Experimental characterization of HOTNES: A new thermal neutron facility with large homogeneity area

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ABSTRACT

A new thermal neutron irradiation facility, called HOTNES (HOmogeneous Thermal NEutron Source), was established in the framework of a collaboration between INFN-LNF and ENEA-Frascati. HOTNES is a polyethylene assembly, with about 70 cmx70 cm square section and 100 cm height, including a large, cylindrical cavity with diameter 30 cm and height 70 cm. The facility is supplied by a ^{241}Am-B source located at the bottom of this cavity. The facility was designed in such a way that the iso-thermal-fluence surfaces, characterizing the irradiation volume, coincide with planes parallel to the cavity bottom. The thermal fluence rate across a given isofluence plane is as uniform as 1% on a disk with 30 cm diameter. Thermal fluence rate values from about 700 cm^{-2} s^{-1} to 1000 cm^{-2} s^{-1} can be achieved. The facility design, previously optimized by Monte Carlo simulation, was experimentally verified. The following techniques were used: gold activation foils to assess the thermal fluence rate, semiconductor-based active detector for mapping the irradiation volume, and Bonner Sphere Spectrometer to determine the complete neutron spectrum. HOTNES is expected to be attractive for the scientific community involved in neutron metrology, neutron dosimetry and neutron detector testing.

1. Introduction

Thermal neutron fields based on sealed fast neutron sources, such as Am-Be or Am-B, embedded in large (few cubic meters) polyethylene or graphite moderator assemblies, are traditionally used for neutron dosimetry. The neutron field leaking from the cavity, usually highly thermalized, is used to irradiate large devices as well as phantoms [1]. Irradiation areas exhibit homogeneity figures in the order of 10% across few hundreds of square centimetres [2,3]. Since the field is highly attenuated by the moderating block, neutron sources as large as 10^8 s^{-1} are required to achieve values of thermal neutron fluence rates in the order of 10^2–10^3 cm^{-2} s^{-1}.

Using a different facility design, recently proposed by Bedogni et al. [4], very uniform (within 1–2%) thermal neutron fields can be obtained across irradiation areas as large as 30 cm in diameter, together with an improved value of useful thermal fluence per unit source strength. Instead of exploiting the leakage field from a large moderating block, the Bedogni design relies on a large cavity, with reflecting walls, containing the neutron source and the irradiation volume. The latter is separated from the source by means of a shadowing object. Thus neutrons can only reach the irradiation volume through multiple scattering with the cavity walls. The thermal neutron fluence in the irradiation volume may represent 90% of the total fluence, featuring a good thermalization level. The "isofluence" surfaces correspond to planes parallel to the facility bottom, and their size is 30 cm in diameter or more. Thermal neutron fluence across a given isofluence plane is very uniform (within 1–2%), and fluence rate values as high as 10^3 cm^{-2} s^{-1} are achieved with source strengths in the order of 3–4×10^6 s^{-1}.

The experimental prototype of this new concept is HOTNES, the HOmogeneous Thermal NEutron Source, set up at ENEA Frascati by an ENEA – INFN (Frascati) collaboration.

This paper shows the complete experimental neutron characterization of HOTNES in turn providing a benchmark for other facilities, based on the Bedogni design, and currently under establishment at Politecnico di Milano (ESTHER facility) and INFN-LNF (ETHERNES facility).

Different experimental methods were used, namely (1) gold-activation foils to determine the thermal fluence rate at the reference position; (2) active semiconductor-based thermal neutron detectors

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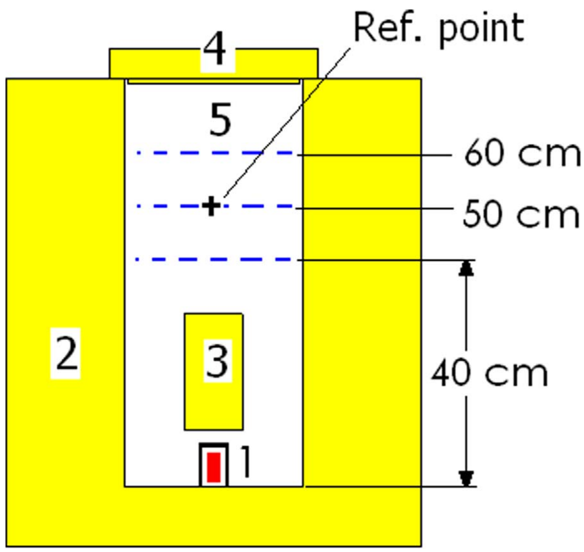

