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Monte Carlo studies for the radiation shielding in the bunker of the electron beam accelerator using PHITS

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Abstract. Particle and Heavy Ion Transport Code System (PHITS) is a Monte Carlo simulation program used for transport and collision of nearly all particles over wide energy range. One of its useful features for accelerator facility design is the calculation of dose distribution. This paper describes how the geometry of the bunker for low electron beam accelerator in Nuklear Malaysia (NM) was modelled and used to calculate the equivalent dose caused by the radiation for specific region in the bunker by using PHITS. The dose distribution and energy deposition were obtained. Finally, the simulation results are compared to the measured value from the dose measurement testing inside the bunker facility and found both results are in a good agreement.

1. Introduction

The low energy electron beam accelerator in Nuklear Malaysia (NM) was developed. Although the target energy of 300 keV is relatively low, the radiation shielding design is necessary to protect the workers during the accelerator operation from the secondary radiation. Previously, shielding design has been done analytically to construct a facility to accommodate this electron beam machine and an experiment to measure the dose at certain region in the room has been done during the final phase of the construction. Monte Carlo method simulation has become an essential tool to calculate radiation shielding design. Although in our case, the analytical calculations already suffice in the shielding design calculation, the use of Monte Carlo simulation as our principal design tool for our accelerator facility is beneficial due to its better accuracy and abilities to calculate a much more complex geometry. Furthermore, an extensive dose distribution around the room and at specific regions is important for our next steps in development and improvement of our accelerator. Therefore, the Monte Carlo simulation has been done in the irradiation room of our facility by using Particle and Heavy Ion Transport Code System (PHITS) to provide dose distribution in the irradiation room and at certain important regions for radiation shielding. This calculation is compared with the analytical and the experimental measurement.



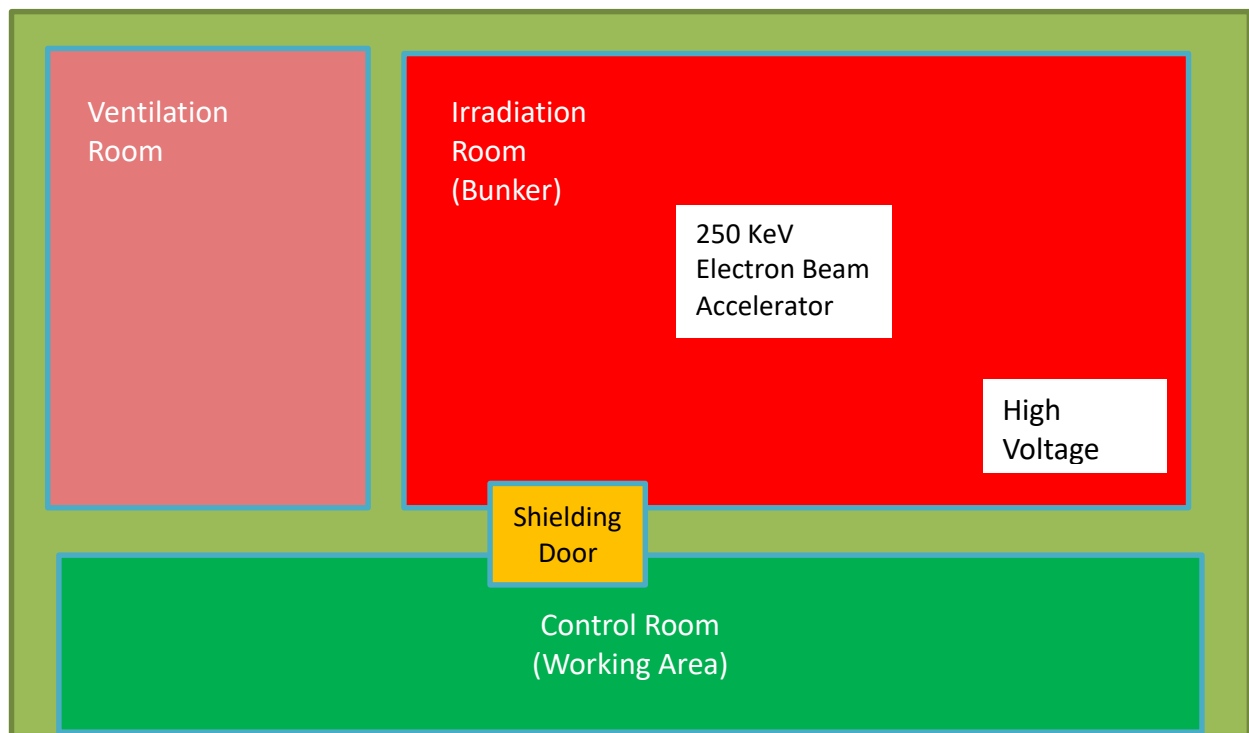


Figure 1. Top-view layout of the low energy electron beam accelerator facility in Nuklear Malaysia comprised of three areas.

