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Modelling of Tritium Breeding for Fusion Blanket Using Geant4

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Abstract

Nuclear fusion is considered a potential future energy source that generates energy cleanly and sustainably. However, a major problem associated with fusion reactors is maintaining a steady fuel supply of tritium, which is done by breeding tritium in a fusion blanket. This research work aims to model and investigate tritium breeding in a conceptual fusion blanket using the Geant4 Monte Carlo simulation framework. It focuses on a multi-layer blanket design consisting of a steel first wall, a lithium ceramic breeder, a beryllium neutron multiplier, and a graphite reflector. A neutron source with an energy of 14.1 MeV is used to copy fusion neutrons. It is seen that tritium is well bred within the lithium ceramic breeder material, and an increase in this breeding is possible with neutrons in beryllium. These findings demonstrate that Geant4 is a reliable tool for modeling tritium breeding, providing valuable insights for the design and optimization of fusion blanket systems in future fusion reactor applications.

1. Introduction

Nuclear fusion has been widely explored as one of the alternative sources of energy that can serve the future energy needs and reduce environmentally harmful effects [1] [2]. Advantages associated with the use of light nuclei to generate energy include richness of the resource pool of fuel, safety by design, and less generation of radioactive stable wastes as compared to the traditional nuclear fission-based systems. Fusion energy is therefore an area of intense study globally, particularly with regard to the next generation power generation technologies.

Out of all the possible fusion fuel cycles, the deuterium-tritium (D-T) reaction is virtually considered as the most practical due to its relatively large reaction cross-section at the possible plasma temperature [3]. The problem with that, however, is that relying on tritium causes a major operation issue as tritium is not the most natural element that has a small half-life. Thus, the in situ tritium generation in the fusion reactor is needed to sustain the operation, and a tritium self-sufficiency is established as a basic need of the following fusion power plants.

One of the most important components of a reactor is the tritium breeding blanket which was invented to obtain the self-sufficiency in tritium. The blanket is placed in the vicinity of the plasma chamber and it converts high-energy neutrons produced by fusion into tritium through nuclear reactions with lithium-containing material [3] [4]. Other than using tritium, the breeding blanket is also used to moderate neutrons, depositing energy as well as shielding radiations, all of which influence the performance of the reactor in its entirety. The reflector materials, neutron multipliers, and breeder materials to use are vital to the breeding of tritium and use of neutrons.

The neutron transport, nuclear reaction rates, material properties and geometric configuration of a breeding blanket greatly complicate the design of an efficient breeding blanket. The experimental determination of blankets performance at fusion-relevant conditions is challenging and costly to conduct technically and therefore limits the supplies of experimental information to optimize designs. As a result, the use of a computational model has emerged as a crucial resource to evaluate causes of tritium breeding and guide further work on the blanket design in the initial stages of the fusion reactor development [5].

The Monte Carlo neutron transport is a powerful technique for studying the neutron interaction in complex three-dimensional problems. More specifically, the Geant4 simulation toolkit provides detailed features to a model of particle transport, material composition specification, and relevant nuclear physics process modelling [6] [7]. All these qualities render Geant4 a suitable package to study reactions caused by neutrons and the production of tritium in conceptual fusion blankets.

This study presents the simulation and analysis of tritium breeding in a simplified multi-layer fusion blanket using the Monte Carlo simulation framework, Geant4. Here, the tritium breeding property of a blanket layout comprising of multi-layer structure of blankets, multiplier, breeders, and reflector layer has been calculated along the lines of tritium breeding ratio.

2. Methodology

Geant4 Monte Carlo toolkit, which is a popular model used to describe particle transport and nuclear reactions in radiation and nuclear engineering, was used to conduct the simulation [6] [7]. The Geant4 package enables the user to specify 3D geometries, material building blocks and physics processes of relevance to neutron transport and tritium generation. Elaborating on this paper, the production of tritium was studied by using Geant4 simulations of neutron interactions within a hypothetical fusion breeding blanket.

