Determination of Optimum Materials Thickness for Converting E-Beam Energy into Bremsstrahlung X-Rays on a 10 MeV High Energy Electron Accelerator Using MCNP

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Abstract. The e-beam produced by the high-energy electron accelerator has a relatively small penetrating power. To increase the penetrating power, a converter must convert the e-beam energy into bremsstrahlung x-rays. This research aims to determine the optimum thickness of tantalum, tungsten, and lead as a converter of e-beam energy into bremsstrahlung x-rays at a 10 MeV high-energy electron accelerator. The optimum thickness of tantalum, tungsten, and lead is determined using simulation with MCNPX software. The electron source modeling with an energy of 10 MeV is made in the form of a flat plane with a size of 120 cm by 10 cm at a distance of 1 mm from the converter. The converter has dimensions of 160 cm by 24 cm and its thickness varies from 1 - 7.5 mm. Then two planar detectors are placed at a distance of 2 cm in front and behind the converter. The simulation results show that the optimum thickness for tantalum, tungsten, and lead converter is 2.0 mm, 1.8 mm, and 2.8 mm respectively. The maximum forward scattered bremsstrahlung x-rays energy are 2.1137 MeV, 2.1287 MeV, and 2.1850 MeV, respectively. And the maximum conversion efficiency is 21.137%, 21.287%, and 21.850%, respectively. These results can be used as a reference in the design of the converter for the 10 MeV high-energy electron accelerator.

1. Introduction

An electron accelerator is a device to accelerate an electron beam (e-beam) that can be used to irradiate products according to their needs, for example, for the sterilization of various food products, agricultural products, wires, medicines, and medical devices [1,2]. To irradiate medical device products (medical sterilization) a high-energy e-beam of up to 10 MeV is required [3]. However, the penetrating power of e-beam irradiation produced by electron accelerators is relatively much lower than the penetrating power of gamma-ray irradiation produced by gamma irradiators with Co-60 sources. Therefore, for the purpose of irradiating medical device products using high-energy electron accelerators, the energy of the e-beam must first be converted into a bremsstrahlung x-ray (BXR) beam whose penetrating power is much greater than that of the e-beam, it can even exceed the gamma-ray penetrating power of Co-60. E-beams and high-energy x-ray photons are usually generated by linear accelerators [4,5].

In general, the electron accelerator parts consist of an electron source that produces an e-beam, an accelerator tube and an e-beam accelerator system that accelerates the e-beam so that it has a certain desired kinetic energy according to its intended use, a focusing system that functions to focusing the e-beam so that it does not spread and does not hit the walls of the accelerator tube, a scanning window

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system that functions to direct the e-beam that comes out of the electron accelerator to irradiate the product directly using the e-beam, and a BXR converter that functions to convert the energy of the e-beam into a continuous BXR [6] to irradiate products that require high penetrating power. In addition, it is also necessary to have a vacuum system to vacuum the e-beam accelerator tube to 10^{-7} torr so that the electrons can be accelerated without being blocked or hitting air particles in the accelerator tube. Then there is also a need for a cooling system to cool the walls of the accelerator tube, a scanning window system, and a BXR converter while the electron accelerator is operating. There are several requirements to be considered in the selection and determination of the BXR converter material from e-beam energy: thin, strong and resistant to electron collision, resistant to corrosion, high melting point, high conversion efficiency, and if a photonuclear reaction occurs, it produces neutron particles with low energy [7,8].

This research aims to determine the optimum thickness of tantalum, tungsten, and lead as a BXR converter at a 10 MeV high-energy electron. If the thickness is too thin, the conversion efficiency will be relatively low because the electron deceleration process by the atomic nucleus of the converter material is not yet maximized. Meanwhile, if the thickness is too thick, the conversion efficiency will also be relatively low because the converter material itself absorbs the BXR energy. So, in this research, we will look for the optimum thickness of BXR converter material made of tantalum, tungsten, and lead with the highest BXR conversion efficiency.

Determination of the optimum thickness of the BXR converter material as mentioned above was carried out by simulation using the Monte Carlo N-Particle X version 2.7.0 (MCNPX v.2.7.0) software. MCNP is computer software written using the Fortran programming language based on the Monte Carlo method and can be used for neutron, photon, electron, or coupled neutron/photon/electron transport [9,10]. The code of MCNP was developed at Los Alamos National Laboratory (LANL), USA [11]. This simulation software is very well used for dosimetry analysis.