Our electron beam accelerator facility can be divided into three areas: working area, ventilation room, and irradiation room (bunker). The working area is the control room which accommodates the control panel monitoring and the open spaces for related accelerator operations. The working area is limited to the radiation worker and is classified as clean area. It is our radiation protection goal for the dose around here to be below 20 $\mu\text{Sv/hr}$ [1].

The ventilation room is where the blower and exhaust motor are placed, and they are connected to the irradiation room by the ventilation duct through the wall. The irradiation room housed the electron beam accelerator, high voltage transformers and ventilation system. The walls enclosing the room was constructed using high density concrete with thickness of 85 cm and the height of the room is five meter high. The shielding door of the room was made by same material as the walls, but it is designed as a 'plug' shape to reduce the radiation leaking through the door [2].

2. Monte Carlo Simulation of the Irradiation Room

This paper is to describe the Monte Carlo simulation around the irradiation room and produced the dose distributions around the room and inside the concrete of the specific regions of interest. Monte Carlo method has been developed intensively to solve the practically unmanageable calculational problems [3]. Almost all major physical processes can be calculated accurately, and this can be done for any target with specific shapes and thickness. It is also considered the most competent method for calculating the distribution of photon track-length [4].

A general-purpose Monte Carlo particle transport simulation code, PHITS (Particle and Heavy Ion Transport Code System) is developed under collaboration between JAEA, RIST, KEK and several other institutes [3].

2.1. Geometry Definition

The first step is to design our geometry of the irradiation room. Geometry of the room is shown as in Figure 2. The regions of interest are numbered as followed: - #1 is inside the room which contains the air and the area is 500 cm across the room both horizontal and vertical. #2 is made up by the high-density concrete which enclosed the room. #3, #4, #5, #6 represents the concrete shielding door and designed as plug shaped to minimize the radiation leakage. The multi-layers design is for safety issue [2]. #7 is the maze, a concrete block with 100 cm width and height to minimize the radiation to the hole for ventilation system which we can see in region #8. #8 is the ventilation system that comprised a hole made up for blower from ventilation room to the irradiation room. #9, #10, #11 is the elliptic cylindrical hole that will be used for power supply and other related things to connect the equipment from ventilation area. #12, #13, #14 is the elliptic cylindrical hole to connect the equipment from the control room. The six holes that connected the cables are designed elliptic cylinder from the higher wall to lower region of the wall near the floor to prevent the radiation from leaking through the hole. An elliptic cylinder is a cylinder with an elliptical cross-section.

