Philippine Journal of Science
149 (3-a): 947-954, October 2020
ISSN 0031 - 7683
Date Received: 28 Feb 2020

Establishment of Neutron Reference Fields in Vietnam: A Review

Le Ngoc Thiem*

Institute for Nuclear Science and Technology, Vietnam Atomic Energy Institute
179 Hoang Quoc Viet, Cau Giay, Hanoi, Vietnam

This paper summarizes the characterizations of neutron reference fields using radionuclide sources at the Institute for Nuclear Science and Technology (INST), Hanoi, Vietnam for the purposes of radiation protection and calibrations. The dosimetric quantities of spectral neutron fluence rates and neutron ambient dose equivalent rates have been calculated and presented using the Monte Carlo N-Particle transport code, version 5 (MCNP5) and Bonner sphere spectrometer (BSS) measurements in the combination with MAXED unfolding code. The characterizations of neutron reference fields have been done, complying with the ISO 8529 and 12789 series. The results confirm the neutron calibration capability at the INST in order to fulfill the domestic calibration demands of neutron ambient dose equivalent rate meters.

Keywords: ambient dose equivalent, reference fields, spectral neutron fluence

INTRODUCTION

The utilization of neutron sources has been rapidly increased for various applications. Therefore, the reliable neutron measurements for radiation safety assessment are essential, which requires the establishment of neutron reference fields to facilitate the domestic calibration demands of neutron ambient dose equivalent rate meters (hereafter, referred as neutron meters). The INST – a member of Vietnam Atomic Energy Institute (VINATOM) located in Hanoi, Vietnam – possesses a unique secondary standard dosimetry laboratory (SSDL) for ionizing radiations in the country. The laboratory is responsible for calibrations of radiation measuring devices, including neutron meters. Recently, there are several neutron reference fields that have been developed and made available in the world for the calibration purposes such as neutron calibration fields of radionuclide sources, simulated workplace neutron fields with neutron spectra (energy distribution of neutron fluence rates) similar to those at workplaces, and nearly mono-energetic neutron fields produced by accelerators [ISO 8529-1:2001 (E); Schuhmacher 2004]. However, neutron reference fields based on radionuclide sources are commonly used at SSDL since they are more easily equipped and lower cost compared to other types.

In this paper, the establishment and characterization of neutron reference fields based on radionuclide neutron sources in Vietnam are summarized as follows: (1) neutron reference field of a bare ^{252}Cf source; (2) neutron reference field of a bare ^{241}Am-Be source; and (3) simulated workplace neutron reference fields of ^{241}Am-Be source moderated by five polyethylene (PE) spheres with different diameters of 15, 20, 25, 30, and 35 cm. The characterizations of neutron reference fields were performed and presented in terms of spectral neutron fluence rates and neutron ambient dose equivalent rates, $\dot{H}^*(10)$, following the recommendations of the International Standard Organization (ISO) series [ISO 8529-3:1998 (E), ISO 8529-2:2000 (E), ISO 8529-1:2001 (E), ISO 12789-1:2008 (E), and ISO 12789-2:2008 (E)]. Other neutron reference field-related quantities, *i.e.* the neutron ambient dose equivalent rate-averaged energy and the fluence-to-ambient dose equivalent conversion

*Corresponding Author: LNThiem@vinatom.gov.vn

coefficient, were also investigated following the ISO 12789 series [ISO 12789-1:2008(E) and ISO 12789-2:2008(E)].

MATERIALS AND METHODS

Neutron Reference Room and Sources

The construction materials of the neutron calibration room followed the international guidance as defined by McConn *et al.* (2011). The neutron room has the inner dimensions of 700 cm x 700 cm x 700 cm. The details of the neutron bunker construction can be found in the previous works (Le *et al.* 2017, 2018, 2019). Figure 1 shows the top view and side view of the neutron reference room at the INST. During measurements, neutron detectors are set up along a half diagonal of the room central plane, which is parallel to the base floor (see Figure 1a).

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 radionuclide) were used to establish various neutron reference fields.

The ^{252}Cf neutron source supplied by Frontier Technology Corporation (Xenia, OH, USA) had the neutron emission rate, *i.e.* the number of neutrons emitted from the source per second, of 1.10×10^{07} s^{-1} on 29 Aug 2003 with the standard uncertainty of 10% (k = 1), as indicated in the supplier's certificate. This source is encapsulated by a cylindrical 304-L stainless steel layer with a length of 1.194 cm and an outer diameter of 0.552 cm (Le *et al.* 2017).

