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Design, fabrication and modeling of an AmBe neutron irradiator for TLD screening for neutron dose measurement in mixed radiation fields

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HIGHLIGHTS

- Pure gamma to neutron-gamma TLD screening transposition is not straightforward.
- Irradiator, made of moderator material, play an important role on field modulation.
- Irradiator designed by Monte Carlo provides a very good homogeneous field.
- Neutron energy spectra choice does not play any relevant role in field homogeneity.

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ABSTRACT

TLDs dosimeters are frequently presented as a viable choice for dosimetric studies when dealing with mixed neutron-gamma radiation fields. However, this choice is not without some drawbacks, because not only TLD response is highly dependent on particle type but also on neutron energy spectrum. Therefore, a correct screening and calibration of the dosimeter are required, and a simple shift from gamma screening methodology for mixed field is not suitable. This paper presents the design, fabrication and tests of an irradiator for TLD screening for neutron dose measurement using an AmBe source and polyethylene as moderator material. The design of the irradiator was conducted through Monte Carlo simulations using the MCNP5 code. The experimental validation and tests were performed using Indium activation foils and TLD 600 dosimeters. The manufactured irradiator demonstrated to be suitable for TLD screening under neutron source radiation field, offering very good homogeneity conditions in the radiation field so to guarantee same radiation dose delivered to the TLDs.

1. Introduction

Mixed radiation fields are common and present in a variety of situations, ranging from Boron Neutron Capture Therapy (BNCT) facilities and medical accelerators to outer space exploration. Those fields are composed of radiation of different types such as photons and neutrons, or even the same type of radiation with a significant difference in energy, for example, fast and thermal neutrons. In many cases, one of the field components is predominant and the others can be ignored, however, when this simplification is not feasible, it can be a very challenging task to properly carry out a dosimetric assessment. For instance, each component usually has a different radiation weighting factor (W_R), this requires a specific dosimeter for each radiation type or a unique dosimeter capable of measuring all components at the same time. Although many dosimeters have been tested to perform such type of measurement, so far thermoluminescent dosimeters (TLDs) have been regularly the detector of choice (Haninger and Henniger, 2016; Kry et al., 2007; Lawless et al., 2013).

That being said, to set up a thermoluminescent dosimetric system can be a wearisome task. Each commercially available TLD has a different sensitivity and, as a consequence, before measurements one must screen, test and calibrate it (Furetta, 2003). The simplest method to do this chore requires the irradiation of all the detectors with the same dose from a calibrated known radiation source, often with aid of an irradiator specific for this purpose, and then they are screened by their responses. In gamma radiation field, a calibrated gamma source, frequently a^{60}Co source, is placed in a central position and the detectors are positioned for the gamma exposition in a circle around it packed in holders, commonly used as build-up material, and no major difficult are expected in that procedure. However, when dealing with mixed neutron-gamma radiation fields, this simple method is not suitable, because not only the TLD response is highly dependent on particle type but also

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on neutron energy spectrum.

Particularly, in neutron-gamma radiation, a pair of ^{6}LiF and ^{7}LiF TLDs are typically used to characterize the radiation field as recommended by ICRU (1976), taking advantage of the large differences on the nuclear reactions between these two isotopes. The thermoluminescent glow curve in the ^{6}LiF is essentially produced by the charged particles (alpha and Triton) emerging from the reaction ^{6}Li (n,α)^{3}H with a thermal neutron cross section of 945 b. On the other hand, the TL glow in a ^{7}LiF dosimeter caused by neutrons is mainly due to elastic and inelastic scattering reactions, which is normally much smaller than that produced by gamma rays in the mixed neutron-gamma field. However, it is impossible to obtain a pure ^{7}LiF dosimeter and the small presence of ^{6}Li will give a contribution from thermal neutrons to the response that can be significant and must be evaluated (Aschen et al., 1999; Liu and Liu, 2011). In 2007, Delgado et al. proposed a method for mixed neutron-gamma field dosimetry, which relies on the different shapes produced by gamma and neutron radiation on the glow curve of ^{6}LiF dosimeters. More recently, Gambarini et al. (2010, 2014) showed that gamma dose and thermal neutron fluence can be also measured with only ^{7}LiF dosimeters by taking advantage of the glow curve and previous gamma and thermal neutron calibrations.