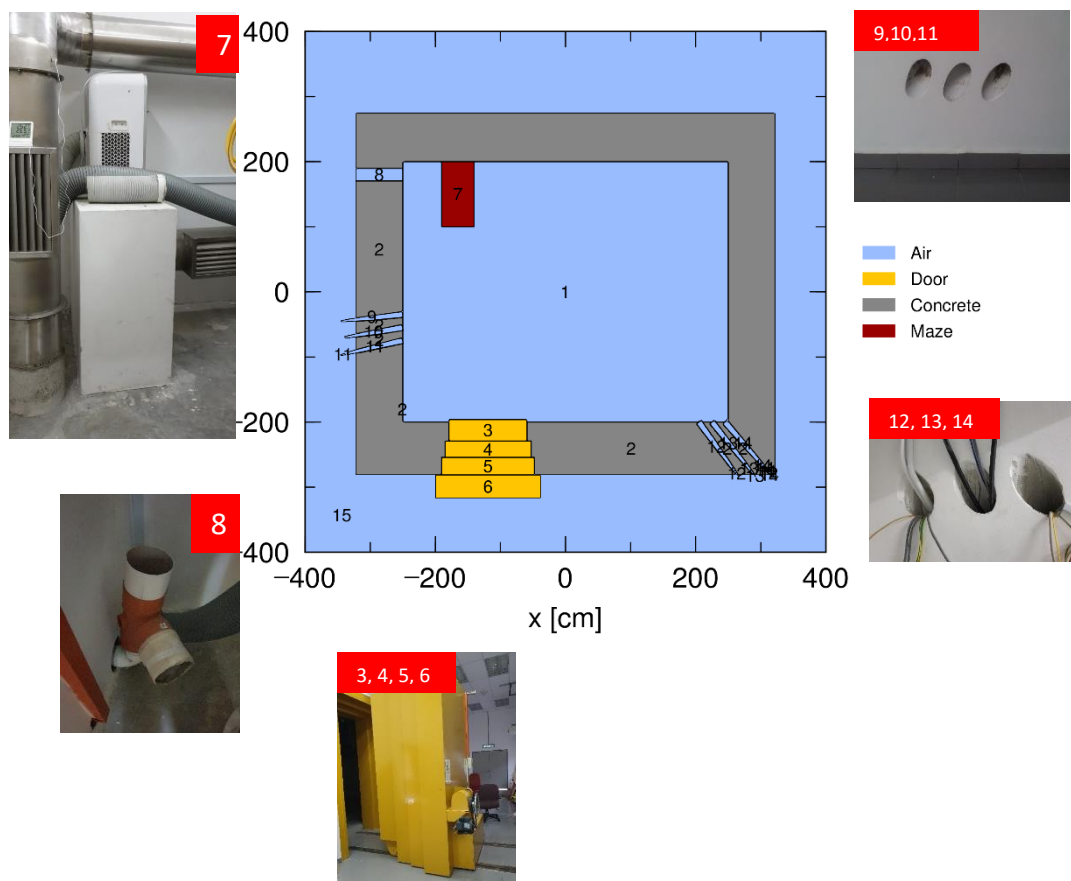


Figure 2. Geometry of the irradiation room from the top view. Each region is marked with a number.

2.2. Source Definition

The parameters that are concerned in radiation shielding in term of electron beam accelerator is electron beam energy E_0 and average beam power P [5]. In this case, electron beam energy is considered small and the types of radiations concerned in the bunker is not the primary electron beams but the secondary beams [6]. The bremsstrahlung that results the photon beams are our main concern for radiation shielding. The previous measurement was done by using Iridium 192 (Ir-192), a gamma ray source to simulate the secondary beams from the interaction of our electron beam with the target

material. We define Ir-192 like the experimental source. The activity is 1.25 TBq. The direction of the source as isotropic and is situated at the middle of the room and, 77 cm above the floor. Ir-192 is chosen for its strong gamma ray source as it can produce a gamma dose of 5 mSv/h at one meter. The energy spectrum will range from 200 keV to 600 keV, which includes the energy range of our electron beam accelerator.

The method used in gamma-ray dose conversion factor is by applying the parameter sets built-in PHITS for photon. We used the conversion coefficient for the ambient dose equivalent $H^*(10)$ from photon fluence [7]. The unit of the dose conversion factors is $(\mu\text{Sv/h})/(\text{n/sec/cm}^2)$ and these conversion factors were estimated with a condition of Antero-Posterior geometry (AP) irradiation [8].

2.3. Variance Reduced Technique

Using the geometry in Figure 2, there is inaccuracy of the calculation. In Figure 3 (a), the value of dose rate stopped short inside the wall. In Figure 3 (b), clearly dose rate calculation failed at $102 \mu\text{Sv/h}$. This is statistically unacceptable as we want to ensure the dose is less than $20 \mu\text{Sv/h}$ with an acceptable accuracy and precision. The efficiency of the Monte Carlo simulation is improved using a variance reduction method which will artificially increase the probability of rare event occurrences is used and this will set out the importance values by cells. This method required the splitting of the geometry of our desired target of region of our calculation. In our case, the wall is split into many layers. Each of the layer has value of Importance, I . By setting the value of importance, the particle passing through the layer are split at the same number with the value we have set. This splitting particles are useful to calculate a much more accurate results for the calculation inside the shielding region. The splitting particles are used for calculation as it will increase the reaction inside the region and so will enhance our calculation to get a much more accurate dose or flux. Figure 3 (b) is an example of the differences between setting the importance for the shielding area. The dose rate for without setting the importance will be dropped to zero sharply after the dose only at around $10^2 \mu\text{Sv/h}$ while with the importance, there are still doses calculated even at the outside of the shielding area.

