Study on fusion blanket with ceramic solid as tritium breeding material

I R Maemunah¹, Z Su‘ud¹*, A Waris¹, D Irwanto¹
¹Nuclear Physics and Biophysics program, Physics Department, Institut Teknologi Bandung, 10 Ganesha Street, Bandung, Indonesia
*Corresponding e-mail: szaki@fi.itb.ac.id

Abstract. Variation of solid ceramic breeding might be one of the excellent candidates in a fusion reactor. The LiAlO₂, Li₄SiO₄, Li₂O, and Li₂ZrO₃ show pretty good requirements in tritium breeding capability and thermodynamic behavior. Especially for LiAlO₂ and Li₂ZrO₃, in which they could be possible to breed without neutron multiplying needed as blanket used generally in order to reach the self-sufficiency reactor. So that, it makes up the material could be possible as high-estimation breeder material.

1. Introduction
The biggest facility of a fusion reactor in the world is DEMO (DEMoNstration reaction), which applies the magnetic coil as plasma confinement. That is an international experimental fusion reactor developed in Cadarache, France. DEMO fusion reactor aims to be a commercial reactor that created a huge number of electric power. Therefore, to support the DEMO come to the real, the Cadarache team built the demonstration reactor, called International Thermonuclear Experimental Reactor (ITER), to exercise many methods and concepts that will apply to the ITER as long as the technology is feasibility in a fusion reactor. The fusion reaction induced by few reactions met the criteria of the largest cross-sections that are [1]:

\[
\begin{align*}
D + T &\rightarrow \alpha (3.54 \text{ MeV}) + n(14.06 \text{ MeV}) \\
D + D &\rightarrow T(1.01 \text{ MeV}) + p(3.02 \text{ MeV}) \\
D + \text{He} &\rightarrow \text{He}(3.6 \text{ MeV}) + p(14.7 \text{ MeV})
\end{align*}
\]

This reaction produces the energy for each reaction in which is higher than the fission reaction. High energy is giving the consequence of extremely high temperature, and it caused the plasma where the fusion reaction occurred to produce the high neutron production from the fusion reaction. The extreme temperature from plasma is attaining to 2 x 10⁹ Kelvin for D-T reaction. Automatically, fusion reactor materials need withstanding at that extreme condition.

In many options of the fusion reaction, it could be possible to react. One of the good chosen is D-T reaction. It has the most significant cross-section and provided quite sufficient energy production according to the risk given. Even the DT reactivity is 20 KeV, which is smaller than deuteron energy [2]. The fusion reaction contained charged particles that were trapped moving in a limited radius. Many scientists give the options, such as a magnetic field or pressurized by a high-energy laser for confining the charged particles.
One of the critical research in a fusion reactor is the tritium breeding module TBM. Furthermore, the essential issue in TBM research is tritium breeding requirement in which achieve self-sufficiency, high tritium breeding ratio [3], tritium extraction and recovery systems, and beryllium as moderator and multiplier of neutron [4].

This report is related to the blanket module in which one of the research considerations developed by DEMO or ITER research team is Helium Cooled Lithium Lead (HCLL) [5-6]. Generally, the design of HCLL module is applied whose modules are centered in an equatorial segment to the other side in upper and bottom ports to be 18 ports. This blanket module used solid ceramic breeding material [7], the ceramic material used not only for the breeder but also for a neutron multiplier. So that, this material gives the benefit to create both of function material in breeder zone.

2. Brief description of the blanket module

The ceramic solid tritium blanket is containing 18 ports that are set up for breeder, coolant, and material structure. The blanket dimensions are as follows: 8.1 m major radius, 5.4 m minor radius, 20 cm width, which reinforces into the radial and toroidal parts, as shown in Fig. 2. Meanwhile, it uses the EUROFER-97 as a material structure for separating the modules, where Helium as coolant applying inside the segment/port for tritium extraction and heat removal system in the blanket.

The module specification design is assembled of the middlebox with ceramic solid tritium breeder, interspersed by helium coolant channel in every 2 cm gap of the middlebox, upper and bottom covers by EUROFER-97 rigid parts. The parameter could be constant on the fusion reactor are fusion reaction energy 14 MeV, the average neutron wall load 2.5 MW/m² [8], neutron wall loading on the first wall > 0.5 MWa/m², and fluence > 0.3 MWa/m². The central solenoid (CS) is the outboard of the blanket. It has the primary function for plasma shaping in reducing the plasma radius that makes the plasma cannot come through to the blanket, including toroidal and poloidal ports contribution.

In addition, inside the box of the blanket, it contains many layers in which the systematics of structure from outer into the center are cover structure from stainless steel, beryllium multiplier layer, coolant layer, breeder zone, coolant, and breeder zone repeatedly, as shown in this figure 1.

