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# Experimental, Computational, and Analytical Methods for the Characterization of a Neutron Field for Calibration of Neutron Monitoring Instruments in the Philippines

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**Despite the many emerging applications of neutron radiation in the Philippines, there is a gap in the country's capability to calibrate neutron radiation monitoring instruments that are necessary for measuring the radiation hazards in the workplace. In this study, the neutron field of a bare Californium-252 source was characterized and established for calibration of radiation monitoring instruments. The fluence rate of the neutron field was experimentally characterized using the shadow cone method, and the results were compared with Monte Carlo simulations and analytical methods. The neutron fluence rate of the neutron source with a nominal activity of 200 MBq was measured at distances of 100 cm, 130 cm, and 150 cm with a reference He-3 spherical proportional counter in a Bonner sphere. The measured fluences were found to be $\varphi_{100}$ = 151.09 cm$^{-2}$s$^{-1}$, $\varphi_{130}$ = 89.13 cm$^{-2}$s$^{-1}$, and $\varphi_{150}$ = 67.31 cm$^{-2}$s$^{-1}$, respectively. Results also show that the experimental values are agreeable with the computational and analytical methods to within 10%. The characterized neutron field is the first of its kind in the Philippines, and can now be used for calibrating neutron radiation monitoring instruments. This study will, therefore, help improve the accuracy of radiation measurements and support the radiation protection program of neutron facilities in the country.**

Keywords: calibration field, dosimetry, MCNP, neutron, secondary standards laboratory

## INTRODUCTION

In the past decade, there is a significant increase in facilities using radiation and neutron technologies in the Philippines. Radiation interactions occurring in the mega-electron voltage ranges produce secondary neutron fields that may pose potential risks for occupationally-exposed radiation workers (Vichi *et al.* 2019, Wang and Cai 2020). In order to bridge the gap of using high-energy radiation and ensuring safety in the workplaces, calibrated neutron radiation monitoring instruments are used to measure the hazard levels and ensure safe working levels for the workers and the environment.

The DOST-PNRI through the Secondary Standards Dosimetry Laboratory (SSDL) calibrates radiation monitoring instruments. The SSDL holds the highest metrological standard for radiation protection level of photon radiation. However, the laboratory currently has no capability to calibrate neutron monitoring instruments because the relevant national radiation standards for neutrons have not yet been established.

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A bare Californium-252 (Cf-252) field is one of the recommended neutron fields in the calibration of neutron radiation monitoring instruments (ISO 2001). To establish the field, the output in terms of fluence rate needs to be measured using a neutron detector that is traceable to a primary standards laboratory. However, the bare neutron field measured by the detector includes both the direct beam and scattered beam components. The direct beam component is the neutron field component that is unaffected by the air and facility structures, while the scattered beam component is the neutron field component affected by the presence of room and associated structures. For calibration purposes, only the direct beam is considered. It is important, therefore, to characterize and directly measure both neutron beam components (IAEA 1988, 2000).

One method to determine the direct beam component is using the shadow cone method. In this method, a shadow cone composed of iron and borated polyethylene is used to shield the direct beam between the neutron source and the detector, where only the scattered beam component is measured by the detector. The scattered component is then deducted from the total beam and, upon application of other correction factors, the direct beam component of the field in terms of neutron fluence is determined (IAEA 1988, 2000).

Apart from the shadow cone measurement method, neutron fluence can also be determined using several methods. Computational methods can be used by simulating the source geometries and material compositions of the neutron source used. On the other hand, if the certified neutron source strength is known, the neutron fluence can be determined analytically by incorporating air attenuation effect and anisotropy (IAEA 2000). However although both the analytical and computational methods present to be invaluable for the verification of measurements and data, it does not accurately incorporate the neutron scattering component into their outcome.

Many studies determine the fluence rate of a neutron source by direct measurement, analytical methods, or by simulations (Dawn *et al.* 2017, Alvarenga *et al.* 2019, Cavalieri *et al.* 2019, Olsher *et al*. 2007). In this study, the fluence rate of a neutron field is characterized using all three methods. This characterization and establishment of a neutron calibration field are the first of its kind in the Philippines. This will significantly increase the Institute's capacity to provide calibration and monitoring services nationwide. It will also contribute to strengthening radiation safety programs involving neutron radiation for the advancement of technology and safety in the country.

