Design calculations for the local radiation shield of a radioisotope production target bombardment station – a comparative study

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ABSTRACT

In this study, Monte Carlo simulations were performed to re-evaluate the radiation shield configuration of a target bombardment station for radioisotope production at iThemba LABS. New calculations performed by means of the Monte Carlo radiation transport code MCNPX are compared with the older calculations performed using the one-dimensional discrete ordinates radiation transport code ANISN for a shield with a spherical geometry. The two types of calculation predict the same general trend and a similar optimum shield geometry, however, away from the optimum the differences are not negligible.

1. INTRODUCTION

Various radioisotopes are produced at iThemba LABS for application in both nuclear medicine and research (e.g. ^{18}F, ^{22}Na, ^{67}Ga, ^{81}Rb, ^{82}Sr, ^{123}I, etc.) For these purposes, appropriate targets are bombarded with 66 MeV proton beams with currents varying from about 50 μA up to 250 μA, depending on the target type and other particulars of the production. The first dedicated target bombardment station for radioisotope production became operational about 18 years ago [1] and has been in regular use ever since. Currently, iThemba LABS operates three dedicated target bombardment stations, the last of which was completed only recently. An application for funding to increase the radioisotope production capacity was approved about two years ago. This facility upgrade, which will be completed by the end of 2007, includes a beam splitter which will make it possible to operate two bombardment stations simultaneously. There is also an active effort to increase the operating beam intensity of some of the target systems, in particular those for the production of the longer-lived radioisotopes (such as ^{22}Na and ^{82}Sr) which generally require more integrated current (charge) to obtain a given amount of activity.

The three bombardment stations are not identical as their purposes are different. The first station built at iThemba LABS can accommodate various batch targets in a rotatable target magazine and is the work-horse for most of the routine production of the medically-important radioisotopes. The second station was designed specifically to accommodate semi-permanent targets and is dedicated to the production of short-lived PET radioisotopes. This station has recently been equipped with an ^{18}O-water target for ^{18}F production. The third station was specifically designed to utilize much higher beam currents and is dedicated to the production of the longer-lived radioisotopes.

In spite of these differences, one common feature of all the stations is the presence of a local radiation shield in close proximity to the target. The purpose of a local radiation shield is to reduce the neutron activation of the vault and its contents and to reduce radiation damage to sensitive components. In particular, organic materials such as rubbers, plastics and other polymers need protection from the radiation. In the case of organic materials, radiation damage is, to a large extent, related to the absorbed dose, irrespective of the type of radiation, as long as dose rates are below the level where damage caused by thermal heating becomes important [2]. Many functional components contain these materials, e.g. all the pneumatic components, stepper motors, drive belts, cable insulation, flexible cooling-water hoses, etc. The design philosophy has therefore been to surround the targets with radiation shields in close proximity and to mount all sensitive components required for the functioning of the stations strictly on the outside.

During the design stage of the first target bombardment station, quite a number of years ago, calculations were performed by means of multigroup discrete ordinates radiation transport codes in order to assist in the design of the local radiation shield. Details of these calculations were published in Ref. [1]. As part of the recent expansion project, radiation transport calculations were again performed, however, a decision was made to employ one of the more modern radiation transport codes based on the Monte Carlo method.

One of the limitations of the discrete ordinates method has always been that only simple geometries can be modeled. In our previous work, shields having a spherical geometry were evaluated using the one-dimensional radiation transport code ANISN (RSIC CCC-254) [3]. Shields having a cylindrical geometry were evaluated using the two-dimensional radiation transport code DOT (RSIC CC-267) [4]. Although the actual shield conform more to a cylindrical geometry than a spherical one, the spherical geometry was nevertheless considered to be a good approximation as the ANISN calculations yielded very similar results to the DOT calculations. The simpler ANISN code was therefore used to evaluate the configuration of the shield in terms of its various material layers, consisting of an inner iron layer, a middle paraffin wax layer which contain 2.5% boron carbide by weight, and an outer lead layer. In fact, the outer lead layer was omitted in the first calculations but added later to shield against the 2.23 MeV γ-rays emitted in the capture of thermal neutrons in the hydrogenous layer.

In the present study, a comparison is made between the results from the older discrete ordinates calculations and Monte Carlo calculations for the same spherical shield geometry, the latter by means of the code MCNPX [5]. This kind of benchmark study was deemed necessary before embarking on the modeling of the bombardment stations and their vaults in their full complexity (something which was not possible previously with the discrete ordinates codes). We limit the present discussion to a two-layered shield and for neutrons only. Note that the focus is on the comparison and not on a particular scheme for optimizing or improving the shield configuration, which can be achieved in different ways using a multi-layered approach. Details of the calculations are given in Section 2, the results and discussions are presented in Section 3, followed by the conclusions in Section 4.