![Figure 1. The interior design of the blanket consisted beryllium multiplier zone, coolant zone, breeder zone, and structure.](image)

This port consists of the small inboard blanket and large outboard that accommodates all of the blanket parts, including tritium breeder, neutron multiplier, and heat removal, even in small inboard. The primary function of cover in this module is to assure robustness of the blanket casing and its support against disruptions. In other ways, it used to be a replaceable segment in the blanket casing that is desirable replaced regarding tritium breeding. These blanket cases give an advantage against disruption from the magnetic coil effect.

Due to increase the tritium breeding effectively, inboard port plants many beryllium plates to produce a large number of the neutron. Meanwhile, ceramic solid contributes another huge effect of
tritium breeding. Aside from that, the helium coolant is heat removal to carry out the heat from the reaction in the blanket board. This paper aims to find the best candidate for the blanket concept by the neutronic and thermal design of the blanket.

This neutronic study concerns nuclear heating distribution and neutron flux distribution in the blanket. The Monte Carlo code that is using provides the temperature profile in the blanket and the local tritium breeding ratio. The blanket design contains a multilayer structure, following as breeder and multiplier layers like a sandwich for providing the highest TBR. Lithium ceramic as breeder material are LiAlO$_2$, Li$_4$SiO$_4$, Li$_2$O, and Li$_2$ZrO$_3$. These lithium-based oxide ceramics have an excellent requirement to become a recommendation material in the breeder zone, cause of this reason as following [9]:

- High tritium breeding ratio
Caused of the solid ceramic breeder has a high neutron capture cross-section, increasing the possibility of the neutron interaction with lithium in a solid breeder. Automatically, lithium concentration that reacts with neutron is enormous, so the tritium production from neutron lithium interaction is vast.

- High thermal and mechanical stability
One of the most substantial solid breeder properties is a high melting point. It makes material can endure in high temperature as in fusion reactor circumstance. Over a thousand centigrade of melting point solid breeders have made high material prevention in hot conditions maximum. Possibility in such severe conditions for this ceramics brings out save condition wherein melting condition, material such failure in one form changing, reduces the avoid effect.

- Low tritium inventory
Low tritium inventory birth on this material in which decreases the tritium trapping possibility in the material. It means gas production on this option will be decreased and benefit a safety system in a reactor.

- Easy fabrication
Meanwhile, the fabrication technique of this ceramic solid is relatively easy, so the production of pellet and pebble is more significant than any material used in the fusion reactor.

- High thermal conductivity
For the thermal-hydraulic aspect, this solid ceramic material has its efficiency. This property of the ceramic solid is high. It is easy to remove the heat and carried out into an electrical turbine. Consequently, rather than the breeder role, this ceramic solid takes the hydraulic role for granted.

- Low activity
Low activity after irradiation of ceramic solid ignores the hazard condition due to the radiation effect involve after an accident.

For detail, it shows in table 1 where it showed evidence of the ceramic solid breeder requirement by JAEA report.

| Li density ($g/cm^3$) | LiAlO$_2$ | Li$_4$SiO$_4$ | Li$_2$O | Li$_2$ZrO$_3$ |
|----------------------|----------|---------------|---------|---------------|
| Melting point ($^\circ$C) | 1610 | 1255 | 1432 | 1600 |
| Thermal conductivity ($W/mK$) at (400$^\circ$C) | 2.6 | 2.5 | 6.0 | 1.4 |

Either tritium breeding or neutron multiplier, ceramic solid is powerful in both aspects. It means solid breeder materials have to consider as good material performance. The systematic of the layer in this blanket is affected by the effects of each material in this blanket.

The neutron multiplier in the Beryllium plate consists of many layers in which for; the first layer located after the first wall containing the pure beryllium due to the high neutron energy from plasma
that can handle by the excellent thermal conductivity beryllium has, and beryllium can avoid neutron absorption by another neutron multiplier material.

3. Research method

Three-dimensional calculations with this type of module were performed using the Monte Carlo code MCNP-5 to evaluate the tritium breeding, atomic displacement, and helium production in the structure. The previous design has performed [11] indifference of breeder material. In a further development, it applies the solid ceramic lithium, which has the best breeder material for ITER or DEMO blanket.

This study adopted the DEMO reactor design where it builds a major and a minor radius are 8 m and 3 m, respectively—this blanket is equipped with a divertor as temporary storage of ash and Helium. Helium is captured by divertor to stabilize the plasma temperature. Besides, First Wall (FW) is also used to capture neutron maximally and moderate this neutron. Besides FW, there is also shielding and cryostat that act as a protective layer. Each shape configures with many layers as first wall, breeder zone, coolant, and structure. It is a solid component where built all up zone as shown in figure 1.