Regardless of employing one or more types of TLD, the screening method requires a well known field, and as for gamma rays, an easy option lays on the use of a sealed alpha-neutron source. This type of source usually emits predominantly fast neutrons, therefore one has to slow them down to the thermal energy range where ^{6}LiF TLDs are more sensitive. Neutron thermalization is achieved by surrounding the source with a low atomic number material. However, this interposition of material between the source and TLDs introduces an extra error source into the TLD screening procedure as the irradiation configuration increases its complexity. To control the magnitude of this error may be unwieldy for a neutron irradiator, i.e. the source and moderator set up, because as the moderator changes the neutron energy spectrum to a more TLD sensitive shape, minimal irradiation geometry differences may produce large differences in TLD responses.

In this respect, this paper describes the modeling, simulation, construction and trial of an AmBe-based neutron irradiator to undertake screening and reproducibility tests of TLDs for use in neutron dosimetry in mixed radiation fields. Such new design ensures the uniformity of the dose delivered at different positions and that all the dosimeters are inside the same irradiation field.

2. Material and method

In order to perform the irradiator construction, some steps are necessary: the study of neutron thermalization and the maximum flux variation due to geometric effects; the fabrication of the symmetrical neutron thermalizer that surrounds the neutron source; and the reliability tests of the irradiator. This section presents the description of each material and procedures used to accomplish the steps above.

2.1. AmBe source

In a AmBe source, neutrons come from the $^9Be(\alpha,n)^{12}C$ reaction which is promoted by alphas from ^{241}Am decay ($T_{1/2} = 432{,}6\,y$) impinging onto ^{9}Be which takes part of the AmBe mixture. This is an adequate source to study mixed radiation fields because it also emits gamma radiation (Vega-Carrillo et al., 2002; Murata et al., 2014).Therefore, in this work, a cylindrical nominal 2 Ci AmBe source was used to provide the mixed irradiation field. Its active part is completely enclosed by stainless steel, so that its external dimensions are 2.24 cm (diameter) x 2.20 cm (height). It is worth to note that source neutrons are mainly in the fast energy region, i.e., neutrons with energies above 0.1 MeV (IAEA, 2001; ISO 8529-3:1998, 1998; Marsh et al., 1995; Thompson and Taylor, 1965).

2.2. Polyethylene cylinder

An irradiator geometry with cylindrical symmetry is aimed, since it allows irradiating a large set of TLDs at the same time by placing them around the source. On the other hand, the irradiator needs to be made of a moderator material, so to slow down the neutrons from the source. Therefore a 13.5 cm diameter polyethylene cylinder was taken as a kick off material to work with, so to provide similar fields around its cylindrical surface where the TLD should be placed.

2.3. Monte Carlo simulations

Simulations were performed using the widely known radiation transport code MCNP5 (X-5 Monte Carlo Team, 2003) in order to help on designing the irradiator and setting the irradiation configuration and also to provide information about possible construction constraints/limitations which might cause uneven irradiation conditions to the TLDs under screening.

To evaluate the adequacy of the irradiator to provide thermal neutrons, the neutron flux was calculated around the irradiator, next to its lateral surface, at its mid horizontal plane. The calculated neutron flux was separated in energy ranges so to distinguish the thermal component from the total neutron flux. Neutron and gamma fluxes and also the neutron capture interaction rates with Indium activation foils have been obtained from the simulations. For neutron and gamma flux calculation the MCNP5 track-length estimator, F4, has been used. As for the In activation rate the calculation has been done according to equation (1).

$$R = C\int \varnothing(E)\sigma(E)dE \tag{1}$$

Where R is the In activation rate; ∅(E) is the energy-dependent neutron flux; σ(E) is the microscopic reaction cross section and C is a constant value expressing the amount of target nuclide, indium, present in the sample/activation probe.

Since four acceptable neutron energy spectra of AmBe source have been found in the literature (IAEA, 2001; ISO 8529–3:1998, 1998; Marsh et al., 1995; Thompson and Taylor, 1965), all four were tested to highlight any hypothetical divergence between them. Fig. 1 presents the four AmBe spectra used in the simulations with their respective average energies of 3.25, 4.07, 4.34 and 4.96 MeV. Since AmBe is a mixed neutron-gamma source, simulations of gamma source were performed considering a monoenergetic 4.4 MeV source (Vega-Carrillo et al., 2002; Murata et al., 2014). Preliminary simulations considering or not the presence of the source material showed no differences in the results, so that, in all simulations, the source material was not considered and the radiation emission was isotropic in the entire volume of the source. MCNP5 simulates all the secondary particles from interactions, including photons from neutron capture in hydrogen. Neutron cross sections from ENDF/B-VI.6 were utilized in the simulations and the thermal neutron scattering by molecules was represented by the S (α,β) treatment using the POLYPOL.20t library. For gamma transport the MCPLIB04 library was utilized.