Fig. 1. Lateral cut of the HOTNES facility. Dimensions of the irradiation cavity (label 5) are 40 cm height x 30 cm diameter. Iso-fluence surfaces are disks parallel to the facility bottom and are denoted by their height from the facility bottom.

of TNPD type [5] for the relative thermal fluence mapping of the irradiation volume, and (3) a Bonner Sphere Spectrometer (BSS) equipped with a ^{6}LiI(Eu) scintillator to determine the neutron spectrum at the reference position.

2. Facility design

HOTNES relies on a ^{241}Am-B neutron source (labelled 1 in Fig. 1) with strength 3.5×10^{6} s^{-1} (nominal value). A cylindrical 5 mm thick lead shield attenuates the 59.5 keV photons from ^{241}Am. The source is located at the bottom of a large cylindrical cavity delimited by polyethylene walls, floor and ceiling. This cavity has diameter 30 cm and height 70 cm. The shadow bar (10 cm in diameterx20 cm in height, labelled 3 in Fig. 1) prevents fast neutron to directly reach the samples to be irradiated. The useful irradiation volume (labelled 5) is delimited, on bottom, by the polyethylene shadow bar, and, on top, by a removable, 5 cm thick, polyethylene cover (labelled 4). The useful volume has diameter 30 cm and height 40 cm. The effects of the shadow bar and of the cavity walls are combined in such a way that the thermal fluence is nearly uniform across the so called isofluence disks, which are parallel to the cavity bottom. Iso-fluence disks are identified through their height (in cm) from the cavity bottom. Dashed lines in Fig. 1 represent some of them. 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. When the polyethylene cover is in place, the field inside the cavity is nearly isotropic. By contrast, a nearly parallel beam can be obtained by removing the cover. HOTNES design was optimized using the MCNPX 2.7 Monte Carlo code [6] with the ENDF/B-VII cross section library [7] for neutrons with energies below 20 MeV, and the room temperature cross section tables for thermal neutrons in polyethylene, $S(\alpha,\beta)$. An accurate description of the Monte Carlo simulations is given elsewhere [8].

3. Thermal fluence rate measurements with gold activation foils

Thermal neutron measurements were performed with a standard metrology technique relying on thin gold activation foils exposed "bare" and shielded by cadmium. The measurements were performed in the central point of the +50 cm irradiation plane of HOTNES, with polyethylene ceiling in place. This is hereafter called “reference point”.

Two types of foils were exposed, namely 10 µm thickness −1.5 cm diameter and 50 µm thickness-1.13 cm diameter. The cadmium boxes were cylindrical, with internal diameter 2 cm, 0.8 cm internal height, and wall thickness 0.8 mm. The foils were gamma-counted using a previously calibrated HPGe P-type 60% ORTEC Poptop Germanium spectrometer.

The formalism reported in Eq. (1) [9] was applied to determine the sub-cadmium cut off fluence rate in the Westcott convention, $\Phi_w(th)$ [10]:

$$\Phi_W(th) = \frac{F_c \bullet \left(A_{s,bare} - \frac{F_b}{F_a} \bullet A_{s,Cd}\right)}{N \bullet \sigma_{Au} \bullet g} \qquad (1)$$

where:

$A_{s,\ bare}$=specific saturated activity in the bare foil
$A_{s,\ Cd}$=specific saturated activity in the Cd-covered foil
N=activable atoms per gram
g=Westcott factor=1.0046
σ_{Au}=capture cross section for ^{197}Au=98.69 b at 0.025 eV

The parameters F_a, F_b and F_c were calculated with MCNPX, realistically modelling the HOTNES facility and the activation foils placed at the reference point, and have the following meaning:

- F_a corrects for the incomplete thermal neutron attenuation in Cd cover and its value is 1.0085 (s.d. 0.1%);
- F_b corrects for the epithermal neutron attenuation in Cd cover and its value is 1.023 (s.d. 1%);
- F_c corrects for the corrects for self-absorption of thermal neutrons in the Au foil and its value is 1.063 (s.d. 0.3%).

The results are summarized in Table 1.

