

Passive neutron area monitor with pairs of TLDs as neutron detector

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H I G H L I G H T S

- A passive neutron area monitor was built and evaluated.
- The monitor uses pairs of TLD 600 and TLD700.
- It was evaluated in the beam port of a TRIGA Mark III reactor.
- The performance was also evaluated in a 15 MV LINAC.

A B S T R A C T

A passive neutron area monitor has been designed using Monte Carlo methods; the monitor is a polyethylene cylinder with pairs of thermoluminescent dosimeters (TLD600 and TLD700) as thermal neutron detector. The monitor was calibrated with a bare and a thermalized ²⁴¹AmBe neutron sources and its performance was evaluated measuring the ambient dose equivalent due to photoneutrons produced by a 15 MV linear accelerator for radiotherapy and the neutrons in the output of a TRIGA Mark III radial beam port.

Keywords:

Neutron
Ambient dose equivalent
Neutron area monitor
Passive
TLD600
TLD700

1. Introduction

In the last decade the interest to determine the neutron-related quantities around different type of facilities has an increased trend. For radiation protection purposes the neutron spectrum, the total fluence rate or dose-related quantities are measured and/or calculated. Behind thick shielding, in underground laboratories or in the environment, where neutron population is very small, neutron measurements are hard to do due to the need of long time to have good statistics (Vega-Carrillo and Manzanares-Acuña, 2004; Niese, 2007; García-Fusté et al., 2010).

Neutron measurements are also difficult when the radiation field is mixed, intense and pulsed, like in hot areas around a nuclear

reactor or particle accelerators used in research or in medical applications (Alevra and Thomas, 2003; Vega-Carrillo et al., 2010), where the use of devices with active detectors present some problems due to dead time and pulse pileup (Zanini et al., 2004; Barquero et al., 2005; Leake et al., 2010; Klein and Schmidt, 2011; Helbig and Henniger, 2012; Takam et al., 2012; Caresana et al., 2013).

Although is highly recommended to determine the neutron spectrum and to use it to estimate the neutron dose, in practical situations the dose is measured using either neutron area monitors or neutron survey instruments. These devices use an active detector surrounded by a moderator. The commercially available single-moderator neutron monitors with active detectors are based upon the design of Anderson and Braun (1963) and Leake (1966). The advantage of these devices is that the neutron dose is measured instantaneously; on the other hand, the drawbacks are the need a power supply (Vega-Carrillo and Manzanares-Acuña, 2004); and the dead time and pulse pile up induced in pulsed, mixed and

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intense radiation fields like those around linear accelerators and cyclotrons, high-energy accelerators or in hot spots inside nuclear facilities. To overcome such drawbacks passive detectors have been used (Vega-Carrillo, 2001; Gómez-Ros et al., 2011) such as: Pairs of thermoluminescent dosimeters (Vega-Carrillo, 2002; Tripathy et al., 2009), activation foils (Thomas et al., 2002; Bedogni et al., 2008; Luszik-Bhadra et al., 2010), bubble detectors (Zanini et al., 2004; Kim and Lee, 2007), and track detectors (Kralik et al., 2008).

In facilities with low intensity isotopic neutron sources or in radiotherapy installations with linear accelerators the radiation workers dosimetry is carried out through personal dosimeters and sometimes is not easy to justify the acquisition of a neutron area monitor, mainly by the cost of purchasing and the yearly calibration.

The aim of this work was to design a passive neutron area monitor, with pairs of thermoluminescent dosimeters (TLD600 and TLD700) as thermal neutron detector, and to evaluate its performance outside the radial beam port of the TRIGA Mark III nuclear reactor and inside the 15 MV linear accelerator bunker.

