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Parameter of neutron calibration field in Viet Nam following international standard

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Abstract – This paper presents the technical parameters of neutron calibration fields available in Viet Nam for calibrations of neutron measuring meters (*i.e.*, neutron ambient dose equivalent/rate meters and/or neutron personal dose equivalent/rate meters – referred to neutron meters). The technical parameters of neutron calibration fields, in this work, consist of physical quantity (*i.e.*, the integrated neutron fluence rate over a neutron spectrum, ϕ); operational dosimetric quantities (*i.e.*, ambient dose equivalent rate, $\dot{H}^*(10)$) and radiation quantities (*i.e.*, fluence-spectrum-averaged energies, $\overline{E}$; fluence-to-ambient dose equivalent conversion coefficient, h^*). The technical parameters of neutron reference fields were reported for different radiation beam qualities following the ISO-8529 and the ISO-12789 series (*i.e.*, for direct neutron component from a neutron reference fields of a bare ^{241}Am-Be, complied with the ISO-8529 series criteria; and for total neutron component from simulated workplace neutron reference fields of a ^{241}Am-Be source moderated by different polyethylene spheres and from a neutron reference field of a bare ^{239}Pu-Be source, complied with the ISO-12789 series criteria). The technical parameters of the ISO-8529 neutron reference field of the bare ^{241}Am-Be source were theoretically calculated based on the total neutron source strength and presented for direct neutron component. In addition, the technical parameters of the ISO-12789 simulated workplace neutron reference fields of the ^{241}Am-Be source moderated by different polyethylene spheres as well as of the ^{239}Pu-Be source were characterized using the Bonner sphere spectrometer system accompanying with the FRUIT neutron spectrum unfolding code for the total neutron component. The technical parameters as well as their combined standard uncertainties of neutron fields were also presented in conjunction with different distances from the sources' centers.

Keywords: Quantities / operational dosimetric / reference fields

1 Introduction

There are various types of neutron measuring devices (referred to neutron meters) to be used for measuring neutron physical quantity (*i.e.*, integrated neutron fluence rate, ϕ) and/or neutron operational dosimetric quantities (*i.e.*, ambient dose equivalent rate, $\dot{H}^*(10)$; personal dose equivalent rate, $\dot{H}_p(10)$) for the purposes of radiation protection and safety assessment. For different purposes of measurements, neutron meters are maybe in active (Fuji Electric; Model 12-4-Ludlum; VF Nuclear) and/or in passive (The Thermo Fisher Scientific) types.

For ensuring the proper operations of neutron meters, calibrations must be done prior to, and periodically after their first use (IAEA, 2000). In a calibration certificate, in term of physical quantity (*i.e.*, ϕ) and/or operational dosimetric quantities (*i.e.*, $\dot{H}^*(10)$; $\dot{H}_p(10)$), radiation quantities (*i.e.*, neutron fluence-spectrum-averaged energies, $\overline{E}$ and/or fluence-to-ambient dose equivalent conversion coefficient, h^*) must be mentioned since indicators of neutron meters are dependent on those quantities. Recent years, neutron reference fields have been established for calibrations of neutron meters, in world-wide (Mazrou *et al.*, 2008; Guzman-Garcia *et al.*, 2015; Vykydal *et al.*, 2015; Vega-Carrillo and Martinez-Ovalle, 2016) as well as in Viet Nam (Le *et al.*, 2016, 2017, 2018, 2019, 2024 ; Nguyen *et al.*, 2024).

