Shielding calculations for industrial 5/7.5 MeV electron accelerators using the MCNP Monte Carlo Code

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Abstract...High energy X-rays from accelerators are used to irradiate food ingredients to prevent growth and development of unwanted biological organisms in food, and by that extend the shelf life of the products. The production of X-rays is done by accelerating 5 MeV electrons and bombarding them into a heavy target (high Z). Since 2004, the FDA has approved using 7.5 MeV energy, providing higher production rates with lower treatments costs. In this study we calculated all the essential data needed for a straightforward concrete shielding design of typical food accelerator rooms. The following evaluation is done using the MCNP Monte Carlo code system: (1) Angular dependence (0-180°) of photon dose rate for 5 MeV and 7.5 MeV electron beams bombarding iron, aluminum, gold, tantalum, and tungsten targets. (2) Angular dependence (0-180°) spectral distribution simulations of bremsstrahlung for gold, tantalum, and tungsten bombarded by 5 MeV and 7.5 MeV electron beams. (3) Concrete attenuation calculations in several photon emission angles for the 5 MeV and 7.5 MeV electron beams bombarding a tantalum target. Based on the simulation, we calculated the expected increase in dose rate for facilities intending to increase the energy from 5 MeV to 7.5 MeV, and the concrete width needed to be added in order to keep the existing dose rate unchanged.

1 Introduction

Industrial electron accelerators are used for many applications such as: irradiation of medical devices, food and wires, etc. [1]. In this study we calculated essential data needed for a straightforward concrete shielding design of an industrial electron accelerator, using 5 MeV and 7.5 MeV X-Rays. These energies are mainly used to irradiate food ingredients. Food irradiation using ionizing radiation is a common process to prevent the growth and development of several types of biological organisms in food. In the past, the main process to provide the desired dose required a ⁶⁰Co irradiation facility. Nowadays, due to their inherent safety, electron accelerators are more in use. When deeper penetration is needed, the electron beam produces bremsstrahlung (X-rays) by using targets with high Z, acting as convertors.

Due to the low range of electrons in matter, irradiation by the electron beam is limited to small packages. To irradiate larger packages, higher penetration is needed, therefore the electron beam has to be converted to bremsstrahlung X-rays. The targets used to convert the electron beam to bremsstrahlung are tantalum, tungsten, gold and aluminum. Aluminum is used as an electron beam absorber.

High energy photons can cause food activation due to (γ,n) reactions. Until 2004, to eliminate the possibility of food activation, the electron energy was limited to 5 MeV X-rays for food irradiation. In 2004, the FDA approved the usage of up to 7.5 MeV, but only with tantalum and gold targets [2].

Higher X-ray energy results an increased flux of X-rays in the forward direction, increased penetration, and higher photon dose rate due to better electron-to-photon

conversion. These improvements could decrease the irradiation time and allow irradiation of larger packages, thereby providing higher production rates with lower treatment cost.

Electron accelerators emit high currents of high energy electrons and X-Ray. The x-ray energies are determined by the beam energy; the higher the energy, the better the X-ray penetration. The magnitude of the accelerator dose rates is mainly a function of the beam current. The typical dose rates in medical accelerator are quite low, up to 100 Gy h⁻¹, compared to the dose rates in industrial accelerators, which are much higher: 100 kGy h⁻¹ in X-Ray mode, and up to 360,000 kGy h⁻¹ in electron irradiation mode [1]. Due to the difference in dose rates, the shielding thickness of industrial accelerator is much higher. Therefore, accurate shielding values such as angular dependence of dose rates and concrete attenuation ratios, is very important for designing the optimal shielding.

Medical accelerators usually work with 6-18 MV electron energy with a tungsten target to convert the electron beam to X-rays. In order to protect the patients, the accelerator head is protected with a heavy lead shielding; therefore, the bremsstrahlung radiation is emitted only in the forward direction. Shielding thickness calculations are based on available bremsstrahlung spectrum data in the forward direction (primary shielding). Secondary shielding is designed to protect against photon scattering from the primary shielding or leakage from the accelerator head, which are two orders of magnitude smaller than the primary beam [3]. There are many publications and standards that guide how to design optimal shielding for medical accelerator rooms [3-5]. The shielding data for medical

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accelerators is not applicable for industrial accelerators, since the data is for different conversion targets, different X-Ray energies, and only for the forward direction.