2. Materials and methods

A passive neutron area monitor with pairs of thermoluminescent dosimeters, PM/TLDs, was designed as a 20.5 \emptyset \times 20.5 cm polyethylene cylinder with a density of 0.94 g/cm³. The size was selected in terms of the commercially available polyethylene piece and reviewing the Bonner sphere response functions where regardless the thermal neutron detector the 20.32 cm-diameter sphere response function is almost constant (flat) for thermal and epithermal neutrons, reaching its maximum for 2–3 MeV neutrons decreasing for larger energies. Approximately, there is one order of magnitude difference between the response for thermal neutrons and 20 MeV neutrons. Thus this spheres has a good response for neutrons ranging from 1E(-9) to 20 MeV (Vega-Carrillo et al., 2005; Bedogni et al., 2008; Gómez-Ros et al., 2011).

2.1. Monte Carlo calculations

The response of the PM/TLDs was calculated with the MCNP5 code (X-5 Monte Carlo Team, 2003) using two irradiation geometries, one with a disk source on the top of the PM/TLDs and another with a lateral square source. For each irradiation condition the response was calculated with the thermal neutron detector in two different orientations, one parallel and another perpendicular to the source. The detector was modeled using a cell with the shape and size of a thermoluminescent dosimeter. In the calculations 47 monoenergetic neutron sources, ranging from 1E(-9) to 20 MeV were used (Guzmán-García et al., 2012), thus 47 MCNP cases were calculated separately. The interaction between thermal neutrons and the nuclei in the moderator is affected by thermal motion of the atoms, chemical binding and lattice structure of the target; these interactions were included using the free gas thermal treatment $S(\alpha, \beta)$ for polyethylene at 300 K (X-5 Monte Carlo Team, 2003). The response functions, $R_{H^*(10)}(E)$, were calculated in terms of the ambient dose equivalent, $H^*(10)$, using the neutron dose conversion coefficients, $h_{10}^*(E)$, from the ICRP 74 (ICRP, 1996) as is shown in Equation (1).

$$R_{H^*(10)}(E) = \int_{10^{-9}}^{20} \Phi_E(E) h_{10}^*(E) dE \quad (1)$$

Here, $\Phi_E(E)$ is the neutron fluence spectrum in the cell used to model the TLD at the center of the moderator. In the Monte Carlo calculations the $h_{10}^*(E)$ are included as a set of discrete values, thus

the $R_{H^*(10)}(E)$ is the product of $\Phi_E(E_i)$ and $h_{10}^*(E_i)$ for the i -th energy bin.

2.2. Experimental procedure

The moderator of the PM/TLDs has two parts, the main cylinder and the plug; when this is fully inserted in the cylinder leaves the thermal neutron detector in the center of the moderator. The thermal neutron detector is 4 pairs of thermoluminescent dosimeters TLD600 and TLD700, each TLD is located in a fixed position inside an acrylic box container, in Fig. 1 is shown the PM/TLDs.

The TLDs are ribbon type 0.3175 \times 0.3175 \times 0.0889 cm from Harshaw. The TLD600 is ⁶LiF:Mg,Ti where 95.6% is ⁶Li and 4.4% of ⁷Li, while TLD700 is 0.1% of ⁶Li and 99.9% of ⁷Li (Yasuda, 2001). Both TLDs have approximately the same density and effective atomic number, having roughly the same response to gamma-rays. When both TLDs are exposed in a mixed, neutron and gamma-ray, radiation field the response to neutrons, S_n , is obtained by equation (2).

$$S_n = R_{600} - k R_{700} \quad (2)$$

In Equation (2) R_{600} and R_{700} are the mean values of the TLD600 and TLD700 readouts respectively, k is an empirical correction factor accounting the difference in the response to gamma-rays between TLD600 and TLD700 (Vega-Carrillo, 2002; Tripathy et al., 2009) whose value depend of the set of TLDs used. In order to obtain the k -value, the set of TLDs were exposed to gamma-rays of ¹³⁷Cs and ⁶⁰Co being 1.02 ± 0.03 , following the procedure reported by Vega-Carrillo (2002).

