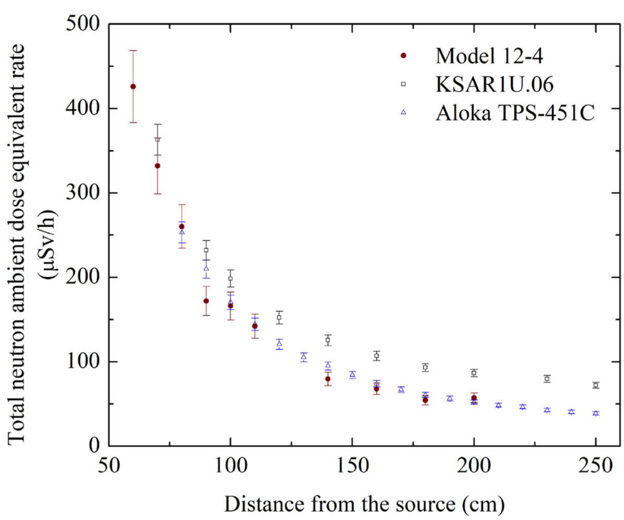

Fig. 2 Total neutron ambient dose equivalent rate measured by the three neutron meters as a function of the distances from the source. The error bars show the statistical error of the measurements

3.4 Calibration factors and uncertainties

From the definition of CF, the equation of $H^*(10)_{\mathrm{FF}}$ [Eq. (4)], and the direct term k/l^2 in the fitting process, the CF can be expressed as:

$$CF = \frac{B \times F_1(\theta)}{4\pi k} \times h_\phi. \tag{5}$$

The standard uncertainty of the CF (denoted as u_{CF}) can be calculated by applying the uncertainty propagation principle. The uncertainty budgets of the CFs due to type A uncertainty of the fitting characteristic constant (u_{k}) and type B uncertainty of the source strength (u_{B}) are summarized and shown in Table 2, together with the u_{CF} values. The CFs of each neutron meter corresponding to the three fit methods are in agreement and close to unity (see Fig. 3), even at different levels of u_{CF} (see Table 2). The averaged CFs of the three neutron meters are 0.99 ± 0.01, 1.00 ± 0.03, and 0.99 ± 0.08, respectively. The largest difference in the CFs due to different fit methods is approximately 4.0% and was obtained with the KSAR1U.06 meter using the GFM and SEM methods. For the other cases, the CF of each meter is consistent within 2.0%. This means that the calibration process is reliable. The CFs satisfy the ISO criteria [2] as a unique property of the neutron measuring device and are independent of the characteristics of the facilities and the calibration techniques. The largest uncertainty of the CFs was determined for the Model 12-4 meter, which can be seen in Table 2. It is also evident that the CF uncertainties due to the RFM fit method are the smallest (in the range from 1.50 to 4.23%) compared to that obtained using the two other methods. This is described as a simple form of the fitting equation [Eq. (3)], where the constant R_{sct} is consistent with the statement of uniform scattered component as noted by Vega-Carrillo et al. [17, 18].

4 Conclusion

Calibrations were performed for three types of neutron ambient dose equivalent rate meters, i.e., Aloka TPS-451C, KSAR1U.06, and Model 12-4, using the GFM, SEM, and RFM fit methods. The direct component of the neutron

Table 1 Fitting parameters of the total neutron ambient dose equivalent rates based on the GFM, SEM, and RFM methods

Method	Fitting parameters	Neutron dose equivalent rate meter		
		Aloka TPS-451C, Hitachi	KSAR1U.06, BSI	Model 12-4, Ludlum
GFM	k	1,535,750 ± 34,790	1,508,230 ± 105,050	1,506,720 ± 277,450
	A' ($\times10^{-4}$)	0.243 ± 2.985	0.000 ± 0.001	9.918 ± 0.004
	s ($\times10^{-6}$)	9.025 ± 0.729	32.631 ± 1.581	0.000 ± 0.144
SEM	k	1,528,160 ± 28,760	1,475,300 ± 98,120	1,516,850 ± 214,160
	A ($\times10^{-4}$)	0.002 ± 3.024	6.211 ± 0.002	7.855 ± 0.003
	R ($\times10^{-6}$)	8.875 ± 1.465	26.912 ± 15.630	0.001 ± 9.009
RFM	k	1,530,730 ± 6130	1,500,560 ± 20,690	1,506,560 ± 60,140
	R_{sct}	13.521 ± 0.195	48.753 ± 0.888	10.500 ± 3.535

Table 2 Standard uncertainty of calibration factor (u_{CF}) and its uncertainty budgets [i.e., type A uncertainty of the characteristic constant (u_k) due to fitting and type B uncertainty of the neutron source strength (u_B)]

Method	Uncertainty budget				u_{CF} (%)		
	u_k (%)			u_B (%)			
	Aloka TPS-451C	KSAR1U.06	Model 12-4	Source strength	Aloka TPS-451C	KSAR1U.06	Model 12-4
GFM	2.27	7.00	18.41	1.45	2.69	7.14	18.47
SEM	1.88	6.65	14.12	1.45	2.38	6.81	14.19
RFM	0.40	1.38	3.99	1.45	1.50	2.00	4.23

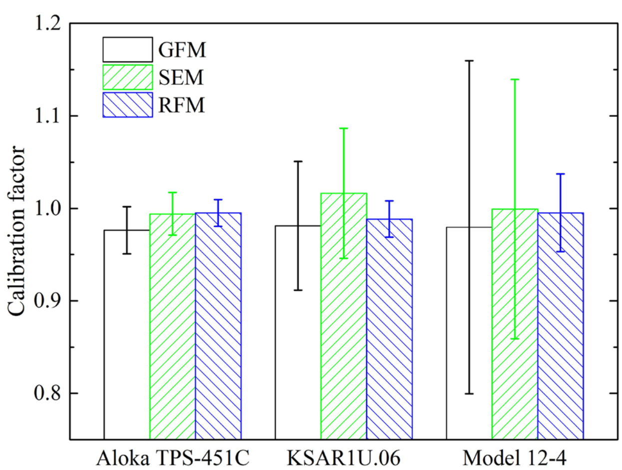

Fig. 3 Calibration factors and their standard uncertainties of the neutron ambient dose equivalent rate meters obtained for the three fit methods

ambient dose equivalent rate, $H^{*}(10)'_{dir}$, obtained using the three meters were analyzed in addition to the conventional true values of the free field, $H^{*}(10)'_{FF}$, to evaluate the CFs of the meters. The results show that the CFs of the three neutron meters obtained based on the three methods are close to unity with a deviation of less than 4%. The average values of the CFs of the meters are 0.99 ± 0.01, 1.00 ± 0.03, and 0.99 ± 0.08, respectively. The standard uncertainties of the CFs obtained via the different methods are in the range from 1.50 to 18.47% depending on the neutron meter and fit method that was utilized. By comparing the three fit methods, it was determined that the uncertainty obtained with the RFM method is the smallest (less than 4.23%). This means that this method is the most suitable for routine calibration.

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