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Original Article

Simulation and design of individual neutron dosimeter and optimization of energy response using an array of semiconductor sensors

R. Noushinmehr [a], A. Moussavi zarandi [a, *], M. Hassanzadeh [b], F. Payervand [c]

[a] Nuclear Engineering and Physics Faculty, Amirkabir University of Technology, Tehran, Iran
[b] Nuclear Science and Technology Research Institute (NSTRI), Reactor and Nuclear Safety School, Tehran, Iran
[c] Nuclear Science and Technology Research Institute (NSTRI), Radiation Application Research School, Tehran, Iran

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ABSTRACT

Many researches have been done to develop and improve the performance of personal (individual) dosimeter response to cover a wide of neutron energy range (from thermal to fast). Depending on the individual category of the dosimeter, the semiconductor sensor has been used to simplify and lightweight. In this plan, it's very important to have a fairly accurate counting of doses rate in different energies. With a general design and single-sensor simulations, all optimal thicknesses have been extracted. The performance of the simulation scheme has been compared with the commercial and laboratory samples in the world. Due to the deviation of all dosimeters with a flat energy response, in this paper, has been used an idea of one semi-conductor sensor to have the flat energy-response in the entire neutron energy range. Finally, by analyzing of the sensors data as arrays for the first time, we have reached a nearly flat and acceptable energy-response. Also a comparison has been made between Lucite-PMMA ($H_5C_5O_2$) and polyethylene–PE (CH_2) as a radiator and B_4C has been studied as absorbent. Moreover, in this paper, the effect of gamma dose in the dosimeter has been investigated and shown around the standard has not been exceeded.

1. Introduction

Neutrons cannot be directly ionized in material and have been often identified using ionizing particles produced by neutron interactions. The most important intermediary reactions in neutron detection are the reactions (n, p), (n, γ), (n, α) to slow neutrons and recoiled light nuclei due to fast neutrons [1]. The neutron emission coefficient changes in terms of energy, and for the continuous energy state, the following equation is approximated [2]:

$$W = 5 + 17e^{-(\ln(2E))^{\frac{2}{6}}} \tag{1}$$

where, W is neutron emission coefficient and E is energy (MeV).

The important characteristics of an active neutron dosimeter include high efficiency, the corresponding dose response for deposited neutron energy to the tissue and minimizing the effect of gamma radiation. It is important to note that the measured dose is proportional to the dose of delivered radiation to the human body. Therefore, it is necessary to calibrate the experimental responses to the personal equivalent dose [3]. Semiconductor radiation sensors often are very reasonable, especially for charged particles [4,5]. Thus, the goal of designing is personal active dosimeter with simple electronics and low power consumption and the result the choice of semiconductor sensor is very suitable [6–8]. Since gamma particles deposit less energy than the charged particles in the semiconductor sensor. Sensors set on the pulse mode with electronic cutting to minimize the effect of gamma.

In the literature, many works have been made in the field of design and construction of individual active dosimeter based on semiconductors such as silicon diode [9–14]. But in this paper, for the first time, the optimized thicknesses of convertor, radiator, moderator and absorber to design a single-sensor semiconductor have been done for creating a linear relationship in the range of energy of 10 keV to 1 MeV. For this purpose, a Monte Carlo MCNPX code has been used to simulate the single-sensor semiconductor [15]. Thus, an ENDF/B-VII library has been applied to calculate

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[*] Corresponding author.
E-mail address: moussavi.zarandi@gmail.com (A. Moussavi zarandi).

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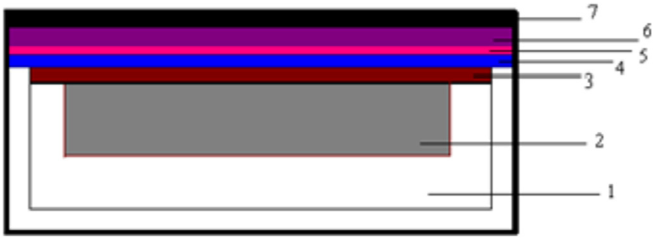

Fig. 1. Individual neutron dosimeter plan 1) silicon diode 2) depleted layer 3) dead layer 4) converter 5) radiator 6) moderator 7) absorber.

physic parameters. Also, in the current study, has been investigated on increasing in the number of sensors that will help to flatten the energy-response. The obtained results have been reported with three sensors data analysis to very flat energy response and compared with obtained dosimeters results in the worlds [14–16].

2. Materials and method

2.1. Base design and optimization of parameters

In order to clarify the effective parameters and plan path, we tried to design a single-sensor semiconductor. Also, in this study, we investigated on increasing in the number of sensors that will help to flatten the energy-response. Thus, with providing a simple dosimeter consists of silicon diode, a convertor layer and a hydrogen-rich radiator layer, it is possible to measure neutron dose equivalent rate in the range of thermal up to the fast with an appropriate sensitivity.

In this scheme, there is a relationship between the equivalent dose rate and the counts of the interactions of neutron products with the converter and radiator. The goal of designing is to create a linear relationship in the area of the energy of 10 keV to 1 MeV due to rapid changes in the doses rate. Thus, a polyethylene layer has been added as moderator which reduced the energy of fast neutrons. But it increases thermal neutron population so should be added to an absorbent layer to reduce those neutrons. Fig. 1 shows a basic scheme of individual neutron dosimeter that connected to the semiconductor sensor without air gap.

