Journal of Engineering Science and Technology Review
Special Issue on Telecommunications, Informatics, Energy and Management 2019

JOURNAL OF
Engineering Science and Technology Review

Conference Article

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Optimised the Neutron Beam for a Transportable BNCT System Based on ^{252}Cf Neutron Source

J. G. Fantidis[1,*], G. Nicolaou[2], D. Parousis[1] and F. Kogia[1]

[1]Department of Electrical Engineering, Eastern Macedonia and Thrace Institute of Technology, Kavala, Saint Loukas 65404 Greece
[2]Department of Electrical and Computer Engineering, Democritus University of Thrace, Xanthi 67100, Greece

Received 28 September 2019; Accepted 27 February 2020

Abstract

A mobile BNCT facility, using a 1 mg ^{252}Cf neutron source, has been studied with the aid of the MCNPX Monte Carlo code. The materials simulated were compatible according to the Directive of European Union on 'Restriction of Hazardous Substances' (RoHS) 2002/95/EC, therefore excluding the use of lead, cadmium and beryllium. Fluental and D_2O were chosen as the moderator materials with a special design and nickel as reflector. Bismuth and titanium was selected as beam filters with intention to improve the beam quality. The results indicate that the proposed facility is capable of producing a quality neutron beam suitable for BNCT treatments.

Keywords: BNCT; MCNPX; ^{252}Cf neutron source; Epithermal neutrons.

1. Introduction

Neutron Capture Therapy (NCT) is a promising method to cancer therapy for tumors such as Glioblastoma Multiforme (GBM), a destructive kind of brain cancer, where typical radiation treatments not succeed. Most experimental work and clinical studies in NCT have been based on ^{10}B. Boron neutron capture therapy (BNCT) is a binary cancer treatment modality. The treatment includes two parts: (i) in order to obtain the desired tumour control chance with minimum effects on healthy cells, a high concentration of ^{10}B has to accumulate next to the tumour cells area with the use of specific boronated drugs, (ii) low energy neutrons (thermal or epithermal) irradiate the patient. In consequence of the fact that the ^{10}B isotope has a huge capture cross section (3830 barns) for thermal neutrons brings about a high possibility of ^{10}B(n, a)^{7}Li reactions. Alpha and lithium particles which are produced from this reaction have total energy about 2.34 MeV on average and their range in tissue is about 10 μm, approximately one cell diameter. The probability is high hence in any case one of the close tumours cells will be killed [1-3].

Thermal neutrons due to their energy are suitable rather for the direct treatment of tumours which are positioned at near-tissue-surface; deep-seated tumours require harder, epithermal neutron energy spectra. When a sick person is irradiated using epithermal neutrons then the neutrons slowed down in the tissue and may be absorbed by ^{10}B destroying the cells which are next to the ^{10}B isotopes; for this reason there is a need for epithermal neutrons with desired energy in the range of 1 eV – 10 keV [4-6]. Epithermal beam peaked (between 1 – 10 keV) is more attractive in order to treat deep tumours [7].

Commonly there are three types of neutron sources: reactors, accelerators, and radionuclides. Clinical BNCT facilities usually based on the use nuclear reactors which are capable of producing the desired epithermal neutron beam without sacrificing the neutron flux intensity [8, 9]. However are expensive, non-transportable, there are limited numbers of these facilities and are not always acceptable from the public opinion. Accelerator-driven neutron beams produce epithermal neutron beams with higher spectral purity, have lower contamination of γ–rays, and have higher social acceptability than reactors. Even though require lower investment cost relatively to nuclear reactors, are neither economical not movable [10-12]. On the contrary, a range of commercially available isotopic neutron sources can be easily incorporated in transportable units, at the expense of beam intensity. In addition, their low cost means that they can be obtained by more hospitals.

In this article, a portable facility for BNCT treatment, via the epithermal neutrons from a ^{252}Cf isotopic neutron source incorporated within it, has been simulated using the MCNPX 2.5.0 Monte Carlo code [13]. The goal is to enhance the effectiveness of the unit with regard to its moderator, reflector and filters. The presented unit is designed in accordance with the article 4 of the RoHS Directive 2002/95/EC, as regards the selection of materials. For this reason, cadmium, lead, mercury, hexavalent chromium, beryllium, polybrominated diphenylethers (PBDE) and polybrominated biphenyls (PBB) have been excluded [14].

