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SPALLATION TARGET OPTIMIZATION FOR ADS BY MONTE CARLO CODES

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Abstract

Accelerator Driven Systems are advanced systems for the use of Thorium as fuel, aiming to reduce nuclear waste through transmutation. The spallation target, which is responsible for producing neutrons, is one of the main parts of the ADS system. In this research, neutronic parameters of spallation targets consisting of several materials LBE, Mercury, and Lead, on the cylindrical, box, and conic shapes using Monte Carlo codes (FLUKA, PHITS, MCNPX) were investigated. Energy Deposition and spallation neutron yield of spallation target with different shapes and dimensions have been calculated to optimization of the target. According to the results, the neutron yield values from MCNPX and PHITS are similar and it's close to the experimental result. On the other hand, the error rate of the values in Fluka is higher.

INTRODUCTION

Accelerator Driven Systems (ADS) are up-and-coming tools that provide reliable energy and transmute long-lived radioactive waste. The simultaneous operation of ADS's passively safe subcritical core and accelerator distinguishes it from conventional fission reactors. So, the unique feature of this system is that the reaction stops shortly after the proton beam from the accelerator is turned off. In this way, it provides safety that will significantly reduce the risk of nuclear accidents. In addition, nuclear waste is a big problem for which no solution can be found [1]. ADS aims to transmute long-lived radioactive waste like Pu, and Np isotopes [2]. Thus, it can figure out this problem and contribute to the sustainability of nuclear energy [3].

Powerful particle accelerators with high proton beam energy, spallation target, and sub-critical system are the main components of ADS [4]. The particle accelerator continuously delivers a dense beam of accelerated particles toward the target. As a result, these neutrons can be multiplied in the subcritical nuclei enclosing the target [5].

The spallation target is the part that connects the accelerator and the subcritical reactor. Therefore, the spallation target design has a key point for ADS design. There are some difficulties for design spallation target; selecting the most suitable material, heat removal, radiation damage, and distribution of power density. To handle these issues, subjects such as neutronic analysis, and energy deposition are required for spallation target design [6].

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The neutron yield per incident proton is the principal data that has been used in the ADS study [7]. Neutron yield calculation with MCNPX has been investigated by several researchers [8-10]. However, a comparison of neutron yield with different Monte Carlo codes such as FLUKA and PHITS was not well reported.

Three well-proved Monte Carlo codes (FLUKA, PHITS, and MCNPX) were used to calculate and compare the neutron yield to determine the most suitable material and select the optimum size and shape for the spallation target.

MATERIALS AND METHODS

In this paper, by using FLUKA, PHITS, and MCPNX, the neutron yield of the cylindrical target was calculated according to different proton beam energies and this process was repeated for 4 different target materials (LBE, Mercury, Lead, and Tungsten). The fixed cylinder target with a radius of 20 cm and height of 80 cm was chosen based on the literature [10]. To compare the different shapes, the dimensions of the Conical target were selected the same (Fig. 1). Proton beam (2.35 mm spatial FWHM) with energies ranging from 600 to 1500 MeV, in the z-direction (0, 0, -2) injected into the target.

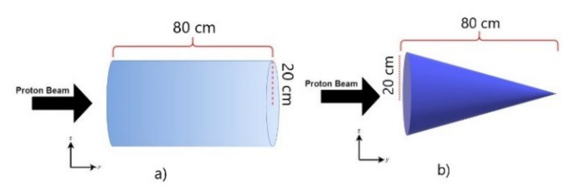

Figure 1: Fixed cylindrical and conical spallation target.

To determine the optimum target shape and dimensions, the neutron yield of the cylindrical target as well as the conical target were calculated and repeated for different materials (Tungsten, LBE, Mercury, and Lead) and dimensions. The length of the cylindrical target has been changed to 20,40,60,80 and 100 cm, and then the radius of the target has been changed to 5,10,15,20,25, and 30 cm. Conical target length has been varied from 40, 60, 80,100 cm and radius 10,20,30,40, and 50 cm. Equation 1 is used to calculate the neutron yield per incident proton [11]. Proton beam energy, target material, shape, and dimensions of the target are the factors affecting the neutron yield. Sp is the number of primary protons and Sn is the number of primary neutrons.

$$\textit{Spallation neutron yield per proton} \quad Yn/p = \frac{Sn}{Sp} \quad (1)$$

