

Analysis and Improvement of Cyclotron Thallium Target Room Shield

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ABSTRACT

Because of high neutron and gamma ray intensities during thallium-203 target bombardment, thallium target room shield and its improvement have been investigated. Leakage neutron and gamma-ray dose rates in various points behind the shield are calculated by simulating the transport of neutrons and photons using Monte Carlo MCNP4C computer code. By considering target room geometry, its associated shield, neutron and gamma rays source strengths and spectra, three designs for enhancing shield performance have been analyzed. A shielding door at the maze entrance, covering maze walls with layers of some effective materials and adding a shadow shield in target room in front of the radiation source, have been considered and analyzed. Dose calculations were carried out for all the considered shielding scenarios separately for different materials and dimensions, then the most suitable shield was selected and built. The disagreement between calculated and measured dose values after upgrading is within 20%.

INTRODUCTION

One of most important radio-nuclides produced by cyclone30 cyclotron, at Agriculture, Medicine and Industry Research School (AMIRS) is Tl-201. This radioisotope is generated by bombarding the thick copper substrate electroplated with enriched ^{203}Tl , with 28.5MeV protons, at $\sim 145\mu\text{A}$ beam current via $^{203}\text{Tl}(\text{p}, 3\text{n})^{201}\text{Pb}$ reaction, which decays to ^{201}Tl with a half life of 9.4 h. The target bombardment results in the production of intense fields of high-energy neutrons and gamma rays. Therefore, in order to avoid the radiation exposure to cyclotron workers and member of the public, the efficient shielding of the target vault plays an important role in the radiological safety of the cyclotron facility. Thallium target vault is a room with ordinary concrete walls and multi-leg maze. The maze is the main passage for personnel and equipments towards the target and cyclotron vault. During the target bombardment, the high intensity prompt neutron/gamma radiation fields are produced and undergo multiple scattering, and consequently attenuate, while propagating along the maze path ways. In a well-designed maze and shield, the total neutron/gamma dose equivalent, ultimately decreases below the stated dose rate limit value at the maze entrance door and behind the shield⁽¹⁾. The attenuation characteristic of neutron and gamma rays along the maze depend on the shape, length, number of bends and the cross-sectional area of the maze^(2,3,4).

In a previous work, we determined the intensity and energy spectra of neutrons and gamma rays produced during bombardment of thallium target with 28.5 MeV protons⁽⁵⁾. Also we have analyzed the neutron and gamma rays streaming along the maze of NRCAM thallium production target room. It has been shown that using 28.5 MeV protons, at $\sim 145\mu\text{A}$ beam current, total neutron and gamma dose equivalent rate at the entrance door is $156\mu\text{Sv/h}$ ⁽⁶⁾. In this research, target room shielding performance has been analyzed and its improvement is investigated using MCNP4C computer code⁽⁷⁾ and the results have been compared with measured values. Figure 1 shows the Geometry setup of thallium target room and its maze.

MATERIALS AND METHODS

Monte Carlo transport simulation

For improving thallium target room shield, the effect of covering layer over the walls of the room and the maze, increasing the number of maze bends (by using a shadow shield) and using an access door with suitable shielding materials have been investigated. The simulations were performed using Monte Carlo N Particle transport code (MCNP4C), in its coupled neutron-photon transport mode. As it can be seen from the previous work(6), the dose equivalent rate of primary gamma rays falls off very rapidly as we go farther from the target along the maze (5), therefore in present work, the contribution of the primary gamma rays have been disregarded. The room and maze walls were first simulated with their initial shape and ordinary concrete. The thickness of walls changes from 1m to 2m according to their position in the shield. The width of the labyrinth is one meter. The concrete has been assumed to have density of 2.35 g cm^{-3} and elemental composition of H, 0.2%; O, 53%; Al, 2.9%; Si, 38%; K, 1.1%; Ca, 4% and Fe, 0.8%⁽⁸⁾. For dose distribution calculations, we used neutron source characteristics from the previous work⁽⁵⁾. We applied the MCNP code for the neutron source in mode (n p) which gives the dose distribution and energy spectrum of neutrons and secondary gamma rays.