Particular attention has been driven to the size of the source holder, seeing that the source placement out of the center of the irradiator will cause a deviation from the cylindrical symmetry. To estimate the largest discrepancy due to this deviation in neutron and gamma flux profiles around the irradiator, the worst scenario was considered, i.e. the source leaning against the inner side of the central hole. Therefore, neutron and gamma flux profiles around the irradiator were calculated for three different holder radius: 1.15, 1.30 and 1.45 cm of radius. The smallest radius - 1.15 cm - was taken as the minimum value to which source insertion/removal would be feasible (Fig. 2).

To characterize the neutron energy flux gradient in the axial direction, axial neutron flux profile was also evaluated.

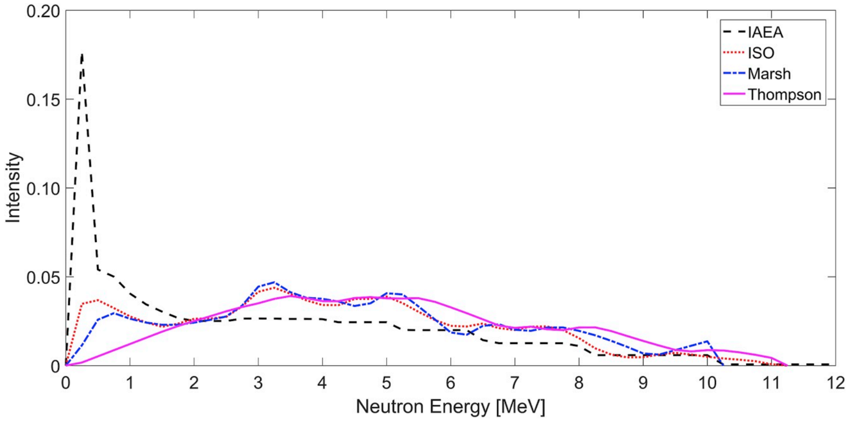

Fig. 1. AmBe spectra used in the simulations (IAEA, 2001; ISO 8529-3:1998, 1998; Marsh et al., 1995; Thompson and Taylor, 1965).

2.4. Activation foils

Experiments using activation foils were carried on to check the conformity of the simulations performed. Three Indium activation foils were used along the experiments. Their average thickness and diameter are 0.06 cm and 2.50 cm, respectively.

Each experiment with Indium activation foils consisted in placing the foils around the irradiator. Whenever the experiment was performed with more than one foil, their relative arrangement was set to minimize their mutual interaction. The foils were irradiated for at least three days, more than enough time to guarantee saturation activity, and later analyzed in a 20% HPGe detector coupled to a digital data acquisition. The analyses of Indium activation foils of this work were performed only for the 417 keV photopeak of the ^{116m}In.

2.4.1. Neutron moderation

In order to check the capability of the irradiator to moderate neutrons and deliver thermal neutrons at the irradiation position a set of experiments were conducted to evaluate the neutron flux delivered at the medium horizontal plane of the irradiator for two energy ranges: thermal ($E_n < 0.625$ eV) and above thermal ($E_n > 0.625$ eV).

To do so, Indium activation foils were irradiated in plain or Cadmium covered arrangements. Except for the Cadmium covered foils, experiments with Indium activation foils followed the aforementioned irradiation and analysis procedures.

2.4.2. Neutron flux profiles

Azimuthal and axial neutron flux and profiles were evaluated experimentally through a set of activation foils irradiations, so to serve as information criteria to optimize the TLD screening irradiation methodology. The azimuthal neutron flux profile experiment was conducted to verify if the irradiator meets the design criteria of providing a uniform neutron flux intensity around its mid horizontal plane. Activation foils were placed at six positions of the irradiator lateral surface along its mid horizontal plane. These positions were distributed at approximately equal azimuthal intervals around the circumference. The axial neutron flux profile experiment was conducted to verify the minimum axial neutron flux gradient at the cylinder lateral surface. Neutron fluxes were evaluated at five axial points along the upper half of the irradiator.

2.5. TLDs

A set of 30 Harshaw TLD-600 chips, with dimensions of 1 mm × 1 mm x 0.3 mm, were arranged around the irradiator at the assumed screening irradiation configuration. This task was preceded by TLD annealing, so to set them at properly useable conditions, and followed by TLD reading. The adopted annealing procedure consists in heating the TLDs at 400 °C for 1 h, and at 100 °C for 2 h. Two dedicated annealing ovens are used to accomplish these steps. After the TLDs are removed from the second oven, they are left to cool down to environmental temperature. A Harshaw 3500 TLD reader was used. The reading parameters used in the analyses are: initial temperature 60 °C;

