Comparative of blanket reactor design in assuring of tritium self-sufficiency

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Abstract. The comparison of four blanket modules in DEMO made up the optimization material having a reasonable requirement as blanket material in this study. Either neutron flux distribution in blanket material or material endurance under neutron irradiation, from four modules, the WCLL has a high tolerance neutron distribution and the best neutron irradiation endurance. Furthermore, many suggestions closed to the statement to use the benefits of water coolant and lithium lead (compose Li-6) as a material component in the blanket.

1. Introduction

Many blanket designs are developing in many countries, including European design created by a European demonstration fusion power station (DEMO) [1]. DEMO is an experimental reactor that supported the ITER (International Thermonuclear Experimental Reactor) further.

In a D-T fusion reaction, the long fusion fuel is essential for sustaining the fusion reaction. The most important blanket capability that might plant inside is tritium breeding. Its need caused by the abundance of tritium in nature is rare, about 10⁻¹⁸ of natural hydrogen within the half-life time of 12.32 years. So that, reactor might be self-produced the tritium with interaction scheme between neutron and lithium. Lithium neutron interaction in the material is following this reaction [2]:

\[ ^{6}\text{Li} + n \rightarrow \alpha + T + 4.7 \text{MeV} \]  \hspace{1cm} (1)

\[ ^{7}\text{Li} + n \rightarrow \alpha + T + n' - 2.47 \text{MeV} \]  \hspace{1cm} (2)

\[ ^{7}\text{Li} + n \rightarrow 2T + 2n' - 10.3 \text{MeV} \]  \hspace{1cm} (3)

Both lithium isotopes produce tritium and some energy which could be the best scheme for satisfying the self-sufficiency condition. The self-sufficiency requirement in a fusion reactor is playing a role in the blanket, not only the breeding system but also tritium transport, heat removal, neutron absorption optimization, etc., in the whole part of the blanket. That is a crucial reason for developing test blanket module (TBM) research studied in recent decades. It evolved with many types of modules.

The four TBM types were tested in DEMO as Helium Cooled Lithium-Lead (HCLL), Helium Cooled Pebble Bed (HCPB), Water Cooled Ceramic Breeder (WCCB), and Water Lithium Lead (WCLL) [3]. Most of these studies are directed to optimize the tritium capability to minimize the thickness of the blanket due to the effect of the neutron source interaction surrounding the plasma.
chamber while ensuring tritium self-sufficiency. Another function of the blanket is heat removal for electrical conversion, carried out by coolant in the blanket.

For instance, a Helium Cooled Lithium-Lead (HCLL) is the blanket module that applies helium as a coolant and lithium lead as tritium breeder; it is a unique design in charge by CEA for DEMO to create the tritium breeding ratio target equals to 1.1 [4]. It employed the Eurofer as a structural material and stainless steel at any other layer to configure the blanket structure [5].

A Water Cooled Ceramic Breeder (WCCB) module evaluated in Japan was performed data by Japan Atomic Energy Agency (JAEA) with collaboration with universities and National Institute for Fusion Science (NIFS). They applied Li$_2$TiO$_3$ pebble and beryllium pebble as a ceramic breeder and neutron multiplier [6]. A Helium Cooled Pebble Bed (HCPB) is one of the enormous blankets employed in many countries for experiments, especially for EU Breeding Blanket programme for DEMO in TBM programme. The concept separated parts between the lithiated solid ceramic as breeder and beryllium as neutron multiplier part in this blanket [7].

A Water Lithium Lead (WCLL) used the liquid alloy Pb-7Li as breeder and beryllium neutron multiplier with water as pressurized coolant. This blanket concept is essentially formed by reduced-activation ferritic-martensitic steel as a structural material with a coolant container near the structure and inside the box [8]. Regarding the simulation with MCNP5, these comparisons calculate the four types of blanket modules. The head design of the blanket module is in the geometry size, part of layers, and the position of parties. The comparison concerns the neutron flux distribution to know the spectrum pattern of every blanket and the damaged material in every single port.

