Technical Note

A REVIEW OF NEUTRON SCATTERING CORRECTION FOR THE CALIBRATION OF NEUTRON SURVEY METERS USING THE SHADOW CONE METHOD

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ABSTRACT

The calibration methods of neutron-measuring devices such as the neutron survey meter have advantages and disadvantages. To compare the calibration factors obtained by the shadow cone method and semi-empirical method, 10 neutron survey meters of five different types were used in this study. This experiment was performed at the Korea Atomic Energy Research Institute (KAERI; Daejeon, South Korea), and the calibration neutron fields were constructed using a $^{252}$Californium ($^{252}$Cf) neutron source, which was positioned in the center of the neutron irradiation room. The neutron spectra of the calibration neutron fields were measured by a europium-activated lithium iodide scintillator in combination with KAERI's Bonner sphere system. When the shadow cone method was used, 10 single moderator-based survey meters exhibited a smaller calibration factor by as much as 3.1–9.3% than that of the semi-empirical method. This finding indicates that neutron survey meters underestimated the scattered neutrons and attenuated neutrons (i.e., the total scatter corrections). This underestimation of the calibration factor was attributed to the fact that single moderator-based survey meters have an under-ambient dose equivalent response in the thermal or thermal-dominant neutron field. As a result, when the shadow cone method is used for a single moderator-based survey meter, an additional correction and the International Organization for Standardization standard 8529-2 for room-scattered neutrons should be considered.

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1. Introduction

The calibration factor or dose equivalent response of a neutron-measuring device (e.g., a neutron survey meter) is a unique property of the type of device, and may depend on the ambient dose equivalent rate, the neutron source spectrum, or the angle of incidence of the neutrons; however, it should not be a function of the characteristics of the calibration facility or the experimental techniques employed. All calibrations should refer to the free field (i.e., with no contribution
from neutrons scattered by the air and room) and the influence of scattered neutrons on the reading of the device should be corrected [1,2]. However, most laboratories engaged in routine calibration generally perform the calibration measurement in a calibration room, not in a free-field space. When neutron survey meters are calibrated with a radionuclide neutron source in a calibration room, the reading should be corrected for all extraneous neutron scattering effects because the neutron survey meter responds to the scattered neutrons and the direct neutrons from the neutron source. The neutron survey meter is placed in a neutron calibration field of a known free-field fluence rate, and the instrument reading is recorded. The reading should be corrected for all extraneous neutron scattering effects such as neutron scattering by the air, walls, floor, and ceiling of the calibration room. In general, the scattering of neutrons may occur by the following scattering effects: neutrons scattered by the floor and walls of the laboratory room (i.e., room scatter); neutrons attenuated by nuclear reactions with the air (i.e., air outscatter); neutrons scattered by the air from outside the direct source-to-detector path (i.e., air inscatter); and neutrons scattered from support structures.

The International Organization for Standardization (ISO) recommends three different approaches to quantify the scattering of neutrons. The 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 the neutron source and the detector. However, these measurements need not be repeated each time an identical device is calibrated [3,4]. In general, the calibration factors obtained from different methods have similar values. However, we found that the calibration factors obtained by the two methods have different values. In this study, the calibration factors of several neutron survey meters were obtained by the shadow cone method and semi-empirical method.

2. Neutron scatter correction for the calibration methods for a neutron survey meter

The accuracy of the shadow cone method depends strongly on the design of the shadow cone and on its position relative to the source detector geometry. If \( M_0(l) \) and \( M_1(l) \) are the detector readings measured with a shadow cone (which is placed between the source and the detector) and without a shadow cone, then Eq. (1) holds [3,4]:

\[
F_A(l) \cdot [M_1(l) - M_0(l)] = F_A(l) \cdot M_1(l) \cdot \left[ 1 - \frac{M_0(l)}{M_1(l)} \right] = R \cdot \phi, \quad \phi = \frac{B \cdot F(\theta)}{4\pi l^2}
\]

