ETHERNES: A new design of radionuclide source-based thermal neutron facility with large homogeneity area

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A R T I C L E I N F O

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A B S T R A C T

A new thermal neutron irradiation facility based on an ^{241}Am–Be source embedded in a polyethylene moderator has been designed, and is called ETHERNES (Extended THERmal NEutron Source). The facility shows a large irradiation cavity (45 cm × 45 cm square section, 63 cm in height), which is separated from the source by means of a polyethylene sphere acting as shadowing object. Taking advantage of multiple scattering of neutrons with the walls of this cavity, the moderation process is especially effective and allows obtaining useful thermal fluence rates from 550 to 800 cm^{-2} s^{-1} with a source having nominal emission rate 5.7×10^6 s^{-1}. Irradiation planes parallel to the cavity bottom have been identified. The fluence rate across a given plane is as uniform as 3% (or better) in a disk with 30 cm (or higher) diameter. In practice, the value of thermal fluence rate simply depends on the height from the cavity bottom. The thermal neutron spectral fraction ranges from 77% up to 89%, depending on the irradiation plane. The angular distribution of thermal neutrons is roughly isotropic, with a slight prevalence of directions from bottom to top of the cavity. The mentioned characteristics are expected to be attractive for the scientific community involved in neutron metrology, neutron dosimetry and neutron detector testing.

1. Introduction

The usual way to produce very stable thermal neutron fields for testing and calibrating neutron sensitive devices, is that of embedding one ore more radionuclide fast neutron sources in large moderating blocks and fixing the testing point outside the moderator. Graphite and polyethylene have been frequently used to build moderating assemblies. Graphite has the advantage of producing fewer gammas than polyethylene, but thicker blocks are needed because of the lower scattering cross section and average energy loss per collision. When using graphite, usually very large moderating assemblies (few cubic metres) are needed. The thermal neutron fluence rate at the point of test is usually very low if compared with the large amount of radioactive material needed. As major examples, two graphite-based moderating assemblies were developed, for metrology purposes, at IRSN-Cadarache (France) (Lacoste et al., 2004; Lacoste and Gressier, 2007) and at PTB-Braunschweig (Germany) (Luszik-Bhadra et al., 2014). The IRSN SIGMA facility (currently unavailable) had 3.3 m^3 volume and embedded six ^{241}Am–Be for a total neutron emission rate of about 2×10^8 s^{-1}. The thermal neutron fluence rate at the point of test (50 cm from the facility lateral wall) was in the order of 1.5×10^3 cm^{-2} s^{-1} and represented 88% of the total neutron fluence. For the purpose of comparing thermal neutron facilities, the factor q is here defined as the quotient B/Φ_{th}, where B is the total emission rate of the embedded neutron sources (in s^{-1}) and Φ_{th} is the useful thermal fluence rate (fluence rate below 0.5 eV, in cm^{-2} s^{-1}). q represents the source emission rate needed to produce a useful thermal fluence rate of 1 cm^{-2} s^{-1}. The q factor for the SIGMA facility was in the order of 1.3×10^5 cm^2.

The PTB thermal calibration field relies on a 4 m^3 graphite assembly. It shows a very thermalized field (thermal fraction 99%) with homogeneity 10% in a 20 cm × 20 cm area at the reference position (30 cm from the assembly). The thermal neutron fluence rate at the reference position is about 80 cm^{-2} s^{-1} and the value of q is about 7×10^5 cm^2.

Smaller moderating assemblies are needed when using polyethylene, such as in the ENEA-Bologna (Italy) thermal facility

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(Gualdrini et al., 2004), currently unavailable, based on a 1 m^3 polyethylene block with a 20 cm × 20 cm extraction cavity. Here the thermal fraction was about 60% and the homogeneity figure at the point of test was 5% on 10 cm × 10 cm area. The thermal neutron fluence rate at the reference position was about 500 $cm^{-2}\,s^{-1}$ and the value of q was about 7×10^4 cm^2.

A different concept of polyethylene-based moderating assembly, developed for simultaneous testing of multiple thermal neutron detectors, was developed by the NEURAPID collaboration. The main idea was to exploit the multiple scattering of neutrons with the walls of a large cavity rather than the penetration in a moderating medium. Objectives of this new design were:

1. Achieving a very large irradiation area (in the order of 30 cm × 30 cm) with very homogeneous value of thermal neutron fluence rate.
2. Minimising the value of q, in order to minimise the cost and the radiation protection issues related to the neutron source.
3. Building the facility by assembling available 100 cm × 100 cm × 10 cm polyethylene sheets.