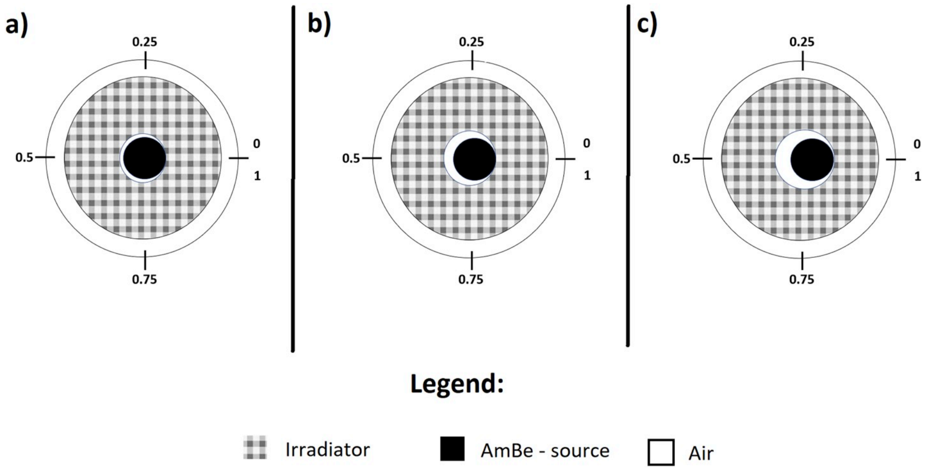

Fig. 2. Schematic view of simulation models considering the worst scenario. The source is represented by the black region, the polyethylene by the hatched region and air by the white region. The three simulations with central hole radius of: a) 1.15 cm; b) 1.30 cm and c) 1.45 cm.

final temperature 400 °C; heating rate 10 °C/s and reading time of 45s. Analyses were performed by the first region of interest (ROI 1), which embraces the 65 to 110 channel range out of the 200 channels of the whole TL spectrum. ROI 1 corresponds to the light emission region around 195 °C and encompasses the LiF TL peaks, which present the most intense response and are less susceptible to fading (Pradhan, 1986).

3. Results

3.1. Design simulations

3.1.1. Neutron moderation

To estimate the neutron moderation capability of the irradiator, each AmBe neutron energy emission source was simulated for two distinct system configurations:

1. Source inside the irradiator and
2. Source standing in the air.

From each simulation run, the total and the thermal neutron fluxes in a volume element at a fixed position from the source were estimated. The volume element adopted as reference was an air annulus (0.5 cm height and 6.75 cm internal and 7.00 cm external radii) laying at the source mid horizontal plane. The thermal flux fraction was obtained by the ratio of the thermal and total neutron fluxes. Table 1 shows the calculated thermal flux fractions for all aforementioned neutron source energy spectra with and without moderator (only air). Uncertainties on thermal neutron fractions estimates are below 1%.

3.1.2. Azimuthal total neutron flux profiles

Figs. 3 and 4 show, respectively, considering the worst possible scenario as described in section 2.3, the normalized neutron and gamma fluxes calculated along azimuthal angles on the cylindrical surface of the irradiator at its mid horizontal plane for three sizes of the source holder. Neutron and gamma fluxes were evaluated for 12 positions around the irradiator. Visual guidelines are used to highlight the different profiles. Although the calculated values from only one neutron source energy spectrum has been shown in Fig. 3 - the IAEA spectrum - all spectra show similar responses. In all simulations the statistical uncertainty was less the 0.2% for neutrons and 0.4% for gammas.

3.1.3. Axial thermal neutron flux profile

Fig. 5 shows the calculated axial neutron flux profile at the lateral surface of the irradiator. Simulated uncertainties were all below 0.2%. Again, the calculated values shown in this figure were driven from the IAEA neutron source energy spectrum, as similar results were obtained from the other 3 spectra.

3.2. Project

The project for the new irradiator was proposed based on the results obtained from the simulations.

The irradiator consists of two polyethylene pieces which assumes a cylindrical outside shape when they are assembled together. Its overall height and diameter are respectively, 21.0 cm and 13.5 cm. This assemble has a cylindrical case (radius = 1.15 cm) right at its geometric center to hold the AmBe source so to preserve the cylindrical and axial symmetries. The pieces are cutout in step shape to minimize radiation leakage. Fig. 6 shows an illustration of the two pieces which make up the irradiator in their upward positions.

To set up an irradiation, the AmBe sealed source is placed in the source case upon the bottom piece (left in the figure). Afterwards the top piece (right in the figure) is coupled to the bottom piece, fitting nicely together.

Table 1
Calculated thermal neutron fractions at the lateral surface of the irradiator with and without (air) moderator material using distinct neutron source energy spectra.