In general, collimators are not in use in industrial accelerators, since human protection is not needed inside the room (e.g. patients), and therefore bremsstrahlung photons can be emitted in all directions. The bremsstrahlung spectrum and dose rate change as a function of the emission angle. The dose rate decreases from maximum in the forward direction (0°) to minimum at 180° by 1-2 orders of magnitude. In order to design and calculate optimal shielding for food accelerator rooms, there is a need to have the bremsstrahlung spectrum data and dose rates in all emission directions, which are different for each conversion target and energy (5 MeV or 7.5 MeV). There are publications and standards available such as: NCRP 144 [6], IAEA Report 188 [7], ANSI N43.3 [8], to guide how to design shielding for industrial accelerator rooms. The shielding data in these guides is suitable for most industrial accelerators, but does not contain data for 5 MeV and 7.5 MeV X-rays, such as used in food irradiation facilities.

One publication written specifically to give data for the shielding design of food accelerator rooms was published by Barkova [9]. The angular dependence of the KERMA rates from aluminum, iron, and tungsten targets irradiated by 5 MeV electrons were calculated using Monte Carlo simulations with the use of the program package SPIN-PC, presented by Barkova [9]. The concrete attenuation ratio was evaluated analytically using Monte Carlo simulations to obtain the bremsstrahlung spectrum for each angle.

Petwal [10] performed MCNP calculations to optimize the design of the conversion target for maximizing the X-ray output. They also presented calculated 5 MeV and 7.5 MeV relative bremsstrahlung spectra, but only for the forward direction, and relative angular dose rate up to 60° . The authors point out that from the three possible targets (gold, tantalum, tungsten), tantalum is the most suitable for reasons of photon yield, residual radioactivity, mechanical properties, and fabrication simplicity.

2 Objective

The following evaluations were done using the MCNP Monte Carlo code system. Simulations for angular dependence calculations of photon dose rate in units of Gy h^{-1} were carried out at the distance of one meter from several common converting targets as a function of the beam current for 5 MeV and 7.5 MeV electron beams. Photon attenuation ratios in concrete were calculated for a range of 0-180 cm for a tantalum target at selected photon emission angles (0° , 90° , 135° , 180°) for the 5 MeV and the 7.5 MeV electron beams. Based on the simulation, we calculated the expected increase in dose rate for facilities intending to increase the energy from 5 MeV to 7.5 MeV.

3 Materials and methods

The simulations were carried out using the MCNP version 4C2 code package [11]. Initiation of MCNP requires an input file that contains complete information about the radiation source, the geometry of the system to be simulated, and both the density and the elemental composition of all interacting materials. The Concrete composition was taken as an ordinary concrete 2.3 g cm^{-3} in density [12].

In addition, the output tallies to be calculated need to be specified in the MCNP input file. The tally F6 in a cell volume was used for absorbed dose calculations. The dose was calculated by employing the MCNP 'F6:p' track length tally and making the KERMA approximation. Since most of the dose is by photons of less than 3 MeV, electron equilibrium is satisfied, than the terms 'dose' and 'KERMA' are thus used synonymously in this work. Tally *F4 of photon fluence was used for the photon spectra graphs.

Simulation of the angular dependence of photon dose rate (Gy h^{-1}) at one meter from the targets as a function of beam current (mA) and beam energy were done by irradiating gold, tantalum, and tungsten targets with a 5/7.5 MeV pencil electron beam. In real accelerators the beam dimension is not narrow, but the distance from the source to the exterior side of the building is more than a few meters. Therefore, for shielding purposes it is possible to simulate the electron beam as a narrow beam to simplify the simulation. The targets depth and radial dimensions were chosen to be about 20% less the CSDA range using ESTAR database [13], which is approximately 20% more than the penetration range of the electrons in the target [14]. Target thickness of Al, Fe, Ta, W and Au were 9.4, 3.2, 1.5, 1.3 and 1.3 mm for 5 MeV electrons, and target thickness of Ta and Au were 2.3 and 2.0 mm for 7.5 MeV electrons.