in which \( l \) is the distance from the center of the source [a \(^{252}\)Californium \(^{252}\)Cf] source was used in this study] to the point of the test, and \( F_A(l) \) is the measured reading corrected for all extraneous effects and appropriate air attenuation (i.e., air outscatter) factor [5,6]. The variable \( R \) is the free-field fluence response and \( \phi \) is the free-field fluence rate. The value \( B \) is the neutron source strength (i.e., the total neutron-emission rate into 4\( \pi \) sr) and \( F(\theta) \) is the anisotropy function of the radionuclide neutron source [4,7]. The variable \( M_0(l) \) is the survey meter’s reading resulting from the total radiation field (i.e., the source neutrons plus the scattered neutrons) and \( M_1(l) \) is the scattered neutrons. Hence, the value of \( M_1(l) - M_0(l) \) is the source neutrons. A schematic diagram illustrating the arrangement and structure of the shadow cone used in the present study is shown in Fig. 1. It consists of two parts: the front end, which is 20 cm long and composed entirely of stainless steel, and the rear section, which is 30 cm long and composed of borated polyethylene. In the present study, all neutron survey meters were positioned 100 cm from the center of the neutron source.

The semi-empirical method is based on the assumption that a fraction of the instrument’s reading resulting from scattered neutrons can be deduced from a deviation of the reading from the inverse-square law [1,2,7]. The various contributions are characterized by a component that is independent of \( l \) because of room-return neutrons and by a component that decreases linearly with the separation.

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**Fig. 1** – The schematic diagram illustrates the arrangement of neutron source (1), shadow cone (2), and neutron-measuring device (3). The shadow cone consists of two parts: a front end, which is 20 cm long and composed entirely of stainless steel (Fe), and a rear section, which is 30 cm long and composed of borated polyethylene (\( \text{CH}_2 + \text{B} \)). The shadow is placed 5 cm from the center of the \(^{252}\)Californium \(^{252}\)Cf neutron source.
distance because of air-scattering. The instrument reading, \( M_{T}(l) \), a function of distance due to the total radiation field (i.e., source neutrons plus scattered neutrons), is related to the fluence response \( R_{\phi} \) as expressed in Eq. (2):

\[
\frac{M_{T}(l)}{\phi} = R_{\phi}(1 + S l^2), \quad \phi = \frac{B \cdot F(\theta)}{4\pi l^2} \tag{2}
\]

in which the room scatter correction is given by \((1 + S l^2)\) and quantity \( S \) is the fractional room scatter contribution at the unit calibration distance. The total air-scatter correction factor \( F_{A}(l) \) is given by \((1 + A l)\), and the value of \( A \) is recommended by ISO standard 8529-2 [4]. The variable \( F_{I}(l) \) is the geometry correction factor and this contribution is negligible \((\approx 1)\). A plot of the left side of Eq. (2) versus \( l^2 \) should yield a straight line. From a weighted linear least-squares fit to the data, the intercept will be the fluence response \( R_{\phi} \) and the slope of the line will give the fractional room-scattered component, \( S \). Once the value of \( S \) has been determined for a particular device, the calibration of similar devices may be obtained from a linear fitting (Eq. (2)).

The neutron spectra of the calibration neutron fields were measured at 100 cm from the \(^{252}\)Cf neutron source. The measured data (i.e., the count rate vs. the diameter of the Bonner spheres) using the Korea Atomic Energy Research Institute’s Bonner sphere system. These data were measured with and without the shadow cone. The count rate (Fig. 2) obtained from the Bonner sphere system was inputted into the “few channel” unfolding program MXD_FC31 (version 3.1; Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany; a modification of the computer code MAXED [9,10], which uses the maximum entropy method for the deconvolution of the multisphere neutron spectrometer data. The Monte Carlo code MCNPX (version 2.5.0) was used to derive the a priori information for the unfolding process (Los Alamos National Laboratory, Los Alamos, NM, USA). The neutron fluence and ambient dose equivalent rate spectra of the calibration neutron fields are shown in Figs. 3A and 3B, respectively. The spectral characteristics (i.e., the neutron fluence and the percentage of the total neutron fluence rate) and the dosimetric characteristics (i.e., the ambient dose equivalent rates and the percentage of the total ambient dose equivalent rate) of the two calibration neutron fields (i.e., with and without the shadow cone) obtained by an unfolding process for neutron energy ranges of < 1 eV, 1 eV–100 keV, and > 10 MeV are summarized in Tables 1 and 2, respectively. The dosimetric values of the two spectra were obtained using the fluence-to-ambient dose equivalent conversion coefficients \( h^{*}(10) \) of International Commission on Radiation Units and Measurements (ICRU) Report 57 (ICRU-57) [11].

