Radiation Shielding Analysis and Optimisation for the Mineral-PET Kimberlite Sorting Facility using a Monte Carlo Code, MCNPX

Eric Mwanyisa Chinaka
Necsa, Radiation and Reactor Theory Section
Building P1900, PO Box 582, Pretoria, 0001, South Africa

E-mail: eric.chinaka@necsa.co.za; echinaka@gmail.com

Johann van Rooyen
Necsa, Radiation and Reactor Theory Section
Building P1900, PO Box 582, Pretoria, 0001, South Africa

E-mail: johann.vanrooyen@necsa.co.za

Zukile Zibi
TIA (formery with Necsa),
83 Lots Avenue, Menlyn, 0063, South Africa

E-mail: zukile@gmail.com

Simon H. Connell
University of Johannesburg, Physics Department
PO Box 524, Auckland Park, 2006, South Africa

E-mail: shconnell@uj.ac.za; simonhconnell@gmail.com

Abstract. Radiation shielding calculations, analysis and optimization processes carried out in order to design shielding for a Mineral-Positron Emission Tomography (mineral-PET) facility are presented. PET is a nuclear imaging technique commonly used in diagnostic medicine. The technique is based on the detection of 511 keV coincident and co-linear photons produced from the annihilation of a positron (produced by a positron emitter) and a nearby electron. This technique is currently being developed for mineral detection and quantification, particularly diamonds in kimberlite rocks through the mineral-PET facility. The facility is aimed at improving diamond mining through the early detection of diamond bearing rocks. High energy photons are produced via bremsstrahlung when a high energy, 40 MeV 5mA, electron beam impinges on a high density target - tungsten. The resultant high energy photon beam is used to irradiate the kimberlite rock, activating the naturally occurring non-positron emitting isotope ^{12}C, producing a positron emitting isotope ^{11}C via a photo-nuclear (γ, n) reaction. The resultant high intensity and high energy radiation field (which includes both photons and neutrons up to 40 MeV) requires appropriate shielding to protect personnel and the environment around the facility. A Monte Carlo based radiation transport code, MCNPX, was used to model the mineral-PET facility including the electron accelerator, the irradiation chamber and the proposed shield. Shielding calculations were performed, applying the theory of interaction of radiation with matter together with the modelling and the radiation transport calculation capabilities of

MCNPX. The calculations were applied to determine the types, optimum combinations and thickness of shielding materials. About 1.6 m of shielding composed of Lead, Iron, Wax and Boron Carbide combined in the shielding matrix were found to be sufficient to drop dose rates to acceptable levels on the personnel side of the shield, where several meters of concrete would have been required.

1. Introduction

Mineral-PET is a revolutionary technology that is expected to improve diamond mining and sorting by introducing efficiency in the usage of equipment, energy and water. The technique is based on the detection of 511 keV coincident and co-linear photons produced from the annihilation of a positron (produced by a positron emitter) and a nearby electron. The technique is popularly used in diagnostic medicine and is now being developed for use in the mining sector and in particular in the identification of diamond from kimberlite rocks. The current diamond extraction process involves the crushing of candidate rocks several times to small pieces, typically to a few millimeters in diameter, exposing the diamonds to the surface. Physical separation techniques are then applied to extract the diamond particles. It has been noted however, that only a small fraction of the crush actually contains significant quantities of diamond particles[1]. The crushing process is energy, equipment and process water intensive.

In the mineral-PET technique, the rocks are only crushed to manageable sizes, equivalent to the 'first crush'. A high energy photon beam at least 23 MeV, is used to irradiate the rocks thus activating the naturally occurring, non-positron emitting ^{12}C, producing a positron emitting ^{11}C via a photo-nuclear reaction namely ^{12}C(γ, n)^{11}C. A 40 MeV electron beam, incident on a tungsten target is used to produce the high energy photon beam through bremsstrahlung.

The high energy photons, the resultant neutrons from the ^{12}C(γ, n)^{11}C reaction, products from other nuclear processes due to the interaction of photon beams with rock constituents, the primary electrons from the accelerator and the γ-rays from resultant radioactive products all create a high energy, mixed radiation field in and around the mineral-PET facility. The need for an appropriate shield to protect personnel and the environment around the facility cannot be over emphasised.

A Monte Carlo radiation transport code, MCNPX, was used to model the facility and together with radiation transport theory, calculations were carried out to develop an optimum shield for this facility.

