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Calibration of a neutron dose rate meter in various neutron standard fields

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Abstract This paper presents the calibration of a neutron dose rate meter and the evaluation of its calibration factors (CFs) in several neutron standard fields (i.e., two standard fields with bare sources of ^{252}Cf and ^{241}Am−Be, and five simulated workplace fields with ^{241}Am−Be moderated sources). The calibration in standard fields with bare sources was conducted by following the recommendations of the ISO 8529 standard. The measured total neutron ambient dose equivalent rates, denoted as $\dot{H}^*(10)_{\text{tot}}$, were analyzed to obtain direct components, denoted as $\dot{H}^*(10)_{\text{dir}}$, using a reduced fitting method. The CF was then calculated as the ratio between the conventional true value of the neutron ambient dose equivalent rate in a free field, denoted as $\dot{H}^*(10)_{\text{FF}}$, and the value of $\dot{H}^*(10)_{\text{dir}}$. In contrast, in the simulated workplace neutron fields, the calibration of the neutron dose rate meter was conducted by following the ISO 12789 standard. The CF was calculated as the ratio between the values of $\dot{H}^*(10)_{\text{tot}}$ measured by a standard instrument (i.e., Bonner sphere spectrometer) and the neutron dose rate meter. The CF values were obtained in the range of 0.88–1.0. The standard uncertainties ($k = 1$) of the CFs were determined to be in the range of approximately 6.6–13.1%.

Keywords Neutron standard fields · Neutron dose rate meter · Calibration factor · ^{252}Cf source · ^{241}Am−Be source

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1 Introduction

Recently, several neutron standard fields have been developed at the Radiation Protection Laboratory of the Institute for Nuclear Science and Technology (Hanoi, Vietnam), including a (1) neutron calibration field for a bare ^{252}Cf source [1], (2) neutron calibration field for a bare ^{241}Am−Be source [2], and (3) simulated workplace neutron fields for ^{241}Am−Be sources moderated by polyethylene (PE) spheres [3]. Thorough characterizations of the neutron calibration fields have been conducted in previous works [1–3]. In particular, the neutron field of a bare ^{252}Cf source has been characterized using a shadow cone technique and Monte Carlo simulations [1]. A Bonner sphere spectrometer (BSS) system has also been used to characterize the neutron field of a bare ^{241}Am$-$Be source and simulated workplace neutron fields [2, 3]. The neutron sources used in workplaces are typically surrounded by various media affecting fluence spectra, which can extend across a wider energy range (e.g., 10^{-9} to 20 MeV) compared to that of a standard field. The neutron ambient dose equivalent rates measured by neutron dosimeters are heavily dependent on incident neutron spectra. Therefore, the calibration of the neutron measuring devices used in workplaces with ISO 8529 neutron standard fields is not sufficiently accurate. Based on the continuous spectra of neutrons, it is challenging to measure the neutron doses precisely. For simplification, a continuous neutron fluence spectrum can be considered as an averaged mono-energy reading (i.e., ambient dose equivalent spectrum-averaged neutron energy). Therefore, it is beneficial to develop neutron fields with a wide range of average energies. For this purpose, the PE spheres can be used to moderate ^{241}Am$-$Be sources and create thermalized neutron fields. As a result, seven neutron standard fields with ambient dose equivalent spectrum-averaged energies in the range of 2.3–4.4 MeV have been developed for calibration purposes.

The calibration of neutron dose rate meters in different neutron standard fields is necessary for evaluating the accuracy of meters used in various workplaces with dosimetric characteristics equivalent to the developed neutron fields. The calibrations of neutron measurement devices have been conducted in various laboratories. The calibrations of Bonner sphere extension (BSE) spectrometer systems have been conducted with various monoenergetic neutrons at Physikalisch-Technische Bundesanstalt, Germany, to verify the operation of BSE systems [4]. The calibrations of three different neutron survey meters were conducted in different neutron standard fields, which were then used to determine the neutron ambient dose equivalent rates in a 15 MeV X-ray medical linear accelerator [5]. The calibration of neutron personal dosimeters was conducted in a realistically simulated neutron irradiation room at the Korean Research Institute of Standards and Science to convert neutron fluence into personal dose equivalent conversion coefficients. The results suggested that the effects of scattered neutrons on personal dose equivalents are non-negligible and should be investigated prior to performing routine work [6].