In this work, technical parameters (including physical, operational dosimetric, and radiation quantities) were presented at different distances from the sources' centers. The technical parameters were respectively presented in manners of theoretical calculations (*i.e.*, for the ISO-8529 neutron reference field of a bare ^{241}Am-Be source) and of experimental data using the Bonner sphere spectrometer (BSS) system (*i.e.*, for the ISO-12789 simulated workplace neutron reference fields of the ^{241}Am-Be source moderated by different

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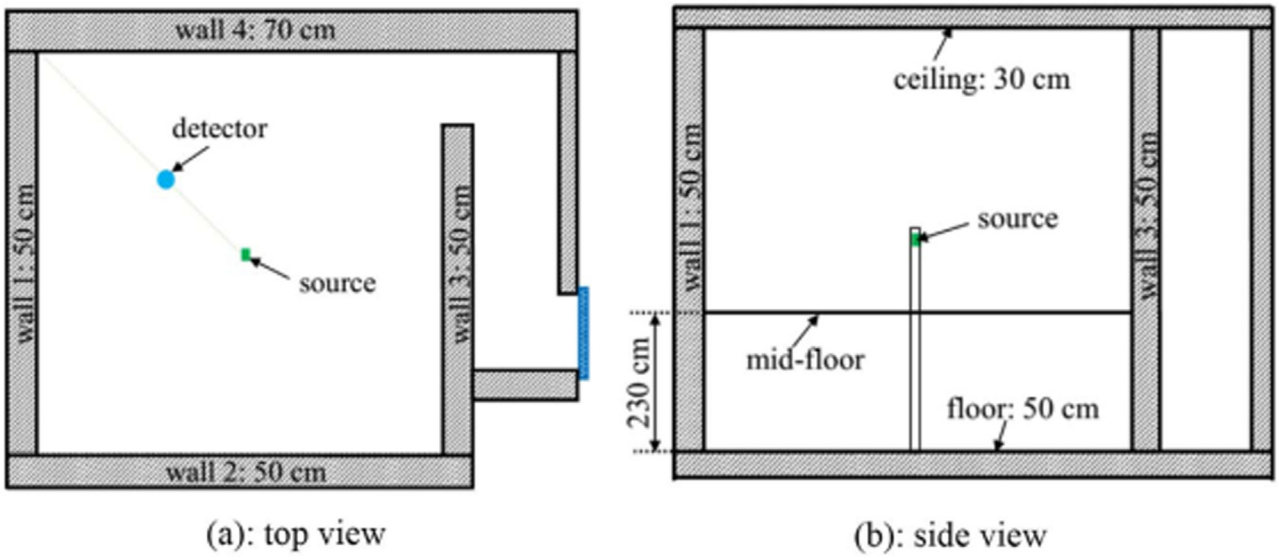

Fig. 1. Top view and side view of neutron calibration room at the Institute for Nuclear Science and Technology.

polyethylene spheres and for the ISO-12789 simulated workplace neutron reference field of the ^{239}Pu-Be source). The combined standard uncertainties of technical parameters of neutron reference fields were also investigated.

2 Material and method

2.1 Neutron reference field in Viet Nam

The neutron room at the Institute for Nuclear Science and Technology (INST) has inner dimensions of 700 cm × 700 cm × 700 cm, satisfied the ISO-8529 recommendation (ISO 8529-2, 2000). The layout of the neutron calibration room can be found in Figure 1. In recent years, a X14-type ^{241}Am-Be neutron source has been installed at the room's center for calibration purposes. The neutron emission rate of the X14-type ^{241}Am-Be source (supplied by Hopewell Designs, Inc., USA) was 1.299×10^7 s^{-1} on 23 January 2015 with the expanded uncertainty of 2.9% ($k = 2$, shown in a certificate), it is traceable to the USA National Institute of Standards and Technology. The source anisotropy correction factor at the angle of 90 degrees (perpendicular to the cylindrical neutron source's central axis at the source center), $F_1(90)$ was investigated as 1.030 using the MCNP5 Monte Carlo simulation code, with the standard uncertainty of 0.1% ($k = 1$). The half-life of ^{241}Am-Be source is 432 yr, considered as an economy advantage point for routine calibrations. More detailed information about the source can be found in Ref. (Le *et al.*, 2018).