The three-dimensional space was subdivided into conical shells to 18 sectors, from 0° (forward direction) to 180° (backward), 10° for each sector. At a radius of 1 meter around the target, 18 volumes of "detectors" were made by generating two concentric spheres at 99 cm and 101 cm, and dividing them by the 18 sectors. All the space around the target was covered by 18 cells, defined as "detectors" filled with standard air. The bremsstrahlung photons were collected by the 18 "detectors". The results were converted to units of ($\text{Gy mA}^{-1} \text{ h}^{-1}$) at a distance of 1 m from the target, for each 10° sector. Since every photon was collected by one of the 10° "detectors", the number of photons reaching each detector was large. Therefore the statistics was adequate, with a small standard deviation (less than 2%) obtained with very short run time (e.g., 1 hour). For shielding purposes, averaging the dose rate at a 10° angle does not consider significant error. In order to validate the correctness of the results, simulations of aluminum, iron, and tungsten were done and compared to the data of Barkova [9]. As can be seen in Figure 1, the results are in good agreement, except in aluminum and iron targets,

in the forward directions the difference that our results are higher up to 20% than the previous study results.

Fig. 1. Angular dependence of photon dose rate (Gy h^{-1}) at one meter from Fe, Al, W targets as a function of beam current (mA) for 5 MeV electron beam. MCNP (our result) vs. Barkova [9].

Simulation of the energy distribution of bremsstrahlung emission for gold, tantalum, and tungsten targets by 5 MeV and 7.5 MeV electron beams were performed. Energy distribution of bremsstrahlung intensity was calculated using Tally *F4 as $\text{kdn dk}^{-1} \text{d}\Omega^{-1}$ ($\text{MeV MeV}^{-1} \text{Sr}^{-1} \text{electron}^{-1}$), by dividing each bin by its energy interval and multiplying it by the square of the distance. The plots are presented as the number of bremsstrahlung photons of energy k within an increment of energy dk , emitted at angle θ within a solid angle $d\Omega$, by one electron whose initial energy is E_0 . The same geometry configuration like the previous section was provided. The bremsstrahlung photons were collected in the "detectors" cells. The energy bins were 0.2 MeV at the following angles: 0° , 10° , 20° , 45° , 60° , 90° , 120° , 150° , and 180° . Each angle is the average of $\pm 5^\circ$ around it. In order to validate the results, the first simulation was compared to the spectrum of 2.8 MeV electrons hitting an iron target as measured by Dance [15]. Three emission angles were selected for comparison (10° , 45° , 120°); as can be seen in Figure 2, the results showed a good agreement.

Fig. 2. Energy Distribution comparison of bremsstrahlung in Iron target 2.8 MeV. MCNP (our result) vs. Fig. 11 in Dance [15].

Simulation of photon attenuation in concrete of selected photon emission angles (0° , 90° , 135° , and 180°) were performed for 5 MeV and 7.5 MeV electron

beams. The same configurations as the previous section were done. A spherical concentric concrete shield was added between the target and detectors from a thickness of 10 cm up to 180 cm, hence the detectors were moved to 200 cm. Every 10 cm addition required a separated run; when simulating concrete shielding thicker than 80 cm, only a few photons were tallied and there was a need to use variance reduction techniques in order to get improved statistics. The attenuation data were calculated for four emission angles. In order to improve the statistics, broad angles were chosen (up to $\pm 20^\circ$). Since there is an increased concentration of bremsstrahlung photons in the forward direction, the collection angle was set to be larger in the backward direction than in the forward direction. The emission angles used were: 0° (0° - 10°), 90° (80° - 100°), 135° (120° - 150°), and 180° (160° - 180°) (Figure 3). For shielding purposes, averaging the backward radiation dose rate in a $\pm 20^\circ$ range does not lead to significant uncertainties. The variance reduction technique that was used is geometry splitting: As illustrated in Figure 3, the concrete was divided to 10 cm sections. The importance of each section was gradually increased from the inner to the outer sections, and the importance of the backwards direction was greater than in the forward direction, so the photon population will be approximately equal. Figure 3 is a cross-section illustration of the geometry, and illustrates a single run with 80 cm of concrete.

Fig. 3. Illustration of concrete shielding between the target and the detectors at 0° , 90° , 135° , and 180° .