In general, the readings of a neutron dose rate meter consist of two components: (1) the direct component of neutrons traveling directly into the meter and (2) the scattered component of neutrons impinging onto the meter following the interactions with surrounding air, walls, and other objects. The calibration of neutron dose rate meters in neutron standard fields with bare sources is typically conducted based on the recommendations of the ISO 8529 standard [7–9]. During the calibration process, a neutron meter is used to measure the total neutron ambient dose equivalent rate, denoted as $\dot{H}^{*}(10)_{\mathrm{tot}}$, at various distances from a source. Next, the direct component, denoted as $\dot{H}^{*}(10)_{\mathrm{dir}}$, can be extracted from the total responses using the fitting methods recommended in the ISO 8529 standard [7, 8]. The calibration factor (CF) of a neutron meter in a neutron field is defined as the ratio between the neutron ambient dose equivalent rate in a free field, denoted as $\dot{H}^{*}(10)_{\mathrm{FF}}$, and $\dot{H}^{*}(10)_{\mathrm{dir}}$. In previous work, three fitting methods have been applied to extract the direct component $\dot{H}^{*}(10)_{\mathrm{dir}}$ from the total responses of $\dot{H}^{*}(10)_{\mathrm{tot}}$ in the ^{241}Am$-$Be standard field: the general fitting method, semi-empirical fitting method, and reduced fitting method (RFM) [9]. It was determined that the uncertainty in the results of the RFM method is smaller than that in the results of the other methods [9]. Thus, the RFM method was adopted in this work. It should also be noted that the RFM method is applicable at a measurement distance l greater than the largest dimension of the meter by a factor of 1.5 [10]. However, because the neutron spectra at workplaces differ from those in the standard fields with bare sources, the calibration of neutron meters in simulated workplace neutron fields should be conducted by following the recommendations of the ISO 12789 standard [11, 12]. According to this standard the values of $\dot{H}^{*}(10)_{\mathrm{tot}}$ measured by a neutron meter should be compared directly to those characterized by a standard instrument (i.e., BSS) to obtain CFs.

In this study, the calibration of a neutron dose rate meter (i.e., Aloka TPS-451C model) supplied by the Hitachi corporation was conducted in various neutron standard fields, including two standard fields with bare sources of ^{252}Cf and ^{241}Am$-$Be, and five simulated workplace neutron fields generated by a ^{241}Am$-$Be source moderated by the PE spheres. The CFs of the neutron meter in the neutron standard fields were evaluated with standard uncertainties.

2 Instruments and methods

2.1 Neutron dose rate meter

The Aloka TPS-451C neutron dose rate meter supplied by the Hitachi corporation consists of a cylindrical proportional counter with a length of 15.5 cm and diameter of 2.5 cm [13]. The effective dimensions of the counter are 7.0 cm in length and 2.4 cm in diameter. The counter is filled with 5 atm ^{3}He gas at 20 °C and covered by a cylindrical moderator made of high-density PE ($\rho = 0.95 g/cm^3$). The dimensions of the cylindrical moderator are 23.0 cm in length and 21.0 cm in diameter. This meter can measure neutrons in a wide energy range from 25×10^{-9} to 15 MeV with a dose equivalent rate as high as 10 mSv/h [13]. In our experimental setup, the effective point of the meter was positioned such that the central axis of the meter was parallel to the base floor and perpendicular to the central beam line [9]. The low sensitivity of the Aloka TPS-451C meter to photons was confirmed by irradiating the photon ambient dose equivalent rate of the ^{137}Cs OB6 Buchlor standard source at 100 µSv/h. Moreover, the contribution of photons in the ^{241}Am−Be field was evaluated to be in the range of approximately 2.3–3.3%, which can be neglected [14].

2.2 Neutron standard fields

The calibration room has inner dimensions of 700 cm × 700 cm × 700 cm [1, 2]. Figure 1 presents the arrangement of the neutron source and detector in the calibration room. In this work, two radionuclide neutron sources (i.e., a spontaneous fission neutron source of ^{252}Cf and an (α, n) reaction-based neutron source of ^{241}Am−Be) were used to conduct calibrations of the neutron meter following the ISO 8529 standard [7, 8].