2.2. Design of the convertor, radiator, moderator and absorber

The most commonly used neutron convertor is Li-6 and B-10 [1,14]. Among these converters Li-6 is preferable, because the reaction ^{6}Li (n, α) ^{3}H charged particles have been created with a higher Q-value (^{3}H; 2.74 MeV and α; 2.0 MeV). As a result of taking, this convertor can be chosen higher threshold Energy Cutoff electronic and the gamma sensitivity reduced. Therefore, it is suggested in the present plan of Li-6 in the form of ^{6}LiF converter is used [16–18]. The thickness of the ^{6}LiF neutron convertor should be determined, in the other words; the number of neutron absorption reactions in the converter has been maximized. On the other, thickness of the converter should not be too high to prevent the passage of products from reacting. The thickness of the neutron converter has an optimal value which is obtained by determining the desired energy level of the reaction products. It has been investigated to eliminate the effects of gamma; the energy input limit is above 500 keV. According to the energy ^{6}Li (n, α) ^{3}H and SRIM/TRIM [17] code calculations with respect to 100 nm of the dead layer and 500 nm of aluminum oxide and about 1 MeV alpha energy can deliver in this sensitive volume as shown in Fig. 2a. We have achieved the best thickness converter is 5 μm.

Dosimetry of high-energy neutrons is to require the interaction recoil nuclei. Elements hydrogen-rich is very good for radiator because same as weight neutrons and transferred maximum energy. Thus, in this research, hydrogen-rich material has been selected as radiator and moderator. Among the materials considered Lucite-PMMA ($H_5C_5O_2$) and polyethylene–PE (CH_2). The oxygen and carbon elements in them do not have a significant contribution to hydrogen [19,20]. In the next discussion, simulations and comparisons between the two materials are carried out and polyethylene is used to radiator and moderator. By increasing the thickness of the polyethylene, the probability of neutron interaction increases and in the result a proton produces. This makes to calculate the number of proton excreted from the PE in terms of the energy of the incident neutron particles has a maximum curve. The determination of optimal polyethylene thickness depends on the energy neutrons as fast neutrons. Finally, the protons above 500 KeV (excreted by the radiator and convertor) can generate counting pulses. In the following, with the assumption that the layer thickness of the ^{6}LiF converter is 5 microns and protons with energies above 500 KeV out of the radiator and the convertor have the conditions for the pulse generation. We continue the simulation as seen in Fig. 2b. We have achieved the best thickness radiator is 100 microns.

Given the energy range from 10 keV to 1 MeV, the protons from this energy range do not arrive due to the converter thickness or reach less than 500 keV of energy which is not counted [21]. Although in the energy range 1 MeV to 2 MeV, the production of appropriate protons increases but in the energy ranges from 10 keV to 2 MeV, there is a significant deviation from the correct response. So the number of protons under energy 2 MeV increases by adding the moderator. Although the deviation is somewhat corrected, But by arraying the sensors response to the sensors is much better, as described below.

Polyethylene material as moderator can compensate to minimum response in the area of energy from 10 keV to 2 MeV. In adding this layer, assuming that aims to reduce the energy of fast neutrons into the middle energy, somewhat compensated the lack of sensitivity. On the other, moderator thickness should be such

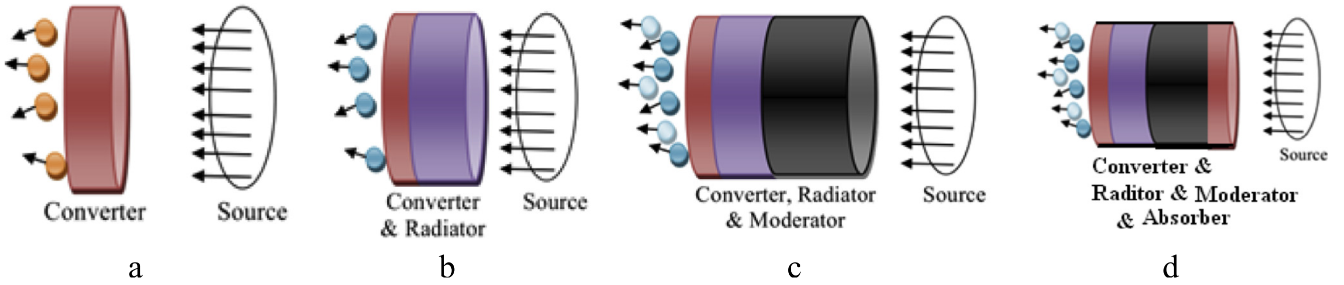

Fig. 2. Geometry simulated by MCNPX code to determine a) the optimal neutron convertor (^{6}LiF), b) radiator (polyethylene), c) moderator (polyethylene) and d) absorber (B_4C) thicknesses.

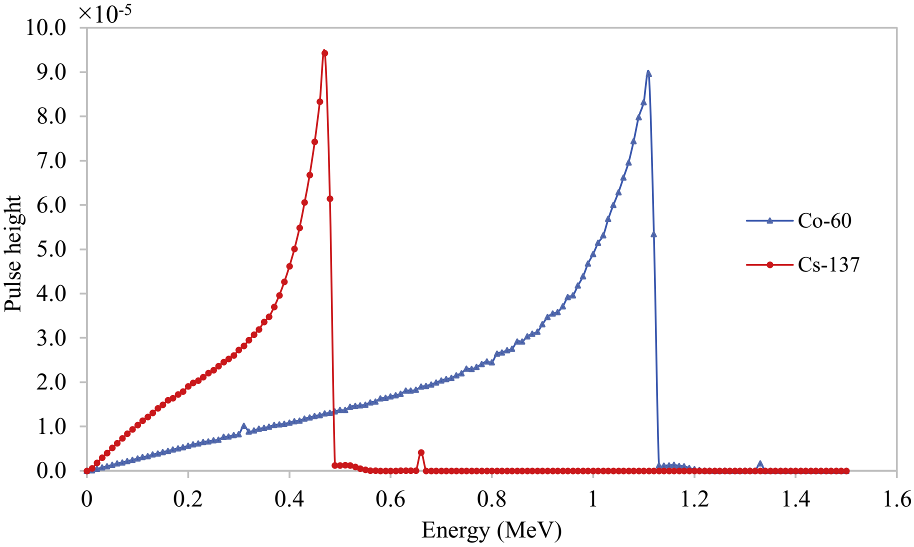

Fig. 3. The abundance of the deposited energy per photon of Co-60 and Cs-137 sources.

that the maximum increase in neutrons creation with energies less than 2 MeV. Finally, in this study, with assuming that the layer thickness of the ^{6}LiF converter is 5 microns and the thickness of the polyethylene is 2.100 mm (radiator 100 microns and moderator 2 mm) as seen in Fig. 2b,2c. Thermal neutrons are increased by adding the thickness of the moderator and this creates an additional response in this energy range. With adding thickness as absorbent (B_4C), it causes to compensate for the increased thermal neutrons as shown in Fig. 2d. We have achieved the best thickness absorber is 1 mm. Then the performance entire collection is investigated and with the suggestion of three array sensors, the energy response is very smooth.