# MATERIALS AND METHODS

The fluence rate in units of neutron $cm^{-2}s^{-1}$ of the bare neutron source is the main quantity determined for the characterization of the bare Cf-252 neutron field. Experimental, computational, and analytical methods are used. In the experimental method, the fluence of the source is directly measured using a reference neutron detector. In the computational method, the Monte Carlo N-Particle Program Version 5 (MCNP5) (X-5 Monte Carlo Team 2008) is used. In the analytical method, the fluence rate is calculated based on the neutron source strength, air attenuation effects, and source anisotropy effects (IAEA 2000). The resulting fluence rate of each method is then compared.

A neutron field consists of both direct beam and scattered beam components. In this study, the fluence rate of the direct beam is measured using the shadow cone method (ISO 2001). The shadow cone is composed of a 20 cm solid iron front end and a 30 cm borated polyethylene back end (ISO 2001). In this method, two measurements are performed: using a shadow cone between the source and the detector to measure the scattered beam, and then without the shadow cone to measure the total beam composed of both the direct and scattered components. The direct beam component is then obtained by subtracting the scattered beam from the total beam and incorporating correction factors.

Figures 1 and 2 show the experimental setup. The detector is placed at a distance equal to or greater than the length of the shadow cone. The Cf-252 source used is a model 100S bare source from Frontier Technology Corporation (FTC), USA, with an activity of 200 MBq. The reference neutron detector system used in this study consists of an ELSE Nuclear SP9 He-3 spherical proportional counter inside a 10-inch polyethylene sphere, traceable to the National Physical Laboratory in the United Kingdom. Measurements were performed at source-to-detector distances (SDD) of 100, 130, and 150 cm. Figure 3 shows the detector system used.

The detector is irradiated until a total of at least 100,00 counts were collected at SDD = 100 cm. This irradiation time is also applied at 130 and 150 cm distances. The measured count rate is then divided with the fluence response to Cf-252 to obtain the neutron fluence rate as shown in Equation 1:

$$\frac{C}{R} = M \tag{1}$$

where $C$ is the instrument count rate with the unit ($s^{-1}$), $R$ is the detector fluence response with unit ($cm^2$), and $M$ is the fluence rate with unit ($cm^{-2}s^{-1}$). The fluence rate of the direct beam, $M_C$, as per ISO 8529-1 is then:

