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MONTE CARLO STUDIES FOR SHIELDING DESIGN FOR HIGH ENERGY LINAC FOR MEDICAL ISOTOPE GENERATION

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Abstract

The widely used radioactive tracer Technetium-99m (^{99m}Tc) is traditionally produced from Uranium via ^{235}U (n,f) ^{99}Mo reactions which depends heavily on nuclear reactors. Design studies for an alternative, cleaner approach for radioisotope generation using a high energy electron linac were initiated at SAMEER to generate ^{99}Mo. The electron beam from a 30 MeV linac with an average current of 350 μA will be bombarded on a convertor target to produce X-rays which will be bombarded on enriched ^{100}Mo target to produce ^{99}Mo via (γ, n) reaction. ^{99m}Tc will be eluted from ^{99}Mo. The photons and neutrons produced in the process should be shielded appropriately to ensure radiation safety. This paper brings out the use of Monte Carlo techniques for photon and neutron shielding for our application. We used FLUKA to calculate the fluence, angular distribution and dose for photons and neutrons. Then we introduced various layers of lead followed by HDPE, 5% borated HDPE and 40% boron rubber to ensure that the proposed shielding is sufficient to completely shield the photon as well as neutron radiation and hence is safe for operation.

INTRODUCTION

The need for particle accelerators is growing around the world, mainly due to various applications in research and civilian society. In particular, the therapeutic use of electrons, protons, ions and X-rays for cancer therapy has enhanced the interest in designing and installing accelerators at various hospitals. In the past decade, the number of working medical accelerators has increased substantially.

Accurate diagnostics is needed to ensure that the extend of disease is understood and treatment modalities can be decided. Clinical diagnosis depends heavily on imaging. Technetium-99m (99mTc) is a widely used radioactive tracer. Traditionally, it is produced from 235U (n, f) 99Mo which is heavily dependent on nuclear reactors [1]. A cleaner alternative is to explore accelerator based mechanism to generate 99Mo.

At SAMEER we are designing and developing a two stage acceleration technique to achieve a 30 MeV electron beam with an average current of about 350 μA at the exit of the linac [2]. This electron beam will hit a convertor target and generate bremsstrahlung X-rays which when bombarded on to ^{100}Mo target will generate ^{99}Mo and thereafter ^{99m}Tc.

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To host the accelerator, a shielded room is needed. Hence, we study the (e, γ) mechanism to find out the nature of outgoing bremsstrahlung pattern. Based on this, the lead shielding has been designed. As the energy of the electrons is large, high neutron flux will be generated. Hence, shielding study of neutron has also been done based on which, the high density poly ethylene (HDPE) shielding has been finalized.

The radiation field of electron accelerator includes several components such as bremsstrahlung photons, fast neutrons, positrons, etc. The production and transport of all these radiations through different targets is very complex and interesting study. Simulations with an effective Monte Carlo code are very helpful to get information of all the particles produced in an accelerator head. We have used FLUKA which is a Monte Carlo code that can simulate transport and interaction of electromagnetic and hadronic particles in any target material over a wide energy range [3].

SIMULATION DETAILS

A 30 MeV electron beam is incident on a tungsten target which is placed in radiation facility as shown in Fig. 1. We define a 0.6 cm thick cylindrical tungsten target with 0.3 cm radius. The local shielding cube consisting of lead and HDPE is defined as rectangular parallelepiped. The lead block has a thickness of 4 TVL in beam direction and 2.5 TVL in all other directions. This lead block is surrounded by a 3 TVL regular HDPE and 1 TVL borated (5%) HDPE on all sides. Finally, a sheet of 0.3 cm of 40% borated rubber layers the full assembly. The local shielding is shown in Fig. 2.

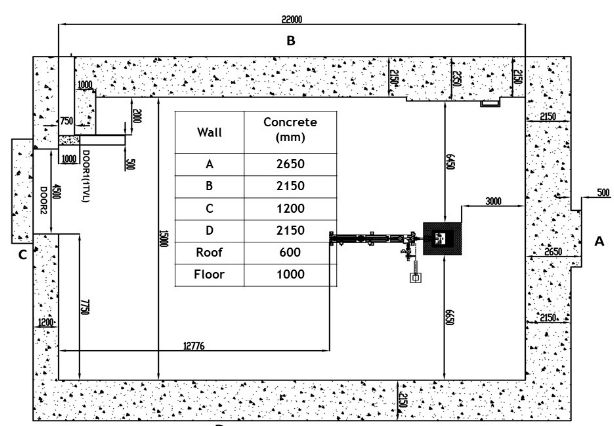

Figure 1: Layout of radiation test facility.