Monte Carlo MCNPX simulation code is used to determine the optimal neutron convertor (^{6}LiF), radiator (polyethylene), moderator (polyethylene) and absorber (B_4C) thicknesses. The geometry of the problem defined by this code is shown in Fig. 2a, b, c and d.

3. Results and discussion

3.1. *Gamma discrimination and obtaining the energy level of charged particles*

Since for hardware design, we are considering a sensor sensitive layer with a thickness of 300 μm which in this sensor deposited energy has been assessed by gamma. After Monte Carlo simulation by the sources of gamma ^{60}Co and ^{137}Cs, the highest energy of the gamma sensor to expose has been investigated. Fig. 3 shows the abundance of the deposited energy per photon of Co-60 and Cs-137 sources.

Due to gamma interactions with matter, the photoelectric proportion have about with $Z^{4.5}$ and since silicon has a small Z. In general, the lower Z and small size of the detector is dominant interaction is Compton [2,22]. Compton's edge in the theoretical relations and the simulation results conforms to Fig. 3. So, according to the curve, Compton's contribution to photoelectric is more than 100 times. Based on counting charged particles above 500 keV has been eliminated the effect of the gamma from ^{137}Cs source. However, as shown in Fig. 3 can be seen in the face of more energetic gamma, dose of silicon can be significant and therefore should be checked dose of ^{60}Co gamma. For this purpose, the use of convertor coefficients flux to dose, dose rate before and after the sensor silicon are calculated and in these calculations the value of dose rate less than 500 keV energy has been ignored. However, calculations have been done for ten million histories per run by Intel Core i7 CPU 3.40 GHz computers. The obtained statistical errors were less than 1% for the long run time. Therefore, we have been calculated about 13% response in the face of Co-60 energy gamma which has been

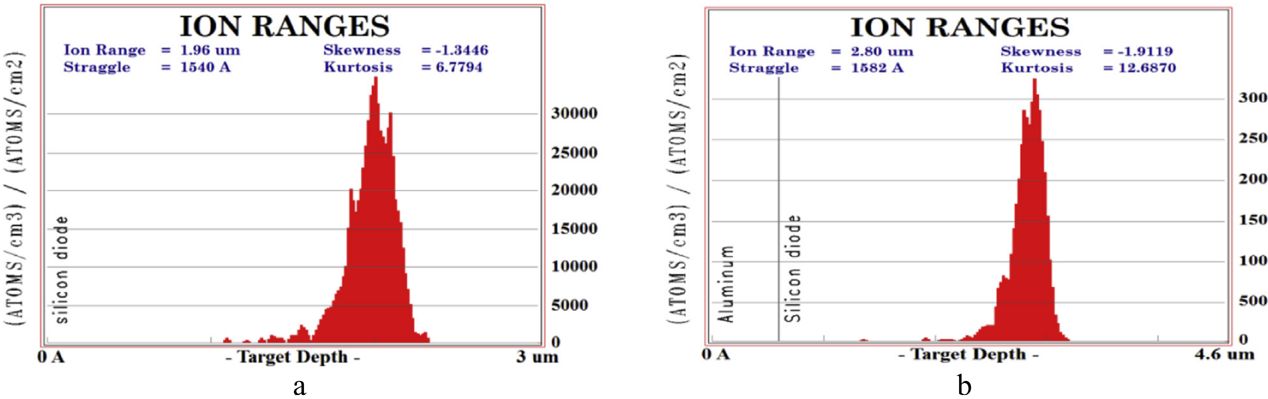

Fig. 4. a) Alpha 500 keV in bare silicone b) 800 keV with 600 nm aluminum thickness (dead layer & electrode).

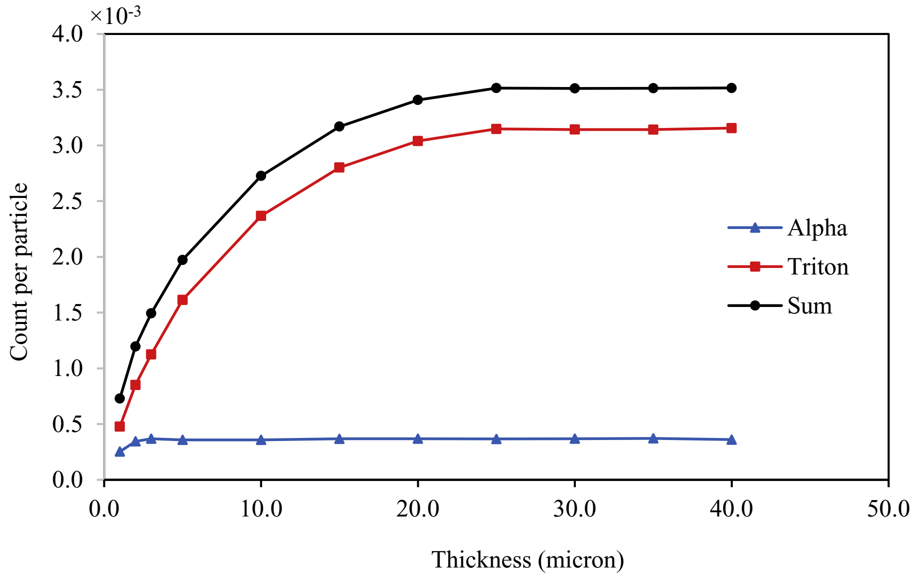

Fig. 5. The number of charged particles with desired energy output at the end of convertor.

usually accepted in most standards by up to 20% [20–23]. Gamma discrimination methods such as differential and pulse shape analyzing have a complexity that cannot be used in the category dosimeter [24,25].