The MCNP5 simulated built the geometry designed by custom mode to create an own-fusion reactor with VISED for monitoring every single path. This code could perform neutronic calculation under high neutron energy, include 14 MeV. The primary resource of nuclear data used by MCNP code evaluated from the Evaluated Nuclear Data File (ENDF) systems [12]. This code is a robust simulation due to the customized geometry that can build to approach the actual reactor and apply the particle transport formulation that is more accurate than diffusion formulation, although the time consuming is so long.

4. Result and Analysis

This research invited many variations of the blanket material, which are supposed to raise the high tritium breeding to figure out the optimum DT fusion fuel production. It might happen just by inserting the lithium-based oxide ceramic materials to breed becoming tritium. Variation of solid ceramic breeder used are LiAlO$_2$, Li$_2$ZrO$_3$, Li$_4$SiO$_4$, and Li$_2$O.

Many research has been developed to find the maximum value of TBR, include using the solid breeder material. TBR produced at this material is around 1.3 until 1.35, and it is a huge and sufficient ratio to give numerous tritium in DT fusion fuel. Solid breeders becoming the excellent material in a fusion reactor creates the possibility high tritium breeding ratio (TBR), where automatically it is used to enhance the fusion fuel in the core. High material thermal and mechanical stability has in this solid breeder to stay long endurance of the material. From the material properties data, which is belonging to the solid material as LiAlO$_2$, Li$_2$ZrO$_3$, Li$_4$SiO$_4$, and Li$_2$O, they have the high melting points shown in table 1.

For this case, it particularly can define the calculation of TBR more comprehensively with a difference of breeder material and thickness variation. It gives a broad perception that can be more precise to specify the requirement of TBR optimization.

As shown in this figure, the higher of breeder zone thickness follow, the higher of TBR value due to the increase of neutron cross-section. It activated a massive number of neutron interactions in the material of this blanket.
Figure 2 performs the highest TBR value performed by Li\(_2\)O, and this is due to the high lithium density it has, as shown in table 1. Higher lithium-containing in material, more efficiency of lithium interaction in Li\(_2\)O, so that the TBR results from lithium-containing inside, followed after Li\(_4\)SiO\(_4\), LiAlO\(_2\), and Li\(_2\)ZrO\(_3\). For Li\(_2\)ZrO\(_3\), it has a lithium density more than lithium alumina, LiAlO\(_2\); then it makes reduced the TBR value. It is due to differences in the neutron reaction cross-section of both of these materials. It took a core of impact in neutron reaction and material effectively. Meanwhile, in 80 cm thickness, for Li\(_4\)SiO\(_4\), LiAlO\(_2\), and Li\(_2\)ZrO\(_3\), their TBR value has no large gap significantly caused of this thickness pretty large to overcome neutron bombarding into the material surface for making high interaction feasibility.

In 20 cm thickness, three of materials tread TBR value more than once, which means this thickness is enough well for taking the self-sufficiency condition and loss issue technical in tritium transportation can be ignored for temporary so that the sufficient thickness makes a judgment of neutron level interaction significant.

The highest TBR value is undebatable had by Li\(_2\)O consistently in any thickness of the breeding zone. Still, this lithium oxide was not a good recommendation for material breeding components due to the low thermal stability that makes material used in technical difficulties. Hence, another option as Li\(_4\)SiO\(_4\) and LiAlO\(_2\) might be better for breeding.

In the melting point category, Li\(_4\)SiO\(_4\) has the lowest, indicating Li\(_4\)SiO\(_4\) cannot be enduring at high temperature of the blanket, but coolant existing participated in reducing and carrying on neutron heat change electrical energy. So that, Li\(_4\)SiO\(_4\) brings out a good tritium breeding ratio without breeding, and easy suppling caused the stock of material to be quite large, but the rest of Li\(_4\)SiO\(_4\) has a lot of repairing work, especially in thermodynamic behavior and swelling ceramic.

Meanwhile, lithium aluminate (LiAlO\(_2\)) has quite an excellent option to become the breeder material. Apart from the high tritium production, it is a good cause of its high melting point, leading to extreme temperature. However, it has a weakness in low tritium recovery, but it is not an issue to be a worry. Because of the high trapping of tritium in material, it will reduce tritium transportation into the core. But, somehow, it could be handled by a mechanism.
Figure 3. The effectivity of Li(n,T)He reaction when Be multiplier occupied 20% in total Breeder volume.

Figure 3 shows the effectivity of Li(n,T)He reaction when 20% of beryllium multiplier occupied in total breeder volume with the rest breeder material and coolant. It figures out that the capture capability of the neutron in solid ceramic materials is quite the same as the downward trend. It means that the ceramic solid can breed without neutron multiplier material component. It cannot say if beryllium is not affected, but it still has a role in improving tritium release, reducing thermal stresses, and accommodate neutron-induced swelling [13].

