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AN MCNP FEASIBILITY STUDY FOR A SWITCHABLE GAMMA SOURCE

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Abstract

Gamma radiation sources are being used for an array of everyday applications, from portal monitors for homeland security to blood sterilization, and as calibration sources in nuclear medicine. This paper presents the preliminary feasibility study of a source that allows the gamma radiation to be turned on and off. The gamma radiation is produced via a sequence of nuclear reactions: an (α, n) reaction, followed by an (n, γ) reaction. Parametric studies in MCNP5 were performed to investigate the effect of different moderators, neutron absorbers, and geometries on the gamma flux and gamma dose produced. The results of the feasibility study are discussed in the context of nuclear medicine applications.

Keywords: MCNP simulation, gamma source design, nuclear medicine applications

1. Introduction

Gamma radiation sources are being used for a wide array of everyday applications, from portal monitors for homeland security [1] to food and blood sterilization [2], and as calibration sources in nuclear medicine [3][4]. Due to their extensive use in a wide array of applications, post September 2001, countries around the world started looking into the possibility of replacing current radiation sources with alternative designs to improve health, safety and security, while maintaining an equivalent performance level of the device [5].

Two main applications of gamma radiation sources provided the motivation behind the current feasibility study: 1) ^{57}Co flood sources used to calibrate gamma cameras used in nuclear imaging devices [3] [4]; and 2) the gamma sources used in self-contained irradiators used primarily for blood irradiation and sterilization processes [5]. In general, the current sources work well, however, a number of disadvantages and limitations were identified, including: 1) frequent replacement of the sources (i.e., ^{57}Co sources need to be replaced every 1-2 years [6], and ^{60}Co sources need to be replaced every 5 years [5]); 2) ^{137}Cs sources, although they have a long shelf-life (i.e., ~30 years), use primarily cesium chloride as the radioactive material, which poses significant hazards to workers, and public safety and security since it is found in powder form and can readily disperse in the environment if not properly contained and dispensed [5]; and 3) the sources are continuously active, that is, the radioactive material continuously emits gamma radiation, therefore, permanent shielding needs to be in place to minimize the dose to personnel, in accord with the ALARA (As Low As Reasonably Achievable) radiation protection principle.

The feasibility of a new gamma source design has been investigated. This new design was proposed to eliminate the need for frequent replacement of the sources, eliminate the use of cesium chloride as the gamma emitter, aid in the simplification of the storage, transportation and handling procedures, and to reduce the time of radiation exposure and dose received by medical personnel.

The current paper describes the concept behind such a gamma source and summarizes some of the preliminary computational results obtained as part of the feasibility study performed using the Monte Carlo computer code MCNP5 [7]. The goal of this feasibility study was to investigate different geometries for the gamma source, various source materials (for both (α, n) and the (n, γ) reactions), and moderator materials. MCNP modelling of the source was used to calculate the gamma flux and the gamma dose resulting from different source designs.

1.1 General description of proposed design

The basic principle behind the new gamma source design is the production of gamma rays via a sequence of two nuclear reactions: an (α, n) reaction, followed by an (n, γ) reaction. The (α, n) reaction can be switched "ON" and "OFF" manually, thus controlling the production of gamma radiation. The neutrons produced via this reaction are then moderated to maximize their absorption by isotopes that will produce gamma rays, via an (n,γ) reaction.

The feasibility of switchable radioactive neutron sources (or SRNS) has been shown at Argonne National Laboratory [8][9] and at Sandia National Laboratories [10]. The "switchable radioactive gamma source" (SRGS) presented in this paper is based on the SRNS. It is important to note that the computer models investigated in this paper focus on the physics of the system and they do not account for any of the mechanical factors (e.g., the mechanism used for switching the source "ON" or "OF").

2. Modelling Methodology

2.1 Neutron source model

The neutron source is at the heart of the gamma source design. Choosing an appropriate neutron source was a key step. Potential alpha-emitting radioisotopes were chosen based on three criteria: 1) a half life long enough to eliminate the need for frequent replacements (i.e., at least 10 years); 2) be safe to store and transport in the "OFF" state; and 3) the (α, n) reaction must result in a neutron yield which will provide a sufficient gamma flux and dose for the intended application. A neutron source based on ^{241}Am - ^{9}Be satisfies these three criteria according to the information summarized by Hertz et. al [10].

First, ^{241}Am has a half-life of 432.2 years. This long half life eliminates the need for replacement of the gamma source every few years, like, for example, in the case of a ^{57}Co source. Americium-241 is relatively safe when compared with other alpha emitting radioisotopes because of its low number of spontaneous fission events (i.e., 5.38×10^{-7} spontaneous fissions/μs/g [10]) and low energy gamma-ray background (60 keV [12]). Americium-241 decays primarily by alpha emission, with an energy of 5.48 MeV, which, based on the empirical relationship derived by Anderson and Hertz [11], results in an estimated yield for the ^{241}Am - ^{9}Be source of 86 neutrons per 10^6 alpha particles emitted.

MCNP5, version 1.40 was used for the feasibility study, however, it does not have the capability to model the (α, n) reaction. A model neutron source equivalent to a ^{241}Am - ^{9}Be source was developed using literature data for the neutron energy distribution of this (α, n) reaction. The modelled neutron spectrum is illustrated in Figure 1, which is based on data reported by Kluge and Weise [13]. The computer code SOURCES-4C [14] was used to determine the neutron source strength. SOURCES-4C has the capability to calculate the production rate from common (α, n) reactions for a number of different geometric configurations, including the two-region interface, which best represents the SRNS. The calculated neutron strength for the models in the current feasibility study was 1.30×10^4 neutrons / s-cm^2.