Fig. 4 a and b show the alpha with an energy of 800 keV after the dead layer and the electrode reaches itself to the same 500 keV alpha range without any interference that obtained by TRIM code. It can be concluded that alpha with energy of 1 MeV is definitely counted. Since alpha products in ^{6}Li (n, α) ^{3}H have energy of 2 MeV, they can leave a maximum of 1 MeV energy in ^{6}LiF.

The simulation results for different thicknesses ^{6}LiF converter is shown in Fig. 5. Based on the data output, if alpha particles have been considered with energies above 1 MeV, optimum thickness the converter will be equal to 3 µm. If tritium particles have been considered with higher energy of 500 keV, the optimum thickness ^{6}LiF neutron converter will be equal to 25 microns. Thus, the converter thickness can be between 3 and 25 microns, both alpha and tritium energy to deliver to the semiconductor. But, whatever the converter thickness less is, the protons with energies higher than 500 keV will be more counting. Hence, we have been chosen 5 microns thickness of moderator.

The simulation results of the number of protons with energies above 500 keV in the converter based on the energy of the neutrons for different thicknesses of the polyethylene are shown in Fig. 6. As we expect, the neutrons below 1 MeV are not capable of producing proton with the proper energy. As seen, for each thickness of the radiator polyethylene, with increasing in the energy of the incident neutrons, the curve of the number of protons (>500 keV) passes through a maximum. Also, as shown in this figure, under energy 2 MeV can be careful with increasing energy, the increase in counting is favorable. The flux conversion factor to the neutron dose increases with increasing energy until about 2 MeV but after that neutron response curve is almost constant with increasing energy [24]. Thus, the thickness above 50 microns has this property. To select the optimum thickness of a few points should be noted:

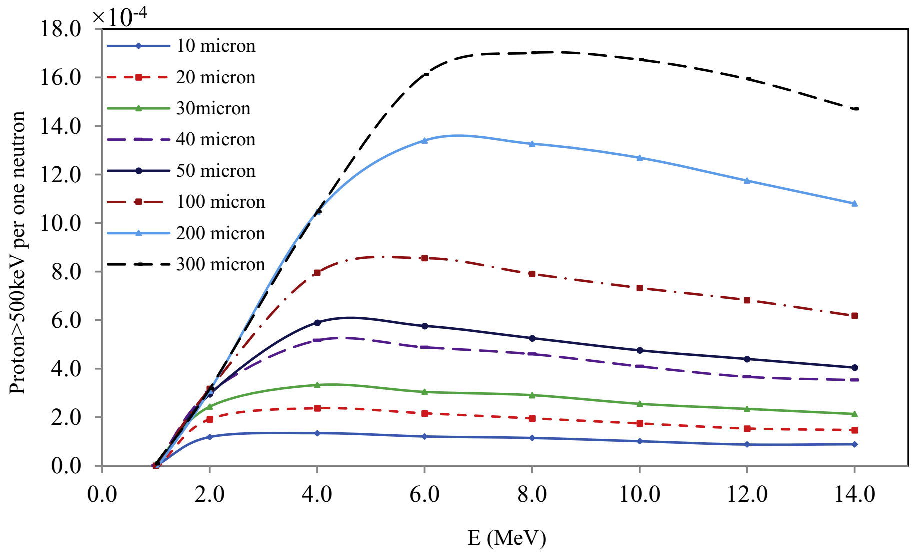

Fig. 6. The number of protons with energies above 500 keV out converter based on the energy of the neutrons for different thicknesses of the polyethylene.

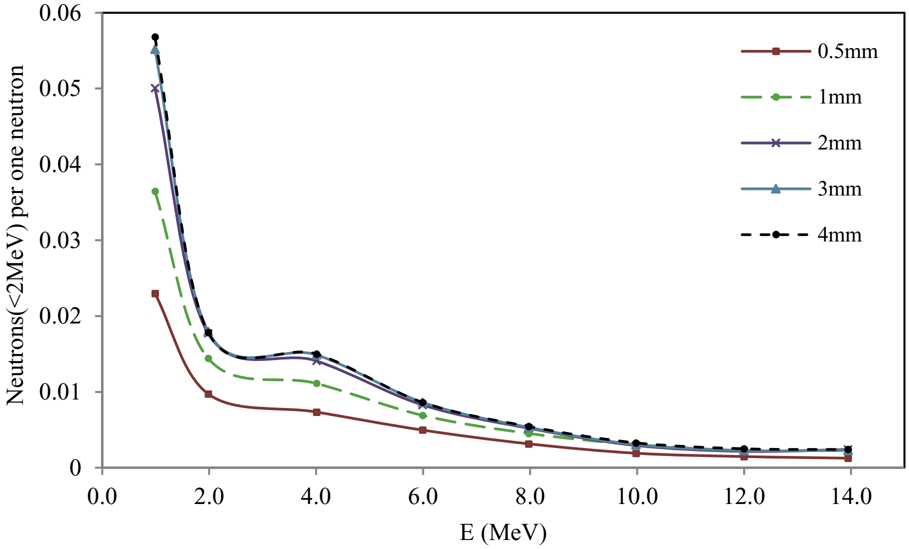

Fig. 7. The number of neutrons (<2 MeV) in terms of the collided neutron energy for different thicknesses of the polyethylene moderator.

1. The maximum thickness curve for energy should be located after 2 MeV.
2. The slope of the counts up to 2 MeV is high.
3. The increase and decrease of the slope after 2 MeV is relatively equal and compensates each other in a mixed field of energy.
4. Considering the above conditions, further counting will be very gratifying.

Finally, according to the result, the thickness of 100 microns is chosen for the radiator.

The simulation results for different thicknesses of polyethylene moderator in Fig. 7 are displayed. As shown in this figure, by increasing the moderator thickness to 2 mm, the number of neutrons under energy 2 MeV, especially low-energy neutrons incident, is greatly increased.