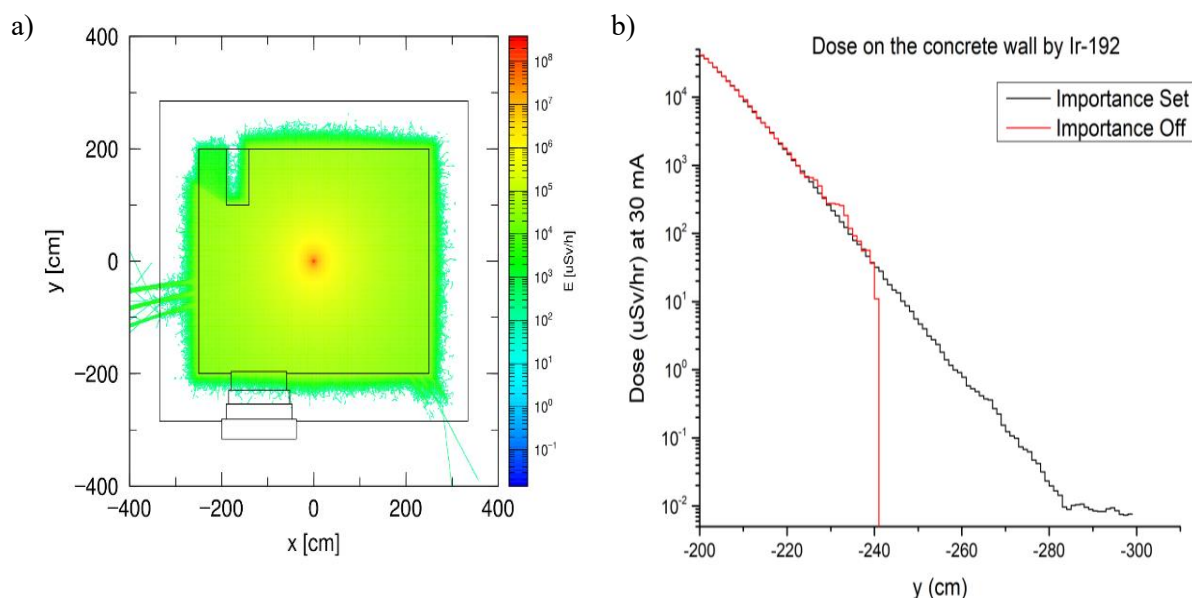


Figure 3. Dose distribution on the wall does not extend to a much higher degree of accuracy in dose rate. In (b), there is a significant improvement in term of accuracy with the variance reduced technique.

In term of statistical error, at 241 - 242 cm of y-axis, the relative error without variance reduction is 66.7% and 7.4 % while using the variance reduction. 242 cm of y-axis is located inside the concrete wall region and that depth is the limit of depth that we can calculate without using variance reduction. Beyond this depth, it will have 100% relative error. Using the variance method, the relative error of particles reaching the air region, which is outside of the bunker is at 34%. Figure 3 shows particle reaching outside but the calculation on that area gives high relative error (almost 100%), which invalidate the output. Therefore, the calculations using variance reduction on the outside region as shown in Figure 4 (b) and (c) are acceptable.

3. Ir-192 Dose Distribution in Irradiation Room

Figure 4 (a) shows the geometry of the room with consideration of the importance for each layer in the concrete wall and door. Figure 4 (b), 4 (c) is the dose distribution inside and outside the room. The dose at the control room is at 10-2 $\mu\text{Sv/h}$ and is comparably lower than the dose at the ventilation room. This is acceptable as our region of interest is in the control room while in the ventilation room, there will be no worker during the operation. In addition, the maze has reduced the radiation leaking through the duct hole for blower.

