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Pathways to Inclusive Societies and Sustainable Development

Computational gamma dose mapping in a TRIGA-fueled subcritical reactor via PHITS Calculations

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Abstract: This paper presents calculations via PHITS simulations to determine the distribution of gamma doses in a subcritical research reactor that utilizes slightly irradiated TRIGA fuel. This work aims to assess the radiological safety of the reactor, which was commissioned after 34 years of dormancy. Although previous studies have indicated the reactor's inherent safety due to its subcriticality and low power core, the emission of gamma rays coming from Cs-137 which is the main fission product in the fuel necessitated further investigation. To address this, a PHITS-based computational model was developed to simulate the transport of gamma radiation within the facility, employing two different source definitions (EDI and IDI). The simulation uses a photon source of 0.6617 MeV, corresponding to the radiation produced by Cs-137. Gamma doses were then calculated at specific locations within the reactor tank, using a total of 10E8 particles for the photon transport code. Comparing the EDI and IDI detectors, a significant difference of 21% was observed at detectors situated 75cm along the positive x-axis, highlighting the substantial impact of source intensity definition on gamma dose mapping simulations. The detectors located on the inside surface of the reactor tank registered dose rates of approximately 11.5uSv/Hr for equal intensities, whereas individually defined intensities yielded a reading of 12.0uSv/Hr. Assuming an estimated conservative exposure time of 500 hours per year at this location, the total annual dose would only reach 5.75mSv and 6mSv respectively, which correspond to 11.5% and 12% of the annual dose limit stipulated by the Code of PNRI Regulation (CPR) – part 3, as established by the PNRI in 2021. With these initial calculations, the PHITS simulation demonstrated that the shielding of PRR-1 SATER is sufficient to ensure the safety of workers and students.

Key Words: Gamma-Dose Mapping; TRIGA-Fuels; Subcritical Research Reactor.

1. INTRODUCTION

For 35 years, there was no locally operating nuclear facility that is available for Filipino, but this ended when the Philippine Nuclear Research Institute (PNRI) restarted the Philippine Research Reactor-1 (PRR-1) through the Subcritical Assembly for Training, Education, and Research (SATER). The commissioning of the PRR-1 SATER served as a landmark for nuclear science in the Philippines as it provides a local facility for nuclear training and education (Astronomo et al., 2022).

Several studies were launched to ensure the safety of workers, researchers, and student apprentices regularly exposed to artificial radiation from nuclear facilities. It is necessary to strengthen the radiation protection program to minimize and optimize exposure to ionizing energy. Radiation levels in a reactor facility should be determined to ensure radiation workers' safety and educate the public about the inherent safety and precautionary measures prepared by the PNRI for the only nuclear facility in the Philippines.

This study aims to develop a computational model of the PRR-1 SATER and calculate the gamma dose distribution using the Particle Heavy Ion Transport Code System (PHITS). Two versions of the computational model were prepared: the equally defined intensity (EDI), and the individually defined intensity (IDI) to check the effects of source declaration on the gamma dose distribution inside the research reactor. The results of this study will provide a reference for improving radiation protection in a small nuclear facility. The work can be used as a reference by other TRIGA reactor facilities in the world that are considering re-using their fuel in a subcritical assembly.

2. The Subcritical Reactor (PRR-1 SATER)

The PRR-1 SATER, as a subcritical facility, is an open-tank, water-moderated reactor that uses slightly irradiated TRIGA fuel rods. It is a zero-power reactor that will be utilized for the education and training of students. The reactor uses an americium-beryllium (^{241}AmBe) isotopic neutron source to sustain the system's chain reaction as the nuclear reactor's neutron multiplication factor is less than 1 (Astronomo et al., 2018).

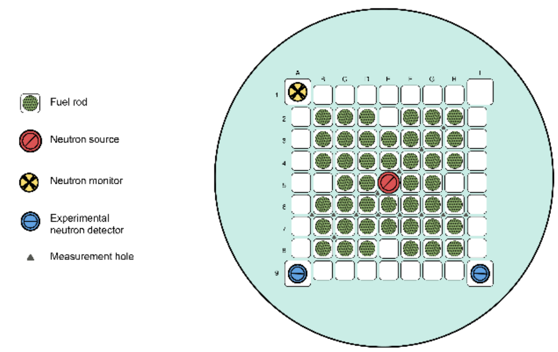

Fig. 1. Fuel Configuration used in the PRR1-SATER

Each TRIGA fuel is 75.2cm long, and the active section of the fuel moderator rod has a diameter of 2.97cm and 50.8cm long. (Astronomo et al., 2018). The fuel is assembled in a 7x7 lattice as shown in Fig 1. The assembly for the fuel rods consists of 44 TRIGA fuel rods, one neutron source, and some empty channels (fig 1). The core and its support structure are submerged in water contained in a stainless-steel tank with 4 m in height and 2 m in diameter.