The ^{241}Am-Be source of X14 type capsulation supplied by Hopewell Designs, Inc., USA was installed in a container at the center of the base floor. The initial neutron emission rate, traceable to the National Institute of Standards and Technology (USA), on 23 Jan 2015 was 1.299×10^{07} s^{-1} with the standard uncertainty of 1.5% (k = 1). More detailed information on the neutron sources can be found in the previous works (Le *et al.* 2018, 2019).

Neutron Spectrometer

The BSS system consists of a thermal neutron sensitive detector of ^{6}LiI (Eu) and six high density (ρ = 0.95 g·cm^{-3}) PE spheres with different diameters of 2, 3, 5, 8, 10, and 12 in, respectively, as shown in Figure 2. The cylindrical ^{6}LiI (Eu) detector with 96% of ^{6}Li has a height of 0.4 cm and a diameter of 0.4 cm. The system configuration allows detecting neutrons from thermal energy up to 20 MeV. The

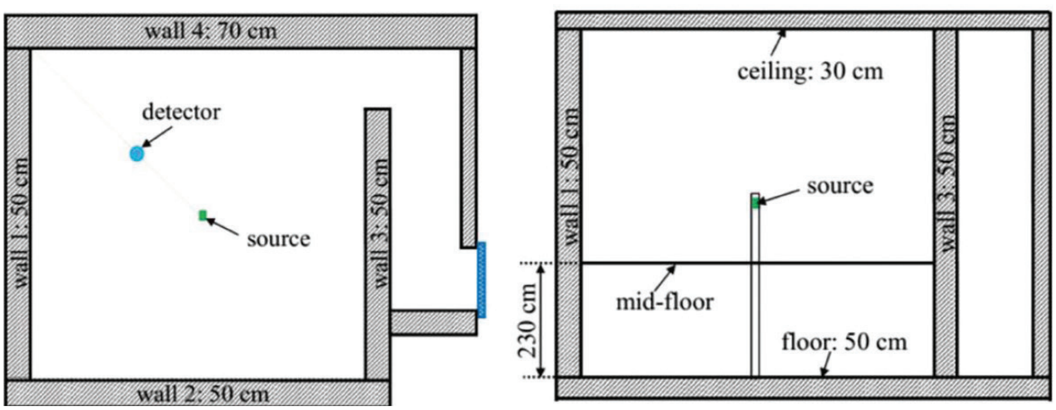

Figure 1. Top view (left) and side view (right) of the neutron reference room.

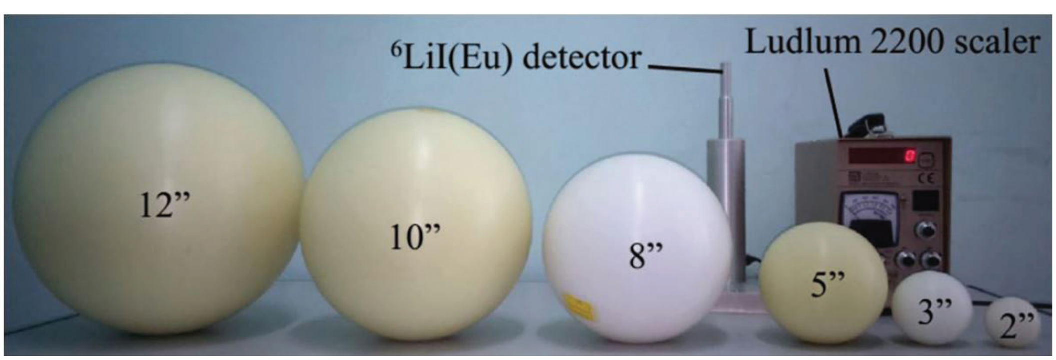

Figure 2. BSS system.

thermal neutrons are detected by a reaction ^{6}Li (n, α) ^{3}H (Q = 4.78 MeV); then, the Ludlum 2200 scaler counts the electronic pulse height from a photomultiplier. The BSS system is basically not sensitive to photons by applying a suitable discrimination level (Cruzate *et al.* 2007; Knoll 2010). In general, the BSS is the most common system frequently used in neutron measurements for the purposes of safety assessment and calibrations applied for decades in scientific leading countries such as Germany, Japan, South Korea, *etc.* (Eisenhauer and Hunt 1988; Mazrou *et al.* 2010; Guzman-Garcia *et al.* 2015).