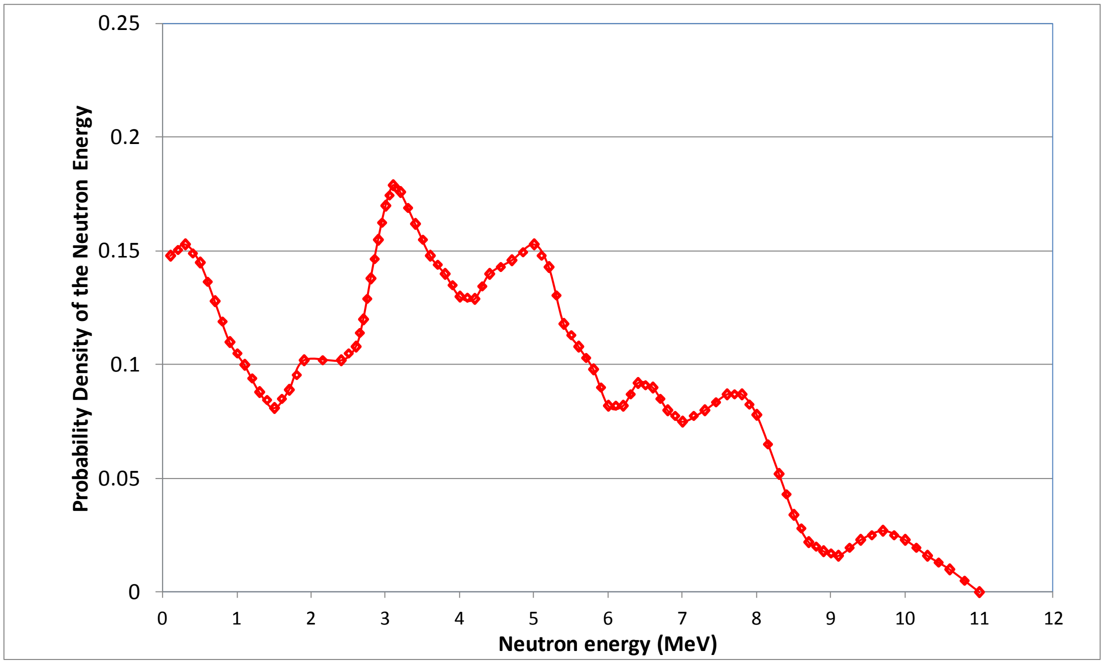

Figure 1 Modelled neutron spectrum for the ^{241}Am - ^{9}Be source

2.2 Gamma Source Models

The neutron source described in Section 2.1 was enclosed in Zircaloy-2 (0.2 cm thick) and surrounded by a neutron moderator of variable thickness. Two neutron moderators were investigated: deuterated polyethylene (CD_2) and heavy water (D_2O). The moderator was enclosed in a Zircaloy-2 shell (0.2 cm thick), which was surrounded by a variable thickness of neutron absorber on the outside. A number of neutron absorbers were investigated (e.g. ^{147}Sm, $Sm_{natural}$ and $Gd_{natural}$). Figure 2 shows an example of an MCNP model for a 40 cm x 40 cm planar source (referred to as the "large source" in this paper), which is equivalent to the size of a standard gamma camera used for Single Photon Emission Computed Tomography (SPECT) imaging. The gamma flux and the dose deposited in the air surrounding the source were calculated for three different regions: (1) the two planar regions in the front and back of the source (see Figure 2A - air region 1 and air region 2); and (2) the air surrounding the source on all other sides (see Figure 2B - air region 3).

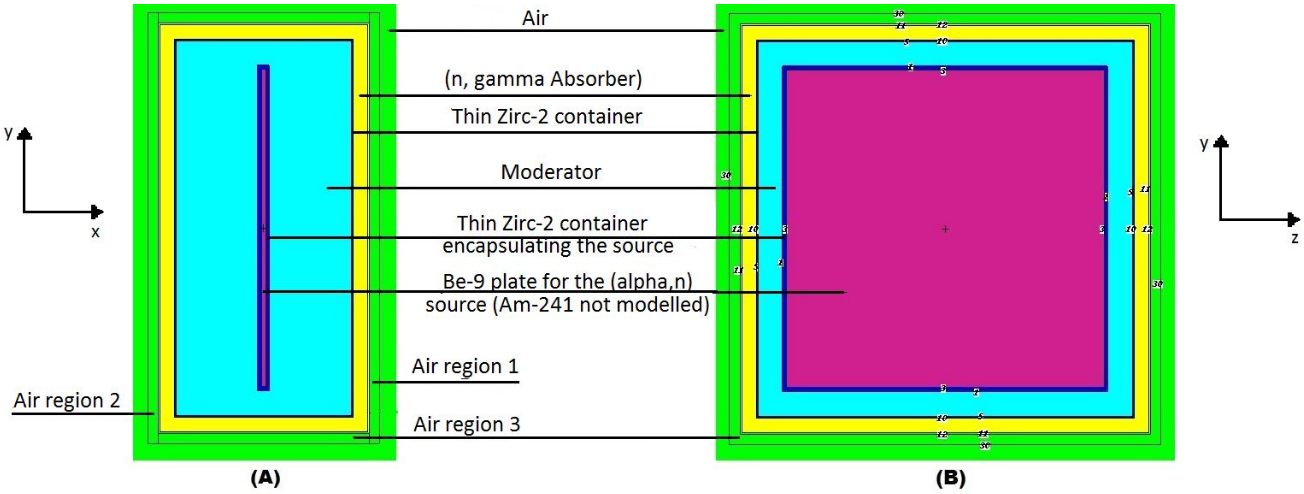

Figure 2   Sample modelled design for the (n, γ) source. (A) X-Y view of a 40 cm x 40 cm source; (B) Z-Y view of the same source.