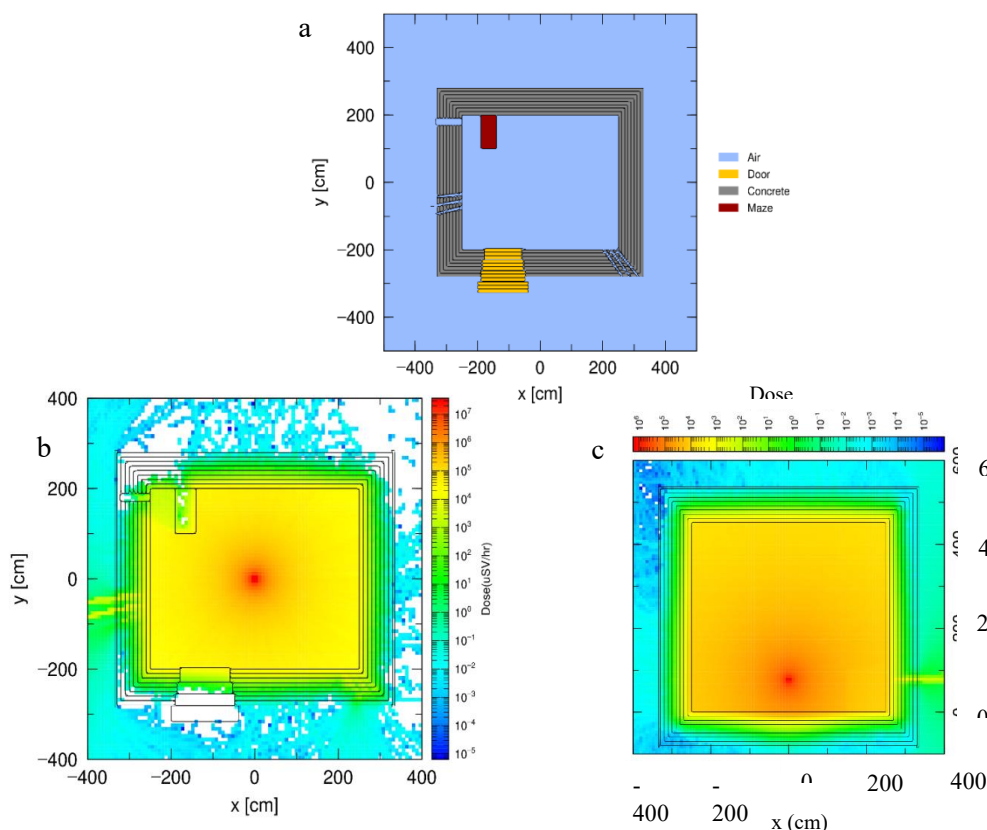


Figure 4. (a) Geometry of the irradiation room. (b), (c). are dose distribution in and outside the room using Ir-192 as source.

Figure 5 (a) is the effective dose inside the room along the width (x-axis) of the room. The dose taken at each point is the average distribution inside the room from the floor to the ceiling and from the front to the back (y-axis). The air attenuates one-tenth of the average effective dose from 10^4 to 10^3 . Therefore, the shielding design reduce the dose by 10^3 . Figure 5 (b) and 5 (c) is the dose rate

inside the concrete for different regions at the front side of the room. The dose on the concrete wall dropped below $20 \mu\text{Sv/h}$ passing through 45 cm of concrete wall. There is an extra of 40 cm thick concrete for our shielding using this source definition. Through the holes, the dose rate dropped below $20 \mu\text{Sv/h}$ at maximum of 61 cm through concrete. It can be observed that inside the elliptical cylinder holes, the statistics are not good especially hole #6 which might be due to its location at the far corner of the room. However, as reference to the wall, we can accept the dose rate as it is statistically acceptable outside the hole. Figure 5 (d) shows the attenuation factor by one-tenth of the dose.