Neutrons generated from a radionuclide source are normally moderated using a variety of moderators. This is done by surrounding the sources or placing them between the sources and the detector in order to create a wider range of neutron energies and doses, in the fulfillment of the practical demands on neutron meter calibrations. In this work, five PE spheres with the respective diameters of 15, 20, 25, 30, and 35 cm with a high density of 0.95 g·cm^{-3} were used for moderating neutrons from the ^{241}Am-Be source in order to create the simulated workplace neutron reference fields, following the recommendations of ISO 12789 series [ISO 12789-1:2008(E) and ISO 12789-2:2008(E)]. For the purpose of radiation safety assessment and calibration, the characterization was focused mainly on dosimetric quantities of the neutron fields such as spectral neutron fluence rates and neutron ambient dose equivalent rates.

The densities of the Bonner spheres and the moderated spheres were estimated based on the evaluation of their weights and volumes. The weights of the PE spheres were measured at Vietnam Metrology Institute (VMI) using a standard balance, while the volumes were calculated based on the geometries. The densities of the Bonner spheres and the moderated spheres were obtained as 0.955 ± 0.002 and 0.940 ± 0.005 g·cm^{-3}, respectively. In the MCNP5 simulations, the density value of 0.950 g·cm^{-3} was used for both types of PE spheres.

Monte Carlo Simulation

The MCNP5, developed by Los Alamos National Laboratory, is the internationally recognized code for analyzing the transport of radiation including neutrons by the Monte Carlo method (X-5 Monte Carlo Team 2003). In MCNP5 simulations, the ENDF-B/VI data library was used for neutron cross sections while thermal neutron cross-section $S(\alpha,\beta)$ was taken from "poly.60t." The MCNP5 simulations have been conducted in the previous works (Le *et al.* 2017, 2018, 2019) for several purposes, such as:

+ to simulate the spectral neutron fluence rate;
+ to evaluate the source anisotropy correction factors; and
+ to estimate the initial guess solutions of spectral neutron fluence rate for the unfolding process.

Unfolding Spectral Neutron Fluence Rate, $\varphi(E_b)$

In general, when a set of n Bonner spheres exposed to the same neutron fluence rate spectrum at a specific distance, a set of n readings C_i (i = 1 to n) is recorded corresponding to each BSS sphere. In this work, n = 7 including the bare ^{6}LiI (Eu) detector. The reading C_i of the i^{th} detector is an integral of the product of the energy response function $R_{ib}(E_b)$ of the i^{th} detector in the energy bin E_b and the spectral neutron fluence rate in that bin, $\varphi(E_b)$. The relationship can be written as:

$$C_i = \sum_{b=1}^{m} R_{ib}(E_b).\,\varphi(E_b);\ (i = 1 \text{ to } n) \qquad (1)$$

where b = 1 to m is the neutron energy bins; and m = 47, in this work, for energies ranging from 10^{-09} to 20 MeV. For unfolding the spectral neutron fluence rates in order to obtain the values of $\varphi(E_b)$ as a function of neutron energies, the MAXED code applying the maximum entropy principle was used. The MAXED is an adjustment code requiring an initial guess solution of spectral neutron fluence rates. It is expected that the final solution is close to the true value if the initial guess solution is good (Reginatto and Goldhagen 1998). In the unfolding processes of this work, the initial guess solutions were taken from the MCNP5 simulations, which are presented together with those unfolded from MAXED code in Figure 4 (Le *et al.* 2019). The energy response function $R_{ib}(E_b)$ was taken from the IAEA compendium (IAEA 2001). In addition, the response functions of the BSS system were also calculated using the MCNP5 code. Comparisons between R_{ib} (E_b) obtained from MCNP5 simulations and those from the IAEA compendium show good agreements for most of BSS spheres, even if the values from the IAEA compendium are a little greater than those from MCNP5 simulations, as depicted in Figure 3. The biggest difference was found for the bare detector (especially at the lower energy region, smaller than 10^{-06} MeV). These results are also consistent with those stated in other works (Vega-Carrillo *et al.* 2008; Tursinah *et al.* 2017). That means the use of R_{ib} (E_b) from the IAEA compendium is acceptable. During the unfolding process, the value of the chi-squared was set as 1.01; the uncertainties of BSS readings were set in the range of 1–3% due to experimental measurements. The final spectra were only selected when the differences between unfolded C_i and experimental values (for all BSS spheres and bare detectors used in the unfolding process) were smaller than 3%.

