Studied of Tritium Breeding Ratio on HCLL (Helium Cooled Lithium-Lead) Fusion Blanket by Using MCNP Program

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Abstract. The fusion reactor using a tritium-deuterium reaction is going to be a prolific source of 14.1 MeV (80% of fusion energy) neutrons, which will release from the plasma. This reactor features a major radius of 8.1 m and a minor radius of 2.5 m. Thus, one part of the fusion reactor, which is a basic design is Blanket Module (BM). One of the two European blanket concepts is Helium Cooled Lithium Lead (HCLL). HCLL blanket uses Pb-Li as a neutron multiplier, Li as a breeder, and He as a cooler is in high pressure (8 MPa). The study goal is to investigate the feasibility of blanket reactors, such as neutron analysis, shield efficiency, and tritium breeding capabilities. This calculation was simulated to achieve TBR value more than one, which will assure tritium self-sufficiency in steady-state operations. The MCNP program with Monte Carlo is a tool for calculating this. The neutron flux produced by this simulation shows that the reactor does no leak. And the production of tritium from breeding blanket will be optimal when the utilizing of breeding materials is Pb-Li.

1. Introduction
In this study, we research about nuclear analysis of blanket fusion reactor for International Thermonuclear Experimental Reactor (ITER) project. This fusion reactor is confined by a magnetic coil with blanket reactor concept using Helium as coolant and lithium-lead as tritium breeding material. This blanket adopted the European DEMO baseline with Helium Cooled Lithium Lead (HCLL) blanket module that has been presented in ITER [1].
In the D-T fusion reactor, blanket studied is essential part of fusion technology development, exceedingly tritium produced. Due to the tritium abundance in the earth is low [2], so this reactor should provide their tritium, from reaction between neutron and lithium, which can produce tritium [3]. This idea becomes leading by neutron energy supported; it carries 80% (14 MeV) from the total fusion energy or equals to the number of neutron flux of $10^{14}$ n/cm²/s [4]. Considering the ITER concept, the magnetic field can confine plasma in a limited radius [5]. Recently, the fusion reactor puts on a torus-shaped vacuum chamber with applying a primary radius size is 8.1 m and a minor radius size is 2.5 m. The main goal of this system is ensuring the tritium stock to achieve self-sufficiency condition. This condition requires Tritium Breeding Ratio (TBR) is more significant
than one. It is a success to reach a self-sufficiency condition when the tritium breed is more excellent than tritium burnt in plasma. The TBR value must be more than one due to reprocessing or radioactive decay possibility which can loss several numbers of tritium particles. To achieve practical tritium breeding, the optimized in blanket configuration and material should research and determine. The Monte Carlo N-Particle (MCNP) as a simulation program for neutron transport investigation, it can review the possibility of neutron distribution based on position and diffusion rate in the blanket reactor [6].

2. Calculation process
The neutron analysis approached by the MCNP program that applies the Monte Carlo method with FENDL as international reference nuclear data library for fusion reactor [7]. These calculated the particle transport for coupled neutron-photon transport, including for neutron interaction and photon production for 63 elements or isotopes [7]. Neutron flux and neutron energy distribution in each cell/part must be investigated to understand TBR.

3. HCLL blanket design
One of the blanket modules that has developed in the European DEMO baseline is HCLL. Using He as a coolant and Lithium-Lead as tritium breeder. This blanket design has a multi-module segment arranged in a toroidal direction [8]. There are 18 blanket port that make up the blanket in the torus-shaped plate formed, where each layer structured as follows:

![Figure 1. Cross-section of HCLL blanket segmentation](image)

The HCLL module consists of first wall, sidewall, tritium breeding, coolant, neutron multiplier channel, back support structures that have their respective functions. This blanket expected which can withstand from high pressure, more than 8 MPa, so it can maximize helium for heat transport and maintain into one phase. Based on FSLMIDTH data, Helium gas can be the best choice for coolant due to its high specific heat capacity [9]. Helium molecular behavior is stable even under high temperature, neutron irradiation, heat conductivity, and heat capacity have superior properties, leading to the best performance. Moreover, helium gas as a coolant has low density that can be complete transparency to neutron so that the tritium breeding possibility can be ignored [10].

3.1 Tritium breeding
The reaction between neutron and lithium can produce tritium, after passing the recovery and extraction phase, tritium will be injected into the plasma. However, it can be accessed with deuterium to create a fusion reaction [11].
For each lithium atom, it has two isotopes which both can produce tritium, $^6$Li and $^7$Li. Both of lithium isotopes can produce tritium, although tritium production has different properties [12]. Tritium derived from the $^6$Li reaction will purify efficiently where it can be useable for fusion fuel compared to the $^7$Li. However, $^7$Li isotope is generally used for multiplying and moderation of neutron, as shown in the above reaction.

Breeding section is relevant discussing because it can support the reactor sustainability. To assure the fuel supplier keeps adequately with the amount of tritium breed must be higher than the amount of tritium burnt in fusion reaction.

Tritium breeding ratio (TBR) defined as the ratio of the rate of tritium breed in the blanket to the rate tritium burned in plasma. To achieve the self-sufficiency fuel condition, TBR must be more enormous than one.

$$TBR = \frac{\text{tritium breed}}{\text{tritium burnt}}$$

Neutron multiplier

The $^7$Li in this model invited as a neutron multiplier, but other materials such as beryllium (Be) and lead (Pb) will also be used. According to the lower (n, 2n) reaction threshold energy, Be yields better enhancement in TBR [13].

