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DOSIMETRIC ASSESSMENT AND CHARACTERISATION OF THE NEUTRON FIELD AROUND A HOWITZER CONTAINER USING A BONNER SPHERE SPECTROMETER, MONTE CARLO SIMULATIONS AND THE NSDANN AND NSDUAZ UNFOLDING CODES

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The Neutron Measurements Laboratory at the Nuclear Engineering Department of the Polytechnic University of Madrid consists of a bunker-like room and was built for neutron dosimetry research purposes and measurements. The facility includes a 74-GBq ^{241}Am–Be neutron source placed inside a neutron Howitzer container. The source can be moved to the irradiation or to the storage position. In this work, a Bonner sphere spectrometer (BSS) was used to measure the neutron fluence spectra with the source in both positions. Ambient dose equivalent rates, $\dot{H}^*(10)$, were measured using a calibrated neutron area monitor LB6411 (Berthold). The measured count rates were used as input to the NSDann and NSDUAZ unfolding programs to obtain the neutron fluence spectra and $\dot{H}^*(10)$. Monte Carlo (MC) simulation methods were used to model the system and to calculate the neutron fluence rate and the ambient dose equivalent rate at the measurement points. The comparison between NSDUAZ and NSDann resulted in relative deviations up to 6.87 % in the total neutron fluence rate and 7.18 % in $\dot{H}^*(10)$ values, despite the differences in the shape of the spectra obtained for the irradiation position. Comparing with the measured values, the $\dot{H}^*(10)$ values obtained with the unfolding programs exhibit a maximum relative deviation of 12.19 %. Taking into account the associated uncertainties, MC simulations seem to be in reasonable agreement with measurements. A maximum relative deviation of 15.65 % between computed and measured $\dot{H}^*(10)$ values was obtained. The computed count rates were applied to the unfolding programs to calculate the total neutron fluence rate and a maximum deviation of 12.83 % was obtained between the original values calculated by NSDann. A sensitivity test showed that the NSDann unfolding program is very sensitive to the uncertainties of the BSS count rates.

INTRODUCTION

The Bonner sphere spectrometer (BSS) was first introduced in 1960 by Bramblett, Ewing and Bonner(1). It consists of a set of spherical polyethylene moderators with different diameters, with a thermal neutron detector at its centre. BSS allows for the measurement of neutron spectra in a wide range of energies (thermal up to around 20-MeV neutrons)(2). However, the spectrometer response may be extended to hundreds of MeV introducing a high-Z metal shell in the polyethylene spheres(3, 4). Since the BSS concept was introduced, the utilisation of Bonner Spheres to perform neutron spectrometry has been extensively documented in the literature(5–8).

There are several unfolding techniques based on different mathematical principles, such as least-squares adjustments(9), maximum entropy(10), iteration methods(9) and artificial neural networks (ANN)(11), which are used to obtain the neutron spectrum using the count rates measured with the BSS. Several computer programs make use of these techniques to characterise the neutron fields. Some examples are MSDANB(12), MAXED(10), FRUIT(13) and BUNKI(14). In this study, two unfolding computer programs, NSDann and NSDUAZ(15, 16), were used to obtain the neutron energy fluence and the ambient dose equivalent rate, $\dot{H}^*(10)$, around a neutron Howitzer container.

NSDann makes use of artificial neural networks to unfold the neutron spectrum, while NDSUAZ makes use of the iterative algorithm SPUNIT and uses the UTA4 response matrix(17). The uncertainties associated with the neutron spectrum unfolding are related to the used unfolding methods, the used response matrix and experimental uncertainties, such as the BSS count rates uncertainty and detector's calibration[9,18,19].

In this work, a six-sphere BSS was used to characterise the neutron field around the neutron Howitzer container of the Neutron Measurements Laboratory at the Nuclear Engineering Department of the Polytechnic University of Madrid (DIN-UPM). The laboratory is equipped with two ^{241}Am–Be neutron sources, with activities 74 and 111 GBq. It includes a facility and associated infrastructure to perform research on neutron dosimetry and neutron spectrometry techniques and for the calibration and controlled irradiation of instruments using neutron fields[20, 21]. The facility is inside a bunker-like room with 9 m $\times$16 m$\times$8 m dimensions and 50-cm thick walls. It was built accordingly to the recommendations and prescriptions of the International Organization for Standardization (ISO) 8529 standard, aiming at featuring equivalent conditions of those existing at calibration laboratories[22, 23]. The facility includes a neutron Howitzer device, placed in a corner of the laboratory and surrounded by a structure of concrete bricks. The radioactive neutron source inside the Howitzer container is a 74-GBq ^{241}Am–Be source. The neutron Howitzer is an aluminum cylinder container allowing for the neutron source to be in two positions: irradiation or storage.