Spectra	Thompson	IAEA	Marsh	ISO
air	0.00	0.03	0.00	0.00
irradiator	0.14	0.27	0.16	0.18

3.3. Validation procedure

3.3.1. Neutron thermalization

To check the moderation power of the irradiator, the neutron capture reaction rate for Indium was calculated. Activation foils were explicitly taken into account and energy discrimination stood close to the experiment by representing the Cadmium cover around the activation foils. The calculated results uncertainties were always below 1%. These simulations were run for all aforementioned neutron source energy spectra specifications and the ratios between the Indium activation rates calculated for plain and Cadmium covered foils are shown in Table 2. The average saturation activity value driven from the experiments for the bare Indium foil was 3284 ± 52 Bq while for the Cadmium covered foil it was 623 ± 14 Bq giving an experimental ratio value of 5.27 ± 0.14.

3.3.2. Flux profiles

Fig. 7 presents the normalized saturation activity obtained for the bare Indium activation foil placed at 6 positions around the irradiator at its mid horizontal plane.

Fig. 8 presents the simulated axial neutron flux profile and the normalized saturation activity experimental profile.

3.4. Measurements with thermoluminescent dosimeters

The assembled irradiator was used in a TLD screening routine to check its functionality.

The irradiation procedure consists in placing the TLDs on the cylindrical surface of the irradiator top piece at its correspondent mid horizontal plane. A plastic film is used to hold them on their place. After the AmBe source has been placed at the irradiator bottom piece, the irradiator is assembled by placing its top piece - with the TLDs sticked to it - over the bottom piece. The 24 h irradiations are finished by removing the TLDs.

Fig. 9 presents the mean responses of 30 TLD-600 obtained by a set of six irradiations performed according to the procedure just described. Each TLD of the set presents an individual sensitivity which differs one from another. The TLD set pictured in Fig. 9 presents a 6% standard deviation value relative to the average value which is 1 (normalized). On the other hand, the error bars represent the estimated mean standard deviation of each TLD response.

4. Discussion

Designing a thermal neutron irradiator which has a retrievable AmBe source as working criteria and producing equivalent irradiation conditions around it to be used as part of TLD screening tool, consists in a far more delicate procedure than just thermalizing fast neutrons in an almost cylindrical geometry. As the source has to be remotely manipulated in an easy way, it cannot fit perfectly in the source case, and therefore this extra room may take away the ideal irradiator cylindrical symmetry. The number of sites of equivalent irradiation conditions could also be incremented depriving a little bit from the symmetry condition by taking different planes along the cylinder symmetry axis. One must however assure that the error these symmetry drifts insert into the experimental procedure stands below 5%, as the intrinsic TLD

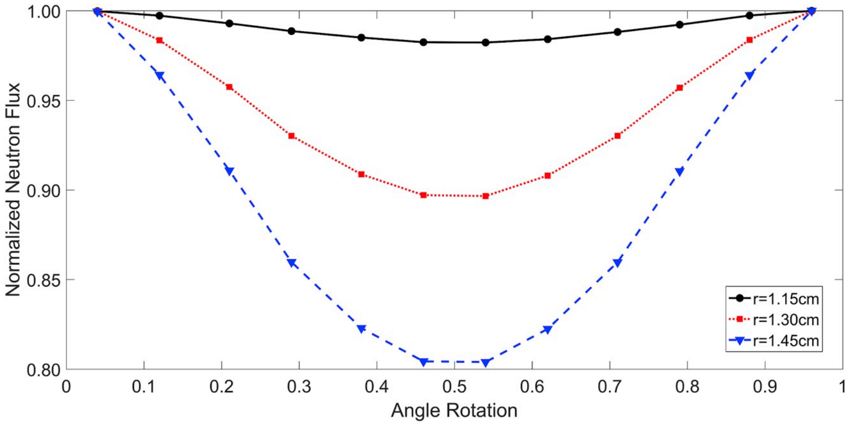

Fig. 3. Simulated azimuthal total neutron flux profiles for different sizes of the source container considering the worst possible scenario.

reproducibility is an additional source of error, and 5% is the limiting reference value for TLD precision.

4.1. Neutron thermalization

Simulations were employed to investigate the neutron energy spectrum of the AmBe source. Many different neutron energy spectra are found in literature and results from four different spectra were evaluated as shown in Fig. 1 and Table 1. Although the neutron emission spectra present markedly differences, they share similarities particularly as the bulk of neutrons are emitted with energies ranging from 1 to 10 MeV, and almost no neutrons are emitted at the thermal energy range.