2. The Mineral-PET Facility

Figure 1 shows the process flow in the mineral-PET facility. Kimberlite rocks are coarse crushed, "the first crush" and carried by a conveyor belt to the irradiation chamber. A photon beam is directed towards the irradiation chamber so that activation can take place. The activated rocks are then fed into a holding chamber where they are held for 20 mins, enough time to allow unwanted short lived activated products, which may interfere with the detection signal, to decay away. The proposed shield should cover the accelerator, the irradiation and the holding chambers, excluding the detection system. It has been determined that the irradiation process does not yield long lived activation products, hence it is not necessary at this stage to design a shield that covers the detection system. This reduces the cost of the shield. It must be noted at this stage, that a static system was modelled, due to MCNPX limitations. In reality, the rocks are continuously fed into the two chambers and into the detection system by the conveyor belts. However, this static system sufficiently approximates the dynamic system from a radiological point of view.

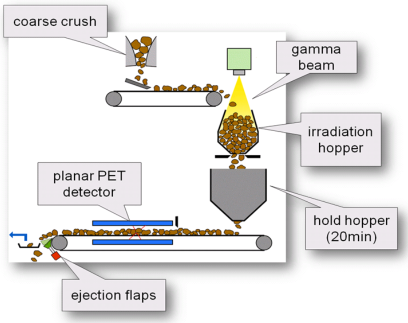

Figure 1. The mineral-PET process flow.

3. Mineral-PET Facility simulation

MCNPX version 2.7.e with ENDF/B-7.0 cross-section data (2008) was used for the shielding calculations. First, a simple model of the facility was developed and the geometry was plotted using a graphic application, Vised X, for debugging purposes especially to check the relative positions of the irradiation chamber, the electron beam and the tungsten target.

4. Source Term Characterization

The first step in the development of a shield is source term characterization. This process was carried out to determine the type of radiation sources and the energy distribution, including the respective directions of radiation particles. The results of the mineral-PET facility source term characterisation are shown in Figures 2 - 3. Figure 2 (A) shows the variation of photon flux with energy at different polar angles around the accelerator and Figure 2 (B) shows the variation of the photon flux with energy at different axial positions from the accelerator. A positive sign represents a position above the accelerator and negative means below (see Figure 2 (B)). It is assumed here that the radiation produced, is symmetric around the azimuthal angle because the beam is un-polarised.

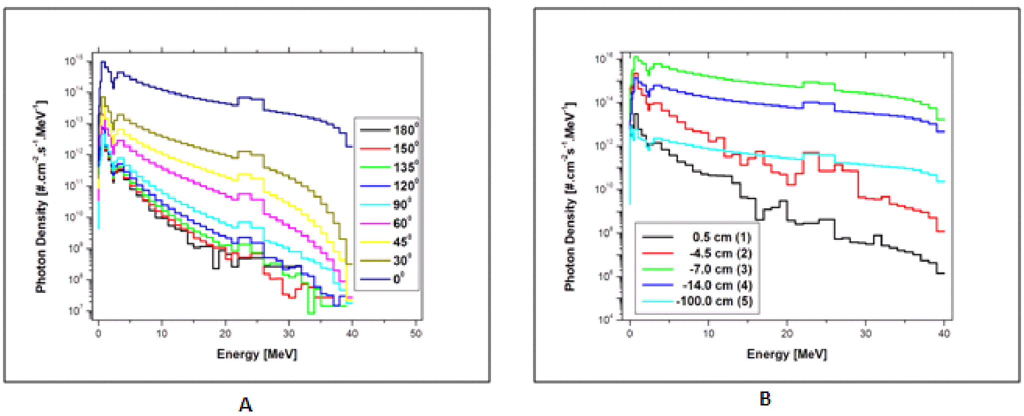

Figure 2. Photon flux at various polar angles and at different axial positions.

A mesh tally was set up around the facility to further calculate the levels of radiation dose produced in with results shown in Figure 4

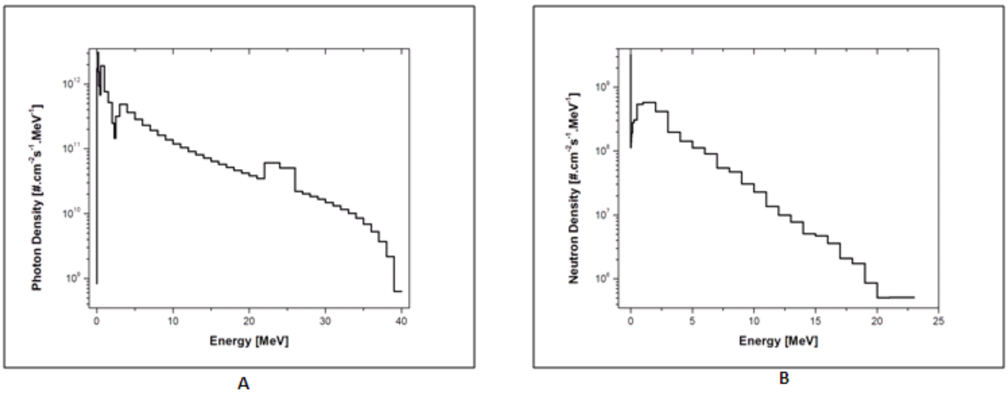

Figure 3. Average photon and neutron flux on the surface of the irradiation chamber.