The two values reported in Table 1 are in good agreement and their weighted average is regarded as the best estimation of $\Phi_w(th)$ in HOTNES reference point. Its value is $\Phi_w(th)_{best}$=763 ± 11 cm^{-2} s^{-1}.

4. Mapping the irradiation cavity

Relative thermal fluence measurements were organized in order to characterize the isofluence disks inside the irradiation cavity. This cylindrical volume, defined in height from the top of the shadow bar till the polyethylene ceiling, was scanned by varying the measurement position over both height (from 30 to 60 cm) and radius (from 0 to 14 cm). TNPD-type [5] Silicon-based thermal neutron detectors were used for this purpose. These are built by depositing a 30 µm thick layer of ^{6}LiF (chosen to maximise efficiency) on commercially available one-cm^2 windowless p–i–n diodes, with 0.3 mm maximum depletion layer. A spectroscopy chain, formed by a charge preamplifier and a shaper amplifier (shaping time 2 µs), is used to amplify the signal from the detectors. Data digitalization is done through a commercial USB digitizer National Instruments 6366. The pulses are analysed in terms of their height distribution (spectrum). The discrimination between thermal neutron and photon signal is operated by means of a pulse height threshold. Measurements with the TNPD "bare" and "under Cd" were performed, and the difference was regarded as "genuine" thermal neutron signal. This quantity at a given position in the cavity, called TNPD(Z,R), is proportional to the thermal fluence rate. Thus, the

Table 1
Results of the gold foil measurements to determine the sub-cadmium cut off fluence rate in the Westcott convention in the reference point of HOTNES.

Foil type	Φ_w (th)
50 µm thickness, 1.13 cm diameter	758 ± 16 $cm^{-2}s^{-1}$
10 µm thickness, 1.50 cm diameter	768 ± 16 $cm^{-2}s^{-1}$

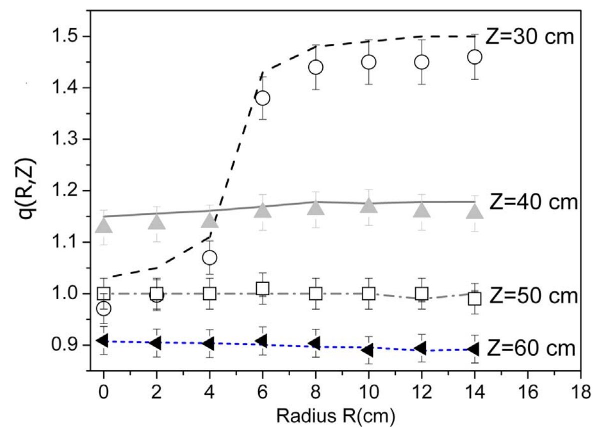

Fig. 2. Experimental (points) and simulated (lines) values of q(Z, R)=$\frac{TNPD(Z,R)}{TNPD(50,0)}$ as a function of Z and R in HOTNES irradiation cavity.

quotient q(Z,R)=$\frac{TNPD(Z,R)}{TNPD(50,0)}$ represents the thermal neutron fluence at that point, normalized to thermal neutron fluence at the reference point (Z=50, R=0). The irradiation volume was mapped in terms of this quotient.

The same mapping was derived with MCNPX, including a realistic model of the TNPD detector. The number of ^{6}Li(n,α) reactions induced by thermal neutrons in the TNPD at a given point (Z,R), based on a modified F4 tally, was normalized to the same quantity at reference point (50,0). This quotient is directly comparable with the experimental one, q(Z,R).

Fig. 2 compares the experimental values (points) of q(Z,R) with the simulated ones (lines), as a function of Z and R. The uncertainty (about 3% s.d.) was evaluated by repeated measurements at the same point in different days (detector reproducibility), including positioning and removal of the detector to account for the positioning uncertainty. The comparison between experiment and calculation is satisfactory.

The curves in Fig. 2 identify the isofluence surfaces and can be explained as follows:

Plane +30 cm coincides with the top end of the shadow bar, and is then directly affected by this absorbing element. The thermal fluence increases with the radius and experiences a steep rise in correspondence of the bar edge (R=5 cm). However, the thermal fluence rate in the 7 cm < R < 14 cm region is homogeneous within ± 0.3% (s.d. of the profile values), and its value is $\Phi_\omega(th)$=1106 ± 33 cm^{-2}.