$$M_C = [M_T(l) - M_S(l)]F_A \tag{2}$$

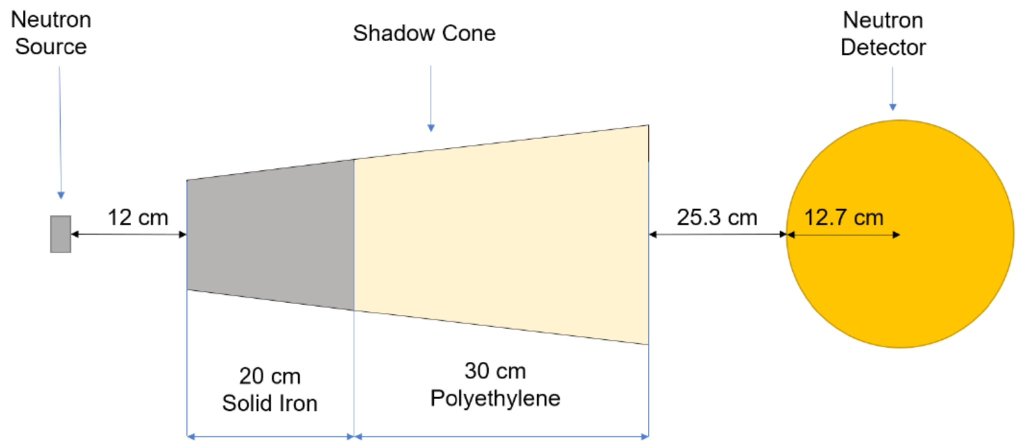


**Figure 1.** Schematic diagram of the experimental set-up used with the shadow cone in position.

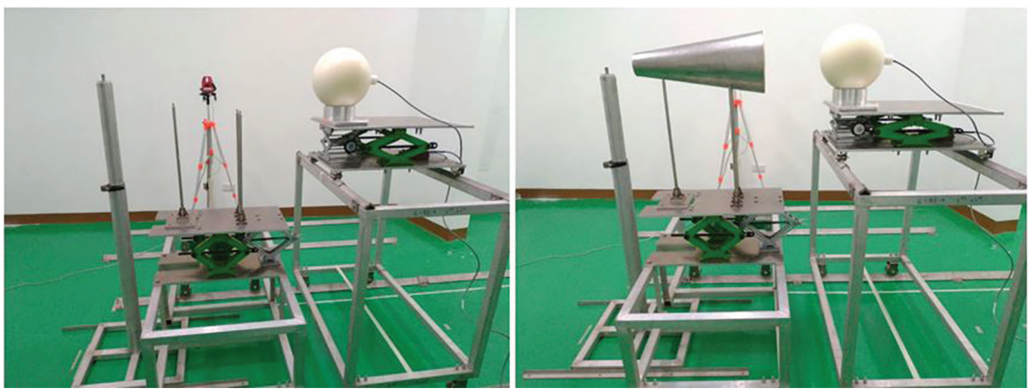

**Figure 2.** Actual experimental set up using the dummy neutron source, without the shadow cone (L) and with the shadow cone (R), and the spherical proportional counter inside the Bonner sphere.

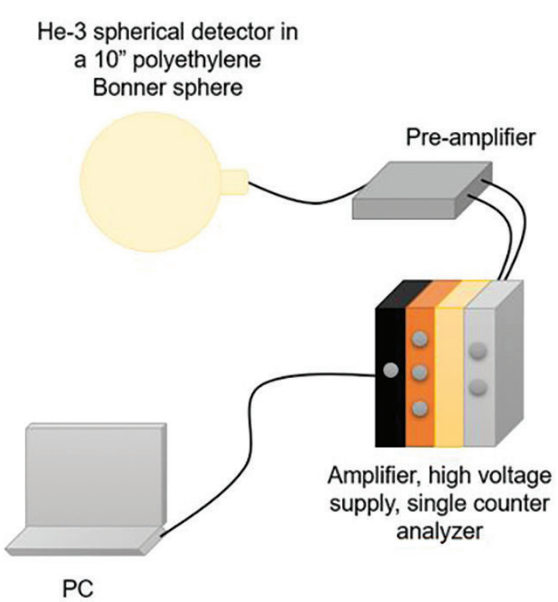


**Figure 3**. Schematic diagram of the reference neutron detector system and its labeled parts.

where $M_T(l)$ is the total fluence rate, $M_S(l)$ is the fluence rate of the detector with the shadow cone, $F_A$ is the correction factor for air attenuation, and $l$ is the distance from the detector to the source. The air attenuation correction factor $F_A$, for Cf-252 is obtained by:

$$F_A(l, E) = \exp[l \cdot \Sigma(E)] \qquad (3)$$

$$F_{A,Cf252}(l, E) = \exp[100\ cm \cdot (1\ 055\ x\ 10^{-7} cm^{-1})] \qquad (4)$$

where $l$ is the SDD in cm and $\Sigma(E)$ is the averaged total macroscopic neutron cross-sections for nitrogen and oxygen over the spectral neutron distribution of the source. For Cf-252, $\Sigma(E)$ is given as 1 055 × $10^{-7}$ $cm^{-1}$. The air attenuation coefficient of the source at the various SDDs are thus $F_{A\text{-}100cm}$ = 1.0106, $F_{A\text{-}130cm}$ = 1.0138, and $F_{A\text{-}150cm}$ = 1.0160.