The objectives of the work reported here were to perform the dosimetric assessment and characterisation of the neutron field around the Howitzer container with the neutron source in both positions. To achieve these goals, both measurements of the count rates in the Bonner spheres and MC simulations of the experimental set-up were performed in order to determine the neutron spectra and ambient dose equivalent. The comparison between the MC simulation results and those obtained from the unfolding programs using the measured count rates was also performed.

The neutron Howitzer geometry and constituent materials, the neutron source and the measurement devices were accurately modelled and simulated using the state-of-the-art MC simulation program MCNPX 2.7[24]. A reasonable agreement was found between the computational results and the measurements, with relative deviations of, in the worst situation, 22.91 %.

MATERIALS AND METHODS

The neutron Howitzer is an aluminum cylindrical container with a diameter of 57 cm and a height of 86 cm. It is internally filled with paraffin and has an inner axial cylindrical hole that allows the neutron source to be moved to the central (irradiation) or to the lower (storage) position by means of a methacrylate bar. Neutron irradiation is carried out when the centre of the source is aligned with two radial cylindrical holes. Figure 1 shows the Howitzer container with a Bonner sphere aligned with the irradiation tube. To characterise the neutron spectrum emerging from the Howitzer, measurements and MC simulations were carried out. Measurements were performed with the UPM BSS and with a neutron area monitor. MC simulations were performed using the state-of-the-art MC computer program for particle transport simulation MCNPX 2.7.

Figure 1. Image of the neutron Howitzer container with a Bonner sphere aligned with the irradiation tube.

Measurements

The ^{241}Am–Be neutron source used in this work has a 74-GBq activity. It is cylindrically shaped and has a radius of 0.740 cm and a height of 3.175 cm. The source has a thickness of 0.21-cm steel cladding.

The neutron fluence spectra were obtained after measurements of the neutron count rates performed using a BSS system composed of six polyethylene spheres (0.95 g cm^{-3}) with diameters of 5.08, 7.62, 12.7, 20.32, 25.4 and 30.48 cm with a 0.4 cm $\times$ 0.4 cm ^{6}LiI(Eu) scintillator. Measurements were also performed with the bare detector, i.e. with the detector without the polyethylene sphere around it. The time acquisition was different for each sphere in order to obtain a statistical uncertainty $<$2 %. The count rates were measured 44.5 cm away from the centre of the container. In both the irradiation and storage positions, the detectors were aligned with the source. This means that in the case of irradiation position, the detectors were also aligned with the irradiation tube.

Figure 2 shows the MCNPX model of the Howitzer container and the 12.7-cm sphere, with

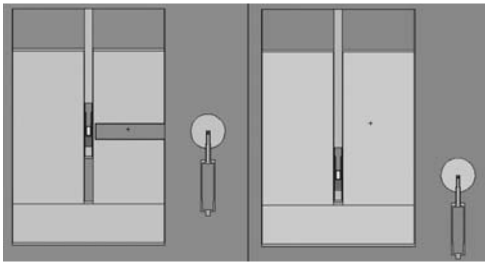

Figure 2. MCNPX implemented model of the neutron Howitzer container and a Bonner sphere. In the left side is shown the source in the irradiation position and in the right side the source in the storage position.

the source in the irradiation and storage positions. The neutron spectra were unfolded with the NSDann and NSDUAZ programs to compare the results. These codes determine the ambient dose equivalent rate, $H^*(10)$, which was also directly measured with the Berthold neutron dose rate meter LB6411[25], at the same position of the count rates acquisition.

MC calculations

In order to calculate the neutron fluence and $H^*(10)$, an accurate description of the geometry and constituent materials of the ^{241}Am–Be source, the Howitzer container, the concrete bricks structure, the floor and walls was implemented in the MCNPX 2.7 code. The source neutron emission spectrum was taken from ISO 8529, which represents the neutron energy distribution of a lightly encapsulated ^{241}Am–Be source[22]. Because MCNPX does not include the thermal dispersion libraries for paraffin, the authors have decided to replace this material by polyethylene in order to include the thermal dispersion in the simulations.