2.1 Simulation Workflow

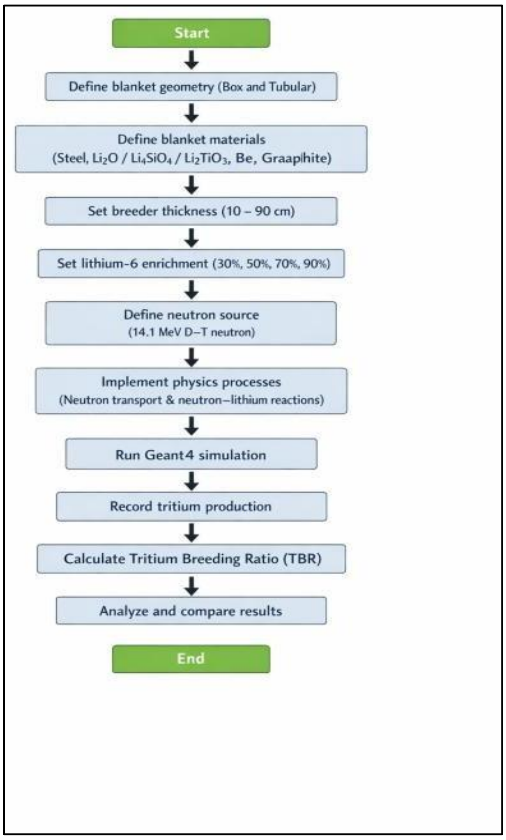

Fig. 1 The Flow of Study

The overall simulation workflow is illustrated in Fig. 1. The definition of the geometry of the blankets started the simulation process, and it was followed by the material choice and specification of the parameters. The parameters studies that followed were aimed at determining the impact of the type of breeder material, breeder thickness, geometry of blankets, and lithium-6 enrichment on tritium breeding. The tritium breeding ratio (TBR) was the major performance indicator used to assess the simulation results.

The main simulation parameters used in this study are summarized in Table 1. These parameters include blanket geometries, breeder materials, neutron source features, and physics processes, as well as performance measures. The table helps get a brief report of the simulation set that was used during the analysis.

2.2 Simulation Parameters

Table 1 Table of parameters for simulation

Parameter	Description
Blanket Geometry	Box(G4Box) and G4Tubs
Blanket Structure	Steel first wall, breeder, Be multiplier, graphite reflector
Breeder Materials	Li_2O, Li_4SiO_4, Li_2TiO_3
	10-90cm
Breeder Thickness	14.1 MeV
Neutron Source Lithium Enrichment	Natural, 20% enriched in
	Li-6 to 90%

The blanket was represented as a simplified multilayer material with a first layer comprising steel, a beryllium neutron multiplier, and a graphite reflector. The steel first wall acts as a structural boundary wall towards the neutron source, providing support while preventing excessive neutron losses before reaching the fuel layers. The ceramic breeder layer holds lithium, which undergoes neutron-lithium reactions to produce tritium. The beryllium layer serves as a neutron multiplier, increasing the number of neutrons via (n,2n) reactions, thereby enhancing tritium production in the breeder material. The graphite reflector helps to decrease neutron losses through the outer boundary, allowing scattered neutrons to return to the breeder material.

The same material composition, layer ordering, and thickness were applied in both G4Box and G4Tubs models, to ensure a fair comparison, but only the shape of blanket was changed. This allows any difference in the tritium breeding ratio (TBR) to be attributed primarily to geometry-driven neutron transport and leakage behaviour rather than differences in layer construction.

The thicknesses were selected based on physical and practical considerations. The steel first wall was set to 2 cm, providing structural realism while minimizing neutron absorption. The baseline breeder thickness was 40 cm, with parametric studies varying it from 10 cm to 90 cm to capture the trend from insufficient neutron interaction to saturation due to self-shielding. The beryllium multiplier thickness was fixed at 10 cm to provide effective neutron multiplication, and the graphite reflector was set to 20 cm to reduce neutron escape. The plasma region size was defined as 20 cm to provide a consistent neutron emission area for both geometries. These fixed and variable dimensions ensure that the effects of breeder thickness, breeder material, geometry, and lithium-6 enrichment can be evaluated systematically.