A 6 cm x 6 cm neutron source (referred to as the "small source" in this paper) was also investigated. As shown in Figure 3 – Model A and Figure 3 – Model B, the neutron source was surrounded by moderator (e.g., CD_2 or D_2O) of thicknesses between 0 cm and 20 cm along the x-direction. The y- and z-dimensions of the Zirc-2 alloy shell containing the moderator and the neutron source were kept constant at either 8 cm x 8 cm or 10 cm x 10 cm. This "smaller" source design (i.e., either 8 cm x 8 cm or 10 cm x 10 cm) would cover one quarter of a standard gamma camera. Also, various absorber thicknesses were investigated to see their effect on the neutron and gamma fluxes and doses obtained outside the source. In addition, a number of models were created using lead as a potential shield / reflector inside the source (see Figure 3 - Model A).

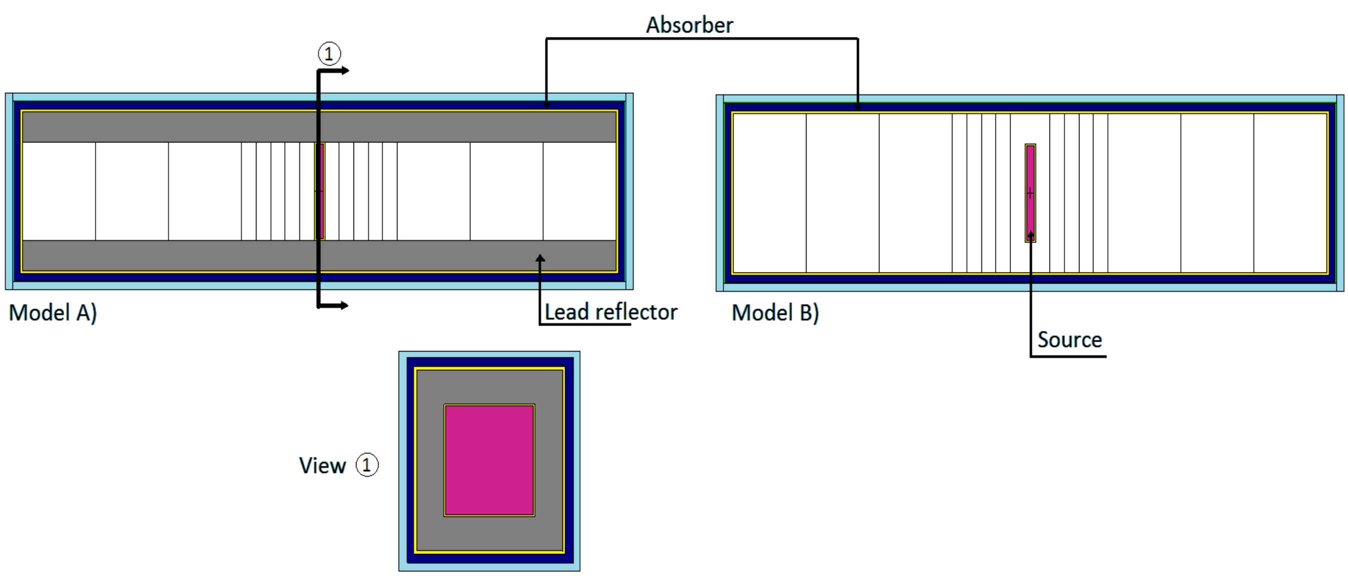

Figure 3 Example of the modelled design for the smaller (n, γ) source. (A) X-Y view of the source with the lead reflector/shield; (B) X-Y view of the similar source without the lead shield.

3. Results and Discussion

Preliminary calculations were performed for the large 40 cm x 40 cm source (the equivalent size of a SPECT gamma camera) using CD_2 as the moderator and ^{149}Sm as the absorber. These calculations resulted in a maximum gamma flux of 2.0×10^3 γ /s-cm^2 for a 5 cm thick moderator on each side of the Am/Be source with 0.1 cm ^{149}Sm absorber surrounding the moderator. The cost of this source configuration, considering the main components, i.e., the Am and Be for the (α,n) source, the CD_2 moderator and the ^{149}Sm absorber, was estimated to be at least 100 times more than the cost of current ^{57}Co sources and thus it was not practical.

The technical feasibility of a smaller neutron source (6 cm x 6 cm) was investigated. The results summarized here are from two studies. First the neutron source was surrounded by two different moderators, D_2O or CD_2, and by either $Sm_{natural}$ or $Gd_{natural}$ as absorbers undergoing the (n,γ) reaction. The y- and z-dimensions of the moderator region were kept constant at 8 cm x 8 cm, while the x-dimension was varied between 0 cm and 20 cm on each side of the planar neutron source. Figure 4 shows the gamma fluxes obtained for each moderator parametric study on the Y-Z faces of the source (i.e., air region 1 or 2, Figure 2A). A separate parametric study was performed to investigate the impact of the absorber thickness on the calculated gamma flux: the thicker the absorber the larger is the calculated gamma flux, because more neutrons are absorbed. Increasing the thickness of the moderator led to more neutrons "leaking" out through the side, resulting in increased gamma production in that region (i.e., air region 3, Figure 2A). There was no significant difference observed between the CD_2 and D_2O moderators, which was expected because these moderators have similar properties for this application. For the $Sm_{natural}$, the maximum gamma fluxes calculated were 23.8 gammas/s-cm^2 for a 1 cm thick D_2O moderator and 1 cm absorber, and 24.7 gammas/s-cm^2 for a 2 cm thick CD_2 moderator and 1 cm absorber.