Calculations were performed to determine the count rate for each Bonner sphere for both source positions, at the measuring positions. The neutron fluence spectra were also directly determined by estimating the flux averaged over a cell, which, in MCNPX terminology, is obtained using the F4 tally. The cell used in tally F4 has a diameter of 20.32 cm, which is the diameter of the Berthold LB6411 used in the measurements. With this configuration, the cell comprises the beam coming from the Howitzer container and the surrounding space occupied by the Berthold. The ambient dose equivalent was obtained from the neutron spectra, using the ICRP 74[26] and the Berthold LB6411 fluence-to-ambient dose equivalent coefficients[25]. The ENDF/B-VI libraries[27] were used in the simulations. An appropriate number of histories were simulated in order to keep the statistical uncertainties <5 %.

RESULTS AND DISCUSSION

Fluence rate: measurements and unfolded results

The count rates measured with the BSS for the irradiation and storage positions are shown in Table 1. The Genie-2000® spectroscopic software[28] permits the analysis of the recorded pulse-height distributions. It was used to obtain the BSS count rates by dividing the area of the peak of the pulse-height spectrum by the live time of the data acquisition.

Using these count rates, the neutron fluence rate spectra were unfolded with the NSDann and NSDUAZ unfolding programs. The obtained spectra for the irradiation position are shown in Figure 3.

It can be observed that both unfolded spectra have the same fluence rate in the thermal region. However, sizable differences are observed in the epithermal and fast regions, even though both present a maximum for higher energies, around 2–4 MeV, as expected, since the neutron energy emitted by the ^{241}Am–Be source extends from 2 to 8 MeV.

Table 1. Measured count rates with BSS, at 44.5 cm from the centre of the Howitzer container.

Sphere diameter (cm)	Source position	
	Irradiation (cps)	Storage (cps)
Bare	9.58 ± 0.09	1.57 ± 0.01
5.08	12.54 ± 0.12	1.81 ± 0.01
7.62	22.71 ± 0.19	2.53 ± 0.02
12.70	36.88 ± 0.23	3.38 ± 0.02
20.32	27.08 ± 0.22	3.03 ± 0.02
25.40	20.52 ± 0.17	2.37 ± 0.01
30.48	14.10 ± 0.12	1.75 ± 0.01

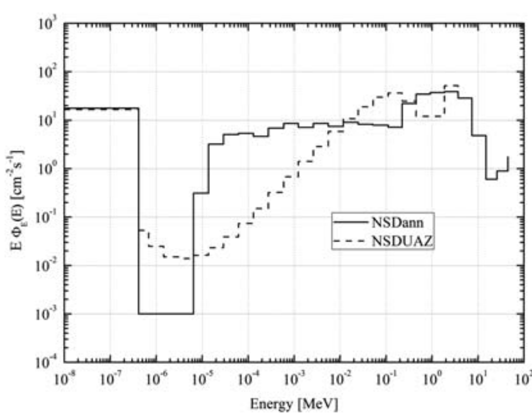

Figure 3. Neutron fluence rate energy spectra with the source in irradiation position, obtained with the BSS measurements. The spectra were unfolded with the NSDUAZ and NSDann unfolding programs.

The observed discrepancies may be attributed to the different methods used by each program to unfold the spectrum.

Despite this, the total neutron fluence rate has a deviation of 4.08 % as shown in Table 2. The presented uncertainties were taken from the uncertainties of the count rates. The uncertainties associated with the unfolding processes are not assigned since these are not provided by the unfolding programs.

Ambient dose equivalent rate: measurements and unfolded results

Table 3 presents the $\dot{H}$*(10) values calculated by the unfolding programs, as well the values measured with the calibrated Berthold LB6411 area monitor. With the source in the irradiation position, the maximum deviation between the values obtained with the unfolding programs and the Berthold LB6411 measurements is 9.61 %. This deviation may be related to the used unfolding techniques and also to the distinct fluence-to-ambient dose equivalent conversion factors used by the unfolding programs and by the Berthold area monitor.