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We use USRBIN, USRBDX and USRYIELD cards to define the detectors to score fluence and dose. Spatial distribution of fluence was scored using USRBIN. The angular distribution was scored using USRBDX and USRYIELD detectors, from which we have calculated dose rates. The number of primaries run are set to 10^6.

SOURCE TERM

We define the geometry and parameter settings in FLUKA to obtain the photon flux and then convert it to dose. The relationship between absorbed dose rate and particle flux is given by [4]

$$\dot{D} = \frac{\Phi E_0 \mu_a \times 1.6 \times 10^{-6}}{100} \tag{1}$$

where, $\dot{D}$ is the dose rate, Φ is the particle flux (quanta/cm^2/s), μ_a is the mass absorption coefficient of gamma rays in air (cm^2/g), 1.6×10^{-6} is the energy equivalent in ergs of 1 MeV, 100 is the energy equivalent in erg/g of 1 rad.

The above expression is used to calculate the photon dose rates from fluence and compared with the standard source term values as shown in Table 1 [5].

Table 1: Photon Source Term for Tungsten Target

Energy (MeV)	Bremsstrahlung Output - Forward (Gy/h/m^2/kW)	
	NCRP	FLUKA
15	3500	3878.51
20	6000	5706.76
30	8500	7569.14

The bremsstrahlung photons generated in an electron accelerator interact with the target material and produce neutrons via photonuclear reactions. However, photoneutron generation occurs above a threshold energy defined for each material and is in the range of 6 MeV to 13 MeV except, for hydrogen and beryllium that have 2.2 MeV and 1.67 MeV threshold energies respectively [6]. We have calculated the photoneutron yield from the tungsten target using FLUKA and compared the same with NCRP data as shown in Table 2 [5].

Table 2: Photoneutron Yield Tungsten Target

Energy (MeV)	NCRP (neutron/s/kW)	FLUKA (neutron/s/kW)
15	5×10^{11}	8×10^{10}
20	8×10^{11}	3.13×10^{11}
30	1.7×10^{12}	1.05×10^{12}

RADIATION SHIELDING PARAMETERS

Shielding Cube

As the present radiation shielded room is not sufficient to shield the radiation from above source term, it was decided to design a local shielding structure. We will use lead blocks to shield photons as it is a high Z material [7]. For shielding neutrons, low Z materials that can moderate fast neutrons and absorbing materials like boron are preferred. Polyethylene has a high hydrogen content which makes it very effective in attenuating fast neutrons. Boron has a very good macroscopic cross section for thermal neutrons so using borated polyethylene is very effective to capture the thermal neutrons [6]. The boron content in the borated polyethylene ranges from 5% to 15%, but higher boron content makes it difficult for machining. Therefore, a boron rubber sheet with 40% boron content is much more advisable in addition to 5% borated polyethylene. We will use a combination of non-borated polyethylene, 5% borated polyethylene and boron rubber sheet with 40% boron content to ensure neutron shielding is achieved as desirable. Figure 2 presents the local shielding cube design. The entire assembly will be housed inside the concrete walls of the radiation lab.

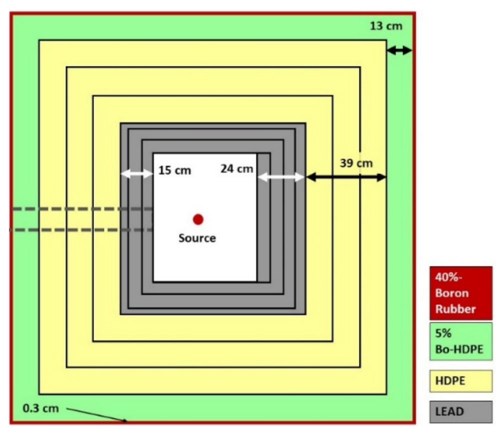

Figure 2: Cross section of local shielding structure.

Tenth Value Layers

Table 3 presents the tenth value layer of bremsstrahlung and the neutron tenth value layer corresponding to fission spectra (average energy 2 MeV) in lead, HDPE and concrete [5].

Table 3: Tenth Value Layer

Material	TVL for Photons (cm)	TVL for Neutrons (cm)
Lead	6	88
HDPE	92	13
Concrete	53	27

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RESULTS AND DISCUSSIONS

Figure 3 shows the spatial distribution of photon dose with 4 TVL of lead shielding in forward direction and 2.5 TVL on all the sides. A reduction in photon dose after the lead shielding is observed. Figure 4 shows the photon dose distribution outside the concrete walls which is in the acceptable limits from the radiation safety point of view. In this figure the entire shielding is shown at location around zero and the front wall is at 3 m from the local shield.