This paper describes the numerical design of this a new facility called ETHERNES (Extended THERmal NEutron Source).

2. The ETHERNES moderator design

ETHERNES was designed using the Monte Carlo MCNPX 2.7 Monte Carlo code (Pelowitz, 2011) using the ENDF/B-VII cross section library (Chadwick et al., 2006) for neutrons with energies below 20 MeV and the room temperature cross section tables for thermal neutrons in polyethylene, S(α,β).

The facility (Figs. 1 and 2) is based on a single ^{241}Am–Be neutron source (labelled 3 in Fig. 2), laterally shielded with a 5 mm thick lead cylinder to eliminate the 59.5 keV photons from ^{241}Am. This source was modelled as a "volume source" uniformly distributed in a void volume, having the same dimensions as the commercial Am–Be source embedded in the facility (Eckert and Ziegler AM1N20 capsule[1] with emission rate $\approx 5.7 \times 10^6$ s^{-1}). As far as the source spectrum is concerned, a recently revised Am–Be "small source" spectrum (Bedogni et al., 2014) was used.

Devices and samples to be irradiated are allocated in the large irradiation cavity (labelled 6), having 45 cm × 45 cm square section and 63 cm height. This cavity is delimited by polyethylene lateral walls (labelled 1), a removable, 10 cm thick, polyethylene cover on top (labelled 5), and a one cm lead plate on bottom (labelled 4). The lead partially shields the irradiation cavity from the capture photons (mainly 2.2 MeV from hydrogen) and the high-energy photons directly emitted by the Am–Be source. The cavity is separated from the neutron source through a polyethylene sphere with diameter 20 cm (labelled 2), acting as a shadowing object. Due to the effects of this sphere and of the lateral polyethylene walls, only scattered neutrons can reach the measurement area. These effects are combined in a way that the thermal fluence is nearly uniform across planes that are parallel to the cavity bottom (upper surface of the lead plate). Owing on an accurate knowledge of the vertical fluence gradient, a given value of fluence rate can be selected by simply varying the vertical quote in the cavity. Dashed lines in Fig. 2 indicated relevant irradiation planes. The indicated quote (e.g. +5 cm) refers to the height in cm with respect to the cavity bottom.

The neutron and photon quantities at different points of the irradiation cavity were calculated using point-like MCNPX f5 tallies (Pelowitz 2011) (exclusion radius 0.5 cm). In a few specific points, these values were compared with the results from f4 tallies getting the same results. Apart few point where detailed multi-group neutron and photon fluence spectra were calculated, the characterisation was performed by dividing the energy range in thermal ($E < 0.5$ eV) and epithermal ($E > 0.5$ eV) neutrons. All field quantities (fluence for neutrons and air kerma for photons) are given per unit source neutron. Calculations have been performed to reach statistical uncertainties lower than 0.3% (for spectrum-integrated quantities) and lower than 3% (fluence per energy bin in multi-group spectra).

Fig. 1. Lateral view of ETHERNES.

To better understand the field quantities in the irradiation cavity, four representative irradiation planes have been chosen for more detailed studies of the neutron and photon spectra, as well as the directional distribution of the neutron fluence. These planes corresponds to:

1. Quote +5 cm: this plane is very near to the cavity bottom and experiences the attenuating effect of the shadow sphere. Here the thermal field, if compared with higher quotes, is expected to be more intense but less uniform.
2. Quote +15 cm combines high thermal fluence with good uniformity.
3. Quote +30 cm is far from both the cavity bottom and the cavity cover, and represents the upper limit of a region where the thermal fluence linearly decreases with the quote. This linear region extends from +10 to +30 cm. Quotes lower than +10 cm feels the effect of the sphere, whilst quotes higher than +30 cm feel the effect of the cavity cover.
4. Quote +60 cm is very near to the cavity cover and delimits a region where the thermal fluence is nearly uniform over a

[1] http://www.ezag.com/home/products/isotope-products/industrial-sources.html.