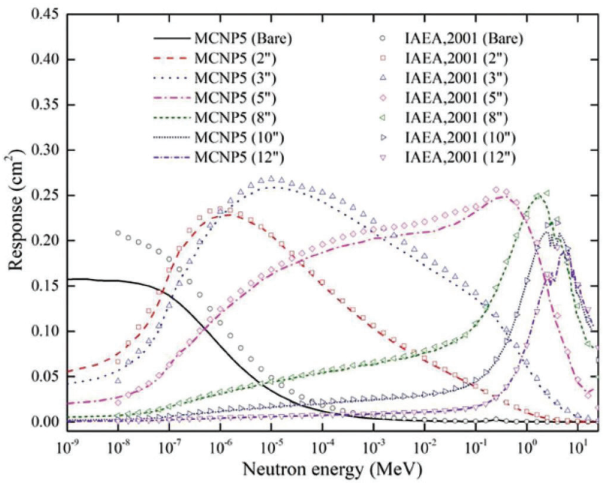

Figure 3. Energy responses, $R_{ib}(E_b)$, of the BSS system as functions of neutron energies obtained from MCNP5 simulations (noted as MCNP5), together with those taken from the IAEA compendium (noted as IAEA,2001).

RESULTS AND DISCUSSION

Spectral Neutron Fluence Rate, $\varphi(E_b)$

Figure 4 depicts the spectral neutron fluence rates due to the total components of neutron fields as functions of neutron energies at the distance of 150 cm from the source for such following cases:

(i) For the bare ^{252}Cf field, the spectral neutron fluence rates were obtained using MCNP5 simulations with an assumption that the neutron emission rate of the source is 1 s^{-1} (see Figure 4a). More detailed information of the spectral neutron fluence rates from the bare ^{252}Cf source can be found in the previous work (Le *et al*. 2017).

(ii) For the bare ^{241}Am-Be field, the spectral neutron fluence rates were obtained using BSS measurements combining with MAXED unfolding code as follows: The total count rates, C_i, due to the total components of the neutron field were measured at various distances (60–250 cm) from the source using the BSS system. The total count rates were then fitted as a function of distances using the general fitting method recommended in ISO 8529-2:2000 (E) to obtain the direct count rates. The MAXED unfolding code was then applied for the total and direct count rates at a specific distance (*i.e.* 150 cm in this work) to obtain the total and direct spectral neutron fluence rates at 150 cm. More detailed information of the spectral neutron fluence rates from the bare ^{241}Am-Be source can be found in the previous work (Le *et al.* 2018). Figure 4c shows the spectral neutron fluence rates due to the total component of the neutron field at 150 cm from a bare ^{241}Am-Be source unfolded using MAXED code, together with its initial guess solution obtained from MCNP5 simulation.

(iii) For the simulated workplace neutron reference fields of a ^{241}Am-Be source moderated using PE spheres with different diameters, the MAXED unfolding code was applied for the total BSS count rates at a specific distance (*i.e.* 150 cm in this work) to obtain the spectral neutron fluence rates due to the total components of the fields at 150 cm from the ^{241}Am-Be moderated sources (see Figure 4d–h for details). Figure 4b summarizes the spectral neutron fluence rates due to the total components of different neutron reference fields obtained from the MAXED code. More information of the spectral neutron fluence rates from the moderated ^{241}Am-Be sources can be found in previous work (Le *et al.* 2019).

From Figure 4, ones can figure out that if the diameters of moderated spheres increase from 0 cm (*i.e.* bare ^{241}Am-Be field) to 25 cm [*i.e.* 25PE (^{241}Am-Be) field], the high neutron energy peaks are decreased while the thermal neutron energy peaks are increased. After then, if the diameters of the moderated spheres are increased [*i.e.* 30PE (^{241}Am-Be) and 35PE (^{241}Am-Be) fields], the high neutron energy peaks are continuously decreased and the thermal neutron energy peaks are also decreased. This means the thermal neutrons are absorbed after being moderating by a PE sphere with a diameter greater than 30 cm (*i.e.* the thermalization is not effective, but the absorbance process is dominant). Since the energy resolution is quite big in the range from 10^{-08} to 10^{-07} MeV (only two energy bins), the thermal neutron energy peaks are not clearly seen at 2.53×10^{-08} MeV. This is not much influenced for neutron safety assessment and radiation protection purposes because the dosimetric quantity, $\dot{H}*(10)$, is more important than the shape of spectral neutron fluence rates.

During the calibrations of neutron meters following the ISO 8529 series [ISO 8529-3:1998 (E), ISO 8529-2:2000 (E), and ISO 8529-1:2001 (E)], the direct components of neutron fields are used and must be extracted from the total ones. Otherwise, the total components of neutron fields are used to calibrate the neutron meters used at workplaces following the recommendations of ISO 12789 series [ISO 12789-1:2008(E) and ISO 12789-2:2008(E)].