Table 2 Layer stack-up and thickness used in the blanket model

Layer (from plasma-facing side)	Material	Thickness	Notes
Plasma	Neutron source region	20 cm	Fixed
First wall	Steel	2 cm	Fixed
Breeder	Li_2TiO_3 / Li_4SiO_4 / Li_2O	10–90 cm	Variable
Neutron multiplier	Be	10 cm	Fixed
Reflector	Graphite	20 cm	Fixed

2.3 Calculation of TBR

The tritium breeding ratio (TBR) was used as the primary parameter to evaluate tritium breeding performance. The TBR was defined as the ratio of the total number of tritium atoms produced within the breeder region to the number of incident fusion neutrons [3], as expressed by:

$$TBR = \frac{N_T}{N_n}$$

where N_T represents the total number of tritium atoms generated in the breeder material, and N_n denotes the total number of incident fusion neutrons.

3. Results and Discussion

This section presents and discusses simulation results generated using the Geant4 model. The analysis examines the influence of breeder material selection, breeder thickness, blanket geometry, and lithium-6 enrichment on the tritium breeding ratio (TBR) to determine the most effective configuration for tritium production.

3.1 Geometry Visualization

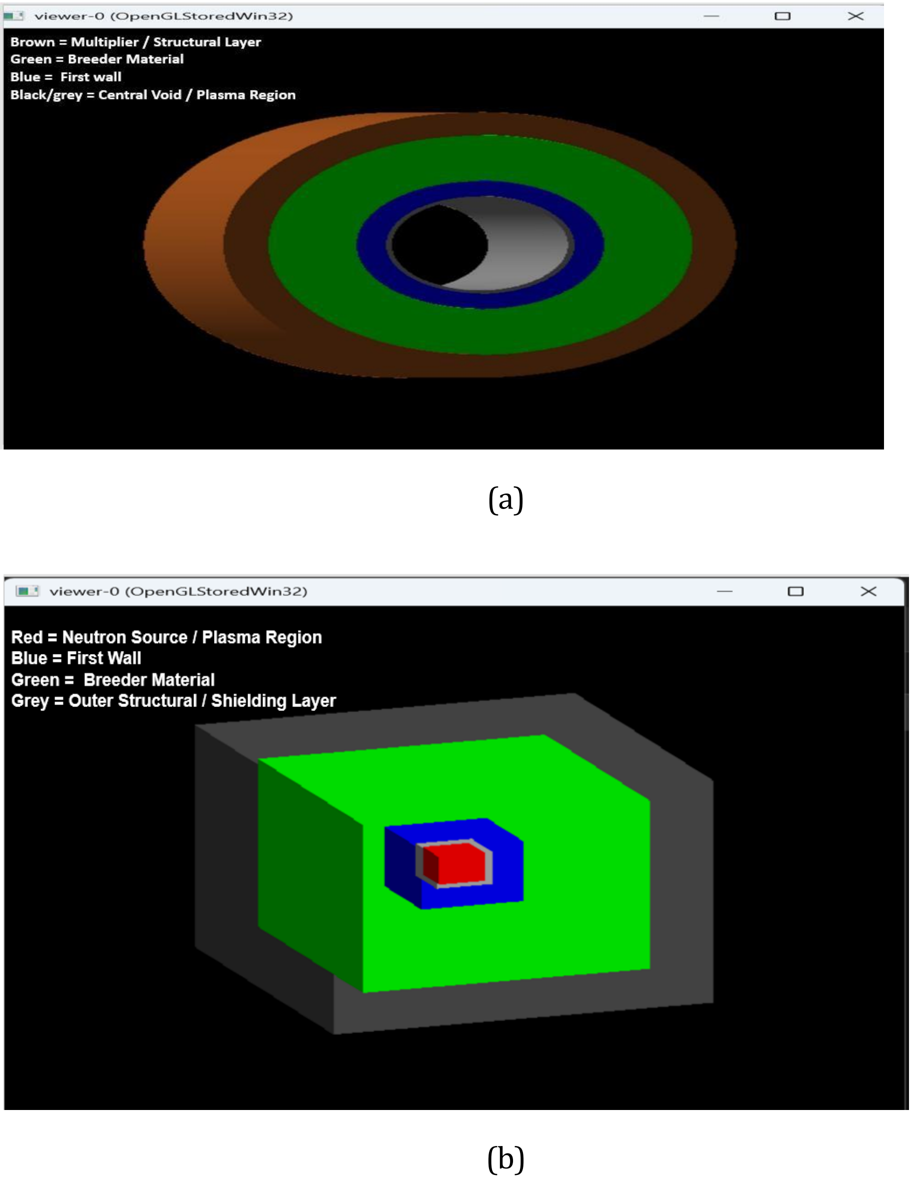

Fig. 2 Blanket Geometry of (a) G4Tubs; (b) G4box

Table 3 Description of Blanket Layers and Their Functions

Layer	Function
Plasma/Neutron Source	Generates high-energy fusion neutrons
First Wall	Protect the blanket from thermal and neutron loads
Breeder Materials	Produces tritium via neutron- lithium reactions
Multiplier	Enhance neutron multiplication and provide structural support