Despite these aspects, the neutron source energy spectrum did not show a distinctive effect on the irradiator design efficiency. The thermal neutron fraction stayed below 0.30 for all but one spectrum. The exception was the IAEA spectrum, which presented a moderation power estimate twice the value obtained for the other spectra. The calculated Indium saturation activity ratios obtained between the bare and the Cadmium covered foils are in a 5.30 to 5.55 range (Table 2) for all spectra, showing differences below 5% between them and in very good accordance with the experimental value (5.27 ± 0.14).

4.2. Azimuthal radiation flux profiles

Figs. 3 and 4 show, respectively, the neutron and gamma fluxes profiles calculated along the circular perimeter at the medial plane for 3 different sizes of the irradiator source case at the source largest displacement condition, i.e., the source touching the surface of the case, as indicated in the schematic representations of Fig. 2.

All fluxes attain their highest values at 0 angle rotation, i.e. for the point at the external surface closest to source. Flux profiles show an inverted bell shape as the point moves around the circumference. i.e., as the azimuthal rotation increases, particle flux decreases down to the minimum at the opposite side of the cylinder and increases as the azimuthal rotation makes its way back to the initial position by completing the circling around. The maximum and minimum flux simulated values coincides with positions on the irradiator surface which are respectively the closest and the furthest to the source.

As would be expected, increasing the central hole radius increases the differences observed in the flux profiles as the distance differences from the source to surface also increase. Gamma profile shows a larger response to the displacement of the source from the center.

For a 1.15 cm source case radius one expects differences in delivered gamma and neutron fluxes no larger than 2%.

Fig. 7 presents the experimental azimuthal thermal neutron flux profile for the irradiator used. They were estimated by observing the saturation activity of Indium activation foils at 6 different spots along the medial circumference of the irradiator, standing therefore, as the experimental data to check the adequacy of the irradiator to provide equivalent irradiation conditions around its medial outer border. The presented data are all statistically in accordance to the saturation activity average value of 3284 ± 52 Bq, as each of them present an estimated experimental uncertainty just below 4%, showing no inverted bell shape.

4.3. Axial neutron flux profile

The calculated neutron flux profile along the axial axis is show in Fig. 5. As the irradiator source case had to present a radius a little bit

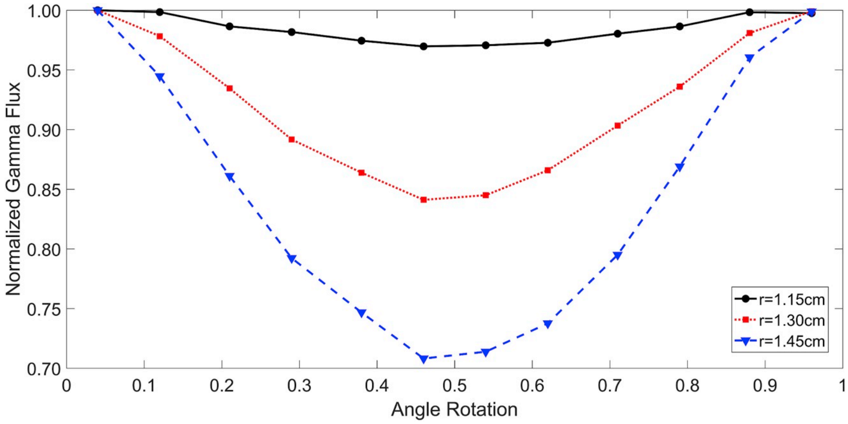

Fig. 4. Simulated azimuthal gamma flux profiles for different sizes of the source container considering the worst possible scenario.

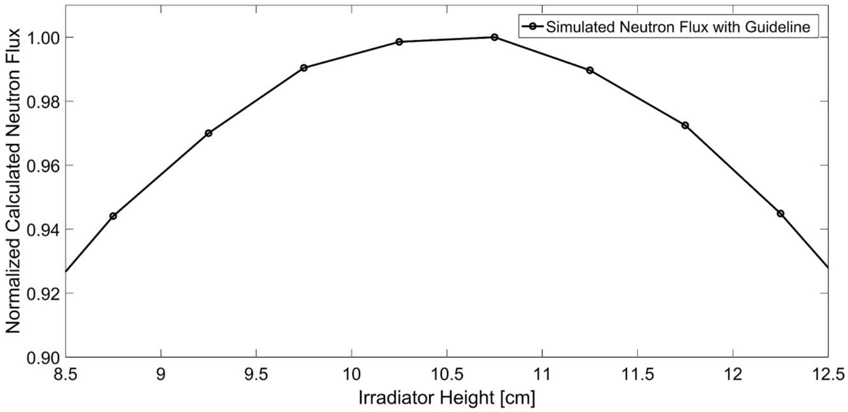

Fig. 5. Simulated axial thermal neutron flux profile.