Based on this neutron source, several neutron reference fields were established at the INST (Hanoi, Viet Nam), following the international criteria: *i.e.*, ISO-8529 series (Le *et al.*, 2018) and ISO-12789 series (Le *et al.*, 2019). These neutron reference fields are routinely used for calibrations of neutron meters at the INST (Le *et al.*, 2019; Nguyen *et al.*, 2020) as well as for delivering standard neutron dose equivalents (Nguyen *et al.*, 2024).

The neutron room at the Military Institute for Chemical and Environmental Engineering (MICEE, Hanoi, Viet Nam) is a cubic one with inner dimensions of 700 cm × 700 cm × 700 cm. The room was constructed at an unoccupied area and at basement floor. The values of $\dot{H}^*(10)$ outside the room were measured before putting the room into operation and yearly investigated to ensure the safety working conditions for radiation workers and public, complied with Vietnamese legal requirements. The MICEE neutron source of ^{239}Pu-Be was granted by Russia some decades ago. It had been stored as a disused source till being used for establishing the neutron reference field at MICEE by 2020. The neutron source strength of the ^{239}Pu-Be source was 4.6×10^6 s^{-1} in 1981 with the standard uncertainty re-assessed within 5.0% ($k = 1$). This neutron emission rate is considered as constant during usage process since the source's half-life is as long as 2.41×10^4 yr. The cylindrical shape of the ^{239}Pu-Be source has a height of 3.3 cm and a diameter of 2.9 cm, which was installed at the floor's center and pumped to the height of 150 cm for irradiation. The source anisotropy correction factor, $F_1(90)$ was investigated as 1.029 using the MCNP6 Monte Carlo simulation code, with the standard uncertainty of 0.3% ($k = 1$) (Nguyen *et al.*, 2024). The layout of the neutron calibration room can be found in Figure 2.

This neutron reference field was established and being used for calibration purposes at the MICEE.

2.2 Bonner sphere spectrometer system

In this work, the Bonner sphere spectrometer (BSS) system was used with different spherical moderators to measure the count rate, M_i (unit in count per second, cps; and "i" stands for the BSS sphere diameter in inches) caused by neutrons from the moderated ^{241}Am-Be, and ^{239}Pu-Be sources. The BSS system has a ^{6}LiI(Eu) thermal neutron sensitive detector and 6 different high density ($\rho = 0.95$ g.cm^{-3}) polyethylene Bonner spheres with respective different diameters of 2, 3, 5, 8, 10, and 12 inches (*i.e.*, $i = 0$, without a moderator; 2; 3; 5; 8; 10; and 12). The cylindrical thermal neutron detector of the ^{6}LiI(Eu) scintillation crystal has 96% purity of ^{6}Li with a height of 0.4 cm and a diameter of 0.4 cm. The BSS system was used to detect neutrons from thermal energy up to 20 MeV.

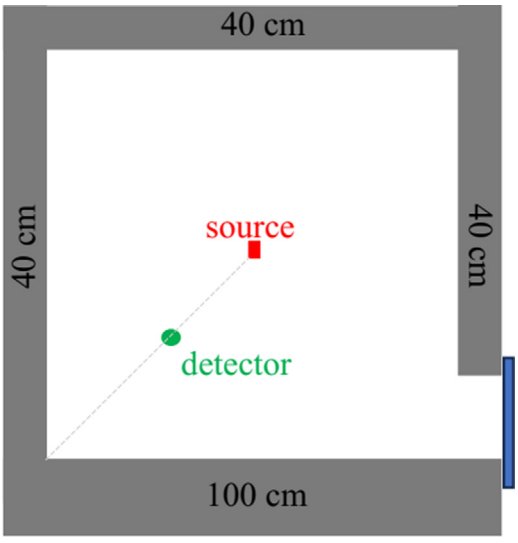

Fig. 2. Top view of neutron calibration room at the Military Institute for Chemical and Environmental Engineering.