2. Method

Determination of the optimum thickness of tantalum, wolfram (tungsten), and lead as an energy converter of e-beam to BXR on a 10 MeV high-energy electron accelerator was carried out by simulation using MCNPX v.2.7.0 software. In general, three steps must be done, namely creating an input file, running the input file, and interpreting the results of running (output). The first step, creating an MCNP input file, is filling in a “card”, consisting of three cards: cell cards, surface cards, and data cards [12]. Cell cards and surface cards are geometric inputs of the object to be simulated, while data cards are information about the material of the simulated object, the definition of radiation sources, and the physical quantities to be calculated (tally). After creating the MCNP input file, the second step is to run the input file with the MCNP code using an Intel (R) Core (TM) i7-8750H CPU @ 2.20 GHz 2.21 GHz, 8.00 GB RAM. After running the input file with the MCNP code, the third step is to take the data from the MCNP code output, which is needed for further interpretation and analysis. One of the most important things in the simulation is that the geometry modeling is made according to the real condition in terms of shape, size, and composition of the elements that make up the BXR converter. Then the definition of a radiation source includes the form of the source, the type of radiation emitted, the energy of each particle, the position of the source, and the direction of the emitted particle beam [10].

The simulation steps for determining the optimum thickness of tantalum, tungsten, and lead as a BXR converter are started by creating an input file for each x-ray converter material with dimensions of 160 cm high by 24 cm wide and varying thickness. The thicknesses are 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4, 2.6, 2.8, 3.0, 3.2, 3.4, 3.6, 3.8, 4.0, 4.5, 5.0, 6.0, and 7.5 mm. An e-beam source with an energy of 10 MeV is in the form of a rectangular field measuring 120 cm high by 10 cm wide with a distance of 1 mm from the surface of the x-ray converter. Then two surface detectors each measuring 300 cm by 300 cm were installed at a distance of 2 cm in front and behind the x-ray converter. The simulation environment is created in a vacuum chamber. The tally F2 is used to calculate the flux of x-ray photons that penetrate the detector surface in front and behind the converter. BBREM is used to reduce the calculation uncertainty of higher BXR energy generated by the x-ray converter. The BXR produced by the converter is emitted in all directions. In practice, the x-rays to be used are x-rays emitted in the direction of the e-beam motion from the source to irradiate the product (in the forward direction). Therefore, the determination of the optimum thickness of the BXR converter material is calculated based on the energy conversion efficiency of 10 MeV electrons into BXR, which is emitted in the forward direction. In this study, each simulation was carried out with nps (number of particle simulations) of 100000 (one hundred thousand).

The MCNP output result is the average value of the simulation of one particle or one photon. So, the BXR energy produced by the x-ray converter is the average BXR energy converted from each electron with a kinetic energy of 10 MeV and emitted randomly in all directions. Therefore, to get the average energy of BXR emitted in the forward direction, it must be multiplied by the fraction of the number of x-ray photons emitted in the forward direction to the total number of x-ray photons emitted forward and backward. To calculate the number of x-ray photons emitted forward and backward by the x-ray converter material, tally F2 and multiplication factor (FMn) are used according to the e-beam current used. This study uses an electron accelerator with an electron kinetic energy of 10 MeV and an accelerator power of 50 kW, so that the number of electrons produced by the accelerator or FMn used in this simulation can be calculated, which is 3.12109863E+16 particle/s

3. Results and Discussion

In the following, regarding the MCNPX simulation result. We will discuss some effects of the converter material thickness on the BXR average energy produced, the forward scattered BXR beam fraction, the forward scattered BXR average energy, and the conversion efficiency.

The relation of the BXR average energy in MeV units produced by each electron with a kinetic energy of 10 MeV to the thickness of the converter in mm is shown in Figure 1. The atomic numbers (Z) of tantalum (Ta), tungsten (wolfram, W), and lead (Pb) were 73, 74, and 82 (Z Ta < Z W < Z Pb). Meanwhile, the density (ρ) of tantalum, tungsten, and lead were 16,654 g/cm^3, 19,300 g/cm^3, and 11,350 g/cm^3 (ρ Pb < ρ Ta < ρ W) [13]. By using the atomic number and density data of the three BXR converter materials, the graph in Figure 1 can generally be explained as follows. For the relatively thin thickness of the converter material up to a thickness of 2.6 mm, the density factor of the converter material is more dominant than the atomic number factor of the converter material. The greater the density of the converter material, the higher the ability of the converter material to convert electron energy into BXR energy. It can be explained that the greater the density of the converter material, the greater the number of atoms per unit of the same volume or the same unit area. This results in more interactions and bremsstrahlung physical processes that occur between the incident electrons and the atomic nuclei of the converter material so that more BXR photons are emitted.