Neutron Ambient Dose Equivalent Rate, $\dot{H}*(10)$

Once the spectral neutron fluence rates, $\varphi(E_b)$, are available, the neutron ambient dose equivalent rates,

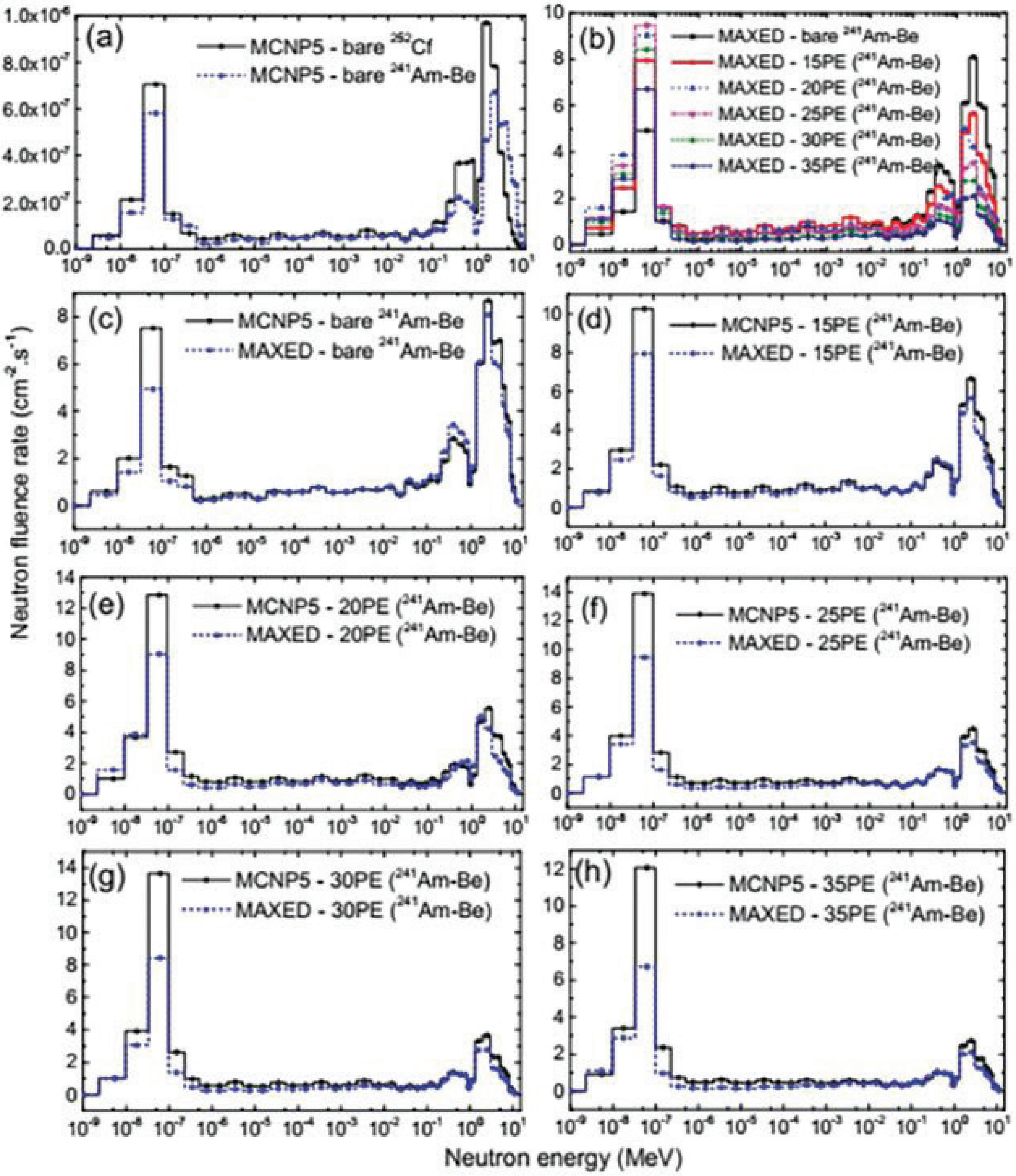

Figure 4. Spectral neutron fluence rates due to the total components of neutron fields as functions of the neutron energies at the distance of 150 cm from the source, in following cases: (a) MCNP5 simulation results for a bare ^{252}Cf source and a bare ^{241}Am-Be source with an assumption that the neutron emission rate of the source is 1 s^{-1}; (b) MAXED unfolding results for various neutron reference fields (*i.e.* of a bare ^{241}Am-Be source and five simulated workplace neutron reference fields of a ^{241}Am-Be source moderated using PE spheres with different diameters of 15, 20, 25, 30, and 35 cm, respectively); (c–h) MAXED unfolding spectral neutron fluence rates of different neutron reference fields with the initial guess solutions taken from the MCNP5 simulations.