The anomaly pattern from the figure is the lowest absorption facing of the LiAlO$_2$ when the thickness of the breeder zone is around 5 cm. The Li density of LiAlO$_2$ causes it to be low, which decreases captured neutron material, and automatically it will be lower of tritium production.

Figure 4. TBR on Li-6 enrichment variation (20 cm in thickness).
Figure 4 shows LiAlO$_2$ has a high tritium breeding ratio due to the highest reaction of $^6$Li(T, n)n'. In this case, Li$_2$SiO$_4$ is the highest TBR due to its properties. Its properties contributing to the breeder proportions are low activation characteristics, low thermal expansion coefficient, high thermal conductivity, high density and stability, and the cheap fabrication cost.

The higher lithium-6 enrichment of the material used makes the higher of tritium breeding ratio it might get. Even Li-6 enrichment in Li$_2$SiO$_4$ is 10%, the tritium breeding ratio is already more than one. Finally, all over the materials are recommended being breeder material with many self-beneficial, especially for Li$_2$SiO$_4$ and LiAlO$_2$. It considers being a good one caused Tritium breeding optimization result and its material properties it is.

5. Conclusions
Li$_2$O has the highest TBR value, but it is not so good for breeder material recommendation caused of low thermal stability it has that makes practically used this material facing difficulties. In addition, other material properties are not as good as other ceramic solid breeders. Another case, for Li$_2$SiO$_4$, has an excellent thermodynamic aspect and material properties, which might be a good choice, such as low activation characteristics, low thermal expansion coefficient, high thermal conductivity, high density and stability, and the cheap fabrication cost. Moreover, Li$_2$SiO$_4$ has a low melting temperature range, so the problem concern is the thermal-hydraulic where heat transport is still working hard to do further. Furthermore, LiAlO$_2$ is an excellent material to create high tritium breeding ratio. Otherwise, it might need to assess as long as it increases the tritium breeding by much neutron multiplier existent. Besides that, the Material property of LiAlO2 is quite the same as Li$_2$SiO$_4$, such as inactivation reaction.

References:
[1] Nuclear Fusion, available from: http://hyperphysics.phy-astr.gsu.edu/hbase/NucEne/fusion.html
[2] M. Rubel 2018 Fusion neutron: tritium breeding and impact on wall materials and components of diagnostic systems J. Fus. Energy 38 315-329
[3] Charles C. Baker 1985 Fusion Blankets-A Comparative Study J. Fus. Eng. 4 Nos. 2/3
[4] U. Fischer, C. Bachmann, I. Palermo, P. Pereslavtsev, and R. Villari 2015 Neutronics requirements for DEMO fusion power plant Fus. Eng. Des. 98-99 2134-2137
[5] G. Aiello, J. Aubert, N. Jonquèresa, A. Li Puma, A. Morin and G. Rampal 2014 Development of the Helium Cooled Lithium Lead Blanket for DEMO Fus. Eng. Des. 89 1444-1450
[6] J. Aubert, G. Aiello, J. C. Jaboulay, B. Kiss and A. Morin 2016 Status on DEMO helium cooled lithium lead breeding blanket thermos-mechanical analyses Fus. Eng. Des. 109-111 991-995
[7] S. Zhen and T.N. Todd 2015 Study of impact on tritium breeding ratio of a fusion DEMO reactor Fus. Eng. Des. 98-99 1915-1918
[8] H. M. Şahin, Ş. Yalcin, T. Altonik and A. Acir 2008 Monte Carlo Calculation For Various Enrichment Lithium Coolant Using Different Data Libraries in A Hybrid Reactor Energy Conv. Management 49 1960-1965
[9] G. W. Hollenberg, T.C. Reuther and C. E. Johnson 1982 Lithium Ceramics as the Solid Breeder Material in Fusion Reactors American Ceramic Society HEDL-SA-2677-FP
[10] H. Kwast 1996 Exotic: Development of Ceramic Tritium Breeding Materials for Fusion Reactor Blankets Netherlands Energy Research Foundation ECN-C-90-042
[11] I. R. Maemunah, I. Putranto, Z. Suud 2014 Optimization of Tritium Breeding and Shielding Analysis to Plasma in ITER Fusion Reactor AIP Conf. Proc. 1677 070021
[12] D. B. Pelowitz 2008 MCNPX user’s manual Version 2.6
[13] L. Giarcarli, H. Golffier, S. Nishio, R. Raffray, C. Wong and R. Yamada 2002 Progress in Blanket Designs Using SiCf/SiC Composites Fus. Eng. Des. 61-62 307-318