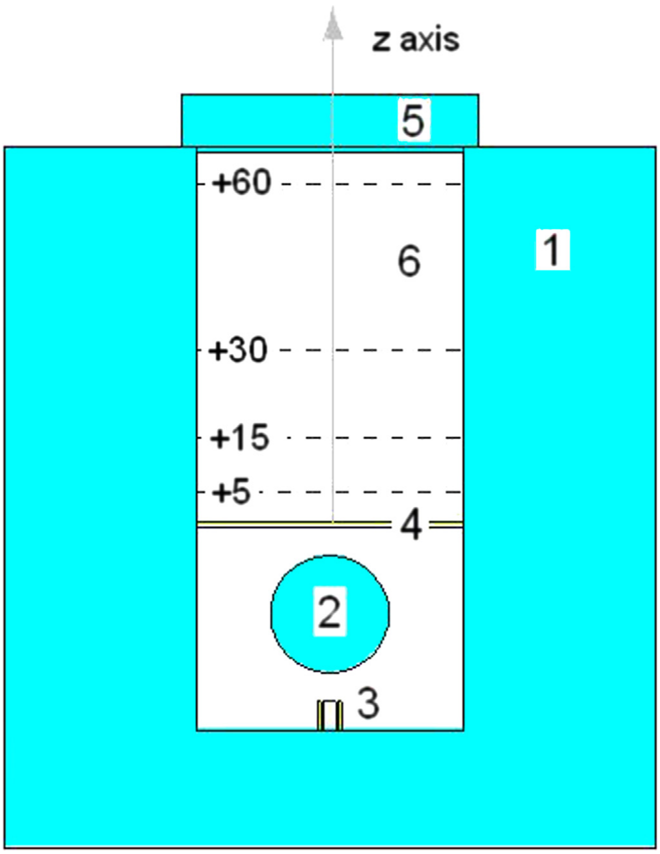

Fig. 2. Lateral cut of the ETHERNES facility. Dimensions of the irradiation cavity (labelled 6) are 45 cm × 45 cm × 63 cm height. Label 1 = polyethylene structure; label 2 = shadow sphere; label 3 = neutron source; label 4 = lead plate; label 5 = cover.

cylindrical volume. This volume extends from +50 to +60 cm.

The simulations of ETHERNES, described in the following sections, are focused on these aspects:

1. Fluence gradient along the vertical z axis, see Fig. 1. Distances on this axis are referred to the cavity bottom.
2. Simulated 102 group neutron spectra at different irradiation planes.
3. Uniformity of the thermal field at relevant irradiation planes.
4. Photon component.
5. Directional distribution of neutron fluence at relevant irradiation planes.

3. Variation of the neutron quantities with height

The variation of the thermal and epithermal fluence components as a function of the vertical quote (distance on z from cavity bottom) was calculated and reported in Fig. 3 normalised per source-emitted neutron. As it has been anticipated at the beginning for the thermal fluence, there is a linear region from about +10 to +30 cm. The slope in this region is about $-1\%\,\text{cm}^{-1}$. Quotes lower than +10 cm are affected by the shadowing effect of the sphere, thus the fluence is lower than it would result from an extrapolation of the straight line. Quotes higher than +30 cm receive a significant albedo component from the cover. Consequently the curve from +30 to +50 cm decreases with decreasing slope and tends to remain constant from +50 to +60 cm. The thermal neutron fluence rate for the commercial Am–Be source presently

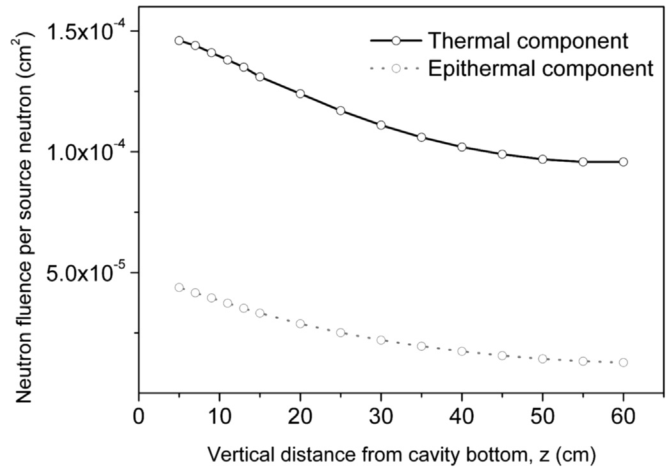

Fig. 3. Variation of the thermal and epithermal neutron fluence with the vertical distance from the bottom of the irradiation cavity.

located in the facility ranges from $8.0\times10^{2}\,\text{cm}^{-2}\,\text{s}^{-1}$ for $z=+10$ cm to $5.5\times10^{2}\,\text{cm}^{-2}\,\text{s}^{-1}$ for $z=+60$.