The fluence rate energy spectra obtained with the source in the storage position are shown in Figure 4. In this case, the fluence rates in the thermal region show a good agreement, whereas the shapes of the spectra are similar for the entire range of energies but exhibit some sizable discrepancies. Also, from Table 2, the deviation between the total neutron fluence rates is 6.87 %. Relatively to the $\dot{H}$*(10) (Table 3), when compared with the Berthold values, the deviation of the values obtained with the unfolding programs is, in the worst case, 12.19 %.

Table 2. Total neutron fluence rate obtained with the unfolding programs.

Source position	Total neutron fluence rate (cm^{-2} s^{-1})		
	NSDann	NSDUAZ	Relative deviation (%) NSDUAZ vs. NSDann
Irradiation	276.51 ± 2.32	265.24 ± 2.23	−4.08
Storage	29.07 ± 0.23	27.08 ± 0.16	−6.87

Monte-Carlo calculations

To compare the simulations with the experimental results, geometries of the source and the Howitzer container were accurately implemented in MCNPX, together with the floor and brick structure around it. According to the manufacturer's certificate, on February of 1969, the ^{241}Am–Be source neutron yield was 5.20×10^6 n s^{-1}. Correcting the value for the date of the measurements (November 2011), a 4.86×10^6 n s^{-1} intensity is obtained as a reference to be used in the calculations.

BSS count rates

To calculate the BSS count rates, all the Bonner spheres and ^{6}LiI(Eu) detector were implemented.

The ^{6}LiI(Eu) scintillator crystal was simulated at the same source-to-detector distance used in the measurements. The ^{6}Li(n, ^{4}He)^{3}H reactions occurring in the crystal were calculated in the MC simulations. Multiplying the number of reactions by the crystal's atomic density and by the detector's active volume and source's intensity, one obtains the count rates of the detection system (Bonner sphere plus ^{6}LiI(Eu) detector). Table 4 displays the calculated count rates and the deviation of the measured ones, for both source positions.

From the table, it can be seen that the maximum deviation between the simulations and the measurements is 19.53 %.

Neutron fluence rate and $\dot{H}$*(10)

The neutron fluence rate was directly calculated in the simulations. To compare the computed total neutron fluence rate, the fluence was computed with the same energy bins used by the unfolding

Table 3. Measured ambient dose equivalent rate with the Berthold LB6411 and corresponding computed values using the BSS count rates and the NSDann and NSDUAZ unfolding codes.

$\dot{H}$*(10) (μSv h^{-1})						
Source position				Relative deviation (%)		
	LB6411	NSDann	NSDUAZ	LB6411 vs. NSDann	LB6411 vs. NSDUAZ	NSDann vs. NSDUAZ
Irradiation	148.93 ± 1.08	164.76	155.58	9.61	4.28	5.90
Storage	21.72 ± 0.44	20.75	19.36	−4.67	−12.19	7.18

programs. Table 5 shows that for the irradiation position the deviation to the values obtained with the unfolding programs goes up to 9.11 % while for the storage position this value goes up to 22.91 %.

The ambient dose equivalent, $H^*(10)$, was obtained by multiplying the fluence by the ICRP 74 and Berthold LB6411 conversion coefficients, for comparison. These values, $MCNPX_{ICRP\ 74}$ and $MCNPX_{LB6411}$, respectively, are present in Table 6. The $H^*(10)$ calculated with the Berthold conversion coefficients were used to compare the simulated results with the measured data.

In the case in which the source is in the irradiation position, the computed values are 9.29 % higher than those measured with the Berthold dose rate meter, and 1.21 and 4.61 % deviated from the values obtained with NSDUAZ and NSDann, respectively. For the storage position, the deviation to the measured $H^*(10)$ values go up to 15.65 %.

For the irradiation position, the neutron spectra is fundamentally typical of a ^{241}Am–Be bare source.

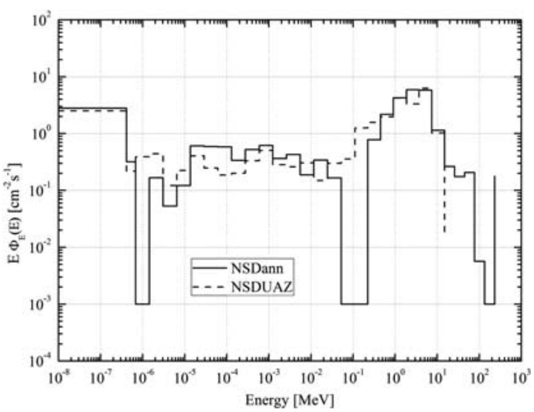

Figure 4. Neutron fluence rate energy spectra with the source in the storage position, obtained with the BSS measurements. The spectra were unfolded with the NSDUAZ and NSDann unfolding programs.