The MCNP5 is a multipurpose program for the transport of neutrons, photons, and electrons (X-5 Monte Carlo Team 2008). In this study, the MCNP5 code is used to simulate the experimental setup. This program was used for the simulation the Cf-252 source using the ENDF/B-VII.0 nuclear data library with thermal scattering treatment. The materials were declared in the model using the compositions and densities as per the details provided in Table 1.

The Cf-252 source has original source strength of $2.37 \times 10^7$ s$^{-1}$ in April 2018, corresponding to an original mass of 10.3 µg. The total relative standard uncertainty (systematic and random) of the original source strength is 3.04%. The active source material is considered as a point source deposited at the pressed-fit end of the source capsule. This capsule was made of stainless steel (304 L), where the threaded end is positioned at the bottom, as illustrated in Figure 4. The current estimate for source strength was obtained by decay equations considering other neutron emitting radionuclides, such as Cf-250 and Cm-248. The energy distribution of the source neutrons was declared using Watt function shown in Equation 5, where a = 1.18 MeV and b = 1.03419 MeV$^{-1}$ (Radev and McLean 2014):

$$N(E) = e^{-E/a} \sinh(\sqrt{bE}) \qquad (5)$$

All simulations were run with $1 \times 10^8$ running neutron histories.

The fluence rate of a neutron source can be analytically determined from the neutron source strength as declared in the source certificate, multiplied by a constant shown in Equation 6. That is:

$$B = 2.31 \times 10^6 s^{-1} \mu g^{-1} \cdot 10.3\ \mu g \qquad (6)$$

This results in a neutron source strength of $2.37 \times 10^7$ s$^{-1}$.

The fluence rate at the point of test can then be determined by using the Equation 7 as given from IAEA Safety Reports Series 16, Calibration of Radiation Monitoring Instruments:

$$\dot{\varphi} = \frac{B}{4\pi \cdot (l^2) \cdot F_A(l)} \cdot F_I(l) \qquad (7)$$

where $l$ similarly is the SDD (cm), $F_I(l)$ is the anisotropy factor of the source, and $F_A(l)$ is the air attenuation factor (IAEA 2000, ISO 2001).

The construction of neutron used in calibration is typical of cylindrical shape. When neutrons emitted by the source pass through the encapsulation material, they undergo scattering resulting in the variation of its effective path length. This then affects the angular distribution of the emitted neutrons and as a result, the neutron emission is not isotropic. The anisotropy factor is essentially the angular variation of the neutron fluence with respect to the source cylindrical axis. In general, it is more desirable to have anisotropy factors closer to unity as this lessens the uncertainty in the measurement of the fluence/dose rate at a point of test. That is, for $F_1(\theta) = 1.0$, no corrections are necessary to account for the effect of source anisotropy (Eisenhauer *et al.* 1985).

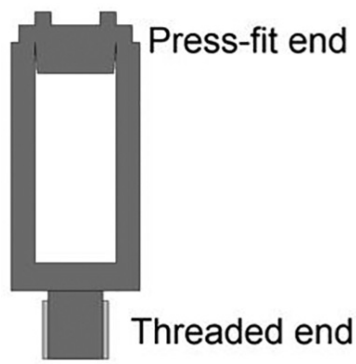


**Figure 4**. The Cf-252 neutron source with FTC Model 100S encapsulation.

**Table 1.** Material compositions and densities used in the MCNP5 model.

| **Material** | **Density (g cm$^3$)** | **Composition (atom fraction)** |
|---|---|---|
| Air [a] | 0.001205 | C(0.000150); N(0.784431); O(0.210748); Ar(0.004671) |
| Stainless steel, 304L [a] | 8.00 | C(0.000687); $^{28}$Si(0.009031); $^{29}$Si(0.000459); $^{30}$Si(0.000303); $^{31}$P(0.000408); $^{32}$S(0.000244); $^{33}$S(0.000002); $^{34}$S(0.000011); $^{50}$Cr(0.008734); $^{52}$Cr(0.168429); $^{53}$Cr(0.019098); $^{54}$Cr(0.004754); $^{55}$Mn(0.010013); $^{54}$Fe(0.039986); $^{56}$Fe(0.627690); $^{57}$Fe(0.014496); $^{58}$Fe(0.001929); $^{58}$Ni(0.063805); $^{60}$Ni(0.024578); $^{61}$Ni(0.001068); $^{62}$Ni(0.003407); $^{64}$Ni(0.000867) |

a) McConn *et al*. 2011.