Geant4 simulation model was made through geometry visualization to ensure that the positions of materials and layer arrangement were correct. In the present study, two types of blankets were used, i.e., a rectangular geometry (G4Box), and a cylindrical geometry (G4Tubs). All configurations contained a first wall made of steel, a breeder layer (lithium) and a beryllium neutron multiplier, as well as a reflector made of graphite. The results of visualization allowed to conclude that all blanket layers were correctly outlined and their positions in the simulating environment were correct. The box geometry was an unsophisticated model that could be considered in benchmarking, but the tubular geometry was more realistic to use in relaxing to fusion blanket application. Through these visualizations, the validity of further neutron transport and breeding simulations of tritium was automatically determined.

3.2 Effect of Breeder Material and Thickness on Tritium Breeding Ratio

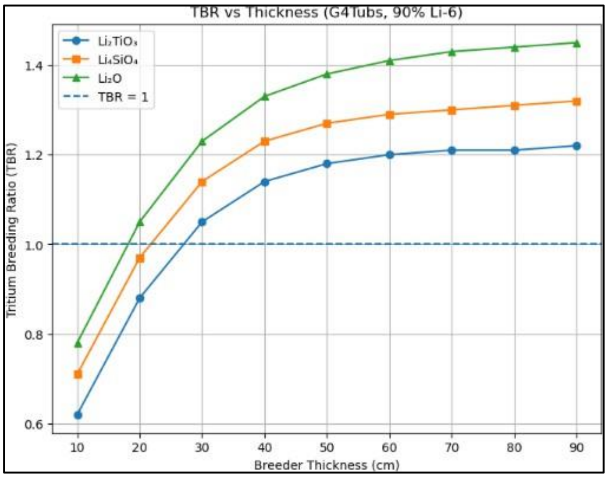

Fig. 3 Effect of breeder thickness on the Tritium Breeding Ratio (TBR) for Li_2TiO_3, Li_4SiO_4, and Li_2O using G4Tubs geometry at 90% Li-6 enrichment

The combined effects of breeder material selection and breeder thickness on tritium breeding performance were systematically examined using three lithium-based ceramic breeder materials: Li_2TiO_3, Li_4SiO_4, and Li_2O. Breeder thickness was adjusted between 10cm and 90cm to determine the effect of the material, as well as the tritium interaction volume, on the neutron-lithium reactions and the general tritium production. Simulation of tritium breeding by Geant4 showed that the ratio of tritium breeding was obviously dependent on the two parameters.