The results of previous calculations in ^{203}Tl target bombarding with 28.5 MeV protons at 145 μA , neutron and gamma ray source strengths were $1.22\text{E}13 \text{ n/s}$ and $1.96\text{E}13 \text{ gammas/s}$ respectively. The energy spectra of neutrons and gamma rays are shown in figures 2 and 3 respectively. We assumed a point source that the angular distributions of neutrons and gamma rays are isotropic^[5].

To calculate the particle flux energy spectrum, we have considered several air-filled spheres of radius $15\text{cm}^{(9)}$, and used the F4 tally in several energy bins (groups): 0 - 1eV- 100eV - 1keV- 10keV- 100keV- 1MeV- 5 MeV- 10 MeV - 20 MeV. Subsequently using equation (1), we have calculated the dose distribution in several positions along the maze, and behind the shield walls.

$$H_i = \sum_g DF_{ig} \phi_{ig} , \quad (1)$$

Where H_i is the dose equivalent rate at position i , DF_{ig} is flux-to- the dose rate conversion coefficient⁽¹⁰⁾ for group $g^{(11)}$ and ϕ_{ig} is the flux density at position i for energy

group g. We have applied eqn. (1) both for neutrons and gamma rays, using appropriate values for neutrons or photons.

For leakage radiation dose equivalent rate calculations, we have assumed real thicknesses for shield walls and considered detectors in different points, behind the shield, while Separate calculations were carried out for determination of streamed neutron and gamma ray dose equivalent rates along the maze; detectors were located in different points along the maze and the thickness of walls, floor and ceiling was simulated to be a few tenth of centimeters, instead of real values. This is due to the negligible contribution of neutrons covering forward and backward distances larger than 30cm⁽⁵⁾. This way, the computation time was conveniently reduced. This causes just about %1 deviation from the reality. To better define the radiation field, importance sampling was also applied in the simulations. For this purpose, the room and maze were subdivided in to cells of different importance.

Depending on particles spectrum, different materials can be used for shielding purposes. High hydrogen content materials such as polyethylene and paraffin are good candidates for neutron moderation and final absorption. Borated materials with high hydrogen content presenting high absorption cross-section for thermal neutrons are preferred among others. Nevertheless, it should be taken into account that 480 keV prompt gamma rays are emitted in the $^{10}\text{B} (n, \alpha) \text{Li}$ reaction (with 94% branching ratio), also 2.2MeV prompt gamma rays are emitted in thermal neutron absorption with hydrogen ⁽¹²⁾.

As a first step, we considered the target room with the walls of ordinary concrete as the reference situation, and the streaming and transport of neutrons and gamma rays in the target room and its maze as well as their leakage through the shield walls have been simulated. Then by assuming a door made from different materials such as polyethylene, borated polyethylene and two-ply iron- polyethylene and iron-borated polyethylene, in different thicknesses, as a shield at maze entrance, the neutron and gamma dose equivalent rates have been calculated at the maze entrance and outside the door. In the other case, we covered the maze walls, with layers of different thicknesses of some effective materials such as polyethylene, borated polyethylene and two-ply iron-

polyethylene and iron-borated polyethylene, and the total neutron and gamma dose equivalent rates have been calculated.

It was also assessed that by increasing the number of maze bends, the dose equivalent rate of neutron and gamma rays could be decreased. Therefore by assuming a concrete wall in the target room, both in front of the source and parallel to the maze wall, the dose equivalent rates have been calculated for several points along the maze. These calculations were performed for 1m, 1.5m, 2m and 2.5m of the added wall lengths.

The calculations for the optimum wall length have been performed for several wall materials, such as paraffin, polyethylene, borated polyethylene and tow-ply wall of iron-polyethylene and iron- borated polyethylene.

Among the above mentioned materials, the material with maximum reduction of total neutron and gamma dose equivalent rates has been selected as the shadow shield material.

Dose equivalent rate calculations have been performed for 7.5cm, 15cm, 20cm, 25cm and 30cm thicknesses of the selected material.