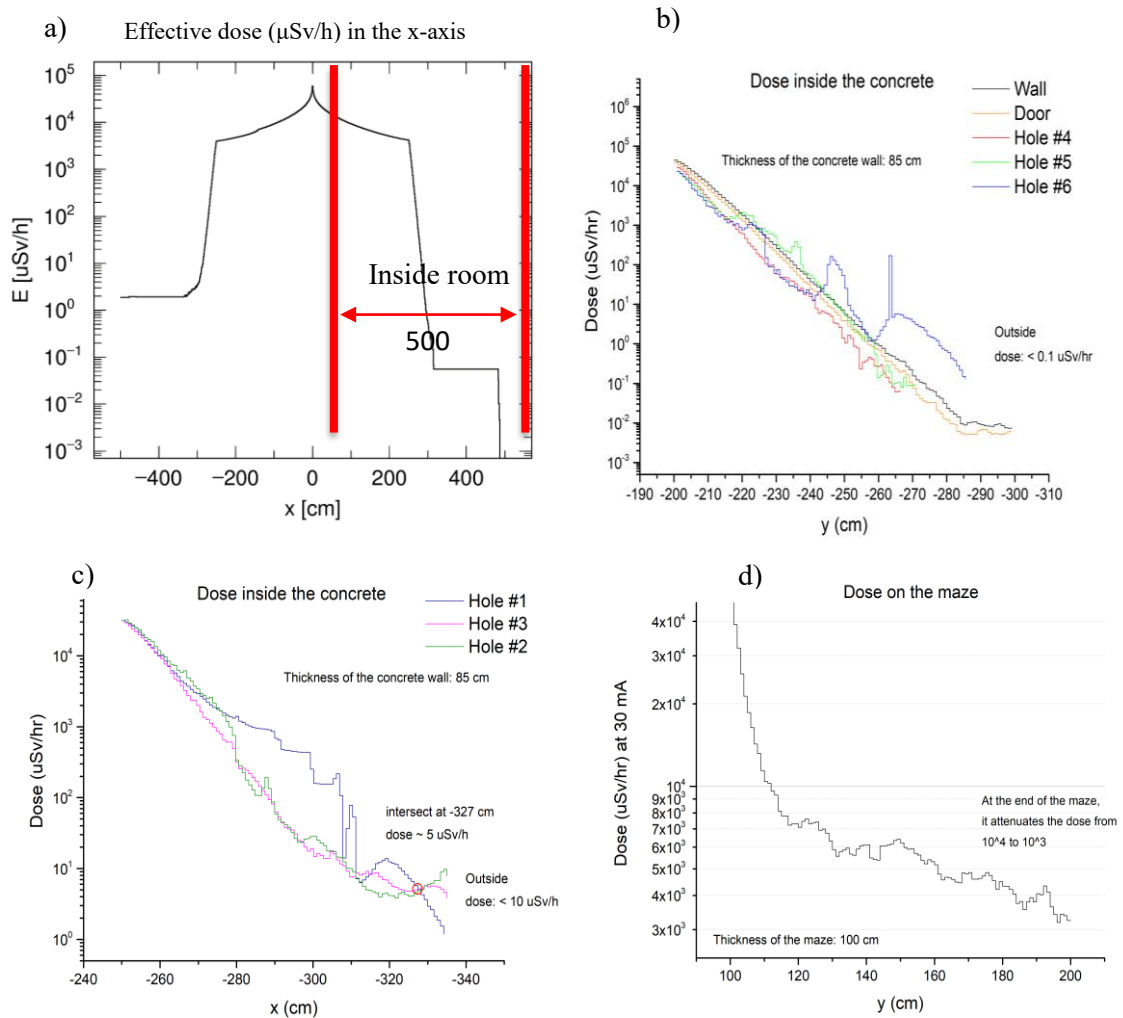


Figure 5 (a). is the effective dose inside the room along the width (x-axis) of the room. (b) and (c). is the dose rate inside the concrete for different regions at the front side of the room. (d) is the dose distribution on the maze.

Table 1 shows the agreement from the simulation to the measured dose on certain regions inside the room. The dose measured in the ventilation duct is done before the construction of the maze and the dose calculated from PHITS shows the attenuation of the maze by one tenth.

Table 1. Comparison between measured dose and calculated dose.

Region	Measured Dose ($\mu\text{Sv/h}$)	Calculated Dose ($\mu\text{Sv/h}$)
Wall	0.03 – 0.05	0.08 – 0.09
Door	0.03	0.05
Ventilation duct	20.0 (without maze)	0.3
Hole #1 (left-side)	2.0	1.19
Hole #2 (left-side)	2.0	4.58
Hole #3 (left-side)	2.0	3.86
Hole #4 (front side)	0.3	0.29
Hole #5 (front side)	2.0	1.55
Hole #6 (front side)	2.0	1.21

4. Conclusion

Dose distribution around the bunker has been calculated by using Monte Carlo method from PHITS and has been compared to the measured dose. The methods and results are shown in the paper and for future works, there is a need to improve the calculation inside the six elliptical cylinder duct holes on the concrete wall. Then, the next step is to do simulation using our current electron beam accelerator parameter as source definition with different target materials and for shielding design, a simulation using different shielding material should be done in order to provide a much better and cost-effective shielding design for the facility.

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