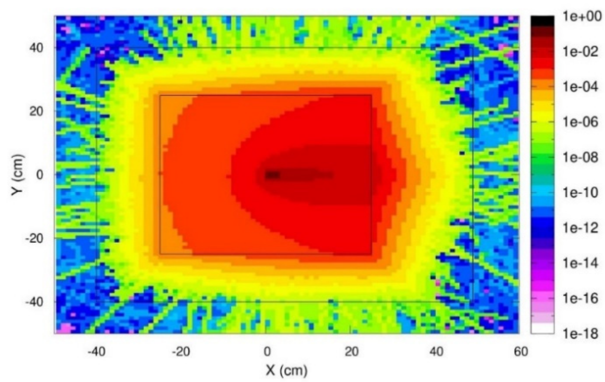

Figure 3: Photon dose outside the lead shielding.

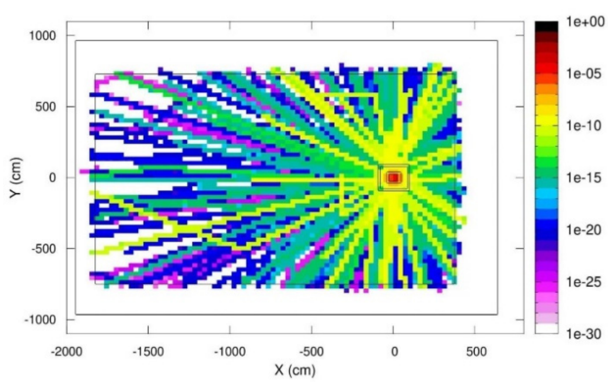

Figure 4: Photon dose outside the concrete walls.

Figure 5 shows the spatial distribution of neutron dose outside 3 TVL of regular HDPE. As expected, some neutron leakage is observed. Next we add 1 TVL of borated HDPE and a 40% boron rubber sheet of 0.3 cm thickness and the resultant flux is shown in Fig. 6. The boron rubber sheet layer will be used as an added safety layer to completely block all neutron radiation from reaching the concrete walls. As seen in the figure, the neutron dose just inside the concrete walls is much below the permissible limits and hence the shielding is safe for our purpose.

Based on the results, it was concluded that a local shielding of 4 TVL lead in beam direction, 2.5 TVL on all sides surrounded by 3 TVL of HDPE along with 1 TVL of 5% borated HDPE and a 0.3 cm of 40% boron rubber sheet is effective in reducing the leakage radiation to attain safety limits for both photons and neutrons during the operation of a 30 MeV electron beam hitting on a 0.6 cm thick tungsten target. One of the major usefulness of these calculations is that further strengthening of the concrete wall is not needed, thus saving time and aiding in cost efficiency.

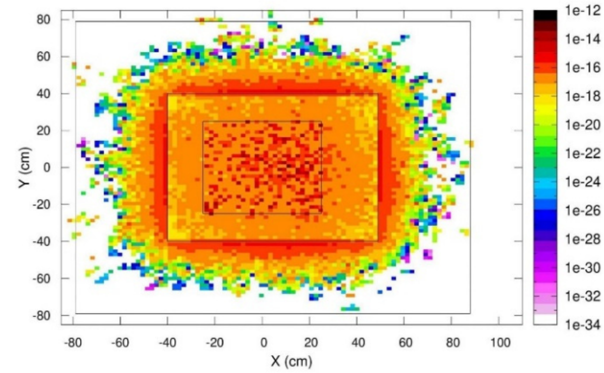

Figure 5: Neutron dose outside 3 TVL of regular HDPE.

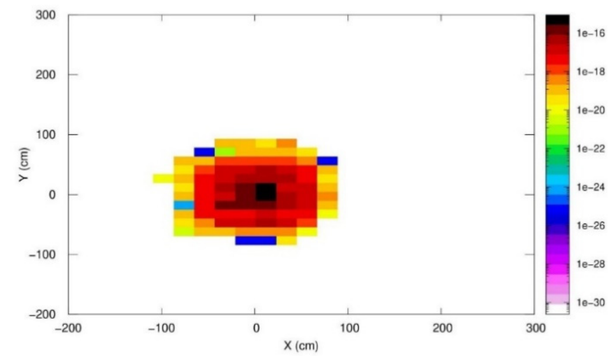

Figure 6: Neutron dose outside 3 TVL of HDPE, 1 TVL of 5% borated HDPE and 0.3 cm of 40% boron rubber sheet.

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