Figure 5 allows a comparison to be made of the gamma output for the (n, γ) absorbers $Sm_{natural}$ and $Gd_{natural}$ using CD_2 as the moderator. As expected, the results show similar trends, because samarium and gadolinium are excellent neutron absorbers. (The absorption cross sections for thermal neutron capture are 49700 barn for $Gd_{natural}$ and 5922 barn for $Sm_{natural}$. [15]) The maximum calculated gamma flux is 24.7 gammas/s-cm^2 for 1 cm $Sm_{natural}$ and 2 cm CD_2 moderator, and 23.2 gammas/s-cm^2 for 1 cm $Gd_{natural}$ and 2 cm CD_2 moderator. These fluxes are orders of magnitude lower than the gamma fluxes resulting from standard 5 mCi or 10 mCi ^{57}Co fixed calibration flood sources [3]. Unfortunately, these calculated fluxes makes this application of the switchable source impractical, because it will significantly increase the calibration times (i.e., from 3-5 min to over a day). Furthermore, the gamma energy range produced by either $Sm_{natural}$ or $Gd_{natural}$ is far from ideal for a flood source. The ideal flood source should have an energy that is similar to that of the isotope used during the medical procedures. For example, ^{99m}Tc, which is the most common isotope used in SPECT imaging, emits 140.5 keV gamma as it decays. The ^{57}Co currently used in calibration procedures emits radiation with two main energies: 122 keV (85.6%) and 136 keV (10.7%), which are sufficiently close to that emitted by ^{99m}Tc [16]. If $Sm_{natural}$ is used as absorber, then the gamma spectrum includes a wide range of gamma energies, from a few keV to as high as 1-2 MeV. Such a wide spectrum of gamma rays could become problematic during calibration procedures for SPECT gamma cameras.

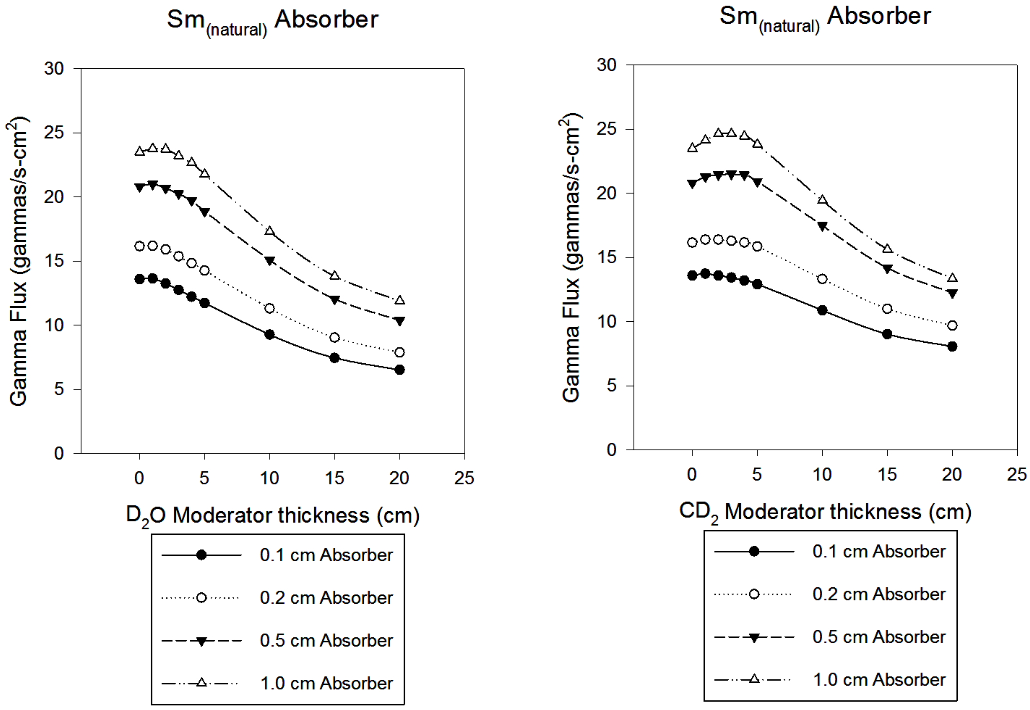

Figure 4 Gamma flux for the small SRG source with CD_2 and D_2O moderators, for varying thicknesses of $Sm_{natural}$ absorber.