2. Material and method

There is a number of radioisotopes which are candidate for a BNCT unit; the ^{252}Cf is a good selection because has low cost per neutron yield, nearly negligible gamma ray

* E-mail address: fantidis@teiemt.gr
ISSN: 1791-2377

background, portable size, and the peak thermal/epithermal flux is the higher relatively to the fluxes emitted by (γ, n) sources of the same total fast neutron yield. For these reasons a ^{252}Cf source is simulated, using an isotropic emission of the neutrons. Based on the fact that 1 μg of the ^{252}Cf source emits 2.316×10^6 neutrons and using the coefficients given by the MCNPX 2.5.0 code, the mean energy of the neutrons is about 2.3 MeV. Except from neutrons the source emits also and 1.3×10^7 photons per second per μg with mean energy 0.8 MeV [15, 16].

The geometrical formation of the facility presented in this article is based on the one described previously, in Ref. 17 and 18 with differences in geometry and based only in materials which are compatible with RoHS directive (Fig. 1). The facility comprises: Fluental (1), which is widely used as a moderator material [19]; consists of aluminium, fluorine and natural lithium, in a cylindrical shape with height and radius 10 and 18 cm respectively. Nickel (2) and graphite (3) with thickness 3 and 5 cm correspondingly, were used as a reflector. The ^{252}Cf neutron source was positioned on a (4) conic collimator with a length of 3 cm and radii 0.5 and 10 cm respectively. Next to the source there was a second part of a nickel reflector (5). A cone (6) with base 14 cm and height 15 cm made of D_2O was used in order to provide higher flux on epithermal neutrons [20]. In fig. 1 all the distances are measured perpendicularly to the axis and all the objects/materials of the unit are located on the same horizontal mid-plane.

Bismuth (7) and borated lithium (8) with length 7 and 5 cm, respectively, were added near to patient as delimiter/shield. Titanium (9) and bismuth (10) were chosen as fast neutron and γ –ray filters respectively. The former was a cylinder with height 3 cm and radius 10 cm and the latter was a cone with height 7 cm and radii 20 and 14 cm. Next to the bismuth filter there was a cylinder void (11) with height 3 cm and radius 7 cm which was surrounded from the borated lithium shielding. Finally bismuth (12) and borated poly (13) was chosen as shielding materials for the unit.

A head phantom according to the data from the ICRU46 was adopted in this work. The head placed in exit of the rectangular void with the intention to receive the epithermal neutrons from the facility. The head phantom comprises from three ellipsoids for scalp, scull bone and brain respectively [21].

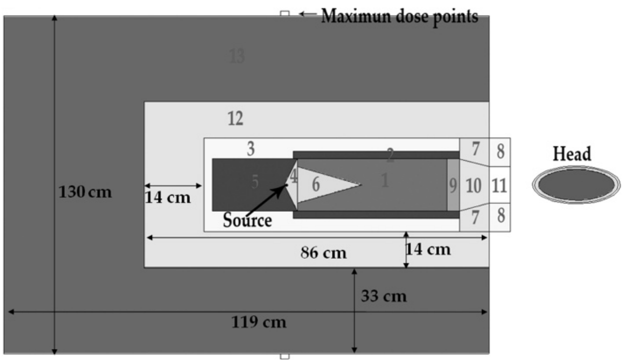

Fig 1. Geometric configuration of the BNCT system. (1) Fluental, (2) nickel reflector (3) graphite reflector, (4) D_2O collimator (5) nickel reflector, (6) D_2O, (7) bismuth, (8) borated lithium, (9) titanium as fast neutron filter, (10) bismuth as γ –ray filter, (11) void, (12) bismuth, (13) borated poly.

3. Results and discussion

The presented facility was simulated with intention the Dose Equivalent Rate (DER) do not overcome the annual occupational dose limit of 0.5 Sv (or 25 $\mu Sv \cdot hr^{-1}$) at the peripheral of the facility [22]. The total DER is the sum of the dose owing to the neutrons (DER1), the photons (DER2) from ^{252}Cf source and the photon dose which accrues from the interaction of the neutrons with the reflector and the moderator (DER3) materials. The maximum total DER (see Fig. 1) is 24.21 $\mu Sv \cdot hr^{-1}$ with DER1, DER2, and DER3 equal to 6.79, 17.3, and 0.12 $\mu Sv \cdot hr^{-1}$ respectively. According to the presented dimensions (a cylinder with height 119 cm and radius 65 cm) and materials the facility has estimated weight of 3155 kg.