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RESULT AND DISCUSSION

Neutron yields at different proton beam energies using four different target materials for a fixed radius and length cylinder target were simulated. Energy from 600 to 1500 MeV with a step of 200 MeV was selected. Figure 2 shows that by increasing proton energy increases, the neutron yield increases in direct proportion, and the highest value throughout the proton energy belongs to the Tungsten target, 43.6803 n/p at 1500 MeV. Next, the highest value was followed by Mercury 43.33 n/p. On the other hand, the lowest yield was seen in Boron, Nickel and Cobalt, which values under 20 n/p at 1500 MeV. Neutron yield values for LBE and Lead targets are very close to each other and are approximately 41 n/p at 1500 MeV. Nickel, Cobalt and Boron target materials have not been used in the next stages because their yield values are quite low.

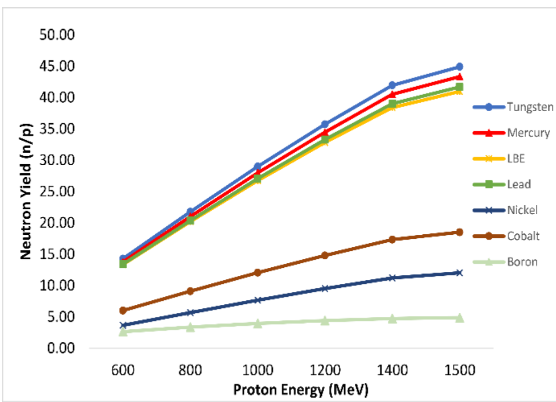

Figure 2: Neutron Yield versus proton energy for different target materials by MCNPX.

Table 1: Comparison of Neutron Yield for Conical and Cylinder Target

Target Materials	Conical Target (R:20cm L:80cm) MCNPX (n/p)	PHITS (n/p)	FLUKA (n/p)	Cylindrical Target (R:20 cm L:80 cm) MCNPX (n/p)	PHITS (n/p)	FLUKA (n/p)	Average Relative Differences (%)
LBE	24.26	25.48	27.52	26.75	28.62	30.95	11.03
Mercury	26.07	27.86	29.72	27.99	28.45	32.47	8.29

Figure 3 shows the neutron yield with a different target radius for a cylindrical target at fixed energy, 1GeV proton beam. Regardless of the target material, it was observed that neutron increases with the increase of the target radius. While there is a rapid increase up to 20 cm, after that there is a gradual increase. It means after 20 cm, the rate of increase is insignificant and almost saturated. Therefore, a 20 cm radius were selected as an optimum target radius and the neutron yield were calculated for the target length varying from 20 cm to 100 cm (Fig. 4). Calculation was repeated for four different materials. According to result, neutron yield increased for the Tungsten target up to 40cm, no change was observed after 60cm for target length. For Mercury Target, this optimum value appears to be between 40 cm and 60 cm target length, while for LBE and Lead target the optimum length was calculated as 60 cm. So, after this optimum value, there is no advantage in terms of neutron yield.

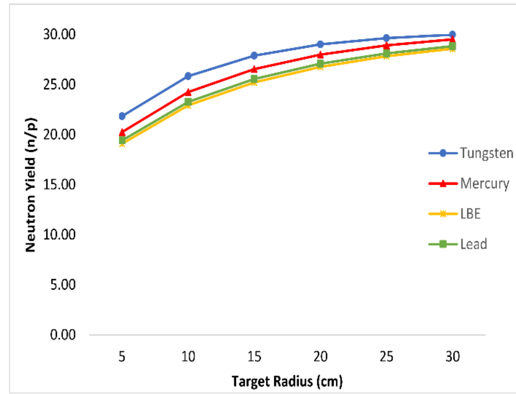

Figure 3: Neutron yield versus target radius at 1 GeV by MCNPX.

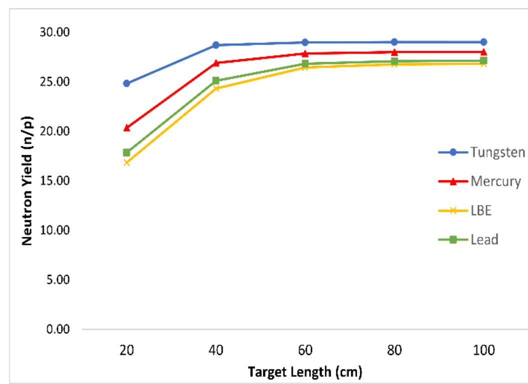

Figure 4: Neutron yield versus target length at 1GeV by MCNPX.