In this study, the anisotropy factors $F_1(\theta)$ were obtained from simulation results using Equation 8, where $\Phi_{sp}$ is the average surface fluence on a ring centered at the source cylinder and $\Phi_{sp,\theta}$ is the fluence on the sphere at the particular angle θ. The former is obtained using the F2 surface tally, and the latter can be obtained using F5 point and F5a ring tallies:

$$F_1(\theta) = \frac{\Phi_{sp,\theta}}{\Phi_{sp}} \qquad (8)$$

# RESULTS

### Experimental Method

The total beam counts measured at 100, 130, and 150 cm were 110 615, 71 874, and 57 540, respectively. The scattered beam counts measured at the distances were 18 535, 17 729, and 16 736, respectively. Applying the air attenuation coefficient obtained in Equation 4, the fluence rate at the test distances were $\varphi_{100} = 151.09$ cm$^{-2}$s$^{-1}$, $\varphi_{130} = 89.13$ cm$^{-2}$s$^{-1}$, and $\varphi_{150} = 67.31$ cm$^{-2}$s$^{-1}$, respectively.

### Computational Method

Taking into account source geometries and air scattering, the computed fluence rate from simulations at the three distances are $\varphi_{100} = 135.73$ cm$^{-2}$s$^{-1}$, $\varphi_{130} = 80.40$ cm$^{-2}$s$^{-1}$, and $\varphi_{150} = 60.42$ cm$^{-2}$s$^{-1}$ using the F5 tally as shown in the mesh diagram in Figure 5. Figure 6 shows the anisotropy factor profile of the source. At the reference angle θ = 90°, the factor obtained is 1.0242.

### Analytical Method

The neutron source strength at the date of measurement is $B = 1.66 \times 10^7$ s$^{-1}$. Incorporating the anisotropy factor and the fluence rate as given in Equation 8, the fluence rates at SDD 100, 130, and 150 cm are $\varphi_{100} = 134.08$ cm$^{-2}$s$^{-1}$, $\varphi_{130} = 79.09$ cm$^{-2}$s$^{-1}$, and $\varphi_{150} = 59.28$ cm$^{-2}$s$^{-1}$, respectively.

The fluence rate at different distances from the bare Cf-252 source was obtained with three methods, and the results are summarized in Table 2. Upon comparison, the fluence rates between the experimental and computational method are agreeable within 10%, while the experimental and analytical method fluence rates are agreeable within 11%.

Neutron sources are not isotropic due to their construction for safety and robustness, and this causes them to emit neutrons irregularly at different points around its encapsulation. At 1 m, the attenuation in fluence is about 1% due to environmental effects (IAEA 2000).