Fig. 8 also shows the percentage increase in protons with energy below 2 MeV to energy of the collided neutrons. By increasing the thickness of moderator up to 2 mm, the protons with energy below 2 MeV increases. But when the moderator thickness of 3 mm exceeds the percentage increase slowly is reduced. Therefore, based on the results, the 2 mm thickness of the polyethylene moderator is considered.

As shown in Fig. 9, with increasing the moderator thickness increases the number of thermal neutrons. Fig. 10, also shows that the percentage increasing of these neutrons that by adding a 2 mm layer of polyethylene moderator, the percent increase of neutrons are from %100.0 to %200.0 which must be corrected in some way.

If a separate layer of the B_4C absorbent is placed before the moderator, thus compensating behavior is also observed. Fig. 11 shows the percentage increase of thermal neutrons (energy below 1 keV). As can be seen in this figure, with increasing in the thickness of the B_4C absorbent, the percentage of increasing thermal neutrons is decreased, so that in the case of 1 mm thickness absorbent, increased thermal neutrons will be partially offset.

Thus, we conclude that the adsorbent substance should be deposited in a separate layer with a thickness of about 1 mm before

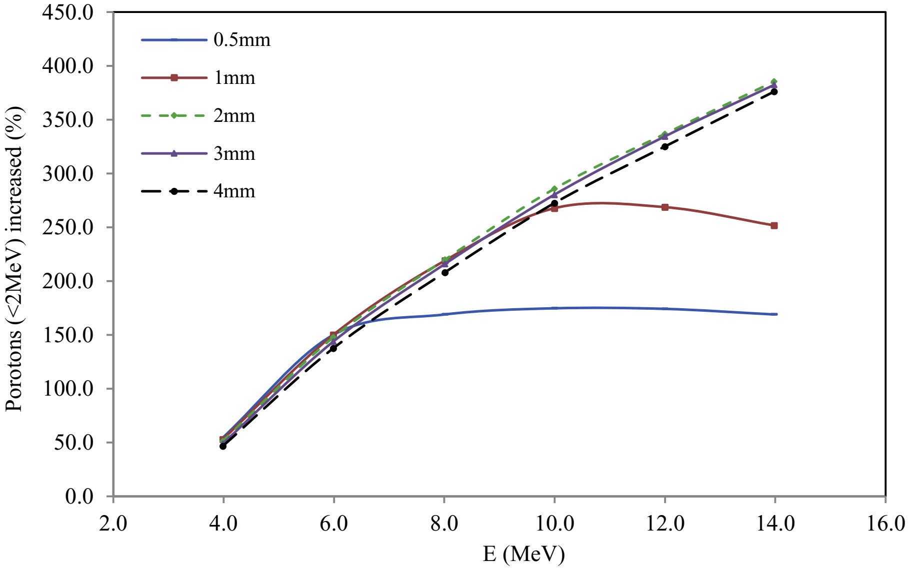

Fig. 8. Percentage of increasing protons with energy below 2 MeV in terms of the neutron energy for different moderator thicknesses.

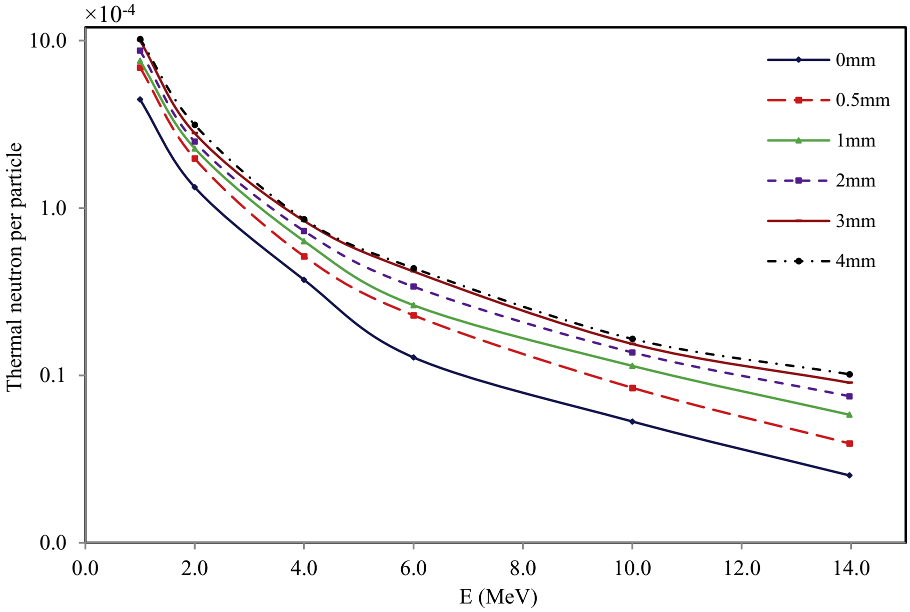

Fig. 9. The number of thermal neutrons in terms of the collided neutron collided energy for different thicknesses of the polyethylene moderator.

the moderator. So by reduction of the number of thermal neutrons, it will compensate for increased unplanned response in this area. Finally, we evaluate the value of the dose rate with optimized thicknesses.

3.2. Calibration and energy response

To obtain an energy response, it is necessary to calibration. The equivalent dose to the reference point at a certain distance from the source standard such as Am-Br, the coefficients flux to dose is achieved as shown in Table 1. Then, under the same conditions, the calculated detector count (with the selected thicknesses) is obtained and the conversion factor of the counting (C) is extracted. After that, by replacing the single-energy source, the true equivalent doses at the reference point as well as the doses calculated by the detector are compared and the detector's energy response is announced. One of the main goals of the designers is the close relationship between responses to one.