In order to validate the results, the attenuation simulations results of an aluminium target with emission angles of 90° and 180° were compared to the data published in Barkova [9]. As can be seen in Figure 4, the results showed a good agreement.

Fig. 4. Dose attenuation by concrete of the bremsstrahlung emission from Al target for beam energy of 5 MeV. MCNP (this study) vs. Barkova [9].

4 Results

Figure 5 presents the angular dependence ($0-180^\circ$) of photon dose rate (Gy h^{-1}) at 1 m from gold, tantalum, and tungsten targets as a function of beam current (mA) for 5 MeV and 7.5 MeV electron beams. 10^6-10^7 histories were used to obtain relative statistical uncertainties lower than 2%. Error bars for less than 5% are too small to be shown in the graphs. The results of tantalum and tungsten for 5 MeV are almost identical. The reason is the close atomic number of the two targets. Due to the larger atomic number of gold its dose rate is slightly higher, but only for the backward angles ($>90^\circ$). This is one of the reasons why a gold target is not cost effective. The 7.5 MeV dose rates curves show almost the same shape of the ones relating to 5 MeV and are higher by a factor from 1.5 up to 2.6.

Fig. 5. Angular dependence of photon dose rate (Gy h^{-1}) at one meter from Au, Ta, W targets as a function of beam current (mA) for 5/7.5 MeV electron beam.

Figures 6 and 7 present the energy distribution of bremsstrahlung emission for gold and tantalum targets by 5 MeV and 7.5 MeV electron beams. 10^7-10^8 histories were used to usually obtain relative uncertainties lower than 5%. Due to the small difference in the atomic numbers of the targets, the spectra are almost identical for each energy. The spectrum of the forward direction photons is higher and "harder" than the spectrum in the backward emission. In the lower energy bins, the fluence in the forward directions is higher by an order of magnitude than the backward emission. As the energy bins increased, the gap increases up to three orders of

magnitudes in the higher energy bins. From these figures we can understand why the dose rate is decreasing as the photon emission angle increases. The fact the spectrum of the backward is softer explains why the concrete shielding is more effective to attenuate backward photon emission.

Fig. 6. Energy distribution of 5 MeV bremsstrahlung in Au (Upper) and Ta (Lower) Targets.

Fig. 7. Energy distribution of 7.5 MeV bremsstrahlung in Au (Upper) and Ta (Lower) Targets.

Figure 8 presents the photon attenuation ratio in concrete (0-180 cm) of a tantalum target in selected photon emission angles ($0^\circ, 90^\circ, 135^\circ, 180^\circ$) for 5 MeV

and 7.5 MeV electron beams. The attenuation ratio was obtained as the ratio between the dose without shielding to the dose behind the concrete shielding. 10^6 - 10^8 histories were used to obtain relative uncertainty less than 5%. As with the dose rate and bremsstrahlung results, the data for gold and tungsten should be similar, and therefore were not calculated here. The photon attenuation in concrete for 5 MeV is higher than for 7.5 MeV by up to an order of magnitude. The attenuation is larger for the backward emitted photons compared to the forward ones by up to an order of magnitude.

Fig. 8. Dose attenuation in concrete of the bremsstrahlung emission from Ta target for electron beam energy of 5 MeV (Upper) and 7.5 MeV (Lower).

Table 1 is an example of how to calculate the expected dose rate behind concrete shielding using the graphs given in this study. The example was set for an accelerator of 1 mA current and a tantalum target. The listed energy, emission angle, and concrete width and distance from the target are reasonably chosen settings. The dose rate at 1 m from the target is taken from Figure 5, and the attenuation ratio is taken from Figure 8; both are based on the settings data given in Table 1. The final dose rate behind the shielding at distance L from the target is obtained by the following equation:

$$D_{out}[\frac{\mu Gy}{mA \cdot h}] = \frac{D_{in}[\frac{Gy}{mA \cdot h}] \cdot 10^6}{(Atten.Ratio_{concrete})} \left(\frac{1[m]}{L[m]} \right)^2 \quad (1)$$

D_{in} - The dose rate one meter from the conversion target; 10^6 is a factor from Gy to μ Gy.

Table 1. Example of shielding calculation for 1mA current with Ta target.