The fact that the computed total neutron fluence and $H^*(10)$ values for the irradiation position are higher than the measured ones may be attributed to the fact that the measured values are being averaged over the surface area of the moderators. This happens because the responses of the detector systems (moderators+detector) are determined with a beam with the same diameter of each moderator and in the experimental situation the radiation emerging from the Howitzer is a mix of direct beam from the source through the radiation tube (5.4 cm) plus scattered and moderated neutrons emerging from the container materials, which is in essence a complex field. Also, besides the uncertainties associated with the unfolding methodologies, the higher deviations when the source is in the storage position may be attributed to the fact that for this position the simulated neutrons have to travel through the thick wall of the container. This enhances the influence of the uncertainties associated with material composition and used libraries.

The MCNPX computed count rates presented in Table 4 were applied to the unfolding programs in order to obtain the corresponding neutron spectra. The NSDUAZ and NSDann neutron spectra are displayed in Figures 5–8, respectively, for the irradiation and storage positions and for both codes. The total neutron fluence rates and the $H^*(10)$ values obtained by using these count rates are present in Tables 7 and 8, respectively.

As expected, since the MNCPX computed and measured count rates are in good agreement for both source positions, the spectra obtained with the MCNPX (referred to as 'NSDUAZ-MCNPX') and with the measured count rates using the NSDUAZ program are similar (Figures 5–6). For each position, both spectra have the same fluence rate in the thermal and fast regions and exhibit the same shape for the whole energy range. The total neutron fluence rates (Table 7) have a maximum deviation of 11.85 % for the irradiation position and 1.12 % when the source is storaged. The $H^*(10)$ values

Table 4. Computed and measured count rates and corresponding statistical uncertainties.

Sphere diameter (cm)	Source in irradiation position			Source in storage position		
	Computed count rates (cps)	Measured count rates (cps)	Deviation (%)	Computed count rates (cps)	Measured count rates (cps)	Deviation (%)
Bare	11.91 ± 0.54	9.58 ± 0.09	19.53	1.58 ± 0.08	1.57 ± 0.03	0.40
5.08	14.01 ± 0.41	12.54 ± 0.12	10.51	2.03 ± 0.06	1.81 ± 0.36	12.27
7.62	20.94 ± 0.51	22.71 ± 0.19	−8.43	2.54 ± 0.07	2.53 ± 0.05	0.59
12.70	33.95 ± 0.65	36.88 ± 0.23	−8.63	3.34 ± 0.08	3.38 ± 0.07	−1.24
20.32	26.76 ± 0.55	27.08 ± 0.22	−1.20	2.90 ± 0.07	3.03 ± 0.06	−4.44
25.40	17.31 ± 0.43	20.52 ± 0.17	−18.53	2.27 ± 0.06	2.37 ± 0.05	−4.29
30.48	12.62 ± 0.36	14.10 ± 0.12	−11.75	1.74 ± 0.05	1.75 ± 0.04	0.42

(Table 8) deviate 1.00 and 5.16 % for the irradiation and storage source positions, respectively.

From Figures 7–8 it can be seen that the fluence rate obtained with NSDann using the MCNPX (referred to as 'NSDann-MCNPX') count rates is the same as that obtained using the measured count rates in the thermal region. Sizable differences are present for the epithermal and fast regions, especially when the source is in the irradiation position. The NSDann-MCNPX total neutron fluence rates are 12.83 % lower than the NSDann values (Table 7) in the irradiation position and 2.16 % in the storage situation. For the irradiation case, Table 8 shows that the NSDann-MCNPX $\dot{H}^*(10)$ value is 25.95 % lower than that obtained with the measured count rates. For the storage position, this value drops to 11.10 %.

As in the NSDUAZ case, these differences can be, in part, explained by the deviation of the MCNPX calculated count rates relative to the measured count rates. On the other hand, having these results in mind, it makes sense to perform a sensitivity test on the unfolding programs. This can be performed by varying a computed count rate with a high deviation relative to the measured values and analysing the variation of the resulting total neutron fluence rate and $\dot{H}^*(10)$ obtained with the unfolding programs. An example is the 25.40 cm sphere value, which has a deviation of 18.53 % relative to the measured value. So, the MCNPX computed count rate of this sphere (17.31 cps) was replaced by the measured count rate value (20.52 cps) and the new set of count rates was applied to the unfolding programs.