The epithermal component decreases similarly to the thermal one, but with higher slope ($-3\%\,\text{cm}^{-1}$ in the linear region). Consequently the fraction of thermal neutrons in the spectrum increases with the quote.

This can be directly verified by looking to the simulated 102 groups neutron spectra calculated at the centre of planes +5, +15, +30 and +60 cm and reported in Fig. 4. As it can be expected, the fractional thermal component increases with the quote and assumes the values 77% (+5), 80% (+15), 84% (+30) and 89% (+60). The intermediate component is in all cases an almost pure $1/E$ spectrum.

The q value, as it has been defined in the first paragraph, varies from $6\times10^{3}\,\text{cm}^{2}$ (+15) to $9\times10^{3}\,\text{cm}^{2}$ (+60). This indicates that the moderation process, converting source neutrons into thermal neutrons at the irradiation plane, is very effective compared to the traditional designs described in the introduction section.

4. Uniformity

Since the irradiation cavity of ETHERNES has square section but

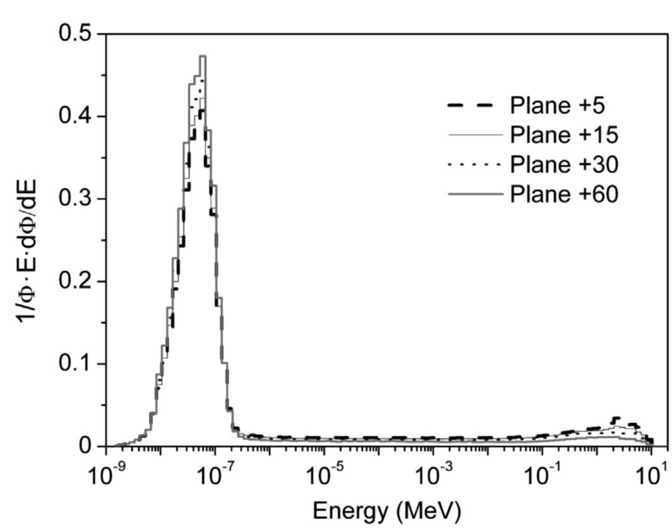

Fig. 4. Calculated 102 groups neutron spectra at the centre of planes $z=+5$, +15, +30 and +60 cm. All spectra are normalised to the unit fluence and are in equi-lethargy representation.

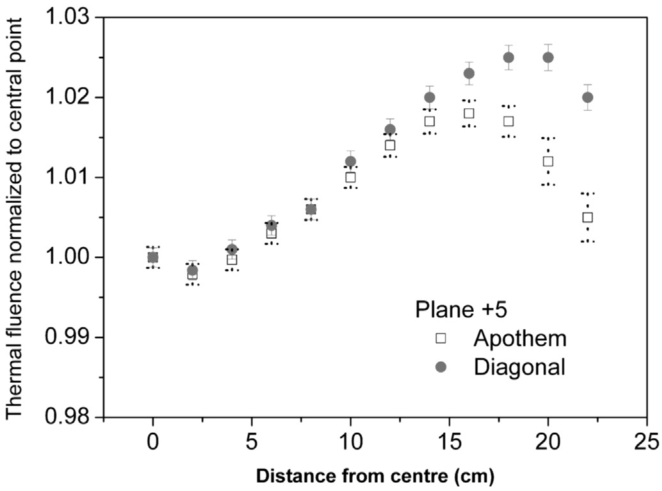

Fig. 5. Thermal fluence profile along the apothem and the diagonal of plane $z = +5$ cm, normalised to the value in the central point.