In the case of all the breeder materials, the results indicate that TBR increases with breeder thickness [4] [8]. The values of TBR at low thicknesses e.g. 10 cm were relatively lower with the values of 0.62, 0.71, and 0.78 corresponding to Li 2 TiO3, Li 4 SiO4, and Li 2 O respectively. These low values imply that the breeder region was not adequate to absorb all incident fusion neutrons which means that the interaction with the neutrons and lithium and subsequent tritium generation was low.

Deposition of greater breeder thickness of 30 cm led to a considerable increase of tritium breeding of all materials. At this thickness, the TBR exceeded unity for Li_2TiO_3 (1.05), Li_4SiO_4 (1.14), and Li_2O (1.23), indicating the onset of tritium self-sufficiency. This is due to the fact that the volume of interaction is more and therefore more neutrons are able to respond to the tritium-producing reaction and not escape out of the breeder region.

Subsequent increases in breeder thickness were observed to further augment TBR although the rate at which this was augmented diminished. The growth in TBR was then slower at the thicknesses between 50 cm and 90 cm, especially in the case of Li 2 TiO 3 and Li 4 SiO 4(Ogino, n.d.). For example, Li_4SiO_4 exhibited a TBR of 1.27 at 50 cm and increased only to 1.32 at 90 cm. Such a behaviour indicates the existence of neutron self-shielding in which neutrons are progressively depleted inside the breeder material and will no longer penetrate deeper areas, bringing further increases in tritium yield.

It was also noted that consistent performance ranking was present among the breeder materials in the whole thickness range. Li 2 O had the highest values of TBR corresponding to all the thicknesses and Li 4 Si O 4 and Li 2 Ti O 3 respectively. At the maximum thickness of 90 cm, TBR values were 1.45 for Li_2O, 1.32 for Li_4SiO_4, and 1.22 for Li_2TiO_3. Li 2O is shown to outperform the other two due to higher density of lithium atoms, which makes it more likely to have neutron capture reactions that result in the production of tritium.

Li 2 O produced TBR highest and Li 4 SiO 4 was used as a preferred breeder material later analyses due to an opportunity to provide a good combination both with tritium breeding performance and material considerations including chemical stability, thermal behaviour and fewer swelling and tritium release problems. Although Li 2 TiO 3 had the lowest TBR of the three materials, it was able to become tritium self-sufficient once it was thicker and could be considered as a practical fusion blanket material in situations where a structural and thermal stable material is the concern.

Overall, the findings have shown that breeder material selection and breeder thickness are very crucial in determining the tritium breeding performance. Breeder thickness increases TBR to a certain maximum where neutron self-shielding reduces the effectiveness of any further material. The results of this study provide an appreciation of the need to maximize the properties and thicknesses of breeder material and at the same time as opposed to mitigating one of these parameters individually.

3.3 Effect of Blanket Geometry

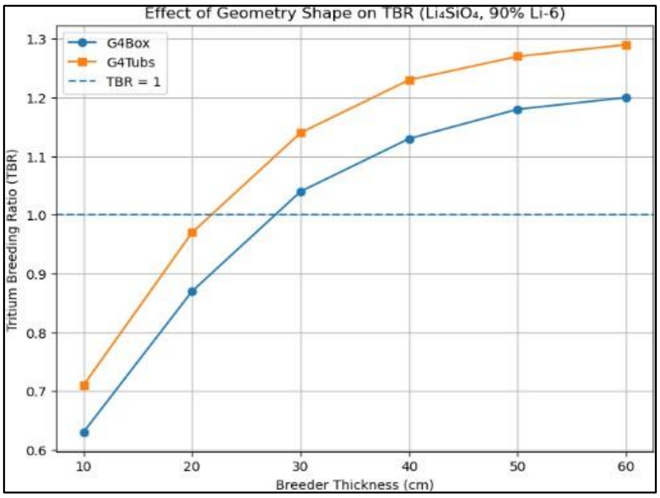

Fig. 4 Variation of Tritium Breeding Ratio (TBR) with breeder thickness for cylindrical (G4Tubs) and box (G4Box) geometries