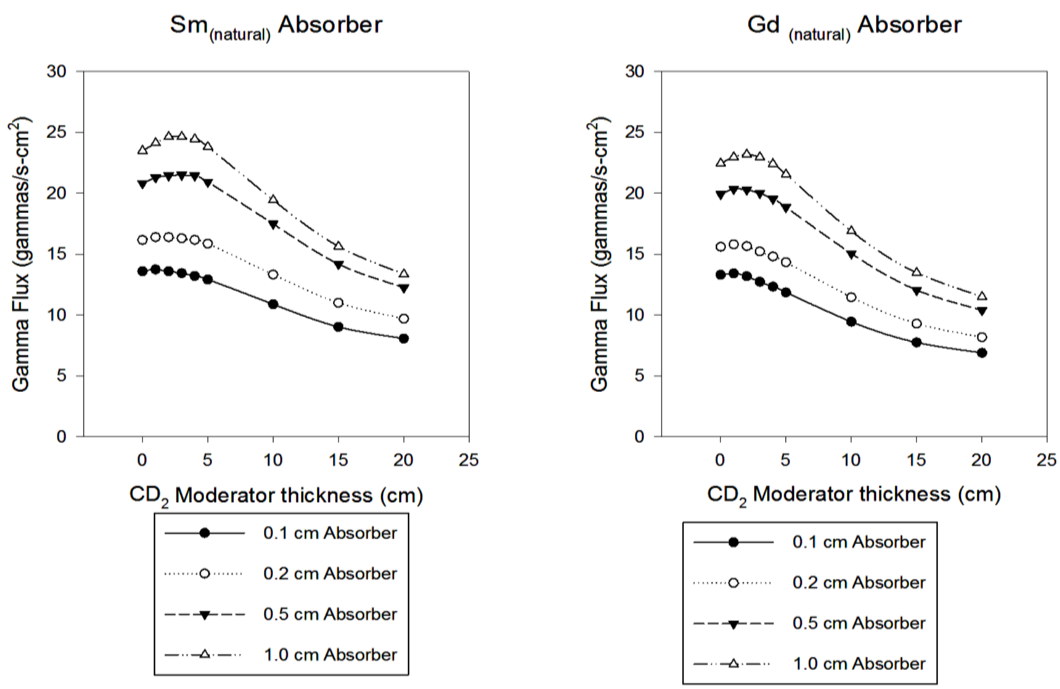

Figure 5 Gamma flux for the small SRG source with $Sm_{natural}$ vs $Gd_{natural}$ using CD_2 as a moderator, for varying thicknesses of absorber

Further studies estimated neutron and gamma fluxes and doses for a CD_2 moderated source using $Gd_{natural}$ as the absorber. The y- and z-dimensions of the moderator region were kept constant at 10 cm x 10 cm, while the x-dimension was varied either between 0 – 15 cm or 0 - 20 cm on either side of the planar neutron source. A parametric study was performed for the configuration illustrated in Figure 3A, which includes a 1.9 cm thick lead shield surrounding the moderator region. Figures 6 and 7 summarize the results for the calculated gamma fluxes and the corresponding gamma doses outside the planar source (i.e., in air regions 1 and 2, illustrated in Figure 2A). The gamma doses were calculated using the photon flux-to-dose conversion factors from ICRP-21, which were included with MCNP5 [7].

Two sets of parametric studies were performed by varying the thickness of moderator inside each source, while keeping the overall source dimensions unchanged. Figures 6A and 7A illustrate results for moderator thicknesses between 0 cm and 15 cm, with the overall source x, y, and z dimensions, excluding the absorber thickness, of 31.1 cm x 10.4 cm x 10.4 cm. Note that, for moderator thicknesses less than 15 cm, the empty space inside the source was modelled as void. Figures 6B and 7B illustrate results for moderator thicknesses between 0 cm and 20 cm, with overall source x, y, z dimensions, excluding the absorber thickness of 41.1 cm x 10.4 cm x 10.4 cm. The maximum calculated gamma flux for the first set of parametric studies was 37.9 gammas/s-cm^2 (Figure 6A), corresponding to a gamma dose on either side of the planar source of 0.00092 mSv/hr (Figure 7A), for a 5 cm moderator thickness and 0.5 cm of $Gd_{natural}$ absorber. The maximum calculated gamma flux for the second set of parametric studies was 23.9 gammas/s-cm^2 (Figure 6B), corresponding to a gamma dose on either side of the planar source of 0.000571 mSv/hr (Figure 7B), for a moderator thickness of 5 cm and 0.5 cm of $Gd_{natural}$ absorber. The corresponding total gamma dose around the source (i.e., air region 3, Figure 2) is 0.0023 mSv/hr for parametric study (A) and 0.0018 mSv/hr for study (B). The gamma spectrum corresponding to the case resulting in the maximum gamma flux of 37.9 gammas/s-cm^2 (illustrated in Figure 6A) is shown in Figure 8. As noted, a significant percentage of gammas have energies greater than 500 keV, with ~30% of the gammas having energies between 2 MeV and 3 MeV. These high gammas would have a negative impact on the performance of the gamma camera and the electronics, making this design not appropriate as a calibration source.

Similar calculations were performed to estimate the corresponding neutron fluxes and doses for the two different source designs. The results are reported in Figure 9A and Figure 10A for the neutron flux and corresponding neutron dose for a moderator thickness of 15 cm, and Figure 9B and Figure 10B for a neutron flux and corresponding neutron dose for a moderator thickness of 20 cm. The calculated neutron fluxes are at least 5 times larger than the corresponding gamma fluxes, which indicates the neutrons are not sufficiently moderated before they reach the absorber region. As shown in Figure 1, a significant number of neutrons produced via the ^{241}Am - ^{9}Be (α, n) reaction have energies greater than 3 MeV (i.e., a fast spectrum), and in order to take advantage of the large absorption cross section for Gd at low energy, they need to be thermalised (i.e., energies <1 eV). Furthermore, as expected, the flux and dose calculated for the source design with a maximum moderator thickness of 20 cm (i.e., larger overall source dimensions) are lower than those for the source design with a maximum moderator thickness of 15 cm, due to an increased neutron leakage through the sides of the planar source. This effect is consistent for the both gamma and neutron tallies - see Figures 6 and 7 for the gamma flux and dose and Figures 9 and 10 for the neutron fluxes and doses.