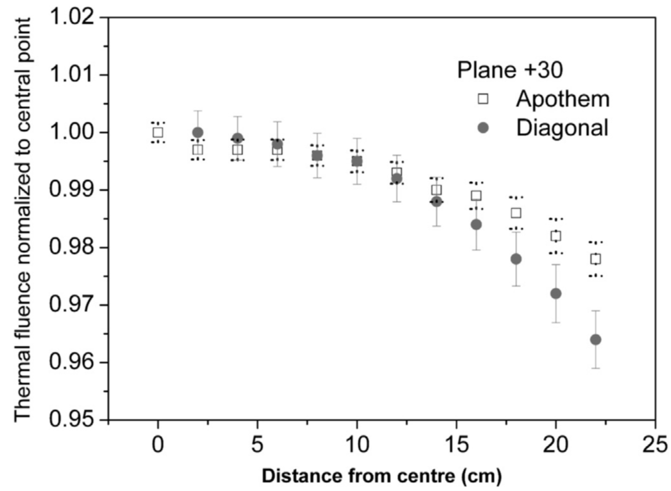

Fig. 7. Thermal fluence profile along the apothem and the diagonal of plane $z = +30$ cm, normalised to the value in the central point.

the shadowing object is a sphere, predicting the shape of the iso-fluence surfaces on irradiation planes is not trivial. Due to their square shape, irradiation planes have been characterized along the diagonal and the apothem. In principle two points equidistant from the centre, but located on the apothem or the diagonal, experience slightly different fields because of the different average distance from the cavity walls. This effect needs to be evaluated to understand the shape and extension of the iso-fluence surfaces on different irradiation planes. For practical purposes it is here assumed that an iso-fluence surface includes all points on an irradiation plane (parallel to the cavity bottom) showing a thermal fluence equal or higher than a given fraction, called *f*, of the maximum thermal fluence for that plane. In this work it is assumed $f = 97\%$, indicating a maximum non-uniformity of 3%. The latter corresponds to a typical experimental uncertainty achievable when a thermal facility is experimentally characterized with the gold activation foils technique (Luszik-Bhadra et al., 2014).

The fluence profiles along the apothem and the diagonal of planes +5, +15, +30 and +60 cm have been normalised to the values in the central point and are shown in Figs. 5–8.

For plane +5 cm (Fig. 5) the apothem-diagonal asymmetry is evident and depends from the vicinity of the shadow sphere. However it stays within the 3% margin established for uniformity purposes, so that the iso-fluence surface at plane +5 cm can be considered a disk with radius 22 cm.

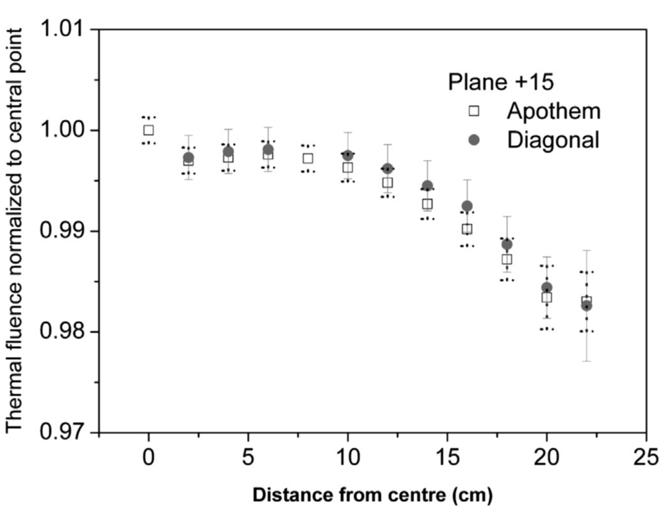

Fig. 6. Thermal fluence profile along the apothem and the diagonal of plane $z = +15$ cm, normalised to the value in the central point.

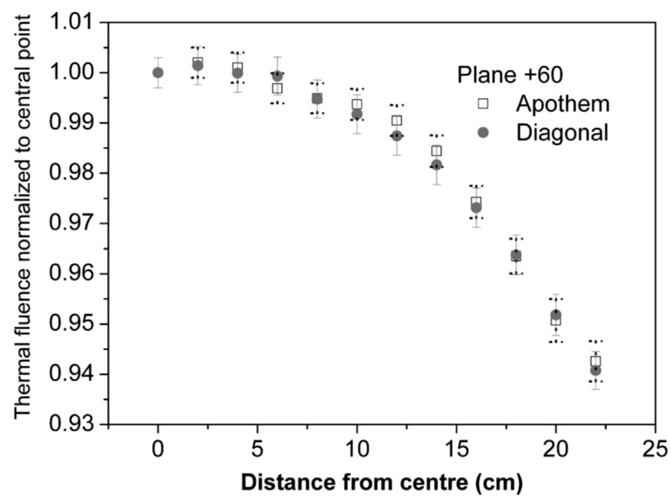

Fig. 8. Thermal fluence profile along the apothem and the diagonal of plane $z = +60$ cm, normalised to the value in the central point.