The uncertainty in the response to neutrons is given in Equation (3).

$$\sigma_{S_n} = \sqrt{\sigma_{R_{600}}^2 + R_{700}^2 \sigma_k^2 + k^2 \sigma_{R_{700}}^2} \quad (3)$$

Here, $\sigma_{R_{600}}$ and $\sigma_{R_{700}}$ are the standard deviation of the TLD600 and TLD700 background corrected readouts respectively, and σ_k is the standard deviation of k value. The monitor has 4 TLD 600 and 4 TLD 700; a mean value and the standard deviation (1 σ) was obtained; both were corrected for background and used to calculate the S_n and σ_{S_n} of Equations (2) and (3).

In order to obtain the relationship between the S_n and the $H^*(10)$, a calibration factor, f_c , was determined calibrating the PM/TLDs at the Neutronics hall of the Nuclear Engineering Department in the Universidad Politecnica de Madrid in Spain (Vega-Carrillo et al., 2012). In the calibration the PM/TLDs was located at 100 cm from a bare 111 GBq ²⁴¹AmBe source on the irradiation bench; also it was

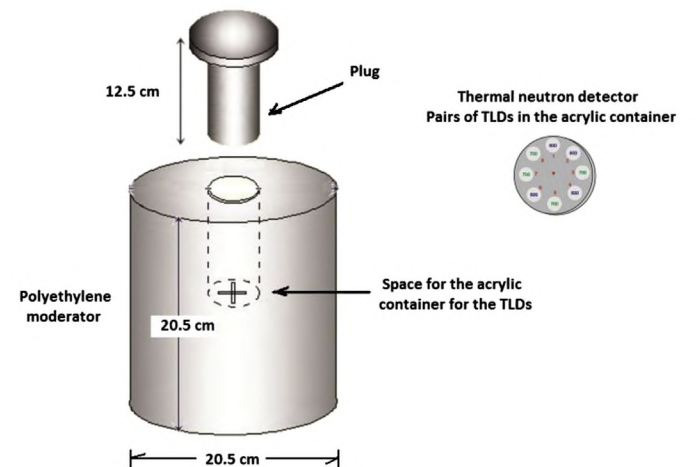


Fig. 1. Passive neutron area monitor.

calibrated with a 74 GBq $^{241}\text{AmBe}$ source located inside a neutron howitzer that produces a highly thermalized neutron field (Barros et al., 2013). At these locations the rate of the ambient dose equivalent, $H^*(10)$, was 80.5 $\mu\text{Sv/h}$ and 6.33 $\mu\text{Sv/h}$ respectively measured with the neutron area monitor Berthold LB 6411 that was calibrated at the Czech Metrology Institute with two neutron sources: ^{252}Cf and $^{241}\text{AmBe}$. The dose range used in the calibration with the $^{241}\text{AmBe}$ was from 29.9 up to 12730.3 $\mu\text{Sv/h}$. According with the manufacturer, the measuring range is from 100 nSv/h to 100 mSv/h for neutrons with energies from thermal up to 20 MeV.

The fc was verified measuring the $H^*(10)$ due to neutron background in the laboratory; thus, the PM/TLDs was left 92.85 h inside the neutronics hall when both sources were inside their storage shielding. In the three situations the $H^*(10)$ was measured with a neutron area monitor LB6411 located at the same sites were the PM/TLDs was allocated. After each measurement the TLDs readouts were measured, the mean readout values of TLD600 and TLD700 were calculated and the response to neutrons was obtained using equation (2). Thus for each calibration the S_n was related to the $H^*(10)$ measured with the Berthold LB 6411 and a mean calibration factor, fc, was estimated. With this calibration factor the PM/TLDs can be used to measure the $H^*(10)$ using equation (4).

$$H^*(10) = fc S_n \quad (4)$$

The relative uncertainty of $H^*(10)$ is calculated using Equation (5).

$$\varepsilon_{H^*(10)} = \sqrt{\varepsilon_{fc}^2 + \varepsilon_{S_n}^2} \quad (5)$$

In this equation ε_{fc} and ε_{S_n} are relative uncertainties of fc and S_n respectively.