The gamma doses calculated here can be compared with the typical doses that are applied to blood bags during the irradiation process used to kill bacteria and prevent transfusion-associated graft versus host disease (TA-GVHD). For such an application, gamma doses between 0.02 - 0.04 kGy (equivalent to 0.02 – 0.04 kSv when looking at gamma radiation) must be applied [6]. The doses calculated for the configurations discussed in this paper are many orders of magnitude smaller than those intended for blood irradiation, however, this application is more promising than the flood source one because there are no specific constraints on the gamma energies that are required during this procedure, which allows for more choices of isotopes for the (n, γ) reactions. Future studies will focus on investigating other isotopes and configurations that can increase the deposited gamma dose, while reducing the neutron dose.

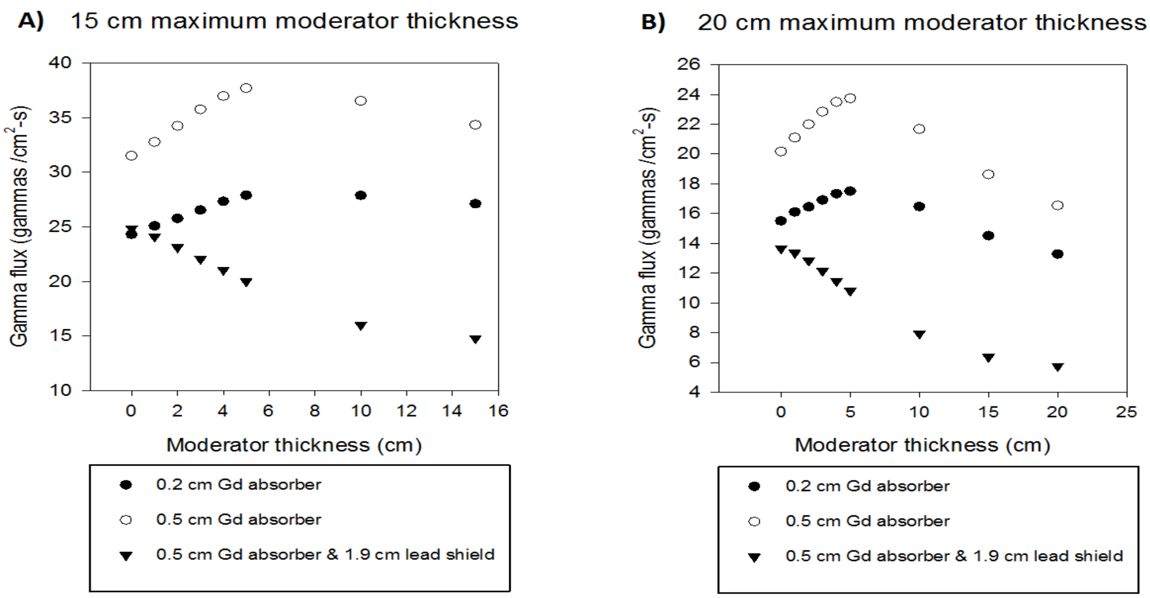

Figure 6 Small SRG source - Gamma flux for $Gd_{natural}$ absorber and CD_2 moderator, for varying thicknesses of absorber. A) Moderator x-, y-, z-dim. 15 x 10 x 10 (cm); B) Moderator x-, y-, z-dim. 20 x 10 x 10 (cm)

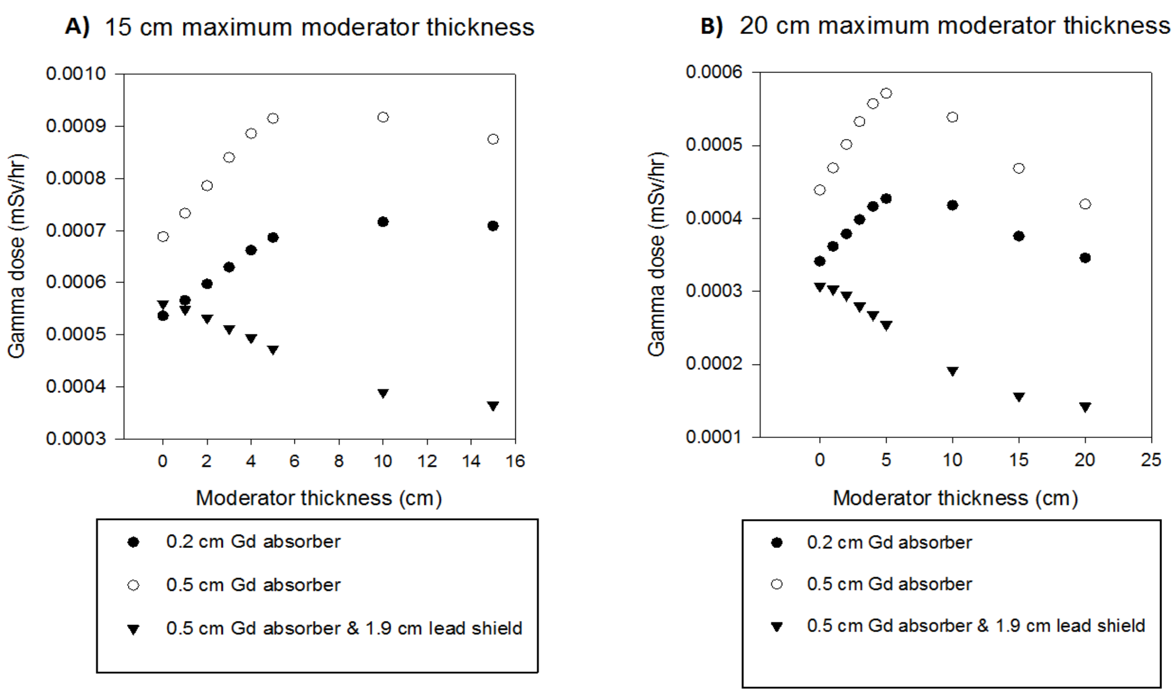

Figure 7 Small SRG source - Gamma dose for $Gd_{natural}$ absorber and CD_2 moderator, for varying thicknesses of absorber. A) Moderator x-, y-, z-dim. 15 x 10 x 10 (cm); B) Moderator x-, y-, z-dim. 20 x 10 x 10 (cm)