Plane +15 cm (Fig. 6) is far enough from the sphere to receive a very homogenous field, with no diagonal-apothem asymmetries. Plane +30 cm (Fig. 7) starts experiencing the distance from the sphere, which acts as main source of scattered neutrons, so that fluence depression effects are observed at peripheral points. The uniform disk has 20 cm radius. This effect is more evident for plane +60 cm (Fig. 8), where the uniformity radius is 15 cm. By contrast, at +60 cm there is no diagonal-apothem asymmetry because of the homogenisation effect of the cover, which is located only few cm above.

5. Photon component

Reducing the photon component of a thermal neutron facility is very important, because many thermal neutron sensitive devices are also sensitive to photons, and their photon response may exhibit significant energy dependence. In ETHERNES design the one cm lead plate certainly protects the irradiation cavity against the 59.5 keV photons from ^{241}Am, and reduces the photons coming form the moderation process (mainly 2.2 MeV from capture in hydrogen) and the high-energy photons directly emitted from the source. According to data from (ISO, 2001), such high-energy

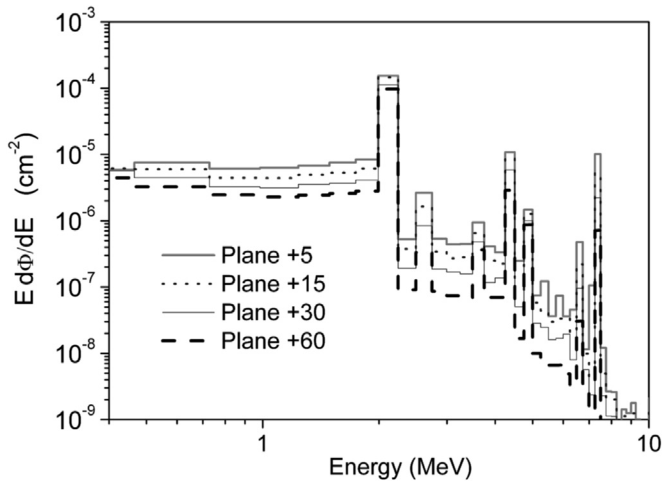

Fig. 9. Simulated photon spectra at the centre of relevant irradiation planes. The spectra are normalised to one source neutron and are in equi-lethargy representation. Only photons arising in the moderation process are considered.

contribution probably supersedes the other components, and is really hard to include in a simulation. The definitive option will be measuring the overall ETHERNES gamma field with an instrument with flat energy response and negligible neutron response, as the GM-1 compensated Geiger counter[2]. However, simulations were undertaken to give an idea of the moderation photon field at the centre of the irradiation planes (Fig. 9). From the plot it is clear that the 2.2 MeV component dominates the photon field. In terms of air kerma, the 2.2 MeV component represents 64%, 67%, 69% and 73% of air kerma due to the moderation field at plane +5, +15, +30 and +60, respectively. The total air kerma is 2.61, 2.26, 1.78 and 1.44, respectively (in units of 10^{-4} pGy per source neutron).

6. Directional distribution of the neutron fuence

Fig. 10 shows the calculated angular distributions of thermal fluence at the centre of planes $z=+15$ cm (Fig. 10a, solid line) and $z=+30$ cm (Fig. 10b, solid line) as a function of the cosine of polar angle θ (related to the Z axis, see Fig. 2, $\theta=0$ is equivalent to cos $(\theta)=1$ and indicates neutrons in bottom-to-top direction). Bottom-to-top directions are slightly favoured and approximately 25% of the thermal fluence lies within the solid angle defined for $0^\circ<\theta<45^\circ$ $(0.7<\cos(\theta)<1)$. If the distribution was perfectly isotropic, this fraction would be 15%. The distribution is basically uniform for other directions $(-1<\cos(\theta)<0.7)$. The angular distribution has been also calculated at these planes for points located along the apothem ($x=10$, 15 cm) without significant changes.