The ^{252}Cf neutron source supplied by Frontier Technology Corporation, Xenia, Ohio, USA, had an initial strength of $1.1 \times 10^7 s^{-1}$ on August 29, 2003, with a standard uncertainty of 10% ($k = 1$), as indicated by the supplier's certificate. This source is encapsulated by a cylindrical 304L stainless steel layer with a length of 1.194 cm and outer diameter of 0.552 cm. The characterization of the neutron standard field with the ^{252}Cf source was conducted using the MCNP5 Monte Carlo simulation code [1]. The anisotropy correction factor of the ^{252}Cf source was calculated to be 1.013. The discrepancy between the $\dot{H}^*(10)_{dir}$ value simulated using MCNP5 code and that obtained from the Aloka TPS-451C neutron dose rate meter was approximately 10% [1].

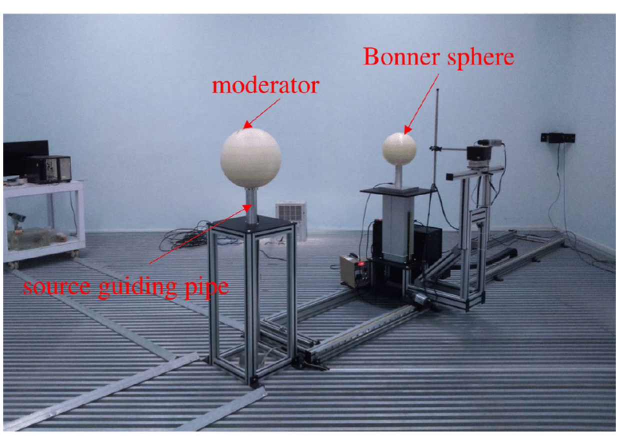

Fig. 1 (Color online) Calibration room with a ^{241}Am−Be source moderated by the PE spheres

The ^{241}Am−Be source with X14-type encapsulation supplied by Hopewell Designs, Inc., USA, was installed in a container in the center of the floor. The source strength on January 23, 2015, was $1.299 \times 10^7 s^{-1}$ with an expanded uncertainty of 2.9% ($k = 2$). The characterization of the neutron standard field with a ^{241}Am−Be source was presented in a previous work [2]. The anisotropy correction factor of the ^{241}Am−Be source was calculated to be 1.030 [2]. This value is consistent with those reported in other works for the same source type (1.027–1.030) [15, 16]. Additionally, the components of the neutron fluxes are in close agreement with a discrepancy of approximately 2%. The discrepancies in the $\dot{H}^*(10)_{dir}$ values obtained using different methods are within 3% [2].

To generate neutron fields with spectra similar to those found in various workplaces, high-density PE spheres were used to moderate the ^{241}Am−Be source. The simulated workplace neutron fields were then characterized using a BSS system. MAXED and FRUIT codes were used for unfolding the total neutron fluence rate spectra [3]. The BSS system consists of a thermal neutron sensitive detector (^{6}LiI(Eu), model 42-5) and a set of six PE spheres with diameters of 2, 3, 5, 8, 10, and 12 inches. The cylindrical ^{6}LiI(Eu) detector containing 96% ^{6}Li has a height of 0.4 cm and diameter of 0.4 cm. The configuration of the system facilitates the detection of neutrons from thermal energy up to 20 MeV. The energy response functions of the BSS system were taken from the IAEA compendium [17]. In our experiments, the BSS and source were installed half diagonally to the room's central plane and parallel to the floor. The MAXED code is based on the maximum entropy principle in the inverse problem of spectrum unfolding [18]. The iterative algorithm for the MAXED code requires an initial estimated spectrum, which can be derived from MCNP5 simulations. The number of energy bins used in the MAXED code is 47, as recommended by the ICRP 74 standard for unfolding neutron spectra in the energy range from 10^{-9} to 20 MeV [19]. Using this code, dosimetric parameters for the fields can be obtained and applied to the calibration process, including fluence spectrum-averaged neutron energy ($\bar{E}$), ambient dose equivalent spectrum-averaged neutron energy ($\widetilde{E}$), and neutron ambient dose equivalent rates. The FRUIT code is based on an iterative Monte Carlo method that varies parameters to derive a final spectrum [20]. The unfolding process using FRUIT was also performed with 47 energy bins to verify the results obtained using MAXED. When comparing the neutron fluence rate spectra obtained from the two codes, good agreement was observed. The discrepancies in the integral neutron fluence rates were less than 12% at all measured distances, which is less than the standard uncertainty of 20% recommended by the ISO 12789-1 standard [11]. The discrepancies of the $\dot{H}^*(10)$ rates are within 6% [3].