3. Quantification of the calibration neutron fields

The calibration neutron fields for the neutron survey meters were constructed at the Korea Atomic Energy Research Institute (KAERI; Daejeon, South Korea). The neutron calibration room of KAERI has the dimensions of 8 m\(^3\) (length) \times 6 m\(^3\) (width) \times 6 m\(^3\) (height). The \(^{252}\)Cf neutron source (i.e., the point source) was positioned in the center of the neutron irradiation room. The neutron spectra of the calibration neutron fields were measured by a europium-activated lithium iodide [LiI(Eu)] scintillator in combination with KAERI’s Bonner sphere system [8], which consists of six spheres of different diameters that range 5.08–30.5 cm. The count rate (Fig. 2) acquired from the Bonner sphere system was inputted into the “few channel” unfolding program MXD_FC31 (version 3.1; Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany; a modification of the computer code MAXED [9,10], which uses the maximum entropy method for the deconvolution of the multisphere neutron spectrometer data. The Monte Carlo code MCNPX (version 2.5.0) was used to derive the a priori information for the unfolding process (Los Alamos National Laboratory, Los Alamos, NM, USA). The neutron fluence and ambient dose equivalent rate spectra of the calibration neutron fields are shown in Figs. 3A and 3B, respectively. The spectral characteristics (i.e., the neutron fluence and the percentage of the total neutron fluence rate) and the dosimetric characteristics (i.e., the ambient dose equivalent rates and the percentage of the total ambient dose equivalent rate) of the two calibration neutron fields (i.e., with and without the shadow cone) obtained by an unfolding process for neutron energy ranges of < 1 eV, 1 eV–100 keV, and > 10 MeV are summarized in Tables 1 and 2, respectively. The dosimetric values of the two spectra were obtained using the fluence-to-ambient dose equivalent conversion coefficients \( h^{*}(10) \) of International Commission on Radiation Units and Measurements (ICRU) Report 57 (ICRU-57) [11].

4. Calibration of several neutron survey meters

Ten neutron survey meters were used for a comparison of the calibration factors (i.e., the reference ambient dose equivalent rate/survey meter reading) obtained by the shadow cone method and semi-empirical method. The 10 neutron survey meters evaluated were (1) two LB6411 meters (Berthold Technologies, GmbH and Co. KG, Bad Wildbad, Germany); (2)
two FHT762 meters (WENDI-2; Thermo Scientific, Waltham, MA, USA); (3) two FHT752 meters (Thermo Scientific, Waltham, MA, USA); (4) two Victoreen-190N meters (V-190N; Fluke Corporation, Everett, WA, USA); and (5) two Ludlum-12-4 meters (L-12-4; Ludlum Measurements, Inc., Sweetwater, TX, USA). The neutron survey meters use different detectors and differ in construction with respect to shape, size, and moderator material around the detector. The LB6411, WENDI-2, and L-12-4 meters are single moderator-based survey meters and utilize a $^3$He gas counter tube as the detector. The FHT752 and V-190N meters are also single moderator-based survey meters, but utilize a boron trifluoride (BF$_3$) counter as the detector. The LB6411 and L-12-4 meters have a spherical shape and the FHT762, FHT752, and V-190N meters have a cylindrical shape. To find a suitable calibration point, the calibration factors of several survey meters were measured at different points (100 cm, 125 cm, 150 cm, 175 cm, and 200 cm), and the calibration distance (i.e., reference point) was finally determined as the 100-cm distance. The calibration factors of 10 survey meters obtained at 100 cm by two methods are summarized in Table 3.