The different diameters of the BSS system have different neutron fluence-response functions, $R_{ib}(E_b)$. A neutron fluence-response function of a BSS is considered as the distribution of the BSS count rate, $R_{ib}(E_b)$ in the energy bin E_b, as a function of neutron fluence in that energy bin). The values of $R_{ib}(E_b)$ of different Bonner spheres were investigated using both of MCNP5 and MCNP6 Monte Carlo simulation codes. More detailed information about the values of $R_{ib}(E_b)$ can be found in previous works (Nguyen *et al.*, 2024; Le, 2020).

2.3 Neutron spectrum unfolding

In order to find a neutron fluence spectrum (understood as the distribution of spectral neutron fluence rate, $\phi_b(E_b)$ as a function of neutron bin energies, E_b), a neutron spectrum unfolding code is needed to solve a series of equation (1).

$$M_i = \sum_{b=1}^{n} M_{ib}(E_b) = \sum_{b=1}^{n} R_{ib}(E_b)\phi_b(E_b), \quad (1)$$

where, the values of M_i and $R_{ib}(E_b)$ are the input data for the unfolding code. More information about the unfolding codes can be found in Refs. (Le *et al.*, 2018, 2019; Nguyen *et al.*, 2024).

In this work, the FRUIT unfolding code (Bedogni *et al.*, 2007) was used to unfold neutron fluence spectra. As results, neutron fluence spectra at the points of interest were derived (*i.e.*, the values of $\phi_b(E_b)$ are available with the unit can be converted to $cm^{-2}.s^{-1}$).

2.4 Calculation of neutron reference field parameter

For the direct component of neutrons from the ^{241}Am-Be source following the ISO-8529 criteria, it was confirmed in previous work (Le *et al.*, 2018) that: there was good consistence (within 3.0%) in the physical quantity (*i.e.*, ϕ) and operational dosimetric quantity (*i.e.*, $\dot{H}^*(10)$) between Monte Carlo simulation, theoretical calculation, and BSS experimental data. Therefore, in this work, the conventional true values of ϕ and $\dot{H}^*(10)$ for the direct component of neutrons from the ^{241}Am-Be source (following the ISO-8529 criteria) were calculated using equations (2) and (3). Where, $B_b(E_b)$ is neutron source strength in the individual E_b energy bin (unit in s^{-1}) at the time of calculation; $F_A(l)$ is the air attenuation correction factor (calculated based on guidance from Ref. (ISO 8529-2, 2000); $F_1(90)$ is the anisotropy correction factor of the source; l is the distance (unit in cm) from the source's center to the detector's center; $h^*(E_b)$ can be taken from international published data, *i.e.*, ICRU-57 (ICRU, 1998).

$$\phi = \sum_{b=1}^{n} \phi_b(E_b) = \frac{\sum_{b=1}^{n} B_b(E_b) \times F_A(l) \times F_1(90)}{4\pi l^2}, \quad (2)$$

$$\dot{H}^*(10) = \sum_{b=1}^{n} \phi_b(E_b) \cdot h^*(E_b), \quad (3)$$

In the other hand, for the total component of neutrons from reference fields of the moderated ^{241}Am-Be source and of ^{239}Pu-Be source, the field characterization process (following the ISO-12789 criteria) was performed in such sequent steps: (i) the BSS count rates (M_i) were measured for all BSS sphere at the point of interest during a suitable period so that the statistical uncertainty of M_i less than 1.0%; (ii) the values of M_i and $R_{ib}(E_b)$ were prepared as input data for the FRUIT unfolding code; (iii) neutron fluence spectrum was unfolded using the FRUIT code with some constrain conditions (*i.e.*, the standard deviation between unfolded and input BSS count rates must be less than 3.0%; calibration factor of BSS as 1.0). As results, the unfolded spectral neutron fluence rates, $\phi_b(E_b)$, were achieved, the conventional true values of $\phi, \dot{H}^*(10)$, as well as the radiation quantities (*i.e.*, $\overline{E}$ and h^*) were then respectively calculated using equations (4)–(7).