Point	Energy [MeV]	Emission Angle [deg.]	Concrete width [cm]	Distance [m]	Dose Rate ² [$Gy \cdot mA^{-1} \cdot h^{-1}$]	Concrete Attenuation ratio ³	Dose Rate Behind Shielding [$\mu Gy \cdot h^{-1}$]
1	5	90	170	7	400	$1.0 \cdot 10^6$	8
2	5	180	120	8	285	$5.3 \cdot 10^4$	84
3	7.5	135	150	7	500	$8.8 \cdot 10^4$	116
4	7.5	90	160	11	700	$9.2 \cdot 10^4$	53

²From Figure 5 (before shielding).

³From Figure 8.

The quantities of concrete required to be added in a case of upgrading a 5 MeV beam to 7.5 MeV in a facility, in order to keep the 5 MeV dose rate are listed in Table 2. The expected difference in dose rate between 5 MeV and 7.5 MeV emitted from a tantalum target at 0°, 90°, and 180° are presented in Table 2. The presented results are taken from Figure 5 (2.6, 1.7, 1.5, respectively), multiplied by the difference in the concrete attenuation, taken from Figure 8. The data are presented for three emission angles (0°, 90°, 180°) as a function of the existing concrete thickness in the facility. The data are not dependent on the distance between the target and the interest point outside the facility.

Table 2. Dose rate ratios of bremsstrahlung emission between 5 MeV and 7.5 MeV beams Ta target as a function of existing concrete for a given angle (left), and the quantity of required concrete to be added for 7.5 MeV facility in order to keep the 5 MeV dose rate (right).

Existed Concrete (cm)	5 MeV and 7.5 MeV Dose Rate Ratio			Required Concrete addition (cm)		
	0°	90°	180°	0°	90°	180°
0	2.6	1.7	1.5	8	5	0.5
10	2.8	1.9	1.6	9	6	2
20	3.3	2.0	1.7	12	7	2
30	3.5	2.3	1.8	13	9	3
40	4.0	2.5	2.0	15	10	4
50	4.2	2.8	2.1	16	12	5
60	4.8	3.3	2.2	18	14	5
70	5.4	3.6	2.5	19	15	7
80	5.9	3.8	2.7	21	16	8
90	6.5	4.3	2.8	23	18	9
100	7.6	4.9	2.9	25	20	9
110	8.2	5.1	3.5	26	20	12
120	9.0	6.0	3.8	28	22	13
130	9.7	6.3	4.1	29	23	14
140	11.1	6.9	4.4	31	24	15
150	12.2	7.6	4.9	33	26	16
160	13.7	8.6	5.2	35	28	17
170	15.3	9.4	5.8	36	29	18
180	16.5	10.5	6.1	38	31	19

By using Table 2, facilities that plan upgrading their accelerator to 7.5 MeV can easily estimate the expected increase in dose rate around the shielded facility. The additional concrete thickness ensuring the same dose rate around the facility can also be evaluated, thus maintaining the same safety status. For example, a

facility interested in the dose rate over a 120 cm shield located 90° from the electron beam direction, can use Table 2 to find that the expected dose rate rises by a factor of 6, or an additional 22 cm of concrete thickness to that area should lower the dose rate back to the original rate.

5 Conclusions

Angular dependence MCNP simulations of dose rate, bremsstrahlung, and concrete attenuation ratio were carried out for 5 MeV and 7.5 MeV accelerators for gold, tantalum, and tungsten targets. Since the targets atomic numbers are similar, there was only a slight difference in dose rates and bremsstrahlung spectra of the targets. The dose rate of 7.5 MeV accelerators is higher than the 5 MeV dose rate by factor of about 2.6 in the forward direction, and a factor of 1.5 in the backward direction. The difference in dose rates from the forward to backward directions is almost two orders of magnitude. Photon attenuation ratios in concrete of 7.5 MeV beam is lower than that of 5 MeV beam by almost an order of magnitude for thick shielding for all emission angles. There is a significant difference in the bremsstrahlung spectrum between the forward emission angles to the backward angles. Since the bremsstrahlung spectrum of the backward angles is softer than in the forward direction, the concrete shielding is more effective in attenuating the backward direction. This difference is small for thin shielding, but for thick shielding of more than 150 cm, the attenuation of the backward emissions is larger than for forward direction by an order of magnitude, for the same concrete thickness.

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