Nuclear Inst. and Methods in Physics Research, A 908 (2018) 361–366

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

The use of electron linac for high quality thermal neutron radiography unit

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ARTICLE INFO

Keywords:
Neutron radiography
MCNPX
Electron linac
Thermal neutrons
Sapphire filter

ABSTRACT

A Thermal neutron radiography facility based on photoneutrons which produced by an electron linac was studied with the final goal to suggest an attractive alternative to the nuclear research reactors neutron sources which are used for radiographic purposes. The design and the optimization of the facility have been simulated using the MCNPX Monte Carlo code. The relevant with thermal neutron radiography parameters such as the thermal neutron flux, the L/D ratio and the thermal neutron content calculated for an extensive range of values. The results specify that the proposed facility meets all the required values for quality thermal neutron radiographies. The overall evaluation of the unit was also realized through the comparison between the studied facility and some published works.

1. Introduction

Radiography is the most popular Non-Destructive Testing (NDT) method. It is a noncontact technique which uses electromagnetic radiation, such as X-rays and γ rays or beams of atomic particles (usually neutrons) in order to examine for imperfections products, structures or human body part. There are numerous applications of radiography in medicine or engineering [1–4]. Radiographic method is based on the fact that different parts of an examined object attenuate different percentages of radiation owing to variations in material composition, density or thickness. The rest (non-attenuated) radiation passes across the investigated object and is captured on detectors. X-ray radiography is the most commonly known radiography method, however the neutron radiography (NR) method which works in the same way but exploits a neutron beam instead, has been also established as a research tool for over than 30 years. Thermal NR is complementary to X-ray and γ-ray radiography because X-rays and γ-rays are used mainly in detection of heavy elements whilst neutrons are sensitive in light elements or in different isotopes of an element [5–7].

There are many thermal NR facilities which are commercially available [8–11]. These facilities require mainly a high flux of strong collimated thermal neutron beam. A number of neutrons beam are presented as candidates for thermal NR. Nuclear research reactors and spallation neutron sources, owing to their high intensity neutrons flux, are the best choice for NR, however, have significant drawbacks because are expensive and considerably sizeable [12–16].

Isotopic neutron sources such as ^{252}Cf and ^{241}Am/Be are suitable for transportable NR facilities but emit a low intensity of neutrons and require adequate shielding of both for gammas rays and neutrons [17–20]. Deuterium–Deuterium (DD) and Deuterium–Tritium (DT) neutrons generators offer an on/of switching of the emitted neutrons and have a compact size but are suitable rather for fast NR because the DT have "harder" spectrum while the DD has usually low neutron intensity [21–26]. Accelerators are rather expensive but with significantly lower cost compare to nuclear reactors and have higher public acceptability. Proton accelerators on lithium or beryllium targets are the most typical and can offer thermal NR facilities with similar quality than this of low or medium power research reactors [27–31].

According to Mokhtari et al. a thermal NR unit must satisfy some recommendations relative with the minimum values of some parameters [32]. These parameters are the collimator ratio L/D (the collimator length to the inlet aperture diameter of the collimator), the thermal neutron flux (f_{th}), the Thermal Neutron Content (TNC), and the relative intensities of the neutron (n) and the photon (γ) components of the beam (n/γ). The suggested values are given in Table 1. The purpose of this article is twofold: firstly, to design a thermal NR facility, based on an electron linac with better NR parameters compared to other facilities which do not use nuclear reactors as neutron source; secondly the proposed facility to satisfy all the recommended for thermal NR values and hence will be a useful alternative to research nuclear reactors. The facility has been designed and has been simulated using the MCNPX Monte Carlo code [33].

2. Materials and methods

2.1. The photoneutron source

In this paper the necessary neutrons derived from a 25 MeV electron linear accelerator while tungsten and uranium were selected as materials for (e, γ) and (γ, n) converters respectively. The probability

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https://doi.org/10.1016/j.nima.2018.08.114
Received 12 May 2018; Received in revised form 23 August 2018; Accepted 29 August 2018
Available online xxxx

Table 1
Design goals for neutron beam parameters for thermal neutron radiography.

f_{th}	L/D	TNC	n/γ ratio
$\geq 10^6$ n cm^{-2}s^{-1}	≥ 90	≥ 90%	$\geq 10^4$ n cm^{-2} mSv^{-1}

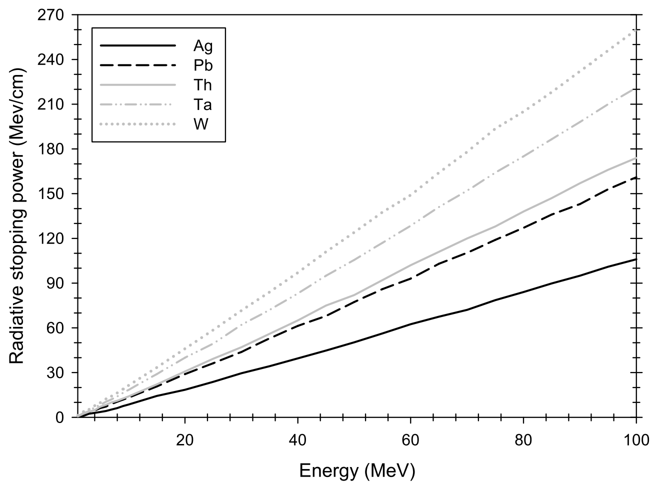

Fig. 1. Radiative stopping power for electrons with different energies for 5 materials-targets for photon production [36].
Source: Based on the data from tables of ICRU Report 37.