Figure 2 presents the neutron fluence rate spectra (total and direct components) at a distance of 150 cm from the sources in the neutron standard fields with bare ^{252}Cf and ^{241}Am–Be sources [1, 2]. The total components of the neutron fluence rate spectra at a distance of 150 cm from the PE-moderated ^{241}Am–Be sources in the simulated workplace neutron standard fields are presented in Fig. 3. The measurement were conducted at various distances (60–250 cm) from the sources. In this work, calibration at a distance of 150 cm is reported. This is a typical distance for calibrating neutron meters in neutron fields. For the ^{252}Cf field, the total and scattered components of the neutron fluence rate spectra can be obtained via Monte Carlo simulations. The direct component can be obtained by subtracting the scattered component from the total component. For the ^{241}Am–Be field, direct neutron fluence rate spectra were obtained as follows. The total count rates generated by the total components of the neutron fields were measured at various distances using the BSS system. The total count rates were then fitted using the RFM to determine the direct count rates. The unfolding process for the direct count rates at specific distances was performed using the MAXED code to obtain the direct components of the neutron fluence rate spectra. More detailed information regarding the neutron fluence rate spectra and field dosimetric parameter characterization can be found in Refs. [1–3, 7, 11].

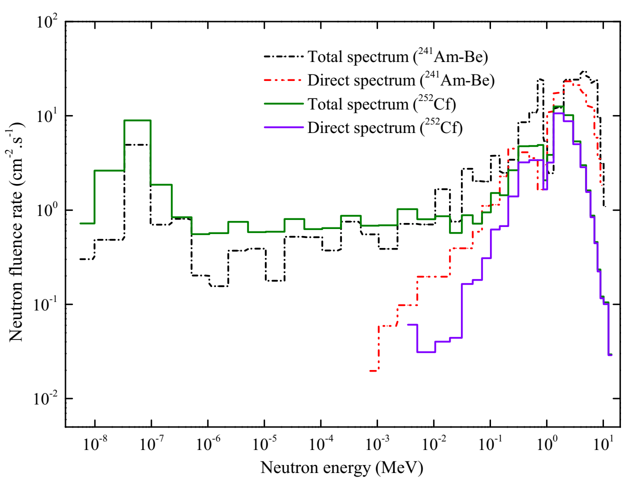

Fig. 2 (Color online) Neutron fluence rate spectra at a distance of 150 cm from the sources in the ^{252}Cf and ^{241}Am–Be standard fields

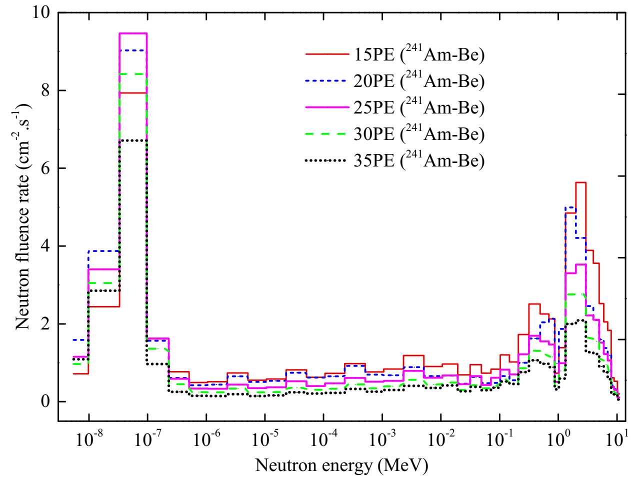

Fig. 3 (Color online) Neutron fluence rate spectra at a distance of 150 cm from the PE-moderated sources in the simulated workplace neutron fields

Table 1 lists the dosimetric parameters of the seven neutron standard fields at a distance of 150 cm from the sources. The direct components of the neutron ambient dose equivalent rates derived from the bare ^{252}Cf and ^{241}Am–Be sources were used for the calibration of the neutron dose rate meters according to the ISO 8529 standard recommendations [8]. The total components of the neutron ambient dose equivalent rates obtained from the simulated workplace neutron standard fields with the PE-moderated ^{241}Am–Be sources were used for the calibration of the neutron dose rate meters according to the ISO 12789 standard recommendations [11].