2. RADIATION TRANSPORT CALCULATIONS

A diagram of the shield and irradiation vault is shown in Fig. 1. The radiation source was chosen to be a copper beam-stop bombarded with 66 MeV protons at a beam intensity of 100 μA, located at the centre of the sphere. The first shielding layer starts at a radius of 30 cm and consists of pure iron. The second layer consists of paraffin wax containing 2.5% B_4C by weight. The thickness of the inner layer was systematically varied between 0 and 60 cm while keeping the total thickness of the shield fixed at a value of 60 cm. At the extremes of this interval, therefore, the shield consists of either 100% iron or 100% paraffin wax, with various ratios of the two materials in between. An observer measuring the absorbed dose was assumed to be positioned at a fixed distance of 150 cm from the source (i.e. at a radius of 150 cm). The concrete wall of the vault starts at a radius of 340 cm and was modeled to be 4.5 m thick. Thus, the radiation shield consists of concentric spherical layers, located inside a spherical vault.

In the case of the ANISN calculations, the source term used was based on the inclusive neutron spectra measured by Broome *et al.* [6] for 72 MeV protons impinging on a copper beam-stop. The values measured at 90° by these authors [1,6] were adopted and the spectrum truncated at 66 MeV, the energy at which the routine radioisotope production programme at iThemba LABS is based. The source was modeled to be isotropic.

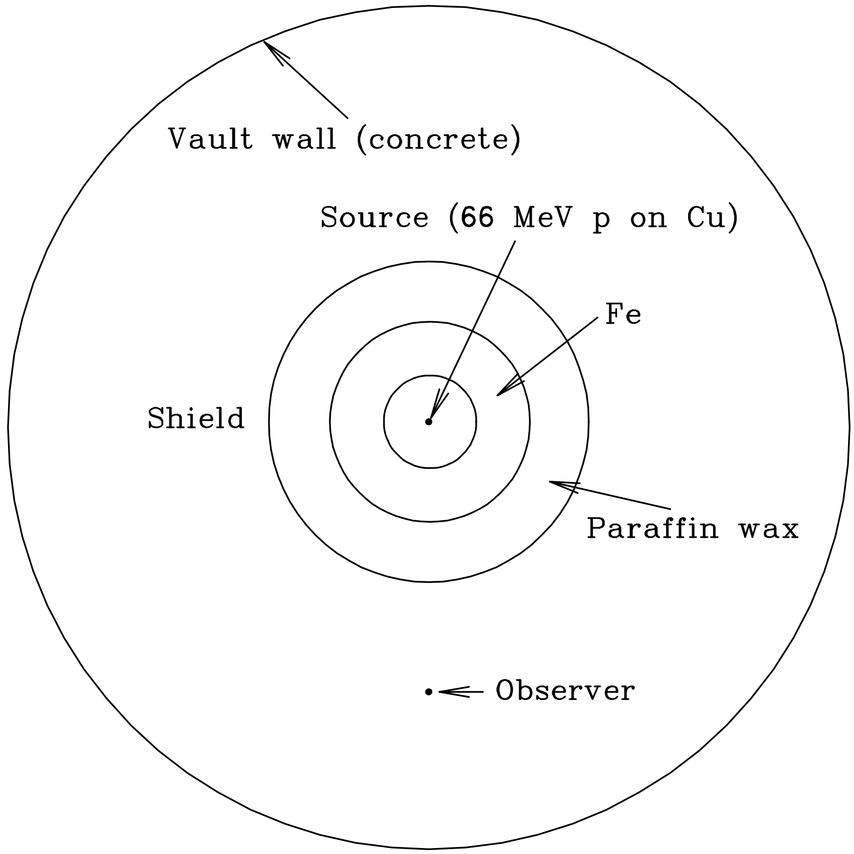

Figure 1: A simplified model of the target bombardment station inside an irradiation vault with thick concrete walls. (Note that only the inside surface of the wall is shown). The source is a Cu beam-stop in the centre of the spherical vault, surrounded by a spherical radiation shield which has two layers: an inner iron layer and an outer paraffin wax layer which contains 2.5 % B_4C by weight. The total shield thickness is 60 cm and the observer inside the vault is located at a position 150 cm from the Cu target.

The source strength was estimated from the published yields of Ryder [7] to be 6 x 10^{13} neutrons per second. For these calculations, the multigroup cross-section library HILO (RSIC DLC-87) [8] was selected. The multigroup scalar flux densities calculated were folded with appropriate absorbed dose response functions [9] to yield absorbed dose-rate values. Spatial intervals of 0.5 cm were used throughout. A symmetrical Gauss-S_{16} angular quadrature order was specified, with P_5 the highest Legendre moment of the polynomial expansion representing the scattering angular distribution. Further details of these calculations can be found in Ref. [1].

The Monte Carlo calculations were performed using MCNPX code version 2.5.e [5]. Care was taken to emulate the same conditions (source and geometry terms) as those adopted in the multigroup discrete ordinate calculations. The source term for neutron emission was internally generated by the code for the case of protons stopped on Cu. These values were compared with the measurements of Ref. [6] and found to be in good agreement.

3. RESULTS AND DISCUSSION

Calculations were performed both for the shield present and no shield present. The results are expressed in Fig. 2 as the dose attenuation factor, i.e. the ratio of the absorbed dose rates at the observer position with and without shielding, plotted as a function of the iron layer thickness. In this way, the ratio of iron to wax that would be required to minimize the absorbed neutron dose at the observer position could be determined.