$$\phi = \sum_{b=1}^{n} \phi_b(E_b), \quad (4)$$

$$\dot{H}^*(10) = \sum_{b=1}^{n} \phi_b(E_b) \times h^*(E_b), \quad (5)$$

$$\overline{E} = \frac{\sum_{b=1}^{n} E_b \times \phi_b(E_b)}{\phi}, \quad (6)$$

$$h^* = \frac{\dot{H}^*(10)}{\phi}. \quad (7)$$

Table 1. Physical (ϕ), operational dosimetric ($\dot{H}^*(10)$), and radiation ($\overline{E}$, h^*) quantities of different neutron reference fields available in Vietnam for calibrations of neutron meters.

Source	Quantity	Source-to-detector distance (cm)			
		100	150	200	250
^{241}Am-Be	ϕ(cm^{-2}.s^{-1})	104.4	46.4	26.1	16.7
^{241}Am-Be (15PE)		120.5	67.4	49.6	42.2
^{241}Am-Be (20PE)		101.7	57.1	43.4	37.0
^{241}Am-Be (25PE)		90.7	53.6	37.2	30.0
^{241}Am-Be (30PE)		69.0	40.0	29.4	25.3
^{241}Am-Be (35PE)		56.5	33.0	23.3	19.7
^{239}Pu-Be		41.3	23.7	18.0	15.0
^{241}Am-Be	$\dot{H}^*(10)$(μSv.h^{-1})	147.0	65.3	36.7	23.5
^{241}Am-Be (15PE)		99.6	52.5	33.3	25.4
^{241}Am-Be (20PE)		82.8	40.5	26.8	20.4
^{241}Am-Be (25PE)		68.1	34.1	21.0	15.8
^{241}Am-Be (30PE)		51.8	25.8	17.4	12.6
^{241}Am-Be (35PE)		38.9	20.4	13.0	9.5
^{239}Pu-Be		44.9	21.8	15.1	11.2
^{241}Am-Be	$\overline{E}$(MeV)	4.16	4.16	4.16	4.16
^{241}Am-Be (15PE)		1.67	1.57	1.36	1.13
^{241}Am-Be (20PE)		1.59	1.21	1.08	0.96
^{241}Am-Be (25PE)		1.74	1.41	1.01	0.90
^{241}Am-Be (30PE)		1.63	1.18	1.14	0.92
^{241}Am-Be (35PE)		1.30	1.28	1.06	0.83
^{239}Pu-Be		2.94	1.97	1.70	1.27
^{241}Am-Be	h*(pSv.cm^2)	391	391	391	391
^{241}Am-Be (15PE)		230	216	187	167
^{241}Am-Be (20PE)		226	197	171	153
^{241}Am-Be (25PE)		209	176	157	147
^{241}Am-Be (30PE)		208	179	164	138
^{241}Am-Be (35PE)		191	172	155	134
^{239}Pu-Be		302	256	233	207

Notation:
^{241}Am-Be: the ISO-8529 neutron reference field of the direct component;
^{241}Am-Be (15PE): understood as the ISO-12789 simulated workplace neutron field, moderated by a polyethylene sphere with a diameter of 15 cm;
^{239}Pu-Be: ISO-12789 neutron reference field of the total component

2.5 Assessment of combined standard uncertainty of technical parameter

Based on the uncertainty propagation principle, one can figure out that the combined standard uncertainties of all quantities (*i.e.*, physical, operational dosimetric, and radiation quantitites – calculation models in equations (2)–(7)) have the same uncertainty propagation rule. In other words, the combined standard uncertainty of an individual quantity (u_Q) is equal to square root of summed squares of its all uncertainty budgets (u_b). In general, the value of u_Q can be calculated using equation (8).

$$u_Q = \sqrt{\sum_{b=1}^{all} u_b^2} \tag{8}$$

3 Result

3.1 Technical parameter of neutron calibration field

Table 1 shows the technical parameters (including of physical – ϕ, operational dosimetric – $\dot{H}^*(10)$, and radiation – $\overline{E}$, h*, quantities) at different distances from the sources' centers for different neutron reference fields.