The effect of blanket geometry on the performance of the tritium breeders was evaluated by comparing two idealized geometry G4Box and G4Tubs with lithium orthosilicate (Li4SiO4) as the breeder material. The conditions and material compositions of both models were considered the same, and they were also subjected to the same conditions with regard to the thickness ranges of blankets to ensure a strict comparative study of the tritium breeding behaviour.

The simulation outcomes show that, all the simulation attempt undertaken revealed that TBR values in the G4Tubs geometry prevailed over the G4Box geometry. Such a direction shows that the influence of geometry in neutron transport and tritium production in the breeding blanket is a significant consideration.

The increased TBR that is found in the geometry of the G4Tubs can largely be attributed to the smoother spread of neutrons throughout the breeder bed. The neutrons produced in the plasma under the cylindrical shape are emitted radially around the plasma column and held by the turning shape therefore the probability of their outflow beyond the outer boundaries of the blanket is reduced. Therefore, more interactions of neutrons in the breeder material are possible, which may cause tritium-producing reactions like $^{6}Li(n,a)T$.

In addition to neutron spatial distribution, neutron leakage plays an important role in explaining the performance difference between the two geometries. In the G4Tubs configuration, the curved boundary reduces direct neutron escape and increases the likelihood of neutron backscattering from the surrounding beryllium multiplier and graphite reflector layers. As summarized in Table 2, identical layer ordering and thicknesses were applied in both geometries; therefore, the observed differences in TBR arise mainly from geometry-induced neutron leakage behaviour rather than material or dimensional variations.

Preferably, on the contrary, the G4Box geometry, though beneficial in providing effective ways of conducting parametric studies because of its simplicity and uniform path length, has been identified to have high neutron leakage at planar boundaries because the neutrons tend to follow straight paths and consequently have less interaction with the breeder material and will escape the slab geometry. The described effect is more significant for higher neutron energies, like the 14.1 MeV neutrons of interest in this study, characterized by large neutron penetration depths.

This increased neutron leakage in the G4Box geometry reduces neutron residence time within the breeder layer and limits the effectiveness of the fixed surrounding layers, namely the 10 cm beryllium multiplier and the 20 cm graphite reflector. As a result, fewer neutrons are redirected back into the breeder region, leading to reduced neutron utilization and lower tritium production efficiency compared to the G4Tubs configuration.

Cylindrical geometry also enhanced the neutron moderation and reflection particularly when coupled with the surrounding beryllium neutron multiplier and the graphite reflector. This geometry of tubes has curved surfaces, which increase neutron backscattering on the breeder region and thereby increase the residence time of neutrons and consequently the overall reaction probability. This also justifies the better values of TBR of tubular model as compared to the box model.

Overall, these findings indicate that neutron utilization is a key criterion to assess the efficiency of the blankets and tritium breeding behaviour. Although box geometry is an effective method of fitting analyses that are both comparative and parametric, the G4Tubs geometry is more accurate in modelling the blanket of fusion reactors and gives a higher tritium breeding potency. Hence, great caution is required when assessing and optimizing breeding blanket designs to be used in future fusion energy systems.