According to the standard ICRP-74 [17], right at the Am-Be neutron dosimeter reference point 0.05 μSv/h and the data obtained from the dosimeter 0.047 μSv/h that good accuracy. The calculated counter of the designed dosimeter is 3.72E-05 and the converting coefficient in the Am-Br calibration is:

$$C = \frac{0.050}{3.72E-05C}1344$$

Fig. 12 shows the designed counting dosimeter. Using the coefficient C, we can compare the dosimeter response with the real

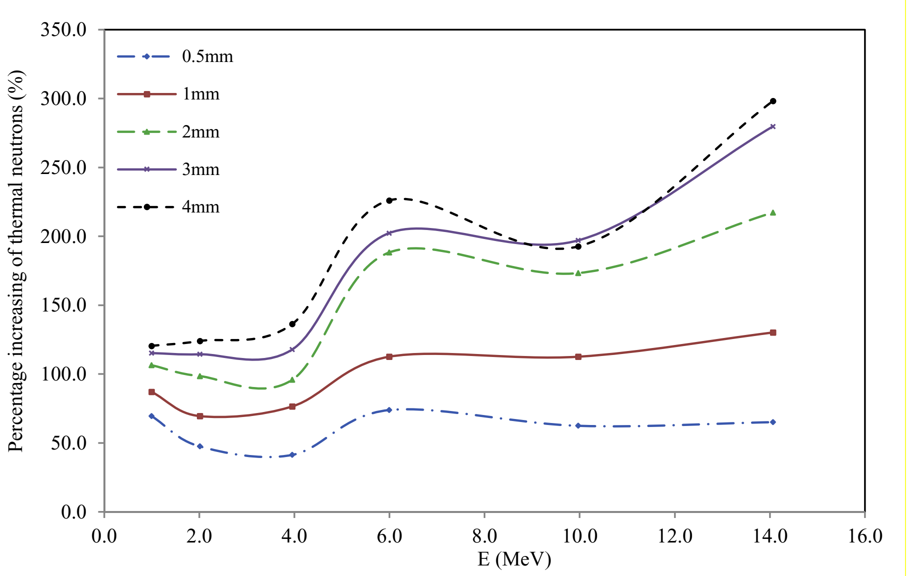

Fig. 10. Percentage increasing of thermal neutrons in terms of the neutron energy of the descendants for different thicknesses of the polyethylene moderator.

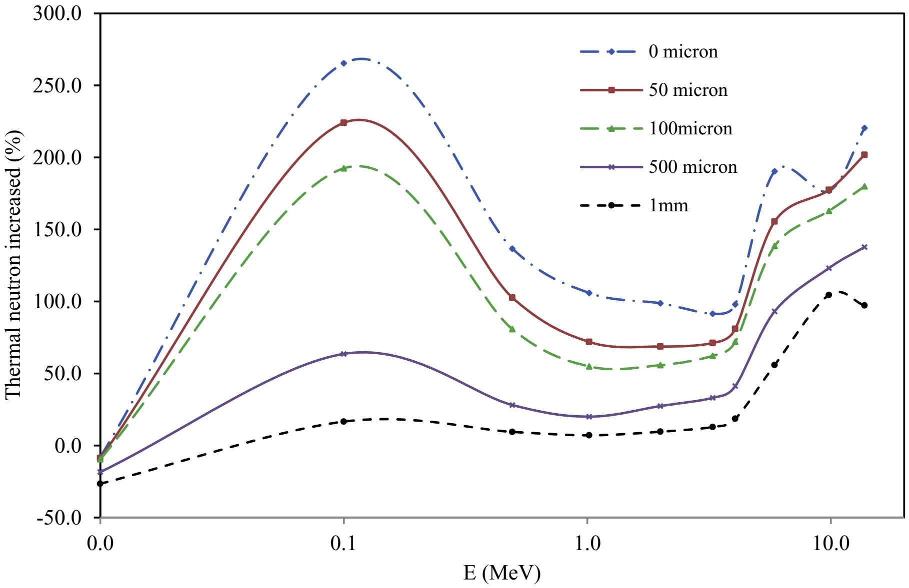

Fig. 11. Percentage increasing of thermal neutrons (energy less than 1 keV) based on the neutron energy for different thicknesses of B_4C adsorbent.

Table 1
Simulation results of equivalent doses at a distance of 30 cm from the Am-Br source.

	Dose rate (μSv/h)		
Am-Be	ICRP-21-1971	ICRP-74-1996	Error%
	0.047	0.050	0.02

answer. By dividing the measured dose, the actual dose of the energy response is obtained from the dosimeter and can be compared with the dosimeters available in the world as shown in this Fig. 13.

As can be seen in this figure, dosimeter has been designed in the worst conditions up to 10 times more false of showing. Also, the energy of 1 MeV where protons cannot pass through the converter up to about 50 times less than the real dose. However, in a complex field may increase or decrease the dose to make up for each other but we are trying to improve the response to our nearly flat curve. Despite the poor response at low energies dosimeter PTB DOS2002 is smoother than the rest of the dosimeter.