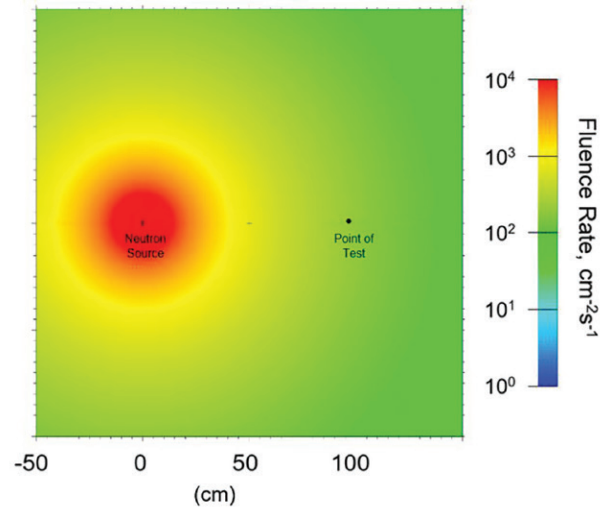


**Figure 5.** Mesh diagram of the neutron fluence rate as simulated in MCNP.

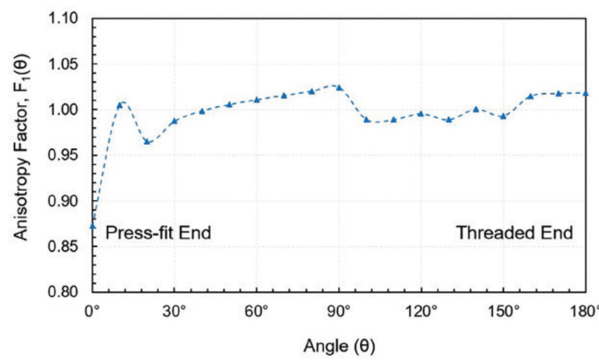


**Figure 6**. Calculated anisotropy factors for the Cf-252 with FTC Model 100S encapsulation.

**Table 2.** Summary of fluence rates obtained at different distances from a bare Cf-252 source.

| Method | Fluence rate at SDD (cm$^{-2}$s$^{-1}$) | | |
|---|---|---|---|
| | 100 cm | 130 cm | 150 cm |
| Experimental method | 151.09 | 89.13 | 67.31 |
| Computational method | 135.73 | 80.40 | 60.42 |
| Analytical method | 134.08 | 79.09 | 59.28 |

The irradiation room has an irregular shape and is constructed with solid concrete walls, floors, and ceilings. The spectrum of a bare Cf-252 source varies greatly if the scattered component of the neutron source is incorporated into the spectrum. Since scattering components are present during the experimental measurements, these can change the neutron fluence rates and spectrum depending on the environment. This demonstrates that computational and analytical methods may not always accurately consider all the scattering components when simulating neutron sources or calculating for radiological quantities from neutron sources.

## DISCUSSION

Four methods can be used according to ISO 8529-2:2001 to characterize a neutron field: the a) generalized fit method, b) semi-empirical method, c) reduced fit method, and the d) shadow cone method. These methods have been applied in different experiments with agreeable outcomes (Le *et al.* 2018, Mendez-Villafane *et al.* 2010, Mazrou *et al.* 2010). Computational methods with unfolding codes are also used to characterize and understand the intrinsic neutron spectra (Le *et al.* 2018). However, among the different methods, the shadow cone method is recommended to experimentally determine the scattered component of the neutron field to correct measurements (IAEA 2000).

This study determined the fluence rates in a neutron field at distances 100, 130, and 150 cm through experimental, computational, and analytical methods. The fluence rates obtained between experimental and computational methods are agreeable within 10%, while experimental and analytical method fluence rates are agreeable within 11%. The results obtained in this study are consistent with previously conducted studies (Le *et al.* 2016, Mazrou *et al.* 2010) that also obtained 10% discrepancy between calculated and experimental values in a neutron field. This suggests that the study conducted and the results obtained show acceptable methods and procedures applied.

## CONCLUSION

The first bare Cf-252 neutron field was established in the Philippines using experimental, computational, and analytical methods. The fluence rates at three distances (100, 130, and 150 cm) from the source were first characterized experimentally by employing the shadow cone method according to ISO 8529-1: 2001. The fluence rates were then compared with simulated results using MCNP5, and results are agreeable within 10%. Experimental fluence rates were also compared with calculations based on neutron source strengths, and have shown to be agreeable within 11% with the analytical methods used.

The established neutron field is the first of its kind in the Philippines and can be used to calibrate neutron radiation monitoring instruments. This significantly increases the Institute's capacity to provide calibration and monitoring services for neutron radiation nationwide. Moreover, this contributes to strengthened radiation safety programs and procedures that encompass many applications in the country, thus contributing to the advancement of technology and safety in the country.

## ACKNOWLEDGMENTS

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## STATEMENT ON CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

## REFERENCES

ALVARENGA TS, POLO IO, PEREIRA WW, SILVA FS, FONSECA ES, CALDAS LVE. 2019. Contribution of the scattered radiation on the neutron beam fluence at the calibration laboratory of IPEN. Radiation Physics and Chemistry (in press), https://doi.org/10.1016/j.radphyschem.2019.03.023.