From Karlsruhe Institute of Technology data, Be is believed to increase the TBR, due to small absorption cross-section [14]. Even though Beryllium handling procedure demands high cost and high activation, but it is still the best choice to be a neutron multiplier candidate. Lead is a minor option due to toxicity from bismuth which can produce natural impurity (e.g., $^{210}$Po and $^{205}$Pb) where it is intricate for waste management process [15]. Furthermore, Pb still employed in breeding zone to be LiPb eutectic. As shown in this reaction:

$$n + Be \rightarrow 2\alpha + 2n' - 3MeV$$
$$n + Pb \rightarrow Pb + 2n' - 10MeV$$

Hence, Be the neutron multiplier can maximize; there was a decrease in the energy multiplication for increasing TBR [16]. So, some neutron can be moderated while it can interact with $^6$Li.

4. Research and Analysis

The material specified in this research is He as a coolant and LiPb as a breeder, while other parts will be varied. It will be useful to generate sufficient blankets in tritium producing and heat transport.

From Fig. 1 in breeding zone, breeding and neutron multiplier material combine (the yellow one), and the cooling channel is arranged poloidally for each 0.5cm gap on the breeding zone.

This research study is to optimize the value of TBR, which can be in several ways:
- Variation in thickness of breeder blankets
- $^6$Li enrichment

From the variety of the breeding blanket thickness, the TBR reached 1.26 when the blanket thickness was 55cm, as shown in Fig. 2.
Fig. 2 occurred because the larger of the volume, the more breeding material is involved so that more neutrons absorb in Li. Automatically, the tritium breed will be more numerous. Therefore the TBR rises in number by increasing the thickness of the breeder blanket. Furthermore, it is not necessary because the geometry of adequate consideration must measure at a low cost. Besides, the cross-section of low neutron energy (<5 MeV) with $^6$Li is much higher compared to $^7$Li, but the abundance of $^6$Li is only 7.5% [17] so that it needs to enrich. Therefore, this research calculated the effect of $^6$Li enrichment in a range of 30% - 60% that showed in this figure:

![Figure 3. TBR value in different $^6$Li enrichment](image)

When enrichment of $^6$Li is enlarged, the number of $^6$Li is higher so that the interaction neutron and $^6$Li enhance. That makes the TBR value increased when the enrichment of $^6$Li is more significant compared to $^7$Li. Moreover, it must be analysed the further calculation to find adequate $^6$Li enrichment. It gives the best of TBR in lower $^6$Li enrichment due to the cost of lithium enhancement is not pretty cheap. Other than that, the research can use a case where the breeding blanket is only pure lithium (7.05% $^6$Li) or reduce the proportion of lead in LiPb material. Shown in the following table:
### Table 1. Influence of the lead portion in LiPb breeder

| Ratio Li (%) | 100 | 70 | 50 |
|--------------|-----|----|----|
| Pb (%)       |     |    |    |
| TBR          | 1.25| 1.21| 1.13|

As shown in table 1, the higher of lithium in the blanket, the higher the TBR value due to more significant number of neutrons that absorb into $^6$Li. Also, Pb or $^7$Li have higher endothermic energy than $^6$Li (exothermic energy), so neutrons are more interested in Pb or $^7$Li than $^6$Li. Consequently, tritium production will decrease caused just a few reactions that occur between lithium and neutrons. Furthermore, there is the effect of neutron multiplier material on the value of TBR, as shown in table 2.

### Table 2. Influence of the neutron multiplier

| Thickness (cm) | Be | Pb |
|---------------|----|----|
|               | 45 | 50 |
| TBR           | 1.15| 1.2| 1.0| 1.07|

Beryllium has lower endothermic energy of the Be(n, 2n) reaction compared Pb(n,2n). In other words, the cross-section of neutron absorption of Be is lower than Pb, which induced Be to be able to absorb fewer neutrons than Pb does. Therefore, it was useful to bring up much neutron to the $^6$Li(n,$\alpha$) reaction. Consequently, TBR increases when neutron multipliers use Be. When the thickness of the breeder zone is 50 cm and no enrichment of $^6$Li, TBR reached 1.2. Oppositely, when neutron multiplier material used Pb, the TBR was facing a decrease of around 0.15.

### 5. Conclusions

The study of tritium breeding ratio (TBR) was calculated using MCNPX simulation where the aim is to ensure the availability of tritium fuel in fusion reactors. The TBR value becomes greater when research proposed some strategies, such as:

1. Enlarging the volume of the breeding zone (BZ) escalated the TBR, which is 1.26 for thicknesses of about 55 cm.
2. Beryllium as neutron multiplication is superior due to the lower endothermic energy of the Be(n,2n) reaction compared Pb. It was used to moderate extreme neutron energy from plasma and propagated to be absorbed by $^6$Li.
3. Increasing the percentage of $^6$Li enrichment in the breeding material practically will give better value of TBR.
4. LiPb as tritium breeder material give great credit to the TBR value. When $^6$Li is higher in LiPb, it stimulated neutron absorption is much more with $^6$Li.

From these results, the research conclusion is, if the greater TBR willing to obtain; the lithium enrichment, more substantial volume of BZ, Be as neutron multiplier, and the ideal proportion $^6$Li in LiPb segment should provide in this blanket system.
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