As for the thickness of the x-ray converter material which is relatively thick above 2.6 mm, the atomic number factor of the converter material is more dominant than the density factor of the converter material. The greater the atomic number of the converter material, the higher the ability of the converter material to convert electron energy into BXR energy. This can be explained that the greater the atomic number of the converter material, the greater the number of protons in each atomic nucleus of the converter material and this will cause the greater the attraction force of each atomic nucleus of the x-ray converter material toward electrons that pass closer to the atomic nucleus. The greater the attraction force of the atomic nucleus towards the electrons that move across it, the greater the brake force and the angle of bending of the electron path near the atomic nucleus, so that in order to fulfill the law of conservation of energy, the electron will emit an even greater BXR.

In general, the three converter materials in Figure 1 have relatively the same characteristics in relation to the average BXR energy produced and the thickness of the converter materials. Initially, the thicker the converter material, the greater its ability to convert electron energy into BXR energy. But after a certain thickness, the x-ray converter's ability to convert electron energy into BXR energy decreases and is relatively stable. This is because the thicker the x-ray converter material, the greater the energy of the x-ray photons absorbed by the converter material itself before the x-ray photons are emitted from the converter material [14]. So, the self-absorption of the converter material plays a role in keeping the amount of BXR energy produced from increasing significantly after reaching a certain thickness.

For the converter materials made of tantalum up to a thickness of 2.8 mm, the ability to convert electron energy into BXR energy increases significantly, and after passing through a thickness of 2.8 mm the conversion ability decreases and is relatively stable. The same applies to x-ray converters made of tungsten and lead at thicknesses of 2.6 mm and 3.6 mm, respectively. Here, it appears that there is a relation between the thickness of the x-ray converter material where the conversion ability decreases and is relatively stable inversely proportional to the density of the converter material (converter thickness limit: Pb 3.6 mm > Ta 2.8 mm > W 2.6 mm, while ρ Pb < ρ Ta < ρ W).

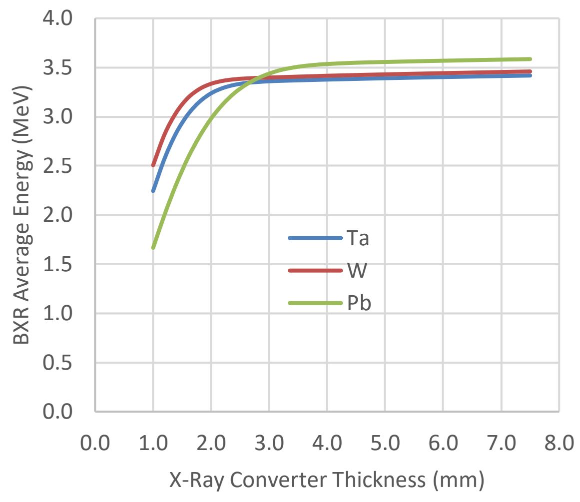

Figure 1. The relationship of the BXR average energy to the x-ray converter thickness.

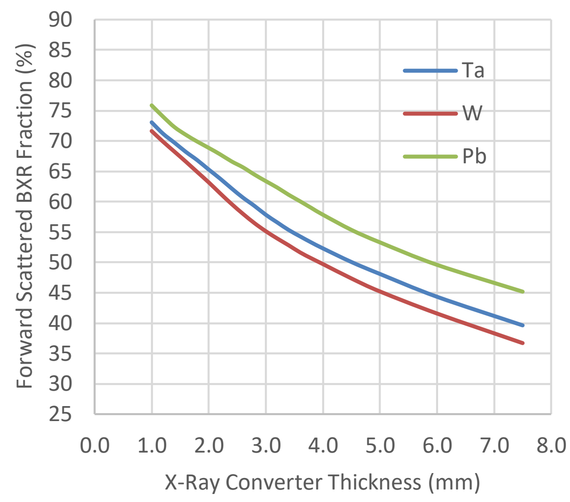

Figure 2. The relationship of the forward scattered BXR beam fraction to the converter thickness.

Figure 2 shows the relation of the forward scattering BXR beam fraction (expressed in %) to the x-ray converter thickness (in mm) for tantalum, tungsten, and lead materials. In general, the three x-ray converter materials show the same characteristics. The thicker the x-ray converter material, the smaller the forward scattering BXR beam fraction, because the converter material itself absorbs more x-ray photon beams. Figure 2 also shows that at the same thickness of the converter material, the greater the density of the converter material, the smaller the fraction of the BXR beam that is scattered forward. It can be explained that the greater the density of the converter material, the greater the number of atoms per unit volume. This results in more interactions and physical processes occurring between the incident electrons and the resulting BXR photons.