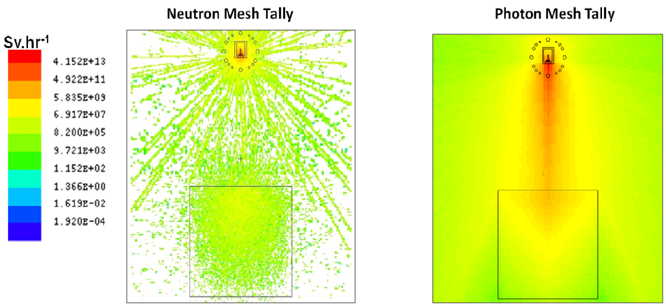

Figure 4. Neutron and photon mesh plots in the mineral-PET.

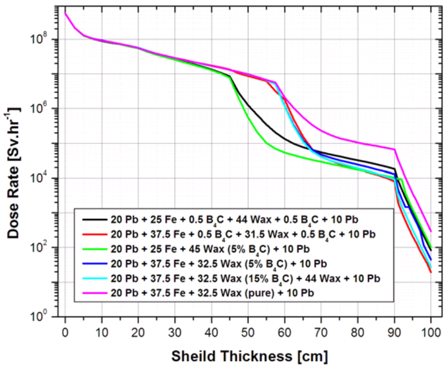

Figure 5. Dose rates for six different shield configurations.

5. Radiation Transport

Ionising radiation can be in the form of electrically charged particles such as alpha particles, beta particles, protons and heavy ions or uncharged particles and radiation quanta such as neutrons, gamma radiation and X-rays [2]. Charged particles do not present major shielding problems because they lose large amounts of energy in each interaction as they interact with matter and as a result, charged particles are characterized by short ranges in matter [3]. However, it is important to note that energetic light charged particles incident on high Z material produce intense secondary electromagnetic radiation i.e. bremsstrahlung photons, which contribute to the radiation field.

Neutrons and photons are the most difficult radiation types to shield and are therefore the centre of focus in this paper. Neutral particles generally move between points of interaction in straight lines. Their mean free path (mfp) and hence the range of neutral ionising radiation is much longer than those of charged particles. Neutral particles cause ionisation indirectly and ultimately transfer their energy to charged particles which then cause direct ionisation [4].

6. Interaction of Radiation with Matter

To design radiation shields, one needs to understand the way in which radiation interacts with matter [5]. A study of neutron scattering kinematics and dynamics [6], [7], [8], [9], [10], [11] shows that the isotope ^{56}Fe has a high cross section for neutron inelastic scattering at high neutron energies and the isotope ^{1}H has a significant elastic scattering cross-section at relatively low neutron energies. Furthermore, the isotope ^{1}H has a useful cross-section for slow neutron capture, albeit with a subsequent production of highly ionising photons. However the isotope, ^{10}B, produces very low energy photons in the ^{10}B(n, α)^{7}Li reaction, hence its introduction into the radiation shield helps to suppress the production of high energy photons.

Ionising photons are "killed" off by using high atomic number, Z, and high density materials within the shield. A beam of monochromatic photons moving through an absorber (shield) displays a characteristic exponential reduction of the number of photons travelling along the original direction[12],[7].

7. Shielding Scheme

From the principles of neutron and photon shielding it can be seen that an effective and optimal shield could contain the following materials:

(i) **Lead** to attenuate gamma rays (high Z, high ρ) and begin to slow down fast neutron.

(ii) **Iron** to attenuate high energy neutrons (via inelastic scattering).

(iii) **Wax** to further attenuate and absorb neutrons slowed down by Iron to within cross-section group of ^{1}H (Wax is rich in ^{1}H)

(iv) **Boron Carbide (B_4C)** - used on its own or mixed with Wax. The isotope ^{10}B suppresses the production of high energy secondary photons. Ammonium Pentaborate can be used as alternative.

8. Shield Optimisation

Six different shield configurations were developed as outlined in Figure 5. The graph shows the total dose rate as a function of distance from the internal surface of the shield to the external surface for each configuration. All six configurations show a considerable reduction of dose rates within 100 cm. Due to space constraints in the mineral-PET facility, the shield was restricted to about 100 cm. By considering the results in Figure 5, the best shield configuration in this study contains 20 cm Lead, 37.5 cm Iron, 31.5 cm Wax flanked by 0.5 cm strips of B_4C and finally 10 cm Lead in laminar sheets.

9. Shield Effectiveness

Figure 6 shows the reduction of neutron and photon dose rates, hence the effectiveness of the selected shield configuration. It can been seen that the internal space has high dose rates, in the order of 10^{17} Svhr^{-1} and in the external environment the dose rates go down, to the order of 10^{-1} Svhr^{-1}.