The new NSDann $\dot{H}^*(10)$ value is 179.92 μSv h^{-1}, which is 32.19 % higher than the value obtained with the MCNPX calculated count rates (122.01 μSv h^{-1}). However, the new NSDUAZ value (164.04 μSv h^{-1}) is only 6.09 % higher than the original value (154.04 μSv h^{-1}). Concerning the total neutron fluence rates, the NSDann new value is 257.61 cm^{-2} s^{-1}, 6.44 % higher than the previous value (241.02 cm^{-2} s^{-1}). The NSDUAZ value with the new set of count rates is 233.78 cm^{-2} s^{-1}, i.e. 0.09 % lower than the previous value (233.81 cm^{-2} s^{-1}). These results show that NSDann is much more sensitive to the count rate modification, especially when calculating $\dot{H}^*(10)$. Besides the deviation between the calculated and measured count rates, this might also explain the 25.95 % deviation when using the MCNPX computed count rates. In fact, a sensitivity study to an ANN unfolding program was previously performed[11] to analyse the impact of the uncertainties of the BSS count rates. It was concluded that by varying the BSS count rates by ±5 %, the worst unfolding case has differences up to 26 % in the $\dot{H}^*(10)$ value.

Figure 9 shows the fluence rate spectra calculated with 20 bins per decade, with the source in both positions, for comparison. It can be observed that the fraction of thermal neutrons ($E_n < 0.4$ eV) increases when the source is placed in the storage position, as expected. In the irradiation position this fraction is 27 % and in the storage, it is 35 %. Placing the source from the irradiation to the storage position makes the epithermal fraction (0.4 eV $< E_n <$ 200 keV) increase from 10 to 15 %, and the fast fraction ($E_n >$ 200 keV) decrease from 63 to 50 %.

Table 5. Total neutron fluence rate computed with MCNPX and comparison with the values obtained with the unfolding programs.

Source position	Total neutron fluence rate (cm^{-2} s^{-1})		
		Relative deviation (%)	
	MCNPX	NSDann vs. MCNPX	NSDUAZ vs. MCNPX
Irradiation	291.84 ± 0.55	5.25	9.11
Storage	35.12 ± 0.15	17.22	22.91

Uncertainty analysis

Associated with the MC simulations (statistical, geometry, material composition and source dimension)

In the present work there are several uncertainty sources that have to be taken into account. There are

Table 6. Computed ambient dose equivalent using ICRP74 and Berthold conversion coefficients, and comparison with the measured values.

$\dot{H}^*(10)$ (μSv h^{-1})					
				Relative deviation (%)	
Source position	$MCNPX_{ICRP\ 74}$	$MCNPX_{LB6411}$	MCNPX vs. LB6411	MCNPX vs. NSDann	MCNPX vs. NSDUAZ
Irradiation	160.10 ± 0.42	162.76 ± 0.44	9.29	−1.21	4.61
Storage	18.45 ± 0.12	18.32 ± 0.12	−15.65	−11.73	−5.39

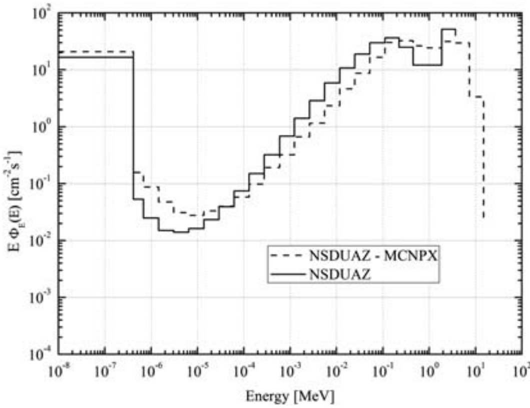

Figure 5. Neutron fluence rate energy spectra obtained with NSDUAZ, with the source in the irradiation position, using the measured (solid line) and the computed (dash line) count rates.