$\dot{H}^*$ (10) – an important quantity for radiation safety assessment – are evaluated as Equation 2:

$$\dot{H}^*(10) = \sum_{b=1}^{m} \dot{H}_b(E_b) = \sum_{b=1}^{m} h_\phi(E_b).\,\varphi(E_b) \qquad (2)$$

where $\dot{H}_b$ (E_b) is a neutron ambient dose equivalent rate in the energy bin E_b and $h_\phi(E_b)$ is the neutron fluence-to-ambient dose equivalent rate conversion coefficient in the energy bin E_b, which is taken from the ICRP 74 (1996). Figure 5 shows the total neutron ambient dose equivalent rates as functions of the distances from the neutron sources. All data in this figure were normalized to 01 Oct 2019 (Nguyen *et al.* 2020).

The standard uncertainty of $\dot{H}*$ (10) generated from the bare ^{252}Cf source (simulated using MCNP5 code) was estimated at about 10% (k = 1) since it is significantly dependent on the standard uncertainty of neutron emission rate of the ^{252}Cf source of 10%. The standard uncertainty of $\dot{H}*$ (10) generated from the bare ^{241}Am-Be source (measured by BSS) was estimated within 5% (k = 1)

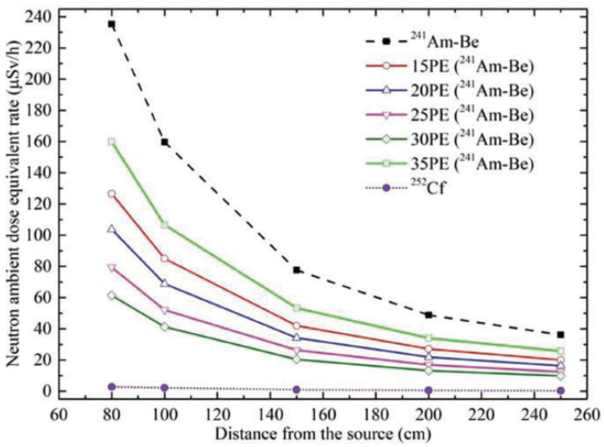

Figure 5. Neutron ambient dose equivalent rates due to the total components of the neutron fields as functions of the distance from the ^{252}Cf source, bare ^{241}Am-Be source, and moderated ^{241}Am-Be sources. All data were normalized to 01 Oct 2019.

when applying the uncertainty propagation principle and the guidance of uncertainty expression on influenced uncertainty budgets, *i.e.* main budgets: fluence-to-ambient dose equivalent rate conversion coefficient of 4%; neutron emission rate of the ^{241}Am-Be source of 1.5%; BSS readings of 1%; and unfolding process of 3% (JCGM 100:2008). The standard uncertainty of $\dot{H}*$ (10) generated from the moderated ^{241}Am-Be source (measured by BSS) was estimated within 7% (k = 1), greater than that from the bare ^{241}Am-Be source since the uncertainty from BSS readings (in moderated fields) considered as from 1–3%.

Dose Equivalent Rate-averaged Energy and Fluence-to-Dose Equivalent Conversion Coefficients

Once the values of $\varphi(E_b)$ and $\dot{H}*$ (10) are available, the neutron ambient dose equivalent rate-averaged energy ($\tilde{E}$) and the fluence-to-ambient dose equivalent conversion coefficient ($\bar{h}_\varphi$) can be evaluated as Equations 3 and 4, respectively. These are also two important quantities of simulated workplace neutron fields.

$$\tilde{E} = \frac{\sum_{b=1}^{m} \dot{H}_b(E_b).E_b}{\dot{H}^*(10)} \quad (3)$$

$$\bar{h}_\phi = \frac{\dot{H}^*(10)}{\sum_{b=1}^{m} \varphi(E_b)} \quad (4)$$

Figure 6 shows the $\tilde{E}$ values as functions of distances from the source obtained from the unfolding process using the MAXED code (Le *et al.* 2019). The values of $\tilde{E}$ vary in the range of 2.5–3.4 MeV. The $\tilde{E}$ values (of a moderated field) tend to be linearly decreased since the distance from the source increased. The deviations of $\tilde{E}$ are satisfied its uncertainties as recommended in series [ISO 12789-1:2008(E) and ISO 12789-2:2008(E)]. The changes in $\tilde{E}$ values when the diameters of moderated spheres changed are not so clear, even though they tend to be linearly decreased since the diameters of the PE spheres increase.