3.2 Combined standard uncertainty of technical parameter

Table 2 shows the combined standard uncertainties of conventional true values of technical parameters of different neutron reference fields in conjunction with the uncertainty budgets.

Table 2. Combined standard uncertainties of technical parameters of neutron reference fields available in Vietnam.

Neutron reference field	Quantity	Combined standard uncertainty, k = 1 (%)
^{241}Am-Be	ϕ	2.1
	$\dot{H}^*(10)$	4.5
	$\overline{E}$	3.0
	h*	5.0
^{241}Am-Be (15PE)	Φ	3.2
^{241}Am-Be (20PE)	$\dot{H}^*(10)$	5.1
^{241}Am-Be (25PE)		
^{241}Am-Be (30PE)	$\overline{E}$	4.5
^{241}Am-Be (35PE)	h*	6.0
^{239}Pu-Be		

Notation: *Value of uncertainty budget,* $\mathbf{u_b}$ *(%):*
$B_b(E_b)$: 1.5% (stated in a certificate);
l: 1.0% (maximum estimated);
$F_A(l)$: 1.0% (based on influenced factors in calculation dependent on different total cross section uncertainty);
$F_1(90)$: 0.3% (maximum investigated);
$h^*(E_b)$: 4.0% (stated in (ICRU, 1998));
M_i: 1.0% (targeted in measurements);
$R_{ib}(E_b)$: 3.0% (estimated).
For direct component of neutrons from a bare ^{241}***Am-Be source (ISO-8529 criteria):***
Uncertainty budgets taken into account for standard uncertainty of ϕ: $\phi_b(E_b)$, l, $F_A(l)$, $F_1(90)$;
Uncertainty budgets taken into account for standard uncertainty of $\dot{H}^*(10)$: ϕ_b, $h^*(E_b)$;
Uncertainty budgets taken into account for standard uncertainty of $\overline{E}$: ϕ_b
Uncertainty budgets taken into account for standard uncertainty of h^*: ϕ; $\dot{H}^*(10)$
For total component of neutrons from other sources (ISO-12789 criteria):
Uncertainty budgets taken into account for standard uncertainty of ϕ: M_i, $R_{ib}(E_b)$
Uncertainty budgets taken into account for standard uncertainty of $\dot{H}^*(10)$: ϕ, $h^*(E_b)$;
Uncertainty budgets taken into account for standard uncertainty of $\overline{E}$:ϕ
Uncertainty budgets taken into account for standard uncertainty of h^*: ϕ; $\dot{H}^*(10)$

4 Discussion

4.1 Feasible range for calibration

From Table 1, ones can figure out that the feasible range of $\dot{H}^*(10)$, for calibrations of neutron meters, is from 10 to 150 μSv/h (for the calibration distance from 100 to 250 cm). This range is limited for calibrations of neutron meters at higher measuring range of $\dot{H}^*(10)$. However, it is acceptable for calibrations of neutron meters with preferred measuring range at radiation protection level.

In the investigated distances, the feasible delivery range of ϕ is from 15 to 105 $cm^{-2}.s^{-1}$ while the fluence-spectrum-averaged energies ($\overline{E}$) of the neutron fields vary from 0.83 to 4.16 MeV (corresponding to the values of h* from 134 to 391 $pSv.cm^2$).

For calibration of neutron meters following the ISO-8529 criteria, the contribution of scattered neutrons to the reading of meter to be calibrated must be less than 40% that of the direct component. It was found that it corresponds to the distance less than 250 cm from the source's center.