3. METHODOLOGY

The study features three major parts: Reactor Modelling, Photon Source modeling, and tally functions.

3.1 Reactor Modelling

The geometry of the PRR-1 SATER model is developed based on the actual dimensions of the facility. The specifications include the detailed material components, density, and dimension of each item in the reactor, which is used to create a 3D computational model of the PRR-1 SATER. Material composition is based on a published compendium (R. Detwiller, 2021) and coded using the Japanese Nuclear Data Library 4.0. The Evaluated Nuclear Data Library VII ENDF VII.0 nuclear data library is used for the neutron source.

3.2 Photon Source Modelling

A monoenergetic source was modeled with an energy of 0.6617MeV corresponding to the peak energy released by Cs-137, which is the dominant fission product in the TRIGA fuel as determined previously (Astronomo et al., 2022). The photon source is modeled in two ways. The first model utilizes equally defined intensities (EDI) for each fuel rod at

7.19mSv/h, the average value measured in previous work (A. Astronomo, 2022).

The second model utilizes individually defined multi-source, with each of the 44-fuel rods' intensity declared as shown in Fig 2.

	A	B	C	D	E	F	G	H	I
1	E	E	E	E	E	E	E	E	E
2	E	4.87	3.81	5.73	E	5.82	8.81	7.56	E
3	E	7.96	10.36	4.40	4.64	5.95	8.36	10.64	E
4	E	8.96	5.86	6.45	5.50	4.34	4.94	9.13	E
5	E	E	9.07	5.87	NS	8.73	7.62	E	E
6	E	7.55	6.42	6.63	7.32	11.71	12.64	7.35	E
7	E	7.50	6.80	6.51	7.12	7.46	7.87	7.32	E
8	E	9.25	4.77	6.32	E	6.88	7.40	6.11	E
9	E	E	E	E	E	E	E	E	E

Fig. 2. Average values of gamma doses in mSv/h measured for each fuel rod in the PRR-1 SATER core.

The results obtained from these calculations were converted using photon fluence to ambient dose H*(10) from the ICRP 74 and were normalized conservatively to correspond to the experimental values.

3.3 Tally Functions

Dose distribution was determined using the PHITS T-track tally option with a 0.5cm x 0.5cm x 0.5cm mesh resolution at z=0 or the center of the fuel rods for the 2D representation of the dose distribution map of the whole reactor. Another T-track tally option that uses surfaces as the mesh is also set in different parts of the reactor (Fig. 3). Calculations were performed using 10e6 particles at 100 batches, totaling 10e8 particle histories.

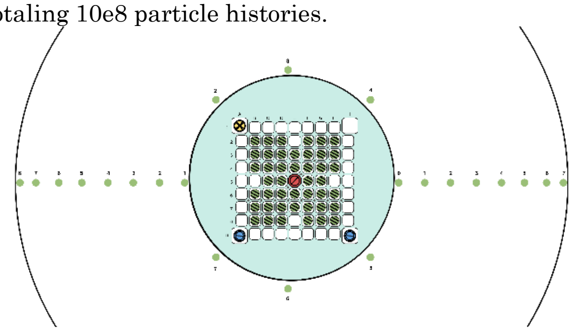

Fig. 3. Fuel Configuration and Detector Placement within the Reactor.

4. RESULTS AND DISCUSSION

The vertical (z=0) and the horizontal (y=0) photon dose distribution are presented in Figure 4 (a-d), respectively.

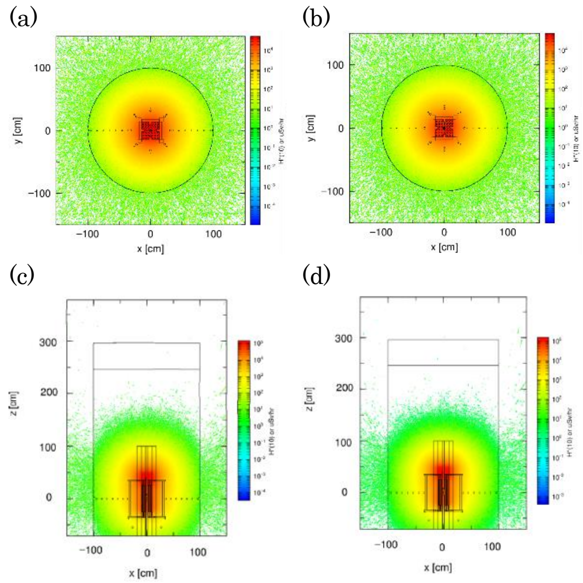

Fig. 4. (a) XY and (c) XZ Photon Dose distribution for Equal intensities. (b) XY and (d) XZ photon Dose Distribution for Individually defined intensity

Results show the effective photon attenuation in the water shielding of the PRR-1 SATER. Thus, the water and the SS-316 shielding of the PRR-1 SATER tank provide sufficient shielding against photons released by the Cs-137 fission product of the fuel. The dose distribution of photons is almost identical in equal intensities and individually in both the XY and XZ planes.