The effect of the shadow bar becomes less effective as Z increases. Indeed, fluence rate homogeneity for the Z=+40 cm plane is ± 1.3% (s.d. of the profile values) considering all radial positions from R=0 cm to R=14 cm.

The homogeneity for the planes at Z=50 and 60 cm is ± 0.7% and ± 0.8% (s.d. of the profile values), respectively.

The high degree of homogeneity found across the irradiation planes allows to uniformly irradiate even large devices.

Once demonstrated that irradiation planes are very homogenous in thermal fluence, an important feature to be assessed is the vertical gradient, obtainable from the quotient q(Z,0), plotted in Fig. 3. Again, experimental (points) and simulated (lines) values are satisfactorily compared.

As in realistic scenarios where a fast neutron source is shielded with a shadow object [11], the scattered field "far" (Z≥40 cm) from HOTNES shadow bar decreases as $\frac{\alpha}{Z} + \beta$, α and β being fitting parameters (α~30 cm, β~0.4). In the "near" region (Z~30 cm) the field mainly experiences the attenuation of the bar. As Z increases (30 cm < Z < 40 cm), the "shadow" effect gradually becomes less effective and the component coming from wall and ceiling gradually dominates the field.

The vertical profile exhibits an average gradient of −1.2% cm^{-1} in the region from Z=40 cm to Z=60 cm. Correspondingly, the $\Phi_\omega(th)$ values decreases from about 900 cm^{-2} s^{-1} for z=+40 down to

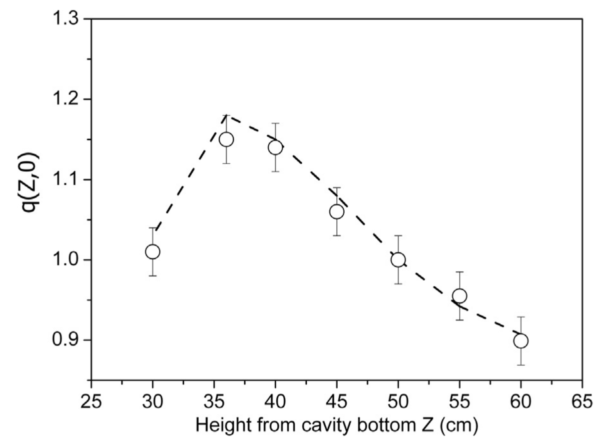

Fig. 3. Experimental (points) and simulated (lines) values of q(Z,0)=$\frac{TNPD(Z,0)}{TNPD(50,0)}$as a function of Z in HOTNES irradiation cavity.

690 cm^{-2}s^{-1} for z=+60.

5. Spectrum determination

The neutron spectrum from the thermal domain up to the maximum emission energy of the internal ^{241}Am-B source (about 6 MeV [12]) was determined using a Bonner Sphere Spectrometer (BSS) [13] with a ^{6}LiI(Eu) scintillation detector. The scintillator has diameter 11 mm and thickness 3 mm. Twelve high-density polyethylene spheres, whose diameters are 6, 7, 8, 9, 10, 11, 13, 15, 17, 20, 25 cm, were used. The diameter and density of these moderators are very well known (less than ± 0.5% s.d.), so that very accurate Monte Carlo models to achieve their response functions [14] could be produced. The twelve mentioned spheres were exposed at the reference point of HOTNES (Z=50 cm, R=0), with polyethylene ceiling in place. The so called "counts profile", i.e. the sphere count rate as a function of its diameter, is reported in Fig. 4. This can be fitted with a smooth curve, indicating that the measurements were performed under "stable conditions, using the right monitors, and are not affected by supplementary uncertainties of unexplained origin" [15].

The count rates measured with the different spheres were unfolded, using the FRUIT unfolding code [16] with the Special Gradient Method (SGM) option [17]. The spectrum derived with MCNPX, including an accurate model of the moderating assembly, was adopted as a realistic "guess" spectrum. After few iterations, the average deviation between measured and folded counts for all spheres was < 1%. Thus the results from the BSS are entirely coherent with the guess spectrum used or, in other words, the guess spectrum is very realistic and well represents the

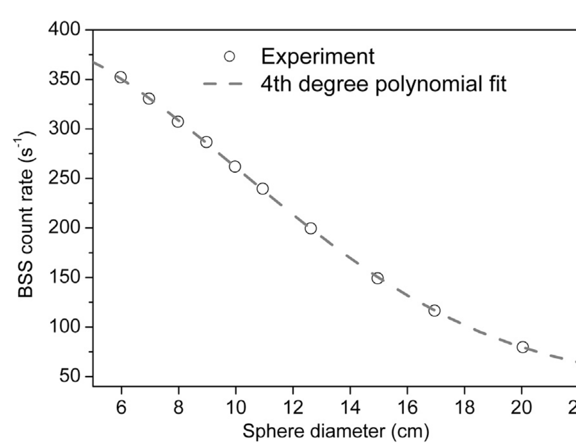

Fig. 4. BSS count rate as a function of sphere diameter. Uncertainties are smaller than graphical symbols.