Figure 7 shows the values of $\bar{h}_\varphi$ obtained from the

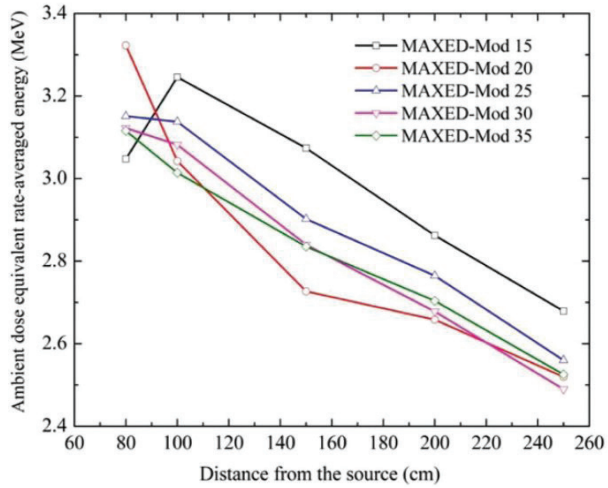

Figure 6. Neutron ambient dose equivalent-averaged energies obtained from the MAXED as a function of the distances from the source.

MAXED code (Le *et al.* 2019). The values of $\bar{h}_\varphi$ vary in the range of 145–281 pSv·cm^2 and decrease by a factor of 1.5 at 250 cm compared to that at 80 cm with the PE moderated sphere of 15 cm in diameter. The increase in diameter of the PE sphere from 15–35 cm leads to the decrease of the $\bar{h}_\varphi$ by a factor of about 1.2. The values of $\bar{h}_\varphi$ tend to be linearly decreased since the distances from the source and the diameters of moderated spheres increased.

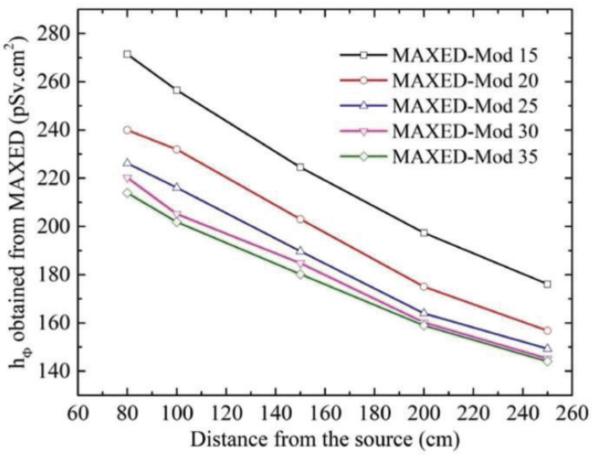

Figure 7. Neutron fluence-to-ambient dose equivalent conversion coefficients obtained from the MAXED code as a function of the distances from the source.

CONCLUSION

This paper summarizes the establishment of the neutron reference fields in Vietnam for the purposes of calibration and safety assessment. The dosimetric quantities in terms of spectral neutron fluence rates and neutron ambient dose equivalent rates have been characterized for such following radionuclide neutron sources: (1) the bare spontaneous neutron source of ^{252}Cf following the ISO 8529 series; (2) the bare (α, n) reaction-based neutron source of ^{241}Am-Be following the ISO 8529 series; and (3) the simulated workplace neutron fields of ^{241}Am-Be source moderated by PE spheres. Comparisons of the results obtained from different methods show the reliable characterization process of neutron calibration fields, which are applied in the calibrations of neutron meters at the INST, Hanoi, Vietnam.

ACKNOWLEDGMENTS

The author would like to thank Dr. Marcel Reginatto for permission to use the MAXED code. Dr. Do Duc Nguyen and Dr. Trieu Viet Phuong (VMI), along with M.Sc Ngoc Quynh Nguyen and Ms. Thi My Linh Dang (INST), are highly appreciated for their assistance during the manuscript preparation. This research was funded by the Ministry of Science and Technology of Vietnam through the supervision of VINATOM under grant No. 08/HĐ/ĐTCB.

STATEMENT ON CONFLICT OF INTEREST

The author has no conflict of interest to declare.

REFERENCES

CRUZATE JA, CARELLI JL, GREGORI BN. 2007. Bonner sphere spectrometer. In: Workshop on uncertainty assessment in computational dosimetry: a comparison of approaches; 2007 October 08–10; Bologna-Italia.

EISENHAUER C, HUNT J. 1988. Anisotropic neutron emission from a ^{252}Cf source. Radiation Protection Dosimetry 22(4): 253–258.

GUZMAN-GARCIA KA, MENDEZ-VILLAFANE R, VEGA-CARRILLO HR. 2015. Neutron field characteristics of Ciemat's neutron standards laboratory. Applied Radiation and Isotopes 100: 84–90.