Fig. 5 shows the dose distribution of Gamma across the specified detectors in the tank. The green plots represent the dose rate in the EDI, while the blue represents the IDI.

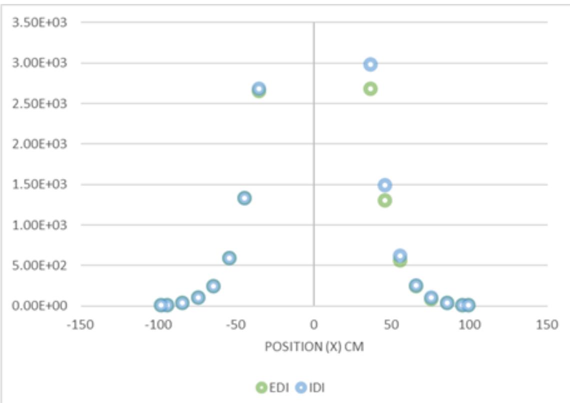

Fig. 5. Scatter plot of dose distribution (uSv/Hr) in detectors across the tank

The detectors positioned on the inner surface at -98.6825cm (detector 8b), the EDI shows around 11.5uSv/Hr, while the IDI gives the reading of 12.0uSv/Hr, a 4.9% difference between the EDI and IDI. The discrepancy, however, increases at the detectors at the positive x positions, where detector 5a located 75cm away from the center of the fuel shows a 21.1% change between the two-source configuration. The discrepancy is better represented in the mesh subtraction plot between the EDI and IDI, as shown in Figure 5.

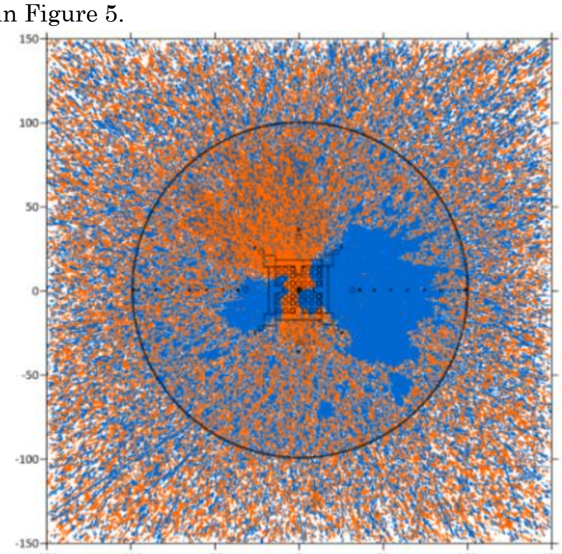

Fig. 6. Mesh Subtraction between IDI and EDI results. Orange positive; Blue negative

The orange regions in Fig. 6 indicate that the EDI shows a higher dose rate reading than the IDI. While blue represents the opposite, it is prevalent from Fig. 6 that there is an imbalance between the dose rate distribution between the two configurations. This implies that a change in the way sources were defined will affect the dose distribution in specific locations or even the whole dose distribution map. Nevertheless, this difference appears to be significant inside the SATER tank. No appreciable difference is observed outside the tank, which is more accessible for radiation workers.

4. CONCLUSIONS

In this paper, PHITS simulation was performed to calculate the gamma/photon dose distribution released by the slightly irradiated TRIGA Fuel in the PRR-1 SATER. The calculations were performed in 2 different source declarations: the EDI and IDI. The results are shown to have significance inside the SATER tank, and no appreciable difference is observed outside the tank. This shows that the EDI declaration is enough for simulating radiation protection. Based on the results, the dose rates at the inside surface of the reactor give around 11.5uSv/Hr for the equal intensities while on the individually defined, it gives the reading of 12.0uSv/Hr. Assuming a conservative estimate of 500Hrs of total exposure at this location per year, the total dose would only result in 5.75mSv and 6mSv which is only 11.5% and 12% respectively of the annual dose limit instituted by the Code of PNRI Regulation (CPR) – part 3 by the PNRI (2021) for an average worker in the facility.

5. ACKNOWLEDGMENTS

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