7. Conclusions

A new concept of thermal neutron irradiation facility called ETHERNES (Extended THERmal NEutron Source) was developed. The facility was assembled using 100 cm × 100 cm × 10 cm polyethylene sheets and a commercial Am–Be source. With respect to traditional radionuclide-based thermal fields, where leakage neutrons from large moderating blocks are used, a novel design was introduced. Here the useful thermal field is produced by multiple scattering with the walls of a large irradiation cavity (45 cm × 45 cm square section, 63 cm in height). Fast neutrons are removed from the field through a polyethylene sphere, separating the irradiation cavity from the source and acting as shadowing object. Irradiation planes parallel to the cavity bottom have been identified. The fluence rate across a given plane is as uniform as 3% (or better) in a disk with 30 cm (or higher) diameter. Relying on this satisfactory level of uniformity, it can be claimed that the value of thermal fluence rate simply depends on the height from the cavity bottom.

The neutron spectrum is highly thermalized, with a fractional thermal component increasing from about 77% (close to cavity bottom) up to 89%, depending on the irradiation plane. The neutron source emission rate needed to yield a thermal fluence rate of one $cm^{-2}\,s^{-1}$, called q, varies from $6\times10^3\,cm^2$ (+15) to $9\times10^3\,cm^2$ (+60). This indicates that the moderation process is very effective, if compared to traditional designs. With the neutron source currently in use, the useful thermal fluence rate ranges from $8.0\times10^2\,cm^{-2}\,s^{-1}$ for $z=+10$ cm to $5.5\times10^2\,cm^{-2}\,s^{-1}$ for $z=+60$. The angular distribution of thermal neutrons at various irradiation planes is slightly peaked in the bottom-to-top direction (angles from 0° to 45°), whilst all other directions are equally represented.

ETHERNES design is easy to achieve in practice, has limited cost, provides extended and very uniform thermal neutron fields, and can be easily replicated in research laboratories equipped with radionuclide neutron sources. This is expected to benefit the scientific community involved in neutron metrology, neutron dosimetry and neutron detector testing.

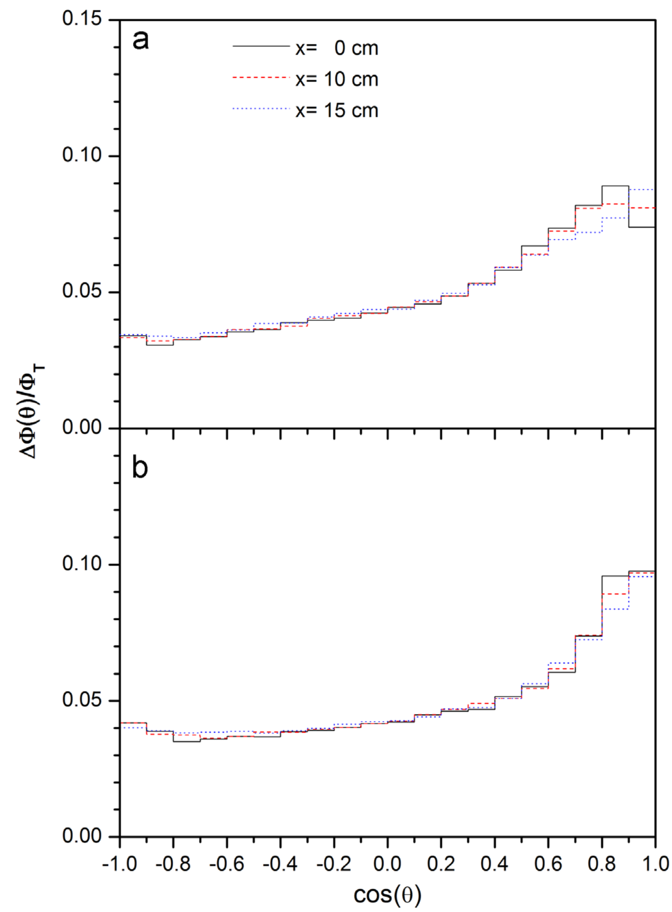

Fig. 10. Calculated angular distributions of thermal fluence as a function of the cosine of polar angle in (a) plane $z=+15$ cm and (b) plane $z=+30$ cm. Distributions have been calculated at the centre of the planes ($x=0$, solid line) and in points located along the apothem ($x=10$ cm, dashed line; $x=15$ cm, dotted line). All the distributions are normalised to the corresponding total thermal fluence.

[2] http://www.fwt.com/detector/gm1ds.htm.

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