5. Results of the measurements and calculations

The spectral characteristics (percentage of the total neutron fluence rate, fluence average energy, and dose equivalent average energy) and ambient dose equivalent rates (percentage of the total ambient dose equivalent rate) of the calibration neutron fields in the different neutron energy ranges of $<1$ eV, 1 eV–100 keV, and $>100$ keV are summarized in Figs. 3A and 3B, respectively. As shown in Table 1 and Fig. 3A in the without shadow cone (SC) neutron field, the neutron fluences for $>100$ keV and for $<1$ eV were $9.65 \times 10^{-6}$/cm$^2$ and $1.28 \times 10^{-5}$/cm$^2$, respectively, and in the without SC neutron field were $7.80 \times 10^{-7}$/cm$^2$ and $1.26 \times 10^{-6}$/cm$^2$, respectively. The values of the neutron fluence for $<1$ eV were nearly the same at $1.28 \times 10^{-6}$/cm$^2$ and $1.26 \times 10^{-6}$/cm$^2$, respectively, which indicates that low energy neutrons ($<1$ eV) that are scattered by the walls, ground, and air were accurately evaluated using the SC. Table 2 exhibits the ambient dose equivalent rates [H$^*(10)$/hr] obtained using the conversion coefficients [H$^*(10)$] of ICRU-57 [11] and the data of Table 1. As shown in Table 2 and Fig. 3B in the without SC and with SC neutron fields, the percentages of the total ambient dose equivalent rate [H$^*(10)$/hr] for $>100$ keV were 99.2% and 92.2% (i.e., 264 $\mu$Sv/hr and 19.4 $\mu$Sv/hr), respectively. This indicates that fast neutrons ($>100$ keV) predominantly contributed to the total ambient dose equivalent rate. According to the ISO recommendations [4], the SC effectively prevents most neutrons that are produced in the forward hemisphere and centered around the neutron detector axis from scattering into the neutron detector, and should have a negligible transmission of the direct neutrons. However, as Table 1 and

![Graphs showing neutron fluence and ambient dose equivalent rate spectra](image)

**Table 1** – Spectral characteristics (e.g., percentage of the total fluence rate and the fluence average energy) in different neutron energy ranges of the calibration neutron fields, as measured using the KAERI’s Bonner sphere system.

<table>
<thead>
<tr>
<th>Neutron field</th>
<th>Neutron fluence (% to the total fluence rate)</th>
<th>$E_{\text{ave}}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$&lt;1$ eV</td>
<td>1 eV–100 keV</td>
</tr>
<tr>
<td>Without SC</td>
<td>$1.28 \times 10^{-5}$/cm$^2$ (11.1%)</td>
<td>$6.61 \times 10^{-7}$/cm$^2$ (5.70%)</td>
</tr>
<tr>
<td>With SC</td>
<td>$1.26 \times 10^{-5}$/cm$^2$ (49.3%)</td>
<td>$5.15 \times 10^{-7}$/cm$^2$ (20.2%)</td>
</tr>
</tbody>
</table>

$E_{\text{ave}}$ fluence average energy; KAERI, Korea Atomic Energy Research Institute; SC, shadow cone.
Fig. 2A show, fast neutrons (> 100 keV) remained, although the SC was used. These fast neutrons may be unmoderated neutrons transmitted through the SC. This suggests that the SC did not fully shadow the fast neutrons from the neutron source.

In the present study, 10 single-moderator-based survey meters of five types exhibited a smaller calibration factor by as much as 3.1\textsuperscript{e}9.3\%, compared to the semi-empirical method, as shown in Table 3. This suggests that neutron survey meters underestimated the scattered neutrons and attenuated neutrons (i.e., total scatter corrections) when using the SC method. The reason for this underestimation of the scattered neutrons can be elucidated with reference to Kim et al\[12\] who found that most single moderator-based survey meters have an under-ambient dose equivalent response ranging \textasciitilde 2\textsuperscript{e}31\% in a thermal or thermal-dominant neutron field.

### 6. Conclusions

According to ISO 8529-2 [4], whichever method is used, it should be checked against one of the other calibration methods, and the different methods may give calibration factors that differ by as much as 3–4\%. The semi-empirical method has the advantage of a relatively exact correction for room-scattered neutrons, but it has the limitation of the room shape (i.e., cubical or nearly cubical). The SC method has the advantages of the ability to directly measure the scattered neutrons and no limitations due to the room shape. However, a disadvantage is the low ambient dose response to the scattered neutrons, which is attributable to the fact that a commercial single moderator-based neutron survey has an under-response to the room-scattered neutrons (i.e., thermal neutrons). In the present study, most calibration factors of neutron survey meters obtained using the SC method were small (3.1\textsuperscript{e}9.3\%), compared to the semi-empirical method. As a result, when the SC method is used for a single moderator-based survey meter, additional scatter correction for the room-scattered neutrons should be sufficiently considered.

### Conflicts of interest

All authors have no conflicts of interest to declare.

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