For calibration of neutron meters following the ISO-12789 criteria, the total component of neutrons can be used. Therefore, the calibrations can be done since the statistical uncertainty of neutron meters whose readings have a statistical uncertainty less than 10%. It was found that the distance from the source's center less than 250 cm is acceptable.

4.2 Accuracy in neutron field parameter

From Table 2, ones can see that the combined standard uncertainties of technical parameters of the neutron reference fields are acceptable in conjunction with those stated in international publications, *i.e.*, acceptable standard uncertainties in determination of ϕ as 5.0-10%; in determination of h* as 15% (ISO 12789-2, 2008). That means the acceptable combined standard uncertainty (k=1) in determination of $\dot{H}^*(10)$ can be even higher than 15% (based on uncertainty propagation principle of equation (7)). Even, the acceptable standard uncertainty in determination of $\overline{E}$ is not yet mentioned in Ref. (ISO 12789-2, 2008) but it could be understood that the uncertainty of $\overline{E}$ can be acceptable if it does not cause the change in $\dot{H}^*(10)$ over 15%.

5 Conclusions

Various neutron reference fields were established in Viet Nam for calibrations of neutron meters. The technical parameters of neutron reference fields were characterized and presented in this work, such as: physical quantity (integrated neutron fluence rate, ϕ), operational dosimetric quantity (neutron ambient dose equivalent rate, $\dot{H}^*(10)$) as well as radiation quantities (neutron fluence-spectrum-averaged energy, $\overline{E}$; fluence-to-ambient dose equivalent conversion

coefficient, h^*). The combined standard uncertainties of technical parameters were also investigated and presented in this work. The conventional true values of technical parameters of the neutron fields indicate that the determination of those conventional true values are reliable with the acceptable combined standard uncertainties. That means the neutron fields can be feasibly used in calibrations of neutron meters in Viet Nam following the ISO-8529 (direct component of neutrons) and the ISO-12789 (total component of neutrons) criteria.

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Conflicts of interest

There is no competing interests regarding the publication of this paper.

Data availability statement

Data will be available upon request.

References

Bedogni R, Domingo C, Esposito A, Fernández F. (2007) FRUIT: An operational tool for multisphere neutron spectrometry in workplaces, *Nucl. Instrum. Methods Phys. Res., Sect. A.* 580(3), 1301–1309. https://www.sciencedirect.com/science/article/abs/pii/S0168900207014556

Fuji Electric; *Portable Neutron Survey Meter.* https://www.fujielectric.com/products/sensors_measurements/radiation/product_series/survey_nsn3.html (accessed on May 15, 2024)

IAEA Safety Report Series No.16 (2000) Calibration of radiation protection monitoring instruments. https://www.iaea.org/publications/5149/calibration-of-radiation-protection-monitoring-instruments

ICRU Publication 57 (1998) Conversion Coefficients for Use in Radiological Protection Against External Radiation, Ann. ICRP 57.

ISO 8529-2 (2000) Reference Neutron Radiations – Part 2: Calibration Fundamentals of Radiation Protection Devices Related to the Basic Quantities Characterizing the Radiation Field.

ISO 12789-2 (2008) Reference radiation fields – Simulated workplace neutron fields – Part 2: Calibration fundamentals related to the basic quantities.

Guzman-Garcia KA, Mendez-Villafañe R, Vega-Carrillo HR. (2015) Neutron Field Characteristics of Ciemat's Neutron Standards Laboratory, *Appl. Radiat. Isot.* 100, 84–90. https://www.sciencedirect.com/science/article/abs/pii/S0969804314003856

Le NT, Hoang TPH, Hui Z, Bui DK, Nguyen NQ, Hoang VK, Dinh TH, Nguyen MC, Cao VH, Tran HN. (2024) Intercomparison of neutron personal dose equivalent measured by thermoluminescence dosimeters, *Appl. Radiat. Isot.* 205, 111175. https://doi.org/10.1016/j.apradiso.2024.111175