The PM/TLDs performance was carried out measuring the neutron $H^*(10)$ at 100 cm from the output of a radial beam port of the TRIGA Mark III nuclear reactor, running to a power of 10 Watts, at the National Institute of Nuclear Research in Mexico (Vega-Carrillo et al., 2014). Using a Bonner sphere spectrometer with 0, 2, 3, 5, 8, 10 and 12 inches-diameter high density polyethylene spheres with a 0.4 cm-diameter \times 0.4 cm-length cylindrical $^6\text{LiI}(\text{Eu})$ scintillator the neutron spectrum was measured outside the beam port; the spectrum is shown in Fig. 2. The spectrum was used to calculate the ambient dose equivalent using the ICRP74 fluence-to-ambient dose equivalent conversion coefficients (ICRP, 1996).

Also the PM/TLDs performance was evaluated measuring the $H^*(10)$ due to photoneutrons produced by a 15 MV linear accelerator, LINAC, of the Centro de Cancerología de Nayarit. Here, the PM/TLDs was located at 100 cm from the isocenter which was 5 cm-depth of a $30 \times 30 \times 15$ cm solid water phantom; this features are used at daily basis by the facility staff to check the linac. During the measurements a 6 Gy_x was applied to the isocenter. In these measurements the passive version of the Bonner sphere spectrometer was used and the neutron spectrum and the $H^*(10)$ were obtained. In the Fig. 3 is shown the neutron spectrum (Benites-Rengifo et al., 2014).

3. Results and discussion

3.1. Monte Carlo calculations

In Fig. 4 are the response functions of the PM/TLDs for the lateral square source and both orientations of the thermal neutron detector, while in Fig. 5 are the response functions for the upper disk source. The uncertainty in each point is less than 5%, therefore for both sources the orientation of the thermal neutron detector orientation inside the moderator is non-important.

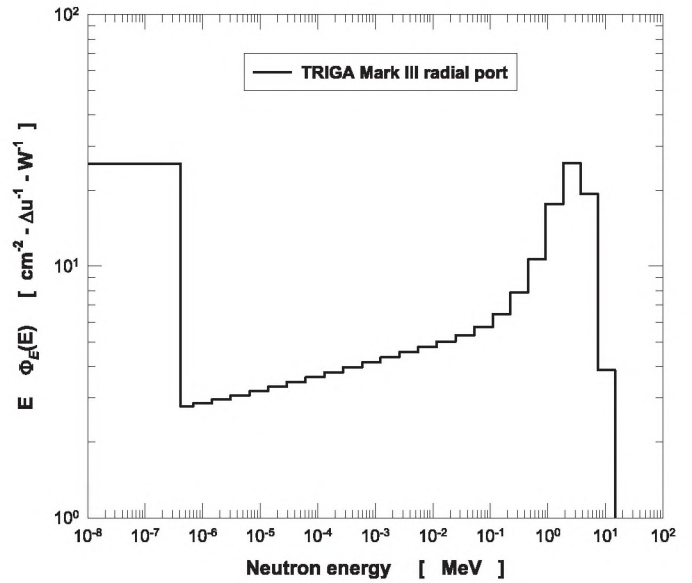


Fig. 2. Neutron spectrum in the output of nuclear reactor radial beam port running to 10 Watts.

The PM/TLDs was calibrated by using a bare $^{241}\text{AmBe}$ and a highly moderated $^{241}\text{AmBe}$, in this procedure the TLDs net neutron signal was related to the $H^*(10)$ measured with a Berthold LB6411 neutron area monitor. In the Table 1 are shown the values of the S_n obtained from the TLDs readout, the $H^*(10)$ measured with the active neutron area monitor Berthold LB6411 and the resulting fc-value.

The fc with the bare source was 71.37 $\mu\text{Sv/nC}$, while with the moderated $^{241}\text{AmBe}$ source the factor was 64.84 $\mu\text{Sv/nC}$. The definitive fc value was obtained through the average of these two values being $68.03 \pm 7\%$ $\mu\text{Sv/nC}$. Both neutron spectra are quite different, therefore the use the mean value for the fc covers neutron spectra with average energies of 5 MeV and those highly thermalized.