3.3. Sensor array

If at least two sensors are added to the dosimeter one that is

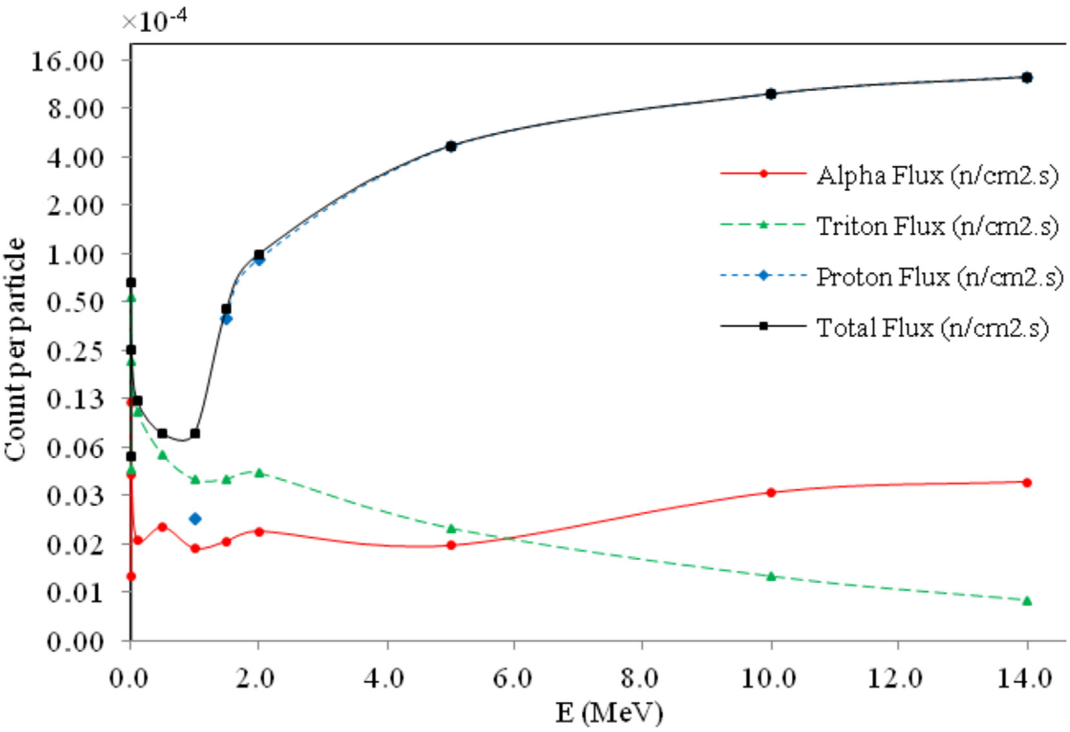

Fig. 12. The detector counts in different energies.

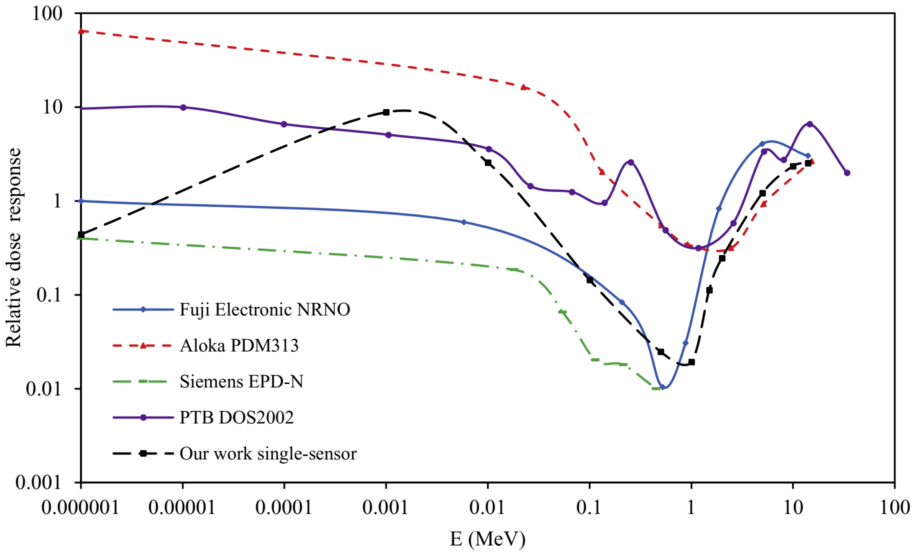

Fig. 13. Designed response dosimeter versus world's dosimeters.

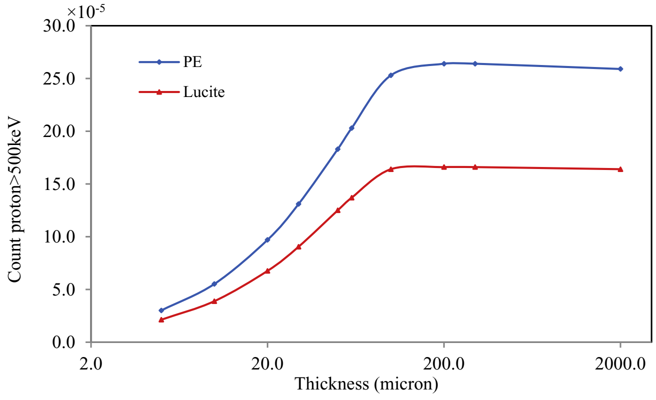

Fig. 14. Count of protons above 500 keV relative to different radiator thicknesses.

only sensitive to low energy neutrons (only with a convertor thickness) and the other is sensitive to fast energies neutrons (only with an radiator thickness), we can estimate to correct the neutron energy response. If we return to Fig. 5, we find with a thickness of 10 μm ^{6}LiF convertor, we will have the highest counts of alpha and tritium.

To design a sensitive detector to fast neutrons, only an radiator layer without moderator is used. In this phase, polyethylene and Lucite also are compared. The purpose of this sensor is to detect neutrons with energy (500keV-3MeV). As shown in Fig. 14, the simulation results are observed PE has a higher count than Lucite and is a more suitable material for counting with a high efficiency. This result confirms the choice of polyethylene as radiator and moderator. And if we look at the curves, the thickness of 100 microns is good for counting because we will not increase in thicknesses in the area up to 3 MeV.

Using data from the sensors 1 and 2 can be corrected main sensor response as shown in Table 2. In other words, by looking at sensor responses 1 and 2, we can estimate the neutron energy range and by applying a proportional factor that extracts from the neural network with trial and error, the response of the main sensor is brought closer to one. According to Fig. 15 (energy response of a single-sensor dosimeter), it is necessary to multiply the answer in proportional number at low energies and in a higher energy, it is divided into numbers. Thus, we continue to energize 14 MeV until responses get closer to flat.

Table 2
Sensors 2 and 3 counts in selected energies.

E (MeV)	Proton count-CH2-sensor 1	Alpha & Triton count-LiF-sensor 2	Error%
6.0E-06	0.0E+00	1.5E-04	0.02
2.5E-02	0.0E+00	2.8E-06	0.02
4.3E+00	3.2E-05	6.1E-07	0.02

In the following, use the MATLAB program and apply some simple conditions that are used in the two rows of Table 2 and we try and errors in the neural network are based on sensors information 1 and 2. The correction factor is extracted and applied to the main sensor and we corrected the energy response as shown in Fig. 15.