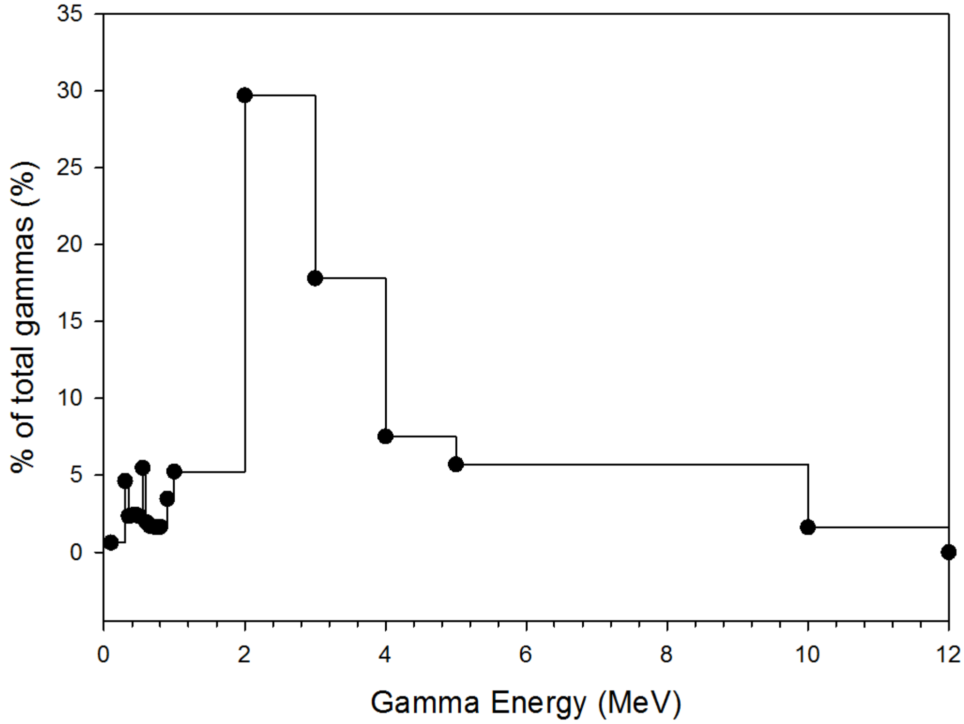

Figure 8 Gamma spectrum corresponding to the source modelled in Figure 6A, at 5 cm moderator thickness and 0.5 cm $Gd_{natural}$ absorber