Le NT, Hoang SMT, Nguyen NQ, Tran HN. (2019) Evaluation of the Calibration Factors of Neutron Dose Rate Meters in a Neutron Field, *Nucl. Sci. Techniq.* 30, 133. https://doi.org/10.1007/s41365-019-0654-7

Le NT. (2020) Establishment of Neutron Reference Fields in Vietnam: A Review, *Philippine J. Sci.* 149(3-a), 947–954. https://doi.org/10.56899/149.3A.20

Le NT, Tran HN, Nguyen NQ, Trinh VG, Nguyen KT. (2018) Characterization of a Neutron Calibration Field with Source using Bonner Sphere Spectrometers, *Appl. Radiat. Isot.* 133, 68–74. https://doi.org/10.1016/j.apradiso.2017.12.012

Le NT, Tran HN, Nguyen TK, Trinh VG. (2017) Neutron Calibration Field of a Bare ^{252}Cf Source in Vietnam, *Nucl. Eng. Technol.* 49 (1), 277–284. https://doi.org/10.1016/j.net.2016.07.011

Le NT, Nguyen NQ, Ho QT, Trinh VG, Nguyen TK, Nguyen HQ. (2016) Neutron Calibration Field at Institute for Nuclear Science and Technology, *Nucl. Sci. Technol.* 6(4), 01–07. http://www.jnst.vn/index.php/nst/article/view/170

Le NT, Hoang SMT, Nguyen NQ, Liamsuwan T, Tran HN. (2019) Simulated workplace neutron fields of source moderated by polyethylene spheres, *J. Radioanal. Nucl. Chem.* 321, 313–321. https://doi.org/10.1007/s10967-019-06577-8

Mazrou H, Sidahmed T, Idiri Z, Lounis-Mokrani Z, Bedek S, Allab M. (2008) Characterization of the CRNA Bonner sphere spectrometer based on ^{6}LiI scintillator exposed to an neutron source, *Radiat. Meas.* 43(2), 1095–1099. https://doi.org/10.1016/j.radmeas.2007.11.004

Model 12-4-Ludlum. *Neutron Dose Ratemeter, Model 12-4.* https://ludlums.com/products/all-products/product/model-12-4 (accessed on May 15, 2024).

Nguyen NQ, Hoang TPH, Nguyen MC, Dinh TH, Cao VH, Le NT. (2024) neutron reference field: physical and dosimetric parameters, *Radiation Physics and Chemistry*, Vol. 217 (111522). https://doi.org/10.1016/j.radphyschem.2024.111522

Nguyen TK, Tran HN, Nguyen NQ, Dang TML, Bui VL, Liamsuwan T, Le NT. (2020) Calibration of a neutron dose rate meter in various neutron standard fields, *Nucl. Sci. Techniq.* 31, 60. https://doi.org/10.1007/s41365-020-00763-0

The Thermo Fisher Scientific, *Thermo Scientific Harshaw TLD Materials and Dosimeters.* https://assets.thermofisher.com/TFS-Assets/LSG/Catalogs/Dosimetry-Materials-Brochure.pdf *(accessed on May 15, 2024)*

Vega-Carrillo HR, Martinez-Ovalle SA. (2016) Few groups neutron spectra, and dosimetric features of isotopic neutron sources, *Appl. Radiat. Isot.* 117, 42–50. https://doi.org/10.1016/j.apradiso.2016.03.027

VF Nuclear; *MDN-01 Neutron Dose Rate Meter.* https://www.vfnuclear.com/en/products/50/neutron-dose-rate-meter *(accessed on May 15, 2024)*

Vykydal Z, Králík M, Jančář A, Kopecký Z, Dressler J, Veškrna M. (2015) Characterization of the Graphite pile as a source of thermal neutrons, *Radiat. Phys. Chem.* 116, 65–68. https://doi.org/10.1016/j.radphyschem.2015.01.028

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