DAWN S, BAKSHI AK, SATHIAN D, SELVAM TP. 2017. Estimation of neutron scatter correction for calibration of personnel dosimeter and doseratemeter against 241Am-Be source-monte carlo simulation and measurements. Radiation Protection Dosimetry 175(2): 149–162.

EISENHAUER CM, HUNT JB, SCHWARTZ RB. 1985. Calibration techniques for neutorn personal dosimetry. Radiation Protection Dosimetry 10(1–4): 43–57.

CAVALIERI TA, SIGUIERA TD, SHORTO JB, GENEZINI FA, YORIYAZ H. 2019. Design, fabrication and modeling of an AmBe neutron irradiator for TLD screening for neutron dose measurement in mixed radiation fields. Applied Radiation and Isotopes 150: 31–38.

[IAEA] International Atomic Energy Agency. 1988. Technical Report Series no. 285: Guidelines on calibration of neutron measuring devices. Vienna, Austria.

[IAEA] International Atomic Energy Agency. 2000. Calibration of radiation protection monitoring instruments. Safety Reports Series No. 16. Vienna, Austria.

[ISO] International Organization for Standardization. 2001. Reference neutron radiations – Part 1: Characteristics and Methods of Production (ISO 8529-1: 2001). Geneva, Switzerland.

[ISO] International Organization for Standardization. 2000. Reference neutron radiations - Part 2: Calibration fundamentals of radiation protection devices related to the basic quantities characterizing the radiation field (ISO 8529-2: 2001). Geneva, Switzerland.

LE TN, TRAN H, NGUYEN QN, TRINH GV, NGUYEN KT. 2018. Characterization of a neutron calibration field with 241Am-Be source using Bonner sphere spectrometer. Applied Rad and Isotopes 133: 68–74.

LE TN, TRAN H, NGUYEN KT, TRINH GV. 2016. Neutron calibration field of a bare $^{252}$Cf source in Vietnam. Nuclear Engineering and Technology 133: 68–74. http://dx.doi.org/10.1016/j.net.2016.07.011

MAZROU H, SIDAHMED T, ALLAB M. 2010. Neutron field characterisation of the OB26 CRNA irradiation in view of it suse for calibration purposes. Rad Pro Dosi 141(2): 114–126.

MCCONN RJ, GESH CJ, PAGH RT, RUCKER RA, WILLIAMS III R. 2011. Compendium of Material Composition Data for Radiation Transport Modeling. Richland, WA: Pacific Northwest National Laboratory.

MENDEZ-VILLAFANE R, LOS ARCOS MERINO M, GALLEGO DIAZ E, LORENTE FILLOL A. 2010. Determination of the emission rate of an Am-Be neutron source with a Bonner sphere spectrometer. Radiation Measurements 45: 1271–1275.

OLSHER RH, MCLEAN TD, MALLETT MW, SEAGRAVES DT, GADD MS, MARKHAM RL, MURPHY RO, DEVINE RT. 2007. Characterization of neutron reference fields at US Department of Energy calibration fields. Radiation Protection Dosimetry 126(1–4): 52–57.

RADEV R, MCLEAN T. 2014. Neutron Sources for Standard-Based Testing [Report No. LLNL-TR-664160]. Los Alamos National Laboratory.

VICHI S, ZAGANI F, CICORIA G, INFANTINO A, RIGA S, ZELLER M, CARZANIGA TS, NESTERUK KP, BRACCINI, MARENGO M, MOSTACCI D. 2019. Activation studies of a PET cyclotron bunker. Radiation Physics and Chemistry 161: 44–54.

WANG Z, CAI J. 2020. Reconstruction of the neutron radiation field on nuclear facilities near the shield using Bayesian inference. Progress in Nuclear Energy 118: 103070.

X-5 MONTE CARLO TEAM. 2003. MCNP – Version 5, Vol. 1: Overview and Theory. La-Ur-03-1987.