In the present paper neutron are divided into three energy groups: Fast neutrons (E > 10 keV), epithermal neutrons (1 eV ≤ E ≤ 10 keV) and thermal neutrons (E < 1 eV). In all circumstances 1 mg ^{252}Cf source with fluxes 2.316×10^9 neutrons s^{-1} and 1.3×10^{10} photons s^{-1} were considered. Table 1 shows the obtained results for the different components of the reflectors for Fluental moderator. Both the maximum reduction in fast neutrons and the maximum epithermal neutron flux were achieved with nickel. For these reasons nickel was chosen as the reflector.

With intention to improve the results a cone of D_2O was added inside of the Fluental moderator (part 6 on Fig. 1). The results are presented in Table 2. Table 2 indicates clear that the presence of D_2O improves the effectiveness of the unit because increase the percentages of epithermal and thermal flux and decreases the percentage of fast neutrons. In order to decrease further the fast neutron flux, a filter made from titanium with 3 cm thickness was used. Calculations, which are shown in Table 3, indicate that the presence of titanium not only reduced the percentage of fast neutrons on beam (19.55% from 26.72%) but also improved the percentage of epithermal neutrons (78.07% from 70.43%). The total γ–rays (γ_{total}) would contain two components; the γ–rays emitted by the source (γ_1) and the induced γ–rays owing to the interaction of the neutrons with the moderator and reflector materials (γ_2).Owing to use of the titanium filter the γ_{total} is reduced from 1.64×10^5 photons s^{-1} to 9.81×10^4 photons s^{-1}.

Table 1. Distribution of the neutron fluxes for different materials as reflectors.

Neutrons flux	Reflector				
	Graphite	D_2O	Al_2O_3	Nickel	Iron
Thermal	1.19e+4	1.23e+4	1.18e+4	1.18e+4	1.12e+4
Percentage	2.89%	3.02%	2.86%	2.83%	2.76%
Epithermal	2.73e+5	2.71e+5	2.73e+5	2.80e+5	2.68e+5
Percentage	66.35%	66.28%	66.37%	66.95%	66.12%
Fast	1.27e+5	1.25e+5	1.27e+5	1.26e+5	1.26e+5
Percentage	30.76%	30.70%	30.77%	30.21%	31.12%
Total	4.12e+5	4.08e+5	4.11e+5	4.18e+5	4.06e+5

Table 2. The improvement in the beam quality owing to the new moderator design.

Neutrons flux	Configuration	
	Without D_2O moderator	With D_2O moderator
Thermal	1.18e+4	1.23e+4
Percentage	2.83%	2.85%
Epithermal	2.80e+5	3.03e+5
Percentage	66.95%	70.43%
Fast	1.26e+5	1.15e+5
Percentage	30.21%	27.72%
Total	4.18e+5	4.30e+5

Table 3. The improvement in the beam quality owing to the two filters.

Neutrons flux	Configuration		
	D_2O moderator	D_2O moderator + 3 cm titanium filter	D_2O moderator + 3 cm titanium filter + 7 cm bismuth filter
Thermal	1.23e+4	7.52e+3	7.89e+3
Percentage	2.85%	2.37%	3.69%
Epithermal	3.03e+5	2.48e+5	1.68e+5
Percentage	70.43%	78.07%	78.85%
Fast	1.15e+5	6.20e+4	3.73e+4
Percentage	27.72%	19.55%	17.46%
Total	4.30e+5	3.17e+5	2.14e+5
γ_1	6.80e+4	5.19e+4	1.05e+4
γ_2	9.56e+4	4.62e+4	1.26e+3
γ_{total}	1.64e+5	9.81e+4	1.17e+4

The γ_{total} flux is reduced more with 7 cm bismuth filter (1.17×10^4 photons s^{-1}). The bismuth filter reduces the neutron flux on each energy group but improve the beam quality both for neutron and photons. Fig. 2 illustrates the γ spectrum with and without the two filters. The peak between 2 and 2.5 MeV derived from the 2.223 MeV photons from the $^1H(n, \gamma)^2H$ reaction. The neutron spectrum of the system is shown in Fig. 3. According this spectrum approximately 80% from neutrons have energy into the epithermal region (1 eV – 10 keV) and the maximum peak was presented in the area of 1 and 10 keV. Moreover, the greater part of the fast neutrons was shown in the energy range from 10 to 100 keV.