3.4 Effect of Lithium-6 Enrichment

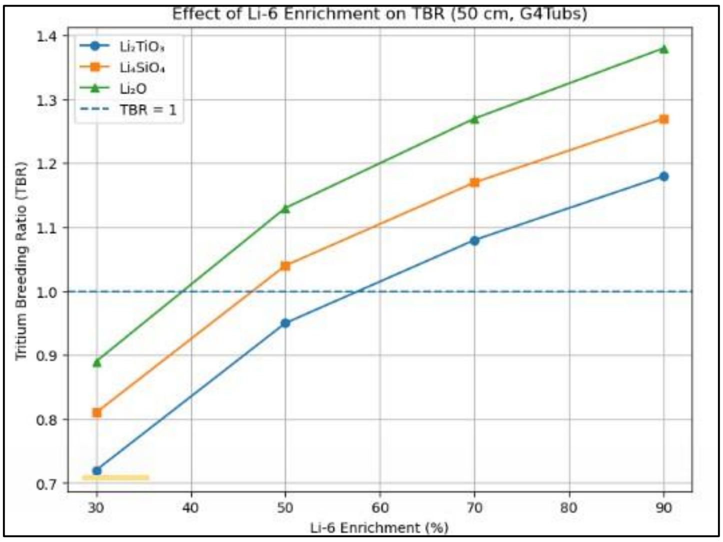

Fig. 5 Effect of lithium-6 (Li-6) enrichment on the Tritium Breeding Ratio (TBR) for Li_2TiO_3, Li_4SiO_4, and Li_2O at a breeder thickness of 50 cm using G4Tubs geometry

The impact of lithium-6 enrichment on tritium breeding performance was assessed by systematically varying the enrichment level from 30% to 90% in Li_4SiO_4 breeder material with a common tubular blanket configuration. The experiments were conducted under similar neutron sources [9]. Results obtained using the simulation indicate a strong increase in TBR with the increase in the level of lithium-6 enrichment within the range of interest. For lower values of enrichment, the scarcity of lithium-6 results in fewer neutron capture collisions leading to the production of tritium, thereby leading to lower TBR values. With the increase in enrichment, more neutrons get captured by the lithium-6 nuclei, thus increasing the rate of tritium production in the breeding blanket.

This trend aligns with the established nuclear properties of lithium-6, which has a high cross-section for the tritium-producing 6Li(n,α)T reaction, particularly at thermal and epithermal neutron energies. Increased lithium-6 concentration raises the probability of neutron absorption events that result in tritium generation, especially when combined with neutron multiplication and moderation effects in the tubular blanket configuration.

The maximum values of TBR were obtained with 90% lithium-6 enrichment, thereby proving that a high degree of lithium-6 isotopic enrichment is vital for achieving maximum tritium breeding rate. Though the rate of increment decreases with higher enrichments, it implies that factors such as costs, material, and availability of enriched lithium-6 may be taken into account to match the ideal composition. The result verifies that enriched lithium-6 is a vital requirement in making tritium self-sufficiency possible, which must be optimized with respect to designing fusion breeding blankets.

4. Conclusion

To enhance knowledge on parameter that affect tritium production, this paper offers a Geant4 Monte Carlo model of tritium breeding in a hypothetical fusion blanket. The simplification of the multi-layer blanket model was developed and propagated effectively, where the makeup consisted of steel FW, Lithium-based ceramic breeder, beryllium neutron multiplier, and a graphite reflector.

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The outcomes of the simulation indicate that the type and thickness of the breeder material have a big effect on the TBR. Li_4SiO_4 was the best of the lithium-based ceramics examined, as it demonstrated good tritium breeding behaviour and stability of the material at room temperature. Additional breeder thickness increased tritium production of all materials, and all reached self-sufficiency at moderate thickness. At an increased thickness, the enhancement of TBR was lessened due to neutron self-shielding.

Comparing the geometries of blankets, G4Box and G4 Tubs exhibited a benefit of a tubular shape as they are better in terms of using neutrons, and provide higher values of TBR. Moreover, the further lithium-6 enrichment contributed greatly to the growth of tritium production and TBR. This paper has shown that Geant4 is a versatile and efficient software in simulating neutron transport and tritium breeding in a fusion blanket. The results suggest a basis on which to comprehend the factors that affect tritium breeding, and they help in supporting the more advanced studies that will be done in the future. It can be further refined through research on refined geometry and further materials, and physics modelling to enhance the accuracy of the simulation.

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