Measurement of neutron and gamma dose rate distributions

As reference data, the neutron and gamma ray dose equivalent rates at various positions along the maze and behind the shield walls have been measured using Berthold LB6411⁽¹³⁾ neutron dosimeter and Rados RDS-110⁽¹⁴⁾ gamma dosimeter. Due to very high neutron dose equivalent rate at the end of the maze (near to the target source), we have measured the neutron dose equivalent rate at 3 μ A proton beam current and normalized the results for 145 μ A of operational proton current in actual bombardment of thallium target. On the other hand, because of low neutron and gamma dose equivalent rates behind the room walls and for the points into the maze far from the target, the measurements have been performed at 145 μ A.

Duration of measurements was chosen such that the counting statistical errors were less than 10% for each measuring position.

All the measurements and calculations have been performed at the center of the maze 100 cm above the floor.

The neutron dosimeter was calibrated for Cf-252 neutron source spectrum; therefore the readings at each position have been corrected according to the energy spectrum of

neutrons. The correction factor for each position has been calculated using the energy spectrum calculated by MCNP according to equation (2):

$$F(a) = \frac{\sum_g F_g \varphi_g(a)}{\sum_g \varphi_g(a)} , \quad (2)$$

where $F(a)$ is the overall correction factor at point “a” , F_g is the calibration factor at energy group “g” and $\varphi_g(a)$ is the neutron flux at the energy group g and position a. The corrected dose equivalent rates are then calculated using equation (3):

$$D(a)_{\text{corrected}} = F(a) D(a)_{\text{non-corrected}}. \quad (3)$$

The gamma dose equivalent rate measurement does not suffer a strong energy dependence as the neutron measurement.

RESULT AND DISCUSSIONS

By analyzing the thallium target room and its maze, it was found that except the maze, maximum leakage occurs from location located in figure 1 with “c” (approximately 100cm from the floor, the same as the source height). Results from MCNP calculations and measurements have been shown in figure 4. According to figure 4, calculations and measurements confirm that the location “c” is the zone has more leakage than other points behind the walls.

Calculations performed with MCNP code showed that by covering the maze walls with polyethylene and borated polyethylene, the reduction of exposure due to neutrons and capture gamma rays is negligible for all the chosen materials.

For further reduction of neutron dose equivalent at the maze entrance, the effect of few centimeters of borated polyethylene liner on the maze door has been investigated. For simultaneous reduction of the neutron and gamma dose equivalent rates, outside the maze entrance door, we planned two-ply sheet of iron and borated polyethylene on the maze door. The results for several thicknesses of liner materials are summarized in table 1.

By considering a shadow-shield in the target room, calculations performed using MCNP code showed that shadow-shield length of the order of 2m can reduce dose equivalent rates effectively along the maze. It can also be observed that, the dose equivalent rate reduction for higher shadow-shield length increasing is low (figures 5 and 6).

By assuming a 2m length and 30cm thick shadow-shield in the target room of: concrete, polyethylene and paraffin, from figures 7 and 8 it can be concluded that polyethylene is more efficient in reducing neutron and gamma dose equivalent rates than paraffin and concrete.

From MCNP calculations we found out that pure polyethylene and borated polyethylene shadow-shields behave in the same way against both neutron and gamma rays, probably because of the contribution of the fast neutron in the spectrum in shadow-shield position. Also polyethylene shadow-shield is better than two-ply iron- polyethylene shadow-shield in that place in order to reduce dose equivalent rate in maze door entrance.

Although according to calculations, dose equivalent rate reduction of shadow-shield with lengths greater than 2m dose not differ very much from that with 2m length, but because of sufficient space available in the target room, we selected a 3.5m length of polyethylene. In table 1 calculation results for two different thicknesses of shadow-shield in 3.5 m length have been given. Commercial polyethylene blocks that are available in the NRCAM are 7.5 cm thick hence our calculations have been performed for 7.5cm and 15 cm thicknesses. According to table 1 and figure 4, by applying a 7.5 cm thick shadow-shield, total neutron and gamma dose equivalent rates might be reduced to one third of initial values both at the maze entrance door and at location “c”.

As mentioned before, leakage of neutron and gamma rays through the shield is lower than the maze, but because of higher occupancy factor near point “c”, we preferred to construct shadow-shield instead of a shield door in order to reduce the dose rate at the maze entrance position and point “c” simultaneously. Also this can be considered as a removable shield.