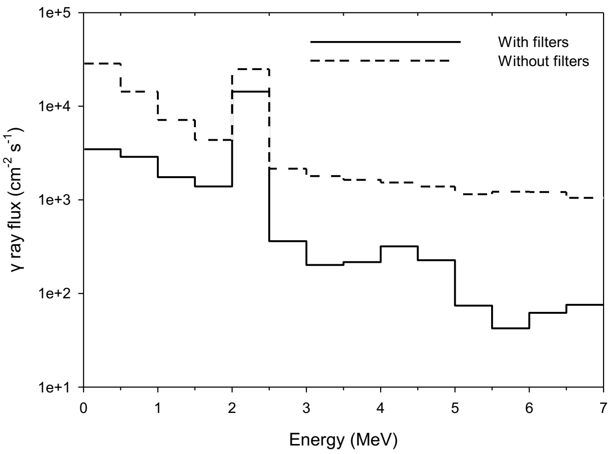

Fig 2. The γ ray energy spectra at the exit of the system with and without the beam filters.

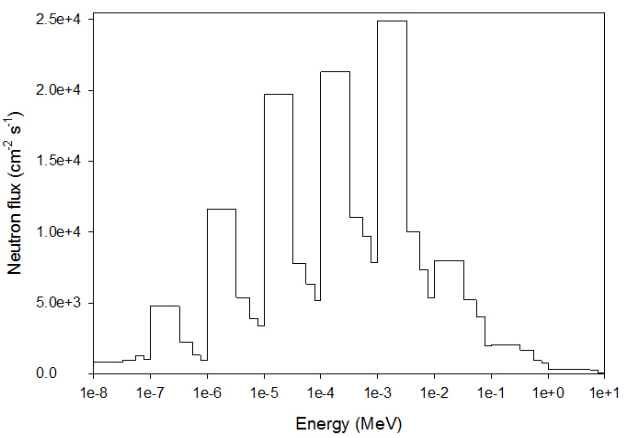

Fig 3. Neutron energy spectrum at exit of the facility.

According to IAEA [23] the suggested value for the epithermal neutron flux is $5 \times 10^8 - 10^9$ n s^{-1} while in this work using 1 mg ^{252}Cf neutron source simulaions show that the epithermal neutron flux is 1.62×10^5 n s^{-1}. However, the last 15 years the international BNCT community works in order to find new alternative neutron sources despite the fact that many of the new facilities have epithermal neutron flux which is below than the recommended value [7, 10, 24]. Increasing the source strength the proposed unit can come close to the reactor or accelerators capabilities, however then the necessary shielding demands a not transportable system.

The γ_{total} and the neutron fluxes on a perpendicular plane at the head place are presented in Fig. 4. It is obvious from the Fig. 4 that the symmetrical geometry is responsible for the symmetrical fluxes both for neutrons and photons. In addition it is clear that the collimation of neutrons is more effective than this for photons. Just 1 cm outside from the exit of the unit the total neutron flux is at least 42% lower while the γ_{total} is decreased more than 18%. The correspondingly reductions 2 cm outside of the beam-port are 56% and 21%.

According to the simulations from the MCNPX the neutron and γ_{total} fluxes on the ellipsoidal head phantom are presented in Fig. 5. The results indicate that epithermal and fast neutron fluxes have the highest values at the scalp and decrease with the depth. Maximum thermal neutron flux take places at a depth of 2.7 and 3.3 cm. The γ_{total} flux has small fluctuations but always is noticeable lower than the neutron flux.