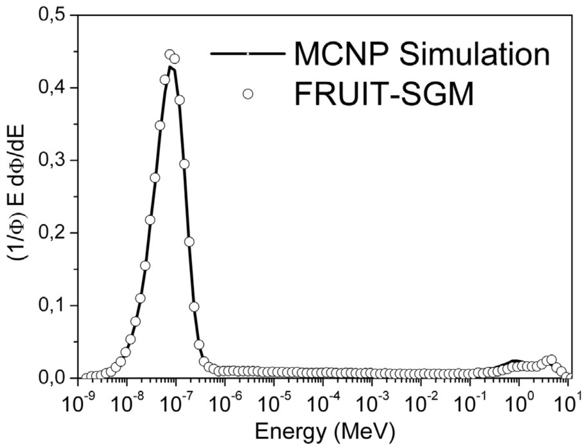

Fig. 5. Measured and simulated neutron spectra in HOTNES reference point with polyethylene ceiling in place. Spectra are normalized to unit fluence and in equi-lethargy representation. Errors are smaller than graphical symbols.

experiment. Both guess and final spectra are reported in Fig. 5.

As expected, the field is thermalized. The fluence fraction below 0.4 eV is indeed 85%. The fluence fraction in the region 0.4 eV–0.1 MeV is 9.5% and 5.5% is the fluence fraction from 0.1 MeV up to the maximum energy. According to the simulations, the thermal fraction increases as the height in the cavity increases up to about 90% at Z=60.

6. Discussion and conclusions

The neutron characterization of a new thermal neutron irradiation facility called HOTNES (HOmogeneous Thermal NEutron Source) was presented. This is a polyethylene moderator, with about 70 cmx70 cm square section and 100 cm height, including a large, cylindrical cavity with diameter 30 cm and height 70 cm. A ^{241}Am-B neutron source with nominal strength 3.5×10^{6} s^{-1} located at the bottom of the cavity, produces the primary fast neutrons. Due to a shadow-bar located between the source and the irradiation volume, the devices to be irradiated mainly receive neutrons that experienced multiple scattering events with the cavity cylindrical wall. Irradiation planes are disks with 30 cm diameter, located above the shadow-bar and parallel to the facility bottom. The value of thermal neutron fluence across a given irradiation plane is very uniform and its value range from about 700 to 1000 cm^{-2} s^{-1}, according to the irradiation plane chosen. When in place, the polyethylene ceiling causes a nearly isotropic field in the cavity. When the ceiling is removed, a nearly parallel field emerges from the cavity in the upward direction.

The facility was designed using MCNPX.

This experimental characterization was performed using:

1. Gold activation foils for determining the $\Phi_{\omega}(th)$ value at the facility reference point (Z=50 cm, R=0, polyethylene ceiling in place);
2. Silicon-based active thermal neutron detectors to map the irradiation volume as a function of Z and R;
3. A Bonner Sphere spectrometer to determine the neutron spectrum at the reference point.

All experimental results well compared with the corresponding simulated ones.

Further work is in progress to characterize the gamma field in the irradiation cavity, but preliminary measured kerma rate values in the order of 4–8 μGy h^{-1} (according to the irradiation place chosen) can be considered at this stage.

A metrology comparison with NPL (UK) is in progress to confirm the measured values of thermal neutron fluence rate.

HOTNES exhibits attractive features, like the simple and accessible design, the high values of thermal fluence rate achievable with modest neutron sources, and the high degree of homogeneity of the thermal field in the irradiation planes. In addition, the different irradiation scenarios achievable by using or removing the polyethylene ceiling, are suitable for a variety of applications. These characteristics are expected to trigger some interest in the scientific community involved in neutron metrology, neutron dosimetry and neutron detector testing.

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