This factor was verified measuring the ambient dose equivalent rate due to neutron background in the laboratory with the PM/TLDs and with the Berthold LB6411. With the PM/TLDs the $H^*(10)$ was 0.225 ± 0.030 $\mu\text{Sv/h}$, while with the active monitor was

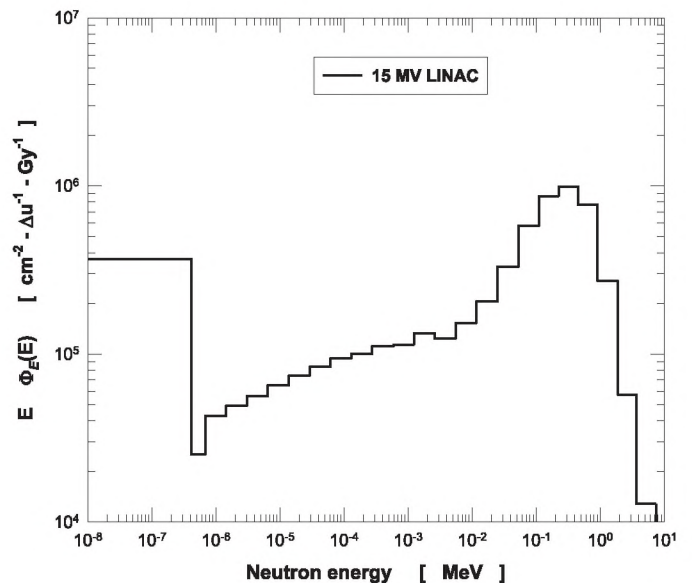


Fig. 3. Neutron spectrum to 1 m from the isocenter in the LINAC.

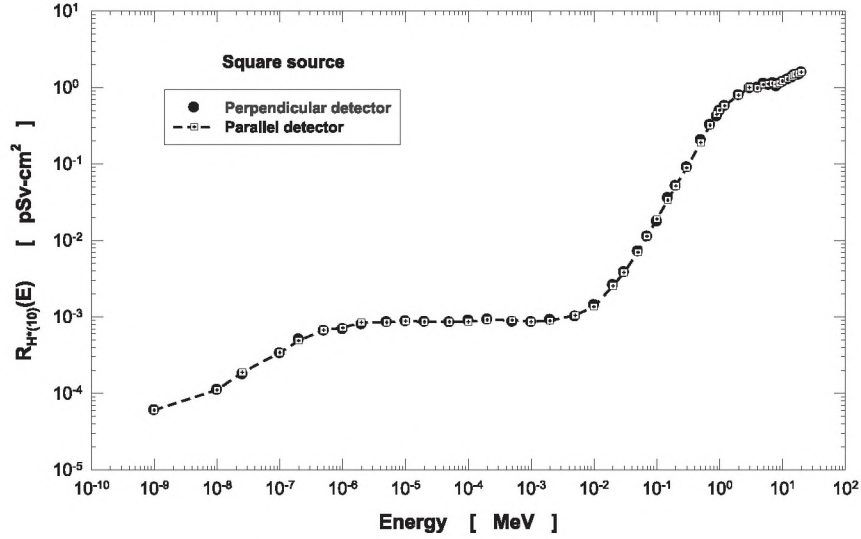


Fig. 4. Response functions for the lateral square source for both orientations of the thermal neutron detector.