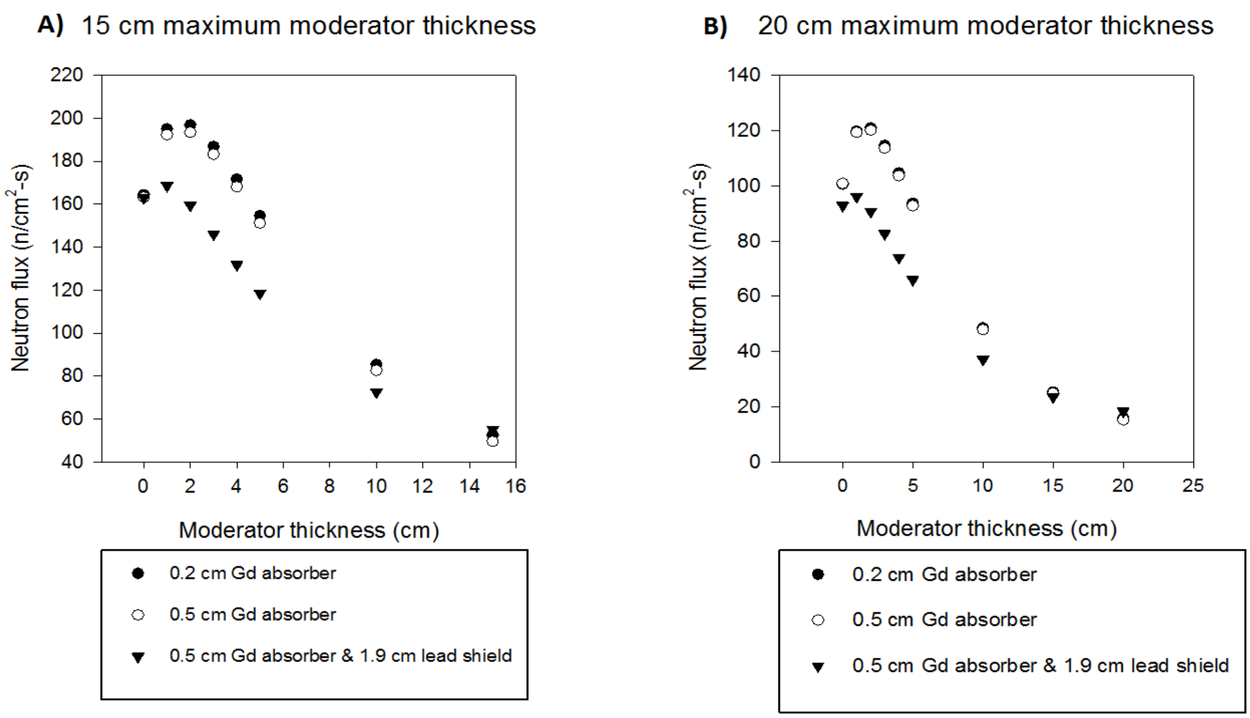

Figure 9 Small SRG source - Neutron flux for $Gd_{natural}$ absorber and CD_2 moderator, for varying thicknesses of absorber. A) Moderator x-, y-, z-dim. 15 x 10 x 10 (cm); B) Moderator x-, y-, z-dim. 20 x 10 x 10 (cm)

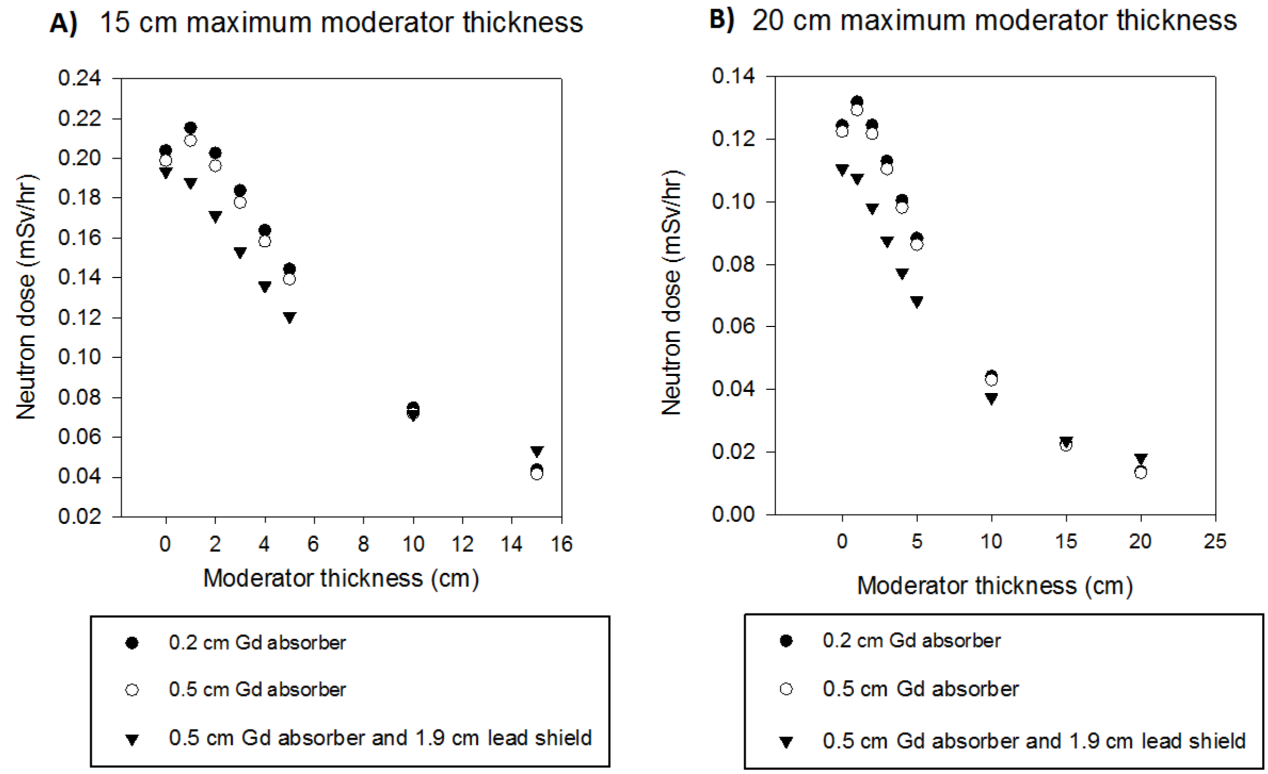

Figure 10 Small SRG source - Neutron dose for $Gd_{natural}$ absorber and CD_2 moderator, for varying thicknesses of absorber. A) Moderator x-, y-, z-dim. 15 x 10 x 10 (cm); B) Moderator x-, y-, z-dim. 20 x 10 x 10 (cm)

4. Conclusions

This paper introduced a switchable radioactive gamma source (SGRS) that can be turned “ON” and “OFF” as required by the user. The feasibility of this source was investigated for two potential applications: 1) a flood source to calibrate gamma cameras used in SPECT imaging; and 2) a self-contained blood irradiator. Preliminary investigation showed that a SGRS would be difficult to apply as a flood source, because 1) the gamma flux produced would be too low to provide a quick calibration of the gamma cameras; and 2) the gamma spectrum would present a wide array of gamma energies (some of which are > 500 keV) that would interfere with the calibration of the gamma cameras. These calibrations require gamma that 1) are close in energy to those of the isotope used during the medical procedure; and 2) have a very narrow energy spectrum. However, preliminary MCNP results show potential promise that a SGRS could be used in a self-contained blood irradiator, as long as the gamma dose deposited around the source is increased and the neutron dose is decreased. Further studies will focus on different absorber isotopes and different source geometries (e.g., a cylindrical source). Furthermore, increasing the strength of the current neutron source will be considered, since a stronger neutron source will help increase the gamma flux and dose for the intended application.

5. References

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