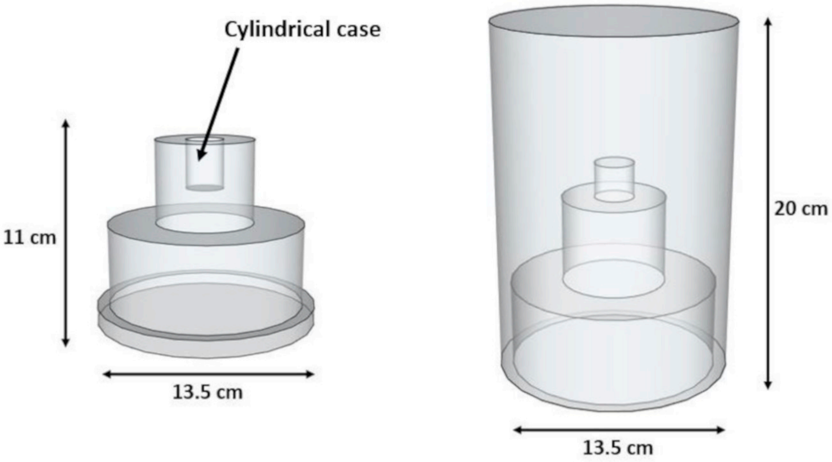

Fig. 6. Schematic view of the new irradiator. Left: bottom piece; right: top piece.

Table 2
Calculated ratio between activation rates of bare and covered Indium foils with different neutron energy spectra. The uncertainties are less than 1%.

Spectra	Thompson	IAEA	Marsh	ISO
Ratio	5.31	5.32	5.38	5.55

larger than the source radius to allow source insertion into the source case, so did its height to allow positioning the irradiator top piece onto the bottom piece. This extra room accounts for the symmetry point standing a little bit above the midplane at 10.5 cm. Nonetheless differences in the neutron flux stay below 1% for displacements up to 0.5 from the mid plane. However, the larger the drift from the mid plane the more intense is the reduction on the calculated neutron. A 1 cm drift from the middle plane turns in a 2% reduction of the thermal neutron flux and one expects to observe up to 5% differences in thermal neutron flux intensity for a 1.5 cm drift.

Fig. 8 shows both calculated and experimental thermal neutron flux profiles along the axial axis. Only the upper part of the axial profile is shown, as a symmetrical response is expected for lower part. Uncertainties related to experimental values took into account the

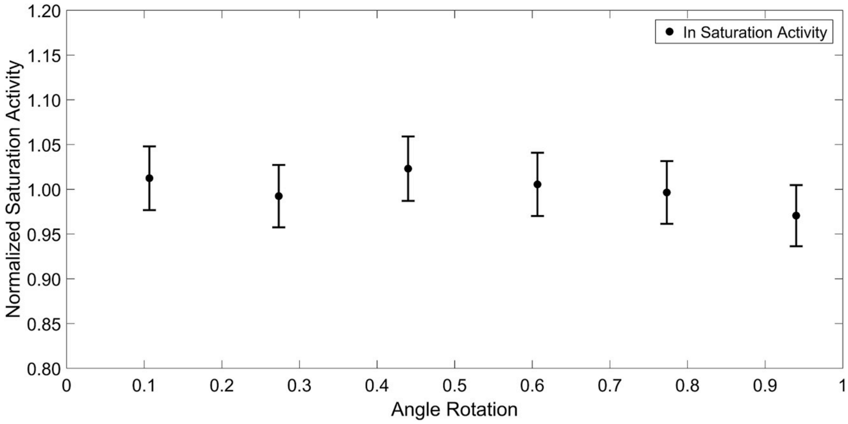

Fig. 7. Normalized induced azimuthal activity profile of bare Indium activation foil.