2.3 Calibration process

To calibrate a neutron dose rate meter in the neutron standard fields with ^{252}Cf and ^{241}Am–Be sources by following the ISO 8529 standard, the direct components of $\dot{H}^*(10)_{\mathrm{dir}}$ were extracted from the $\dot{H}^*(10)_{\mathrm{tot}}$ values measured by the neutron meter using the RFM. In the RFM, $\dot{H}^*(10)_{\mathrm{tot}}$ is described as a function of the distance from the source according to Eq. (1) [8, 9].

$$\dot{H}^*(10)_{\mathrm{tot}}(l) = \frac{k}{l^2} + R_{\mathrm{sct}}, \tag{1}$$

where k/l^2 determines the direct component $\dot{H}^*(10)_{\mathrm{dir}}$ at a distance l from the source. R_{sct} is the neutron ambient dose equivalent rate caused by the room-scattered component, which is constant within the space of the calibration room [1, 21, 22]. The calculations of the conventional true values of $\dot{H}^*(10)_{\mathrm{FF}}$ for the neutron standard fields recommended by the ISO 8529 standard can be found in a previous work [9].

Table 1 Dosimetric parameters of neutron standard fields at a distance of 150 cm from the sources

Neutron standard field	Distance (cm)	$\overline{E}$ (MeV)	$\widetilde{E}$ (MeV)	$\varphi_{(E)}$ [b] ($cm^{-2}\,s^{-1}$)	$\dot{H}^*(10)$ [b] (μSv/h)	h_ϕ (pSv cm^2)
^{252}Cf	150	2.13	2.30	0.7	0.9	385
$^{241}Am-Be$	150	4.16	4.40	45.9	64.5	391
15PE ($^{241}Am-Be$)[a]	150	1.57	2.97	68.3	53.2	225
20PE ($^{241}Am-Be$)	150	1.27	2.59	57.3	41.5	203
25PE ($^{241}Am-Be$)	150	1.26	2.95	53.9	33.5	190
30PE ($^{241}Am-Be$)	150	1.27	2.90	41.0	26.8	185
35PE ($^{241}Am-Be$)	150	1.25	3.04	33.5	20.3	180

$\overline{E}$, fluence spectrum-averaged neutron energy. $\widetilde{E}$, ambient dose equivalent spectrum-averaged neutron energy

[a] $^{241}Am-Be$ source moderated by a PE sphere with a diameter of 15 cm

[b] Data normalized relative to October 1, 2019. $\varphi_{(E)}$, integral neutron fluence rate over neutron spectrum. h_ϕ, neutron fluence-to-ambient dose equivalent conversion coefficient

Conversely, to calibrate the neutron meter in the simulated workplace neutron standard fields with a $^{241}Am-Be$ source moderated by the PE spheres, the values of $\dot{H}^*(10)_{tot}$ measured by the neutron meter, denoted as $\dot{H}^*(10)_{meter}$, were directly compared to the conventional true values of $\dot{H}^*(10)_{tot}$ measured by the BSS system, denoted as $\dot{H}^*(10)_{std}$, to obtain CFs. The conventional true values, $\dot{H}^*(10)_{std}$, measured by the BSS are presented in Fig. 4 [3].

3 CFs and uncertainties

Because the CF of the neutron dose rate meter in the ISO 8529 neutron standard fields, denoted as CF_1, is defined as the ratio of the conventional true value of the neutron ambient dose equivalent rate in a free field to the direct component obtained from the RFM process, it is expressed as follows [9]:

$$CF_1 = \frac{B \times F_1(\theta)}{4\pi k} \times h_\phi, \quad (2)$$

where the neutron source strength, B, is normalized relatively to October 1, 2019. $F_1(\theta)$ is the anisotropic correction factor of the neutron source. k is the characteristic constant obtained from the RFM process. h_Φ is the neutron fluence rate-to-neutron ambient dose equivalent rate conversion coefficient. Our experimental results demonstrate that the CF_1 values of the neutron dose rate meter in the neutron standard fields with ^{252}Cf and $^{241}Am-Be$ sources are 0.99 and 1.00, respectively, as shown in Fig. 5. These results indicate that the Aloka TPS-451C neutron dose rate