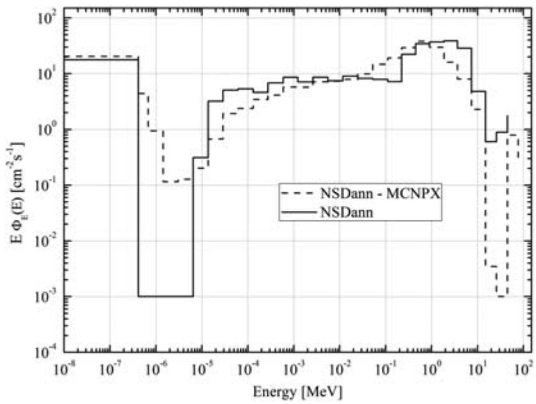

Figure 7. Neutron fluence rate energy spectra obtained with NSDann, with the source in the irradiation position, using the measured (solid line) and the computed (dash line) count rates.

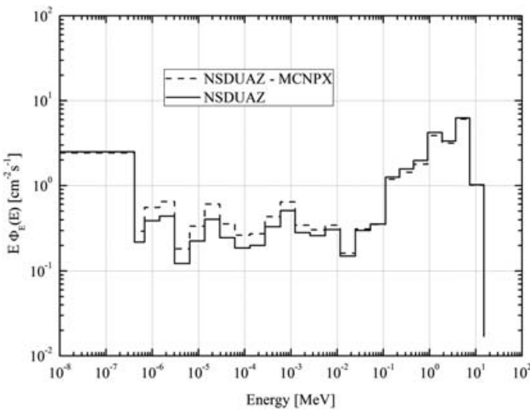

Figure 6. Neutron fluence rate energy spectra obtained with NSDUAZ, with the source in the storage position, using measured (solid line) and computed (dash line) count rates.

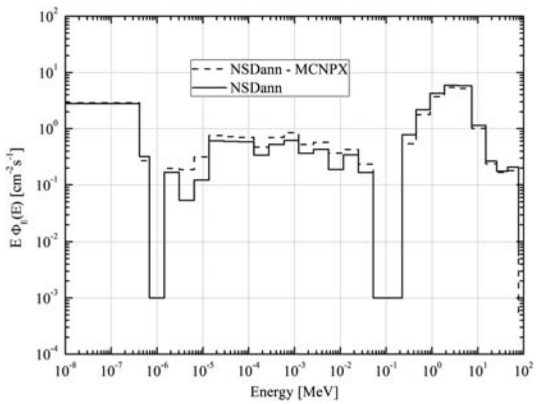

Figure 8. Neutron fluence rate energy spectra obtained with NSDann, with the source in the storage position, using measured (solid line) and computed (dash line) count rates.

a number of factors that introduce uncertainties in the MCNPX simulations. Besides the statistical uncertainties, which are assumed to be ± 5 %, there are geometrical and material composition uncertainties. These geometrical uncertainties are related to the source-to-detector distance (± 5 mm) and to the position of the detector relatively to the centre of the source (± 5 mm). There are also uncertainties associated with the dimensions of the source, several parts of the container and the detectors, and the used nuclear reaction (neutron cross-section) data.

Associated with the neutron source (intensity and energy spectrum)

Concerning the neutron ^{241}Am–Be source, the manufacturer's certificate does not specify the uncertainty associated with the source intensity and neutron energy. An experiment to determine this uncertainty was done in a previous work[20], where a similar source from the same manufacturer was used. In the mentioned work, a ± 4.4 % uncertainty was obtained and a conservative uncertainty of ± 10 % was assumed[20].

Table 7. Total neutron fluence rate obtained using the computed count rates in the unfolding programs.

Total neutron fluence rate (cm^{-2} s^{-1})				
			Relative deviation (%)	
Source position	NSDUAZ-MCNPX	NSDann-MCNPX	NSDUAZ-MCNPX vs. NSDUAZ	NSDann-MCNPX vs. NSDann
Irradiation	233.81	241.02	−11.85	−12.83
Storage	27.38	28.44	1.12	−2.16

The deviation to the values obtained using measured count rates is shown.

Table 8. Ambient dose equivalent rate obtained using the computed count rates in the unfolding programs.

$\dot{H}$*(10) (μSv h^{-1})				
			Relative deviation (%)	
Source position	NSDUAZ-MCNPX	NSDann-MCNPX	NSDUAZ-MCNPX vs. NSDUAZ	NSDann-MCNPX vs. NSDann
Irradiation	154.04	122.01	−1.00	−25.95
Storage	18.36	18.45	−5.16	−11.10

The comparison with the values obtained using the measured count rates is shown.