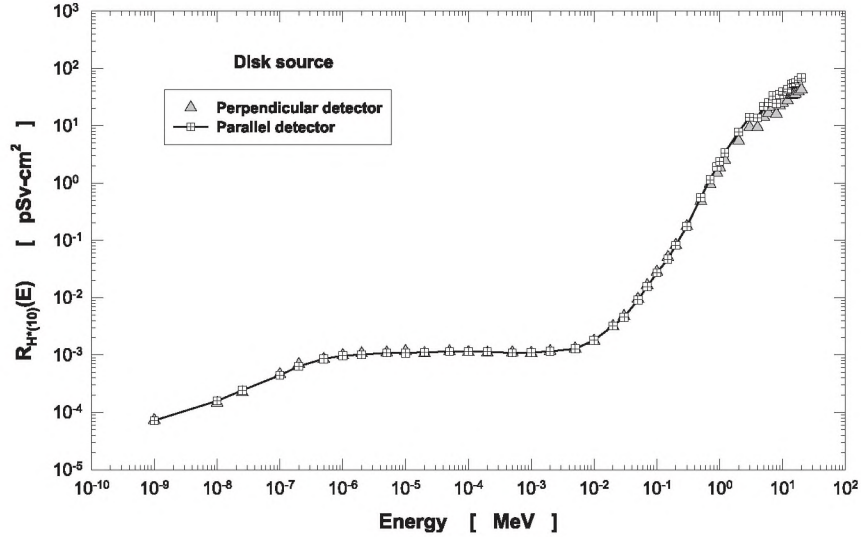


Fig. 5. Response functions for the upper disk source for both orientations of the thermal neutron detector.

$0.267 \pm 0.067 \mu\text{Sv/h}$. The difference was 19% due to the randomness and low intensity of background neutrons that causes poor statistics in the TLD's readouts and the Berthold LB6411 values.

The performance of the PM/TLDs was evaluated measuring the $H^*(10)$ in the radial beam of a TRIGA Mark III reactor; here, the $H^*(10)$ was also obtained with a Bonner sphere spectrometer with ${}^6\text{LiI}(\text{Eu})$ scintillator. The $H^*(10)$ measured with the spectrometer was $1345 \pm 80 \mu\text{Sv}$, while the ambient dose equivalent measured with the PM/TLDs was $1404 \pm 112 \mu\text{Sv}$. From the $H^*(10)$ measured with the PM/TLDs the standard deviation is approximately 8%, this spread is due to TLDs readouts. On the other hand the standard deviation of $H^*(10)$ measured with the Bonner sphere spectrometer

is approximately 6% that correspond to the uncertainty of net count rate under the alpha peak (5%), the matrix response (3%) and the spheres allocation (1%).

The PM/TLDs performance was also evaluated by measuring the $H^*(10)$ due to photoneutrons produced in a 15 MV LINAC. The $H^*(10)$ was also measured using the passive version of the Bonner sphere spectrometer.

The $H^*(10)$ measured with the PM/TLDs was $0.55 \pm 0.11 \text{ mSv/Gy}_x$ while the $H^*(10)$ measured with the passive Bonner sphere spectrometer was $0.60 \pm 0.09 \text{ mSv/Gy}_x$. This value is close to 0.63 and 0.69 mSv/Gy_x reported by Kim and Lee (2007) and Thomas et al. (2002), respectively, to 1 m from the isocenter (IC) of 15 MV LINAC. The difference is probably due the linear accelerator type and irradiation conditions they used.

Table 1

Data used to obtain the calibration factor of the PM/TLDs with the ${}^{241}\text{AmBe}$ sources.

Calibration condition	S_n [nC]	$H^*(10)_{\text{LB6411}}$ [μSv]	f_c [$\mu\text{Sv/nC}$]
Bare ${}^{241}\text{AmBe}$	$1.1279 \pm 3\%$	$80.5 \pm 1\%$	$71.37 \pm 3.2\%$
Moderated ${}^{241}\text{AmBe}$	$9.7625\text{E}(-2) \pm 5\%$	$6.33 \pm 2\%$	$64.84 \pm 5.4\%$

4. Conclusions

A passive neutron area monitor has been designed and their response functions were calculated. The PM/TLDs was calibrated

with bare and moderated $^{241}\text{AmBe}$ sources. The monitor performance was evaluated with neutrons produced by a research reactor and a LINAC for radiotherapy.

The monitor is a polyethylene cylinder that has different response due to the non-isotropic response. Regardless the source, the thermal neutron detector orientation in the center of the cylinder is irrelevant.

The PM/TLDs performance evaluation the measured $H^*(10)$ is in agreement with the dose obtained with the Bonner sphere spectrometer in the TRIGA Mark III nuclear reactor, and with the dose measured with a neutron area monitor Berthold LB 6411 in a 15 MV linac.

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