Some disadvantages of borated polyethylene and iron-borated polyethylene sheets on the maze door are: 1) iron because of its cobalt impurity can be activated, and two-ply door is not light.

2) Such materials are non-transparent, therefore not very suitable for door purpose.

Therefore the 7.5cm thick and 3.5m length polyethylene shadow-shield has been constructed. In table 1, neutron and gamma dose equivalent rates in presence of shadow-shield have been compared with other proposed shields.

After shadow shield construction, neutron and gamma dose equivalent rates were measured outside the maze entrance door and behind the shield walls, at the maximum leakage point “c”. Calculation and measurement results are summarized in table 1, and are in good agreement, showing a reduction factor of 1/3 for both positions.

CONCLUSIONS

The shielding analysis of the thallium target room and its maze, allow to asses that the maximum neutron and gamma leakage is due to streaming through the maze. Except for a small region behind the shield where the total neutron and gamma dose equivalent rate is $6\mu\text{Sv/h}$, the dose rates at any point behind the shield are negligible. To evacuate the radiation leakage as a function of position, we investigated three kinds of shields to reduce leakage values:

1- Sheets of borated polyethylene or iron- borated polyethylene on the maze entrance door, 2- A shadow shield of polyethylene in the target room and the addition of one more bend in the maze, 3- Overlaying the maze walls with a neutron absorbing material.

Shadow shield was preferred to the two others, because of its ability to reduce both neutron and gamma dose equivalent rates at maze entrance position and position “c”. The application of the significantly reduces the leakage dose rate behind the shield.

The setup of a polyethylene shadow shield (7.5cm thickness and 3.5m length) the total dose equivalent rate at the maze entrance and behind the shield (position “c”) is reduced by a factor of 3. Calculations and measurements are in satisfactory agreement.

Table1. MCNP results for neutron, gamma and total dose equivalent rate at the entrance door for two different thicknesses shadow shield (3.5 m fixed length) during $145\mu\text{A}$ 28.5 MeV proton beam bombardment.

	Thickness (cm)	Neutron Dose Rate ($\mu\text{Sv/hr}$)	Gamma Dose Rate ($\mu\text{Sv/hr}$)	Total Dose Rate ($\mu\text{Sv/hr}$)	Dose Attenuation Factor
Door	0	109	47	156	1
	2 cm Polyethylene	10	42	52	0.33
	5 cm Polyethylene	6	35	41	0.26
	10 cm Polyethylene	0.3	28	28.3	0.18
	5 (3cm Polyethylene + 2cm Iron)	6.16	16.7	22.86	0.15
	7.5 (5cm Polyethylene + 2.5cm Iron)	5.5	15	20.5	0.13
	10 (5cm Polyethylene + 5cm Iron)	5.5	12	17.5	0.11
	12.5 (5cm Polyethylene + 7.5cm Iron)	5	9	14	0.08
Shadow Shield	7.5 cm Polyethylene Shadow Shield	25	24	49	0.31
	15 cm Polyethylene Shadow Shield	14	10	24	0.15

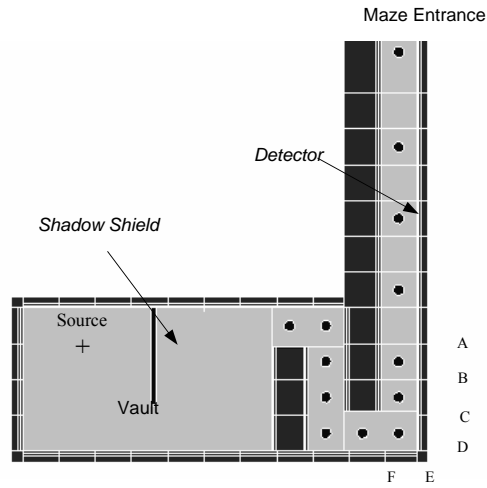


Fig.1. Geometry setup of thallium target room with the position of the employed detectors and splitting surfaces for variance reduction.