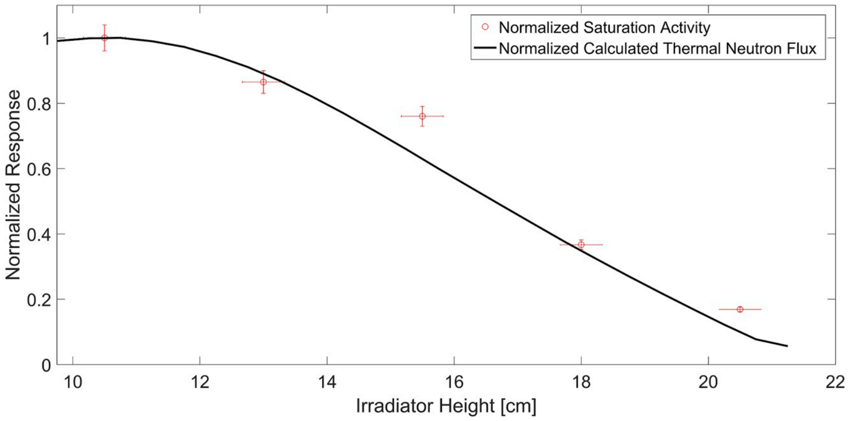

Fig. 8. Axial neutron flux profile: Normalized calculated thermal neutron flux and normalized saturation activity of bare Indium activation foils.

uncertainties due to foils measured counting rates but uncertainties due to sources sizes and positioning are much larger. However, experimental and calculated results show similar responses, i.e., as the irradiation position gets away from the middle plane both calculated and experimental neutron fluxes diminish systematically.

4.4. TLD screening

Fig. 9 shows the average values of a set of 30 TLDs normalized responses of six irradiations performed under an AmBe source irradiation procedure using the irradiator described in this work.

TL glow curves presenting TL peaks that can be associated with the TLD thermal neutron response were observed for all TLDs, indicating that the neutron signal has been turned on, and therefore, the irradiator has provided thermal neutrons successfully. Besides, one sees that the average values do fluctuate around unity showing no trending profile. In other words, although TLDs present individual responses which vary from one to another, there is no systematic fluctuation which might be attributed to improper neutron/gamma field inhomogeneity produced by the irradiator.

This TLD response distribution presents a similar pattern to that observed for response induced by a pure gamma source, except for a slight increase on the TLD response fluctuations.

In the screening process adopting 5% minimum accuracy, Fig. 9 demonstrates the adequacy of the method using the irradiator since the maximum standard deviation of each TLD mean response was 3.5% which is below the minimum adopted value.

5. Conclusion

Simulations performed to provide information about the irradiator working conditions and applied in its construction process presented good agreement with the evaluation experiments executed with activation foils.

The irradiator has shown to be adequate to perform TLD-600 screening for neutron response, as neutron irradiation field has been conformed into both energetic and geometrical standards, which were beforehand established. The success in the designing, construction and use of the irradiator may be observed by the equivalence of TLD response distributions obtained for neutron irradiation fields.

This work shows some aspects that distinguish the TLD screening methodologies when the TLDs are irradiated by either a pure gamma or mixed neutron-gamma sources. A straight transposition of methodologies does not apply in this case. Minimal deviations from a pure cylindrical symmetry, which is observed in both cases, turns into irradiation field differences that are not equivalent between source configurations. This effect is particularly enhanced by the presence of moderator materials, because they change the neutron spectrum and increase the TLD sensibility. In these circumstances, Monte Carlo stands as an important tool to evaluate those field differences and to attain irradiation conditions under controlled standards to perform TLD screening. Although the four AmBe neutron source energy spectra used in this work have shown large differences in their shape and mean energy, and have also presented different thermal fraction estimates after been moderated by the irradiator, the results from neutron activated Indium foils have not shown such large differences. This is partially due to the fact that the experimental data have uncertainties large enough to prevent the distinction of those energy spectra.

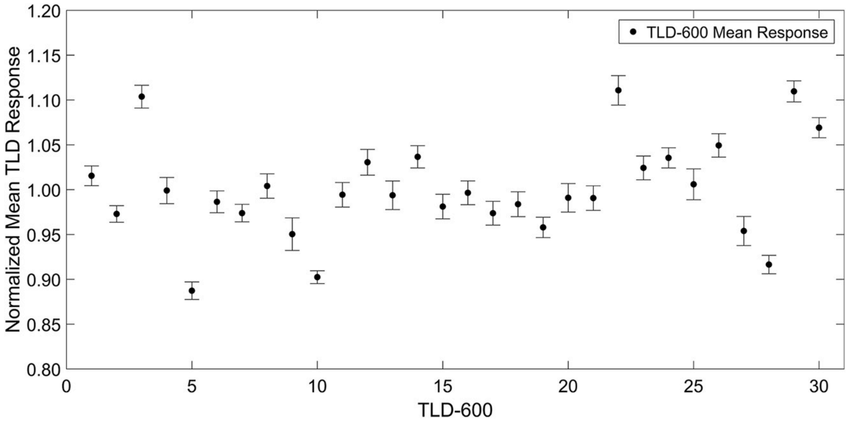

Fig. 9. TLDs-600 mean responses of 6 irradiations around mid horizontal plane of the irradiator.

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