In practice, in the use of a 10 MeV high-energy electron accelerator with e-beam energy converted into BXR photon beam energy using an x-ray converter, not all of the x-ray photon energy beams produced can be utilized because in fact the BXR photon beam is scattered randomly to all directions. Meanwhile, the target of the irradiation product can only receive a beam of BXR photons that are scattered forward.

Therefore, this research is important to calculate the average energy of BXR photons that are scattered forward to irradiate the irradiation product as needed. To calculate the average energy of the BXR photons emitted forward, it is necessary to first calculate the fraction of the x-ray photon beam emitted forward as shown in Figure 2 multiplied by the average energy of the BXR photons produced by the BXR converter as shown in Figure 1. The results of the calculation of the average energy of BXR photons emitted forward and its relation to the thickness of the converter material are shown in Figure 3. So, the average energy of BXR photons emitted forward in the graph in Figure 3 is the result of the product of the average energy of the BXR photons produced by the BXR converter in the graph in Figure 1 and the fraction value of the x-ray photon beam emitted forward in the graph in Figure 2.

In general, the value of the graph in Figure 1 for the three BXR converter materials has an upward trend (at first it rose significantly and then stabilized), while the value of the graph in Figure 2 continues to fall so that when the two graphs the values are multiplied, it will produce a graph in Figure 3 where the trend initially increases until maximum value, then decreases. So, from the graph in Figure 3, it can be obtained that the optimum thickness of the BXR converter material is capable of producing maximum BXR photon energy scattered forward from the electron kinetic energy of 10 MeV. The BXR converter material made of tantalum, tungsten, lead has an optimum thickness of 2.0 mm, 1.8 mm, 2.8 mm and can convert 10 MeV electron kinetic energy into maximum BXR photon energy scattered forward of 2.1137 MeV, 2.1287 MeV, 2.1850 MeV. This means that the optimum thickness of the BXR converter material is inversely proportional to the density of the converter material. The greater the density value of the converter material, the smaller the value of the optimum thickness of the converter material. Meanwhile, the maximum BXR photon energy value is directly proportional to the atomic number of the converter material. The greater the atomic number of the converter material, the greater the maximum BXR photon energy produced.

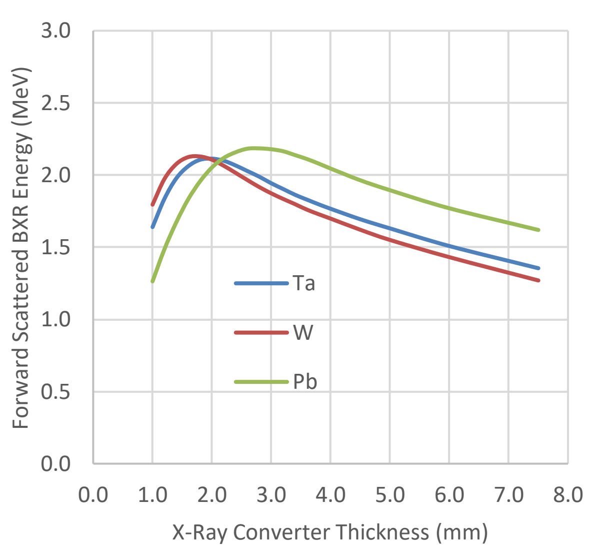

Figure 3. The relationship of the forward scattered BXR average energy to the converter thickness.

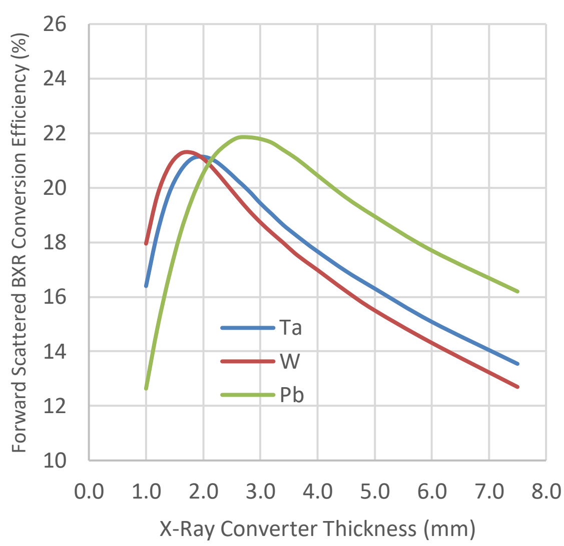

Figure 4. The relationship of the forward scattered BXR conversion efficiency to the converter thickness.