[IAEA 403] International Atomic Energy Agency, Technical Reports Series No. 403. 2001. Compendium of Neutron Spectra and Detector Responses for Radiation Protection Purposes. Supplement to Technical Reports Series No. 318. 276p.

[ICRP 74] International Commission on Radiation Protection, Publication 74. 1996. Conversion coefficients for use in radiological protection against external radiation. Annals of the ICRP 26: 3–4.

[ISO 12789-1:2008(E)] International Standard Organization, 12789-1:2008(E). 2008. Reference radiation fields – Simulated workplace neutron fields – Part 1: Characteristics and methods of production. Geneva. 32p.

[ISO 12789-2:2008(E)] International Standard Organization, 12789-2:2008(E). 2008. Reference radiation fields – Simulated workplace neutron fields – Part 2: Calibration fundamentals related to the basic quantities. Geneva. 22p.

[ISO 8529-1:2001 (E)] International Standard Organization, 8529-1:2001 (E). 2001. Reference neutron radiations – Part 1: Characteristics and methods of production. Geneva. 32p.

[ISO 8529-2:2000 (E)] International Standard Organization, 8529-2:2000 (E). 2000. Reference neutron radiations – Part 2: Calibration fundamentals of radiation protection devices related to the basic quantities characterizing the radiation field. Geneva. 38p.

[ISO 8529-3:1998 (E)] International Standard Organization, 8529-3:1998 (E). 1998. Reference neutron radiations – Part 3: Calibration of area and personal dosimeters and determination of their response as a function of neutron energy and angle of incidence. Geneva. 22p.

[JCGM 100:2008] Joint Committee for Guides in Metrology, Publication 100. 2008. Evaluation of measurement data – guide to the expression of uncertainty in measurement, 1st edition. 134p.

KNOLL GF. 2010. Radiation Detection and Measurement, 4th edition. Wiley & Sons, Inc. 796p.

LE TN, HOANG SMT, NGUYEN QN, LIAMSUWAN T, TRAN H-N. 2019. Simulated workplace neutron fields of ^{241}Am – Be source moderated by polyethylene spheres. Journal of Radioanalytical and Nuclear Chemistry 321(1): 313–321.

LE TN, TRAN H-N, NGUYEN KT, TRINH GV. 2017. Neutron calibration field of a bare ^{252}Cf source in Vietnam. Nuclear Engineering and Technology 49(1): 277–284.

LE TN, TRAN H-N, NGUYEN QN, TRINH GV, NGUYEN KT. 2018. Characterization of a neutron calibration field with ^{241}Am − Be source using Bonner sphere spectrometers. Applied Radiation and Isotopes 133: 68–74.

MCCONN J, GESH CJ, PAGH RT, RUCKER RA, WILLIAMS RG. 2011. Compendium of material composition data for radiation transport modelling. PNNL-15870 Rev. 1. Richland, WA: Pacific Northwest National Laboratory. 124p.

MAZROU H, SIDAHMED T, ALLAB M. 2010. Neutron field characterization of the OB26 CRNA irradiator in view of its use for calibration purposes. Radiation Protection Dosimetry 141(2): 114–126.

NGUYEN KT, TRAN H-N, NGUYEN QN, DANG TML, BUI VL, LIAMSUWAN T, LE NT. 2020. Calibration of a neutron dose rate meter in various neutron standard fields. Nuclear Science and Techniques 31. https://doi.org/10.1007/s41365-020-00763-0

REGINATTO M, GOLDHAGEN P. 1998. MAXED – a computer code for the deconvolution of multisphere neutron spectrometer data using the maximum entropy method. Environmental Measurements Laboratory, USDOE Report EML 595. 40p.

TURSINAH R, BUNAWAS, KIM J. 2017. Neutron Response function of a Bonner Sphere Spectrometer with ^{6}LiI (Eu) Detector. Ganendra Journal of Nuclear Science and Technology 20(2): 65–72.

SCHUHMACHER H. 2004. Neutron calibration facilities. Radiation Protection Dosimetry 110(1–4): 33–42.

VEGA-CARRILLO HR, DONAIRE I, GALLEGO E, MANZANARES-ACUNA E, LORENTE A, INIGUEZ MP, MARTIN-MARTIN A, GUTIERREZ-VILLANUEVA JL. 2008. Calculation of Response matrix of a BSS with ^{6}LiI scintillator. Revista Mexicana de Física 54(1): 57–62.

X-5 MONTE CARLO TEAM. 2003. MCNP – A general Monte Carlo N-Particle transport code, Version 5, Volume I: Overview and Theory. 334p.