of neutron production by a single photon of energy E described by the equation

$$w(E) = \frac{\sigma_{(\gamma n)}(E)}{\sigma_{tot}(E)}[1 - \exp(-\sigma_{tot}(E)n\Delta)] \tag{1}$$

where $\sigma_{(\gamma n)}$ is the photoneutron production cross section, $\sigma_{\gamma tot}$ is the total photon scattering and absorption cross section, n is the target's density and Δ is its thickness. The number of produced neutrons can be calculated by the equation

$$N_n = \int_{E_0}^{+\infty} \frac{dN}{dE} w(E) dE \tag{2}$$

where dN/dE is the bremsstrahlung yield [34,35].

The photonuclear interaction starts when a photon absorbed by a nucleus. In the MCNPX code there are nuclear databases for photons with energy up to 150 MeV. These databases include the BOFOD01U, CNDC01U, ENDF7U, KAERI01U, LANL01U and the LAU150 libraries, which contain the necessary photonuclear cross sections [33]. Elements with high Z number have already used as a target. Based on the data from ICRU report 37 Fig. 1 shows some common materials for this purpose [36]. According to the results from Fig. 1 tungsten seems as the best material for photon converter, in addition in the literature there are many works which demonstrates the advantage of the tungsten [37–40]. The source intensity depends both from the electron energy as well as from the thick of the target.

Neutron flux based on linac can provide higher fluxes when electrons with energy above 10 MeV are used. However, electrons with higher energies offer a "harder" spectrum so it is obvious that some compromise is necessary. In the case of 0.4 cm thick tungsten target the average neutron energy for incident electron beam with energy 10, 15 and 20 MeV is 0.445, 0.713 and 0.798 MeV, correspondingly [41]. Usually, the medical linacs emit electrons with range between 18–30 MeV. For the outcome of mutual compromise to be reached, in this paper the necessary neutrons derived from a 25 MeV electron linear accelerator with beam size 0.5 cm. Based on the analytical data from Torabi et al. [42] the maximum photon yield in the case of hemispherical tungsten target achieves when the radius is 0.4 cm. In accordance with

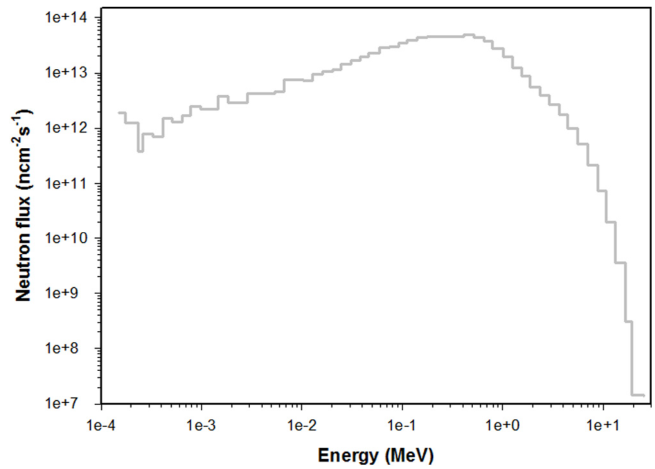

Fig. 2. Neutron spectrum of the source.

this work hemispherical target design offers the maximum neutron intensity and for this reason is adopted in this study. A hemisphere from natural uranium with 6 cm radius around the tungsten target is used as (γ, n) converter and increases the intensity of the source about 2.4 times. The calculated neutron intensity is 5.78×10^{13} n/s for 1 mA current. The neutron spectrum is shown in Fig. 2.

2.2. Thermal neutron collimator

In any thermal NR facility, the collimator ratio (*L/D*) determines the resolution of NR imaging [43]. The facility is governed by the following equations:

$$\phi_i = \frac{\phi_\alpha}{16\left(\frac{L_S}{D}\right)^2} \tag{3}$$

and

$$u_g = L_f \frac{D}{L_s} \tag{4}$$

where: φ_i is the neutron flux at the image plane, φ_a is the neutron flux at the aperture, L_s is the source to object distance, D is the inlet aperture diameter, u_g is the geometric unsharpness and L_f is the image surface to object distance, which usual is equal to 0.5 cm.

Another important parameter which describes the usefulness of the neutron beam near its periphery is the beam divergence which is given by the equation [44,45]

$$\theta = \tan^{-1}\left(\frac{I}{2L}\right) \tag{5}$$

where θ is the half-angle of the beam divergence, I is the maximum dimension of the image plane and L is the length of the collimator. If the neutron beam diverges very rapidly, then the outer portion of the images produced would suffer a significant distortion.

The *TNC* (the ratio of thermal neutron flux to total neutron flux) is another critical parameter for the imaging quality of a thermal NR facility. Last but not least the *n/γ* ratio typically at the image plane should be greater than 10^4 n cm^{-2} mSv^{-1} [46].

2.3. Thermal NR unit

The first critical point in the design of the facility is the thermalization of the fast neutrons which emitted from the source. Many previous researches revealed that high density polyethylene (HD-PE) has the capability to reduce the energy of the fast neutrons in a small number of collisions, while not absorbing them considerably. It has been also