Figure 3 provides information on the optimum thickness of the BXR converter material and the maximum BXR photon energy scattered forward, but it does not provide information on what percentage (%) of the maximum efficiency of the converter material is able to convert the kinetic energy of 10 MeV electrons into the energy of BXR photons scattered forward. Therefore, the maximum efficiency of the BXR converter material is important to calculate and know, namely the maximum BXR photon energy scattered forward divided by the electron kinetic energy of 10 MeV and expressed in percent (%).

The graph in Figure 4 shows the relation of the forward-scattered BXR conversion efficiency to the thickness of the converter material. Because the conversion efficiency of the x-ray converter is calculated using the electron kinetic energy of 10 MeV as the divider, the graphic pattern in Figure 4 is similar to the graphic pattern in Figure 3. From the graph in Figure 4, it can be obtained information about the maximum conversion efficiency of BXR scattered forward for tantalum, tungsten, lead, 21.137%, 21.287%, 21.850%, respectively, with the optimum thickness of each converter material is 2.0 mm, 1.8 mm, 2.8 mm, respectively.

The optimum thickness and maximum conversion efficiency of the tantalum-based BXR converter in this study when compared with the results of DePriest's study [15] are shown in Table 1. The optimum thickness of the tantalum converter in this study was 2.00 mm, while the result of DePriest's study was 2.268 mm. So the optimum thickness of tantalum as a result of this study is 11.82% smaller than the result of DePriest's study. Then the maximum conversion efficiency of the tantalum converter in this study was 21.1%, while the result of DePriest's study was 16.5%. So the maximum conversion efficiency of the result of this study is 28.12% greater than the result of DePriest's study.

Table 1. Comparison of the optimum thickness and the maximum conversion efficiency of tantalum-based BXR converter for the 10 MeV electron kinetic energy

Researcher	Optimum thickness (mm)	Difference (%)	Maximum efficiency (%)	Difference (%)
This research	2,00		21.14	
DePriest [15]	2.268	-11,82	16.50	28,12

Table 2 compares this study's results with the results of other studies regarding the optimum thickness and maximum conversion efficiency of the tungsten-based BXR converters. The optimum thickness of the Tungsten converter in this study was1.80 mm. The result of this study is greater than the results of other studies, namely Tsechanski et al by 1.64 mm (9.76% larger) [16], Berger et al by 1.36 mm (32.35% larger) [17], Alhagaish and Sakharov by 1.61 mm (11.80% larger) [4]. Then the maximum conversion efficiency of the Tungsten converter in this study was 21.3%, which means it is smaller than the results of Tsechanski et al's study by 23.1% (7.79% smaller) [16], Alhagaish and Sakharov by 23.2 % (8.19% smaller) [4], but greater than the result of the study of Berger et al, namely 19.0% (12.11% larger) [17].

Table 2. Comparison of the optimum thickness and the maximum conversion efficiency of tungsten-based BXR converters for the 10 MeV electron kinetic energy

Researcher	Optimum thickness (mm)	Difference (%)	Maximum efficiency (%)	Difference (%)
This research	1,80		21.3	
Tsechanski [16]	1,64	9.76	23.1	-7.79
Berger [17]	1.36	32.35	19.0	12.11
Alhagaish [4]	1.61	11,80	23.2	-8,19

4. Conclusion

Based on the description of the results and discussion above, it can be concluded that the MCNPX code simulation has succeeded in determining the optimum thickness of the BXR converter material. The BXR converter material made of tantalum, tungsten, and lead has an optimum thickness of 2.0 mm, 1.8 mm, and 2.8 mm, respectively. Each is capable of converting 10 MeV electron kinetic energy into maximum forward scattered BXR photon energy of 2.1137 MeV, 2.1287 MeV, and 2.1850 MeV, respectively. The maximum conversion efficiency for tantalum, tungsten, and lead converter materials are 21.137%, 21.287%, and 21.850%, respectively. The optimum thickness value of the BXR converter material is inversely proportional to the density of the converter material. At the same time, the value of the maximum BXR photon energy and maximum BXR conversion efficiency scattered forward by the converter material is directly proportional to the atomic number of the x-ray converter material. These results can be used as a reference in the design of the BXR converter for the 10 MeV high-energy electron accelerator.

5. Acknowledgment

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