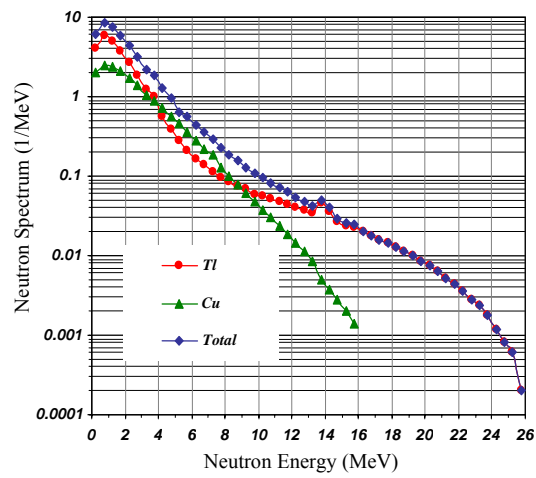


Fig.2. Energy spectrum of neutrons produced in thallium, copper and the whole target assembly, during 28.5 MeV proton beam bombardment (Calculated by ALICE computer code) [5].

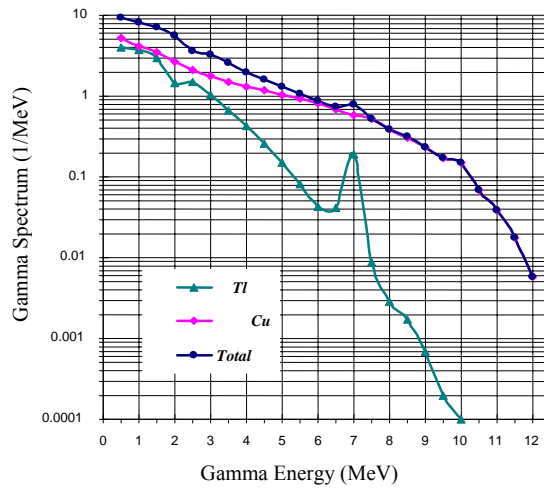


Fig. 3. Energy spectrum of the prompt gammas produced in thallium, copper and the whole target assembly, during 28.5 MeV proton beam bombardment (calculated by ALICE computer code) [5].

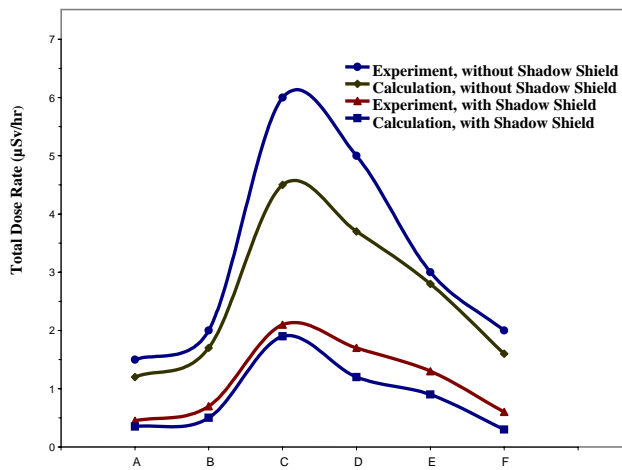


Fig.4. Total leakage neutron and gamma dose rates at positions shown in Figure 1, during 145μA 28.5 MeV proton beam bombardment.

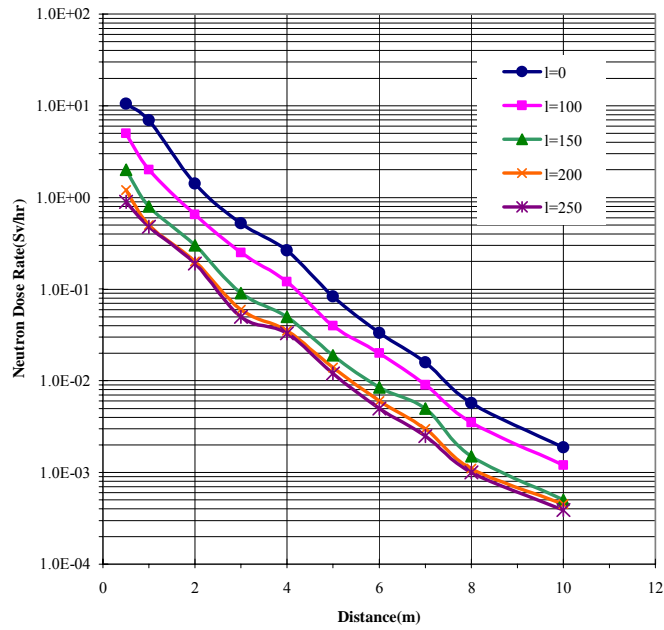


Fig.5. Neutron dose equivalent rate at various points along the maze for a polyethylene 30 cm thick shadow shields and four different lengths (MCNP results)