10. Mineral-PET proposed shield

Figure 7 shows the proposed shield for the mineral-PET facility. The shield forms a 200 cm by 200 cm by 200 cm (internal dimensions) room with walls of about 100 cm thick. Figure 7 (A) shows the full cross section of the room and Figure 7 (B) shows the cross-section of one side the shield wall.

11. Conclusions

The study shows that the operation of the mineral-PET produces very high radiation doses in and around the facility it and a properly designed shield is a necessity. The proposed shield structure in Figure 7 reduces these radiation doses. The resultant dose given in Section 9 are still too high when considering the annual dose limits prescribed in the ICRP [13], [14]. The shield

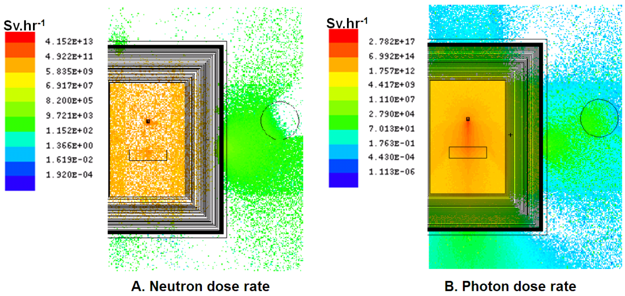

Figure 6. Mesh plots showing the reduction of dose rates from the interior going out through the shield.

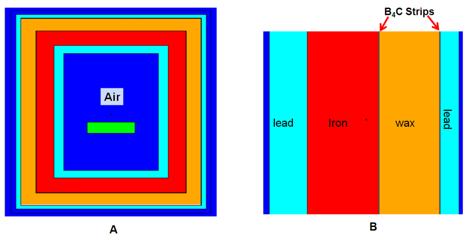

Figure 7. Proposed Shield for the Mineral-PET Facility.

can be made thicker beyond the 100 cm limit to about 160 cm. This adjustment will increase the cost of producing the shield but it will reduce the dose rates to the required μ-Svhr^{-1} range.

References

[1] Ballestrero S 2009 *Proceedings of the 12th International Conference on Nuclear Reaction Mechanisms,* (Villa Monastero, Varenna, Italy) pp 589,602

[2] Wentz C 1998 *Safety, Health and Environmental Protection* ISBN 0-07-069310-2 (http://www.mhhe.com: WCB/ McGraw-Hill)

[3] J Kohl RD Zentner H R L 1961 *Radioisotope Applications Engineering* (120 Alexander St., Princeton, New Jersey: D. Van Norstrand Company, Inc)

[4] Martin A and Harbison S 1979 *An Introduction to Radiation Protection* 2nd ed ISBN 0 412 16230 X (11 New Fetter Lane, London EC4P 4EE: Chapman and Hall Ltd)

[5] Lamarsh J R and Baratta A J 2001 *Introduction to Nuclear Engineering* ISBN 0-201-82498-1 (Upper Saddle River, New Jersey 07458: Prentice Hall)

[6] Martin J E 2006 *Physics for Radiation Protection - A handbook* 2nd ed ISBN 978-3-527-40611-1 (2604 Bedford Road, Ann Arbour M1 48104: Wiley-VCH Verlag GmbH & Co. KGaA)

[7] Lilley J S 2001 *Nuclear Physics: Principles and Applications* ISBN 0 471 97936 8 (Baffins Lane, Chichester, West Sussex PO19 1UD, England: John Wiley and Sons, Ltd)

[8] Lamarsh J R 1972 *Introduction to Nuclear Reactor Theory* ISBN 0-201-04120-X (Reading Massachusetts: Addison-Wesley Publishing Company)

[9] van Rooyen T J *Transport and Shielding of Ionising Radiation* (Radiation and Reactor Theory Section, Necsa, PO Box 582, Pretoria, 0001, South Africa.)

[10] Hebert A 2009 *Applied Reactor Physics* ISBN 978-2-553-01436-9 (pip@polymtl.ca: Presses Internationales Polychnique)

[11] B Dorschel V S and Steuer J 1996 *The Physics of Radiation Protection* ISBN 1 870965 42 6 (PO Box 7, Ashford, Kent TN23 1YW, England: Nuclear Technology Publishing)

[12] Leroy C and Rancoita P G 2004 *Principles of Radiation Interaction in Matter and Detection* ISBN 981-238-909-1 (5 Toh Tuck Link, Singapore 596224: World Scientific Publishing Co. Pte Ltd.)

[13] J Lochard I Bogdevitch E G e a 2009 *Annals of ICRP, ICRP Publication 111* **39 No. 3** 19 –23

[14] Valentin J 2007 *Annals of ICRP Publication 103*