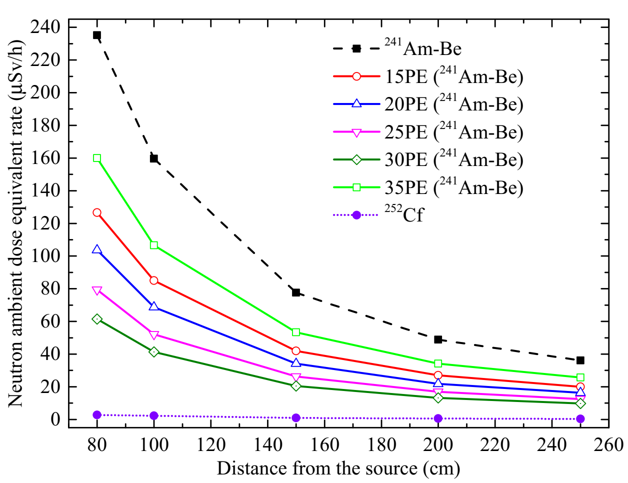

Fig. 4 (Color online) Total neutron ambient dose equivalent rates as functions of the distance from the sources in various neutron standard fields

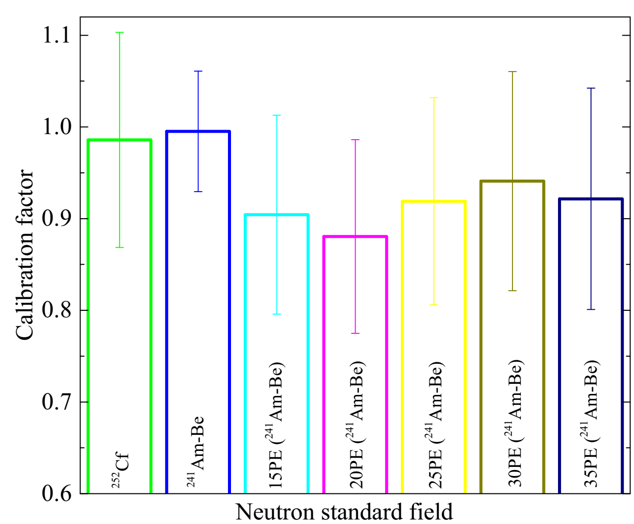

Fig. 5 (Color online) CFs for the neutron meter in various neutron standard fields. The calibrations were conducted at a distance of 150 cm from the sources

meter is well suited to the measurement of the neutron ambient dose equivalent rates in the ISO 8529 neutron standard fields with bare sources.

The standard uncertainty of CF_1 is denoted as u_{CF_1} and evaluated by applying the uncertainty propagation principle and guidance of uncertainty expression for influenced uncertainty budgets [23]. Table 2 lists the u_{CF_1} values and detailed uncertainty budgets for the ISO 8529 neutron standard fields. The standard uncertainty of the neutron source strength B is stated in each source's certificate and the values are 10% and 1.5% for the ^{252}Cf and ^{241}Am$-$Be sources, respectively. The value of $F_1(\theta)$ was estimated via Monte Carlo simulations in previous studies with low statistical uncertainty, meaning the uncertainty related to this parameter can be neglected [1, 2]. The standard uncertainty of the characteristic constant, k, is within 5% according to the results of the RFM process when considering the deviations of the neutron dose rate meter readings of approximately 5% and uncertainty at the distance l of approximately 1%. The standard uncertainty of h_Φ is known to be within 4% according to the ICRP74 standard [19]. Consequently, the values of u_{CF_1} (with a coverage factor $k = 1$) are 11.9% and 6.6% for the standard fields with bare ^{252}Cf and ^{241}Am$-$Be sources, respectively.

In the ISO 12789 simulated workplace neutron standard fields with a ^{241}Am$-$Be source moderated by the PE spheres, the CF of the neutron dose rate meter, denoted as CF_2, was calculated as the ratio of the total neutron ambient dose equivalent rate measured by the standard BSS system, denoted as $\dot{H}^*(10)_{std}$, to that measured by the neutron dose rate meter, denoted $\dot{H}^*(10)_{meter}$. The $\dot{H}^*(10)_{meter}$ value was obtained from the initial measurement, H_2, of the total neutron ambient dose equivalent rate by multiplying the measured value by the influence correction factors, including the angular dependence (f_{ang}), linearity of the neutron dose rate meter (f_{lin}), and uncertainty of the distance measurement (f_{dist}). Therefore, CF_2 can be expressed as follows:

$$CF_2 = \frac{\dot{H}^*(10)_{std}}{\dot{H}^*(10)_{meter}} = \frac{\dot{H}^*(10)_{std}}{H_2 \times f_{ang} \times f_{lin} \times f_{dist}}. \quad (3)$$