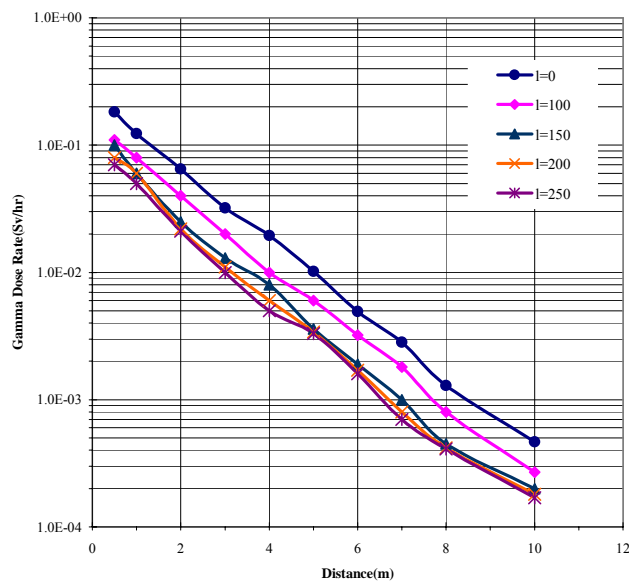


Fig.6. Gamma dose equivalent rate at various points along the maze for a polyethylene 30 cm thick shadow shield and four different lengths (MCNP results)

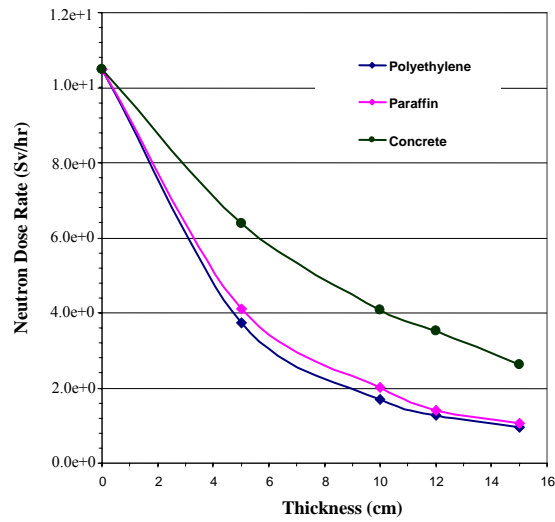


Fig.7. Comparison of neutron dose equivalent rate behind a shadow shield of different materials: concrete, paraffin and polyethylene for the same shield length and various thicknesses 145 μ A 28.5 MeV proton beam bombardment (computer results).

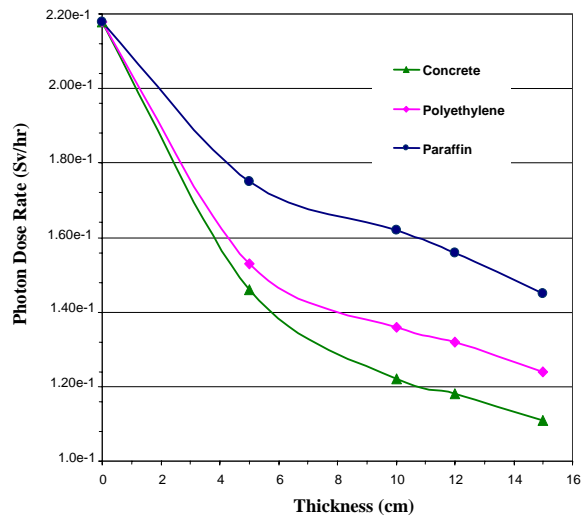


Fig.8. Comparison of photon dose equivalent rate behind a shadow shield of different materials: concrete, paraffin and polyethylene for the same shield length and various thicknesses 145 μ A 28.5 MeV proton beam bombardment (MCNP results).

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