To see the effect of different target shapes on neutron yield, the yield of Cylinder target and Conical target (Table 1) were selected. For the same radius, it was observed that neutron yield for cylinder target is higher than conical target. FLUKA has the highest neutron yield for various target shapes and materials, while MCNPX has the lowest.

In addition, conical target (34.64x80 cm) and cylinder target (20x80 cm) neutron yields with the same volume for four different materials were simulated by FLUKA. There is a more or less ±1 percent difference between the conical target and cylinder target with the same volume. As a result, it was observed that geometry has an effect on neutron yield.

Table 2: Comparison of Our Work and Experimental Data for Lead Target (10.2 cm*61 cm) (diameter x length) and Tungsten Target (10.2 cm*40 cm)

Material	Energy (MeV)	Experimental result (n/p) [12]	MCNPX (n/p)	PHITS (n/p)	FLUKA (n/p)	Relative Differences (%)
Lead	1000	17.5	19.50	19.58	21.12	10.25 / 10.62 / 17.14
	1400	26.3	27.60	26.86	29.55	4.71 / 2.08 / 10.99
Tungsten	1000	20.5	21.95	22.62	24.08	6.60 / 9.37 / 14.86
	1400	28.5	30.90	31.99	34.48	5.28 / 10.9 / 17.34

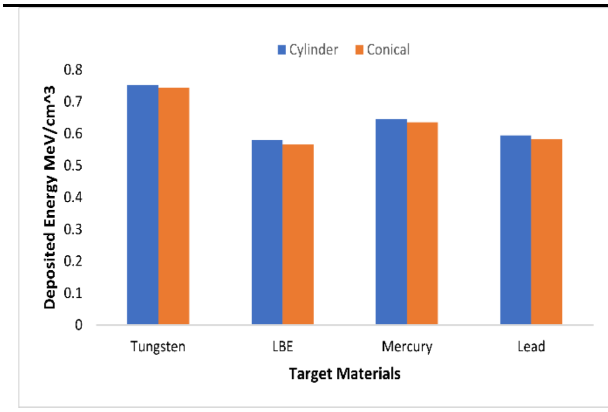

Figure 5: Deposited Energy of 4 different materials for Cylinder and Conical targets.

The deposited energy for Tungsten, LBE, Mercury and Lead target materials because of the collision of 1 GeV protons for cone and cylinder was calculated with FLUKA (Fig. 5). As can be seen, the amount of deposited energy varies depending on the target material, but is nearly identical for the same target shape. So, deposited energy does not depend on geometry. In addition, Tungsten target has the highest energy deposition (0.752 MeV/cm^3), whereas LBE target has the lowest (0.586 MeV/cm^3).

To validate the simulation results, our results calculated by Monte Carlo codes were compared with the experimental data (Table 2). In the experiment conducted by BNL, the neutron yield of two different target materials (Tungsten and Lead) data was used for different proton beam energies (1000 and 1400 MeV) [8,12]. In this study, the obtained data calculated by Monte Carlo Codes has an average uncertainty of less than 0.8%. The average relative differences between MCNPX, PHITS, FLUKA and experimental result for neutron yield were 6.71%, 8.24%, and 15.08%, respectively.

CONCLUSION

In this study, we investigated different spallation target materials with different target shapes and dimension by using 3 Monte Carlo Codes. We confirmed that proton beam energy, target materials, target geometry and dimension have an effect on neutron yield. The conical target and cylindrical target were compared in terms of neutron yield and deposited energy. Although LBE neutron yield is relatively low compared to other target materials, it generates less heat. Obtained results by Monte Carlo codes were confirmed with experimental data. PHITS and MCNPX results are very close to each other, with an average relative difference of 2.61%.

The next step is to design reflector and shielding for ADS system by using Monte Carlo codes. Later we will focus on LBE target cooling to remove heat in the spallation target. To overcome this problem, it is planned to use the Computational Fluid Dynamics (CFD) based approach.

ACKNOWLEDGEMENTS

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