Table 2 Standard uncertainties (u_{CF_1}, $k = 1$) and uncertainty budgets for the CF_1 of the neutron dose rate meter in the neutron standard fields with bare ^{252}Cf and ^{241}Am$-$Be sources

ISO 8519 neutron standard field	Uncertainty budget (%)			u_{CF_1} (%)
	B	k	h_Φ	
^{252}Cf	10	5.0	4.0	11.9
^{241}Am$-$Be	1.5	5.0	4.0	6.6

In Eq. (3), the values of $\dot{H}^*(10)_{std}$ were taken from a previous work [3] and reproduced in Fig. 4. The CF_2 values of the neutron dose rate meter in the simulated workplace neutron standard fields were calculated to be within the range of 0.88–0.94, as shown in Fig. 5. Specifically, the CF_2 values for the fields corresponding to the PE sphere diameters of 15, 20, 25, 30, and 35 cm are 0.90, 0.88, 0.92, 0.94, and 0.92, respectively. These results imply that the neutron meter overestimates the neutron dose equivalent rates by approximately 6–12% in the ISO 12789 simulated workplace neutron standard fields. This accuracy is acceptable for the purpose of radiation safety assessment, particularly in fields with neutron ambient dose equivalent-averaged energies in the range of 2.3–4.4 MeV [1–3, 8].

The standard uncertainty of CF_2, denoted as u_{CF_2}, was also evaluated by applying the uncertainty propagation principle and guidance of uncertainty expression based on influenced uncertainty budgets [23]. Notably, the standard uncertainty of $\dot{H}^*(10)_{std}$ was estimated to be within 10% based on the characterizations of the simulated workplace neutron fields [3]. The standard uncertainty of H_2 was observed to be within 5% during our measurements. The standard uncertainty caused by angular dependence was estimated to be approximately 5% based on the published data in Ref. [24]. The standard uncertainty caused by the linearity of the neutron dose rate meter was estimated to be approximately 3%. (This value was verified by comparing the direct components of the neutron ambient dose equivalent rates obtained using the shadow cone method when varying the distance between the neutron dose rate meter and ^{251}Cf source [1].) The standard uncertainty of the distance was estimated to be approximately 1%. Consequently, the values of u_{CF_2} were calculated to be in the range of 12.0–13.1% with a coverage factor of $k = 1$. Table 3 lists the details of the standard uncertainties and uncertainty budgets of CF_2.

4 Conclusion

The calibration of an Aloka TPS-451C neutron meter was conducted in various neutron standard fields with bare ^{252}Cf and ^{241}Am$-$Be sources and simulated workplace neutron fields with moderated sources according to the international criteria recommended in the ISO 8529 and ISO 12789 standards. The results revealed that the CFs of the neutron meter in the neutron standard fields were within a range of 0.88–1.0. In particular, for the standard fields with bare ^{252}Cf and ^{241}Am$-$Be sources, the CFs were 0.99 and 1.0, respectively, indicating that the meter performs well in the fields generated by bare sources. In the simulated workplace neutron fields with moderated sources, the

Table 3 Standard uncertainties (u_{CF_2}, $k = 1$) and uncertainty budgets of the CF_2 of the neutron dose rate meter in the simulated workplace neutron fields with ^{241}Am−Be sources moderated by the PE spheres

ISO 12789 neutron standard field	Uncertainty budget (%)					u_{CF_2}(%)
	$\dot{H}^*(10)_{std}$	H_2	f_{ang}	f_{lin}	f_{dist}	
15PE (^{241}Am−Be)*	10	3.0	5.0	3.0	1.0	12.0
20PE (^{241}Am−Be)	10	3.0	5.0	3.0	1.0	12.0
25PE (^{241}Am−Be)	10	4.0	5.0	3.0	1.0	12.3
30PE (^{241}Am−Be)	10	5.0	5.0	3.0	1.0	12.7
35PE (^{241}Am−Be)	10	6.0	5.0	3.0	1.0	13.1

*, ^{241}Am−Be source moderated by a 15-cm-diameter PE sphere

CFs were calculated to be in the range of 0.88–0.94. These results indicate that the neutron meter overestimates the neutron ambient dose equivalent rates by approximately 6–12%. This accuracy is acceptable for the assessment of radiation safety. Further, the uncertainties and uncertainty budgets of the CFs were evaluated, and the standard uncertainties of the CFs were in the range of 6.6–13.1% ($k = 1$).

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