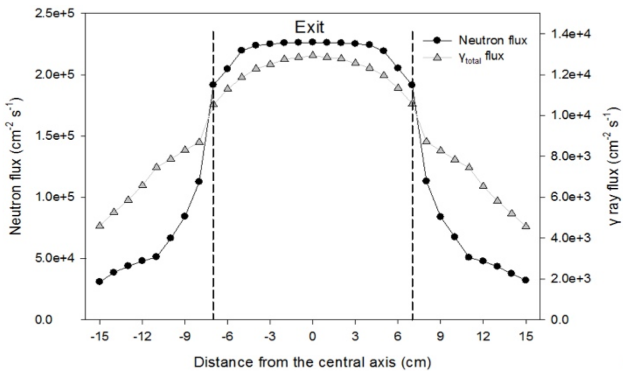

Fig 4. Neutron and γtotal fluxes on a perpendicular plane at the head position.

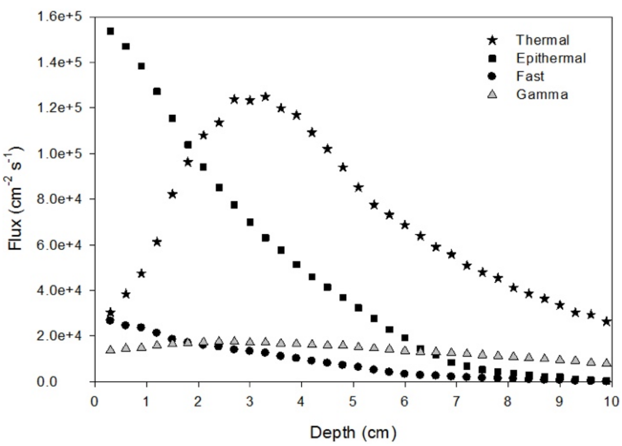

Fig 5. Distribution of the neutron and γtotal fluxes on the head phantom.

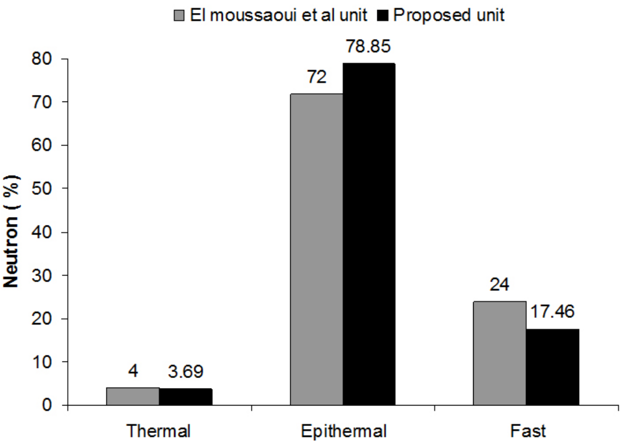

Fig 6. The comparison between the proposed unit and a similar from El moussaoui et al [17].

With the aim to estimate the presented unit the results are compared with other published facilities which are based on ^{252}Cf neutron source. Although there are restrictions on the materials choice the proposed facility has more quality neutron beam than other related systems. Fig. 6 shows the association between the proposed facility and a similar unit simulated from El moussaoui et al. on 2008 [17]. In the facility proposed by El moussaoui et al. the maximum epithermal neutrons flux is about 5×10^5 n s^{-1}, however in the desired range (1 – 10 keV) the epithermal flux is approximately the half compared to the facility which is studied in this work. The comparison between of the proposed facility and a similar study from Ghassoun et al. [18], which is based on ^{252}Cf neutron source, indicates that the presented study have comparable value on the neutron flux/γ_{total} ratio but provides almost the twofold number of epithermal neutrons.

4. Conclusions

A transportable facility based on a 1 mg ^{252}Cf neutron source has been simulated, for BNCT application, using the MCNPX Monte Carlo code. All the materials considered were selected in accordance with the EU Directive 2002/95/EC. Hence materials such as lead, cadmium, and beryllium which are frequently present on BNCT studies were omitted from the design and simulation procedures. However, according to the results simulated, the presented facility can offer high quality neutron beam for a clinical BNCT treatments. In accordance with the results obtained, although in the same way with the other units which uses portable neutron sources, the epithermal neutron flux is below than the proposed value for clinical treatment; the facility in this work appears as an attractive option for medical centers wishing to adopt an uncomplicated BNCT facility.

Acknowledgements
This article is dedicated to Dr. P. Adoniadis, his memory will remain with us.

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