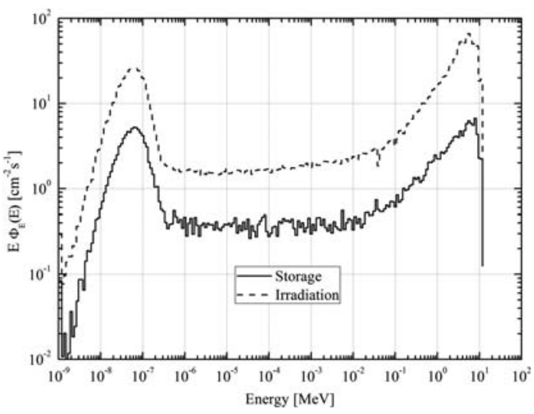

Figure 9. MCNPX computed fluence neutron spectra for the storage and irradiation source positions.

Associated with the neutron detectors

In this work, the BSS count rates have a statistical uncertainty <1 % and the Berthold LB6411 measurements have ±2 % statistical uncertainty. In addition, there are the uncertainties associated with the calibration of the detectors.

Associated with the unfolding methodologies

Finally, there are also uncertainties associated with the response matrix UTA4[17] used by the NSDUAZ program[16]. The used response matrix was calculated assuming a parallel neutron beam of the same cross-sectional area of each sphere. Because the direct beam leaving the Howitzer container does not have the same diameter of the spheres and because the ratio of the beam-to-surface area varies for each sphere, further uncertainties are introduced.

NSDann makes use of artificial neural networks, and thus there are uncertainties associated with the unfolding process related to the architecture design and learning algorithm[29].

CONCLUSION

This work showed that, although the obtained spectra using the neutron spectra unfolding programs NSDUAZ and NSDann exhibit differences in the shape of the obtained fluence rate energy spectra, the total neutron fluence rates obtained using both programs have a maximum deviation of 6.87 %, with the source in the storage position. Concerning the $\dot{H}$*(10) values calculated by the unfolding programs, the maximum deviation is 7.18 %. Comparing these

$\dot{H}^*(10)$ values with those measured using the Berthold LB6411 doserate meter, the difference is, in the worst case, 12.19 % (irradiation position).

The BSS count rates computed using the MCNPX are, in the worst case, a 19.53 % deviated from the measured ones. The computed $\dot{H}^*(10)$ with the source in the irradiation position is 9.29 % higher than the measured value, and 4.61 % lower than the value obtained with NSDUAZ. For the storage position, the value is 15.65 % lower than the measured one and 11.73 % lower than the NSDann value. The computed count rates were used as input for the unfolding programs in order to compare the results with those obtained using the measured count rates. In both programs similar spectra were obtained. The maximum deviation between the total neutron fluence rate obtained with the measured count rates and the count rates computed using MCNPX was 12.83 %, with the NSDann program. Concerning the $\dot{H}^*(10)$ values, the maximum deviations were 5.16 % using NSDUAZ and 25.95 % using NSDann program. A sensitivity analysis done in this study showed that the $\dot{H}^*(10)$ calculation by NSDann is very sensitive to the count rate variation. A variation of 18.53 % of the 25.40-cm sphere count rate led to a 32.19 % variation in the resulting ambient dose equivalent rate. On the other hand, the same variation input to NSDUAZ program led to a 6.09 % variation in the ambient dose equivalent rate value. This indicates that NSDann is very sensitive to the uncertainties of the count rates, since deviations of the count rates lead to high variations in the $\dot{H}^*(10)$ value.

This study further confirms that MC simulations are powerful tools to describe the behaviour detection systems to perform the spectrometry and dosimetry of neutron radiation fields. Indeed, the obtained computational results using the implemented model of the Howitzer counter and the BSS are consistent with the measurements, considering the quoted experimental and computational uncertainties. The deviations of the $\dot{H}^*(10)$ value between the computational results and those measured with the Berthold are 9.29 and 15.65 % for the irradiation and storage positions, respectively. Comparing the MCNPX computed total neutron fluence rate with the values obtained with the unfolding programs using the measurements, a maximum deviation of 9.11 % was observed for the irradiation case and 22.91 % for the storage position.

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