Several important points have been considered in choosing correction factors.

1 As seen, the deviation is reduced from 9 times to 2.43 on the top of the axis.
2 It also reduced by about 50 times less than 5 on the under of the axis.
3 Because of the wide application range of thermal neutrons in industrial reactors and research centers we have tried to make the response in this area very flat. As in the figure, it is 3% deviation from one and to 1 keV energy is completely flat.
4 It was also tried that the error to equal of the level below the graph on the top and bottom of the axis until in mixed energy fields, the effects of each other will be neutralized.

As seen in Fig. 16 designed dosimeter response is much better than the best dosimeter world. Widely used in thermal Energy PTB DOS2002 has more than tenfold error and also at high energies is a great error and in mixed energy fields not properly compensated. But, in this study, in high energy, the number of neutron is almost constant as seen Fig. 7.

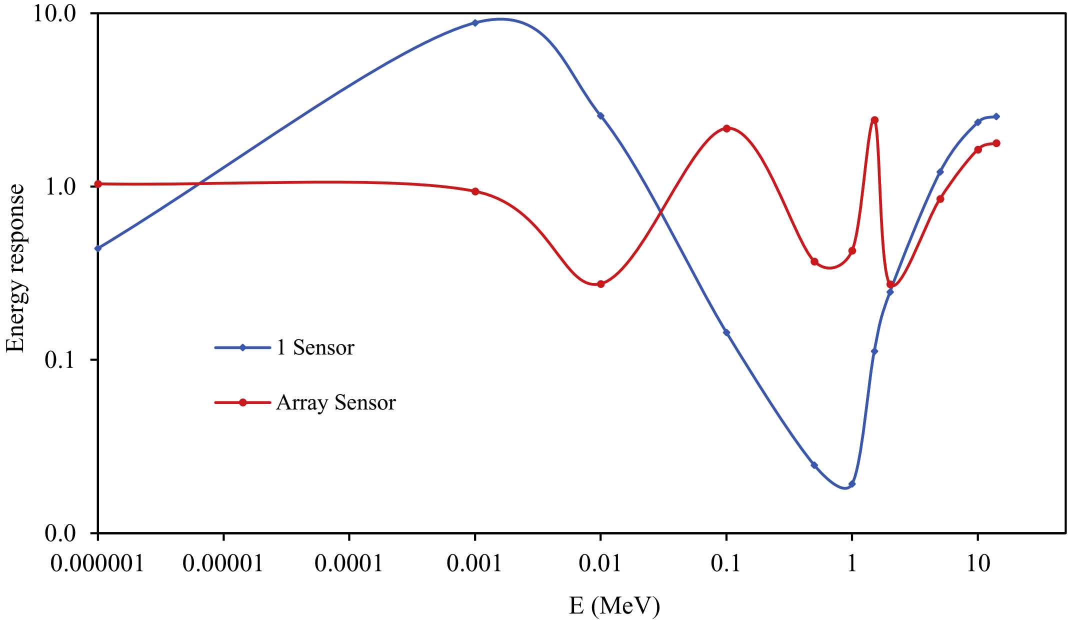

Fig. 15. Correcting the energy response by arraying the sensors.

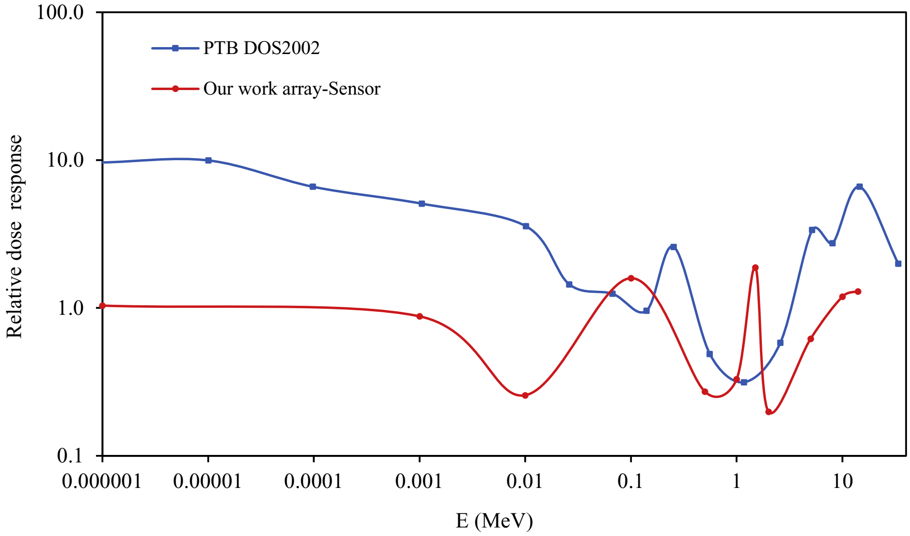

Fig. 16. Compare dosimeter PTB DOS2002 and our work.

4. Conclusions

As described, neutron dosimeters are usually carried out with charged particles from the interaction of neutrons with different materials. The cross-section of interactions is also dependent on neutron energy. In neutron dosimetry, first, it was unknown neutron energy. Second the real-field of neutrons usually there is no single energy. Third changes to energy neutron dose were not linear. Therefore, the main challenges of neutron dosimeter designers (in each active and passive detection method) are to obtain an appropriate energy response. In this paper, the proposed designs of semiconductor sensors are used in counting mode. Also, by cutting energy, we minimize gamma impact. The advantage of this design is light-weight and small in the individual dosimeter category. The design starts with a single sensor and continues with simulation and optimizing the thickness of the converter, radiator, moderator and absorbent. With an array of three sensors and data analysis let us achieve smooth response. In our design, thermal energy response very close to flat and in mixed energy field, the effects of deflection are neutralized. Obviously, by adding semiconductor sensors, the curve can be tilted smoothly but it should be noted, as the hardware is upgraded, the device will be dropped from the individual category.

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