It is immediately evident from the figure that an optimum iron layer thickness is close to 40 cm for the chosen 60 cm thick shield. At this value, both the ANISN and MCNPX curves show a minimum. The curves are similar in shape, which is reassuring. Clearly, there is a good agreement between the data sets around the minimum. Curiously, however, MCNPX yielded substantially higher values for the dose attenuation factor as the Fe thickness increases above ~45 cm, reaching a value which is almost a factor of five higher at 60 cm (i.e. for the case of a 100% iron shield). Also at the other extreme (at 0 cm, i.e. for the case of a 100% paraffin wax shield) a somewhat less efficient shield is predicted by the MCNPX calculations.

Note that at this time we consider these results as preliminary. Although the agreement between the new and previous calculations is acceptable in the region of the minimum dose attenuation factor, the reason for the disagreement outside this region is not yet fully understood.

The philosophy of this kind of shield is quite simple. Neutrons with high energies (above about 4 MeV) are effectively slowed down by means of inelastic scattering in the inner iron layer, while slower neutrons are more effectively slowed down and eventually thermalized by means of elastic scattering with the hydrogen in the outer wax layer. The boron aids in increasing the thermal capture probability, effectively removing a significant fraction of neutrons before they can escape the shield into the vault. We also want to state without further discussion that by adding a relatively thin lead outer layer, this kind of shield also becomes effective for γ-rays.

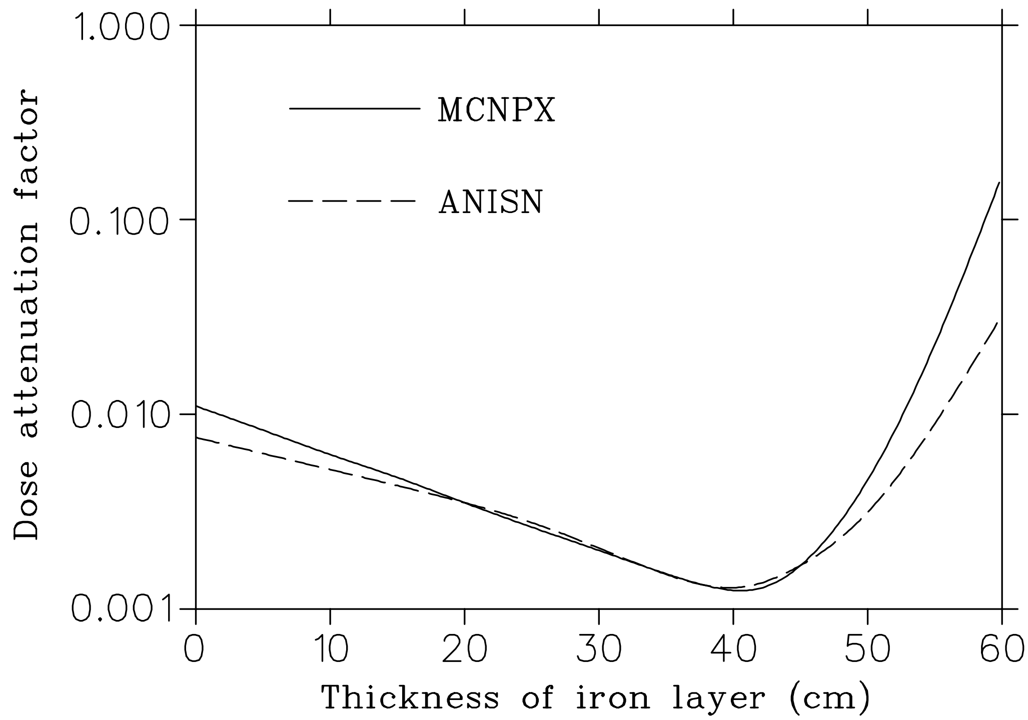

Figure 2: Calculated absorbed dose attenuation factors at a point 150 cm from the centre of the Cu target for a 60 cm thick iron/wax spherical shield, plotted as a function of the inner iron layer thickness. The paraffin wax contained 2.5 % B_4C by weight (see text).

4. CONCLUSIONS

The main purpose of this study was to re-evaluate previous shield design calculations for the first bombardment station built at iThemba LABS for the production of radioisotopes. For this purpose, new calculations performed by means of the Monte Carlo radiation transport code MCNPX were compared with the older calculations performed using the one-dimensional discrete ordinates radiation transport code ANISN. The two types of calculations predict the same general trend and a similar optimum geometry, however, the disagreement away from the optimum geometry is quite pronounced. In particular, the unexpectedly large differences in the predicted dose attenuation factors at iron thicknesses larger than 45 cm is rather disconcerting. Above this value, the MCNPX calculations predict a significantly less effective shield than what was previously predicted by the ANISN calculations. The reason for this disagreement is not yet understood. The good agreement for geometries near the optimum configuration is nevertheless reassuring. The next phase of the project will entail the modeling of the more complex actual geometries of all three bombardment stations.

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