2. Brief Reactor Design
The design of reactor simulated partied into 18 ports (from port-A to port-R), from bottom inboard at the beginning, as we can see in figure 1. The blanket design is partying into 18 ports where every port configures the first wall and blanket where each port has its coolant and breeder material surrounded by the structure. The height of the reactor in vertical is 13 m, and the major radius of the torus is 7.6 m, following the inboard radius toward the outboard radius from 3.4 m to 11 m. All candidates might not be good enough to be a material containment for the blanket; it might be investigated by the effectiveness of the neutron absorption capability, how much huge quantity of neutron leakage, and material endurance under the high pressure. This blanket took a challenge to evaluated material used in this research study in neutron bombarding and radiation damage from these goals.

The design employed for four blanket modules are, in fact, identical and conform to the general design by adjusting the size geometry from DEMO that developed sincerely since 2004 in the completed design. For structural material, Ferritic steel (HT-9) was applied to unite the blanket configuration. Meanwhile, for the neutron multiplier, the one option that is pleasant to multiply neutron effectively is beryllium. The consideration criteria for neutron multiplier are solid at high temperature, difficult swelling, and high supply.
3. Method and Reactor Model
This study adopted the European DEMO reactor that was calculated by Monte Carlo N-Particle (MCNP5) code. As seen in figure 1, it configured into 18 ports with each port built up first wall material towards the blanket. This code has performed neutronic calculation under source energy of 14.1 MeV and neutron wall load of 2.25 MW/m² [9]. The primary source of nuclear data used by MCNP code evaluated from the Evaluated Nuclear Data File (ENDF) systems [10].

This simulation code will be given custom geometry approaching as good as the authentic DEMO design. Moreover, using this code could measure particle transportation in space and time accurately. It might assure the precise calculation than diffusion approaching, although the time consuming is so long.

As mentioned above, the simulation will concern simulated for four blanket modules to find the neutron distribution that represents the material capacity in blanket and radiation damage effected to investigate the endurance of blanket material withstanding under extreme conditions.

4. Result and Analysis

4.1 Neutron flux distribution
The neutron flux distribution is an issue that might be calculated by a representative of the excellent and optimized reactor. An analysis can estimate for knowing the neutron absorption effectively in each material. This calculation presented the best material composition and configuration that created high neutron interaction effectively. For all patterns of the flux distribution in figure 2, it contributed peaking at port-D, and port-N represents the equatorial port of torus. It means if the charged particle mass is concentrated at equatorial.
On the other hand, it showed the neutron flux for each blanket module. For HCLL blanket module, it takes the highest neutron absorption. The HCLL blanket with helium coolant is sensitive and reacted toward thermal neutrons. It is one of the contributed neutron absorptions in the material by this coolant, but the production of this reaction is hydrogen ions [11]. It figures to harm the whole reactor. For this case, helium only reacted to the thermal neutron, so that it needs to moderate the neutron by neutron multiplier, which is supporting by beryllium. This module applied this beryllium layer into a blanket before the breeding zone. Another considerable contribution is lithium lead that produced tritium from neutron absorption. For instant, every port of the HCLL blanket has the highest caused the structure of the reactor used is optimum for neutron absorption.

![Figure 2. Total neutron flux in 18 poloidal ports of breeder zone blanket.](image)

The HCPB module used the lithiated solid ceramic as Li$_2$O in the form of a pebble bed. The lithium atomic applied to this material made up the high of neutron absorption. Lithium-$\text{6}$ isotope is adequate to catch up the thermal neutron for tritium breeding, as seen in equation 1. Lithium-$\text{7}$ roles as neutron multiplier like beryllium and breeder and moderator do thermalize neutron; hence, it is used for Li-$\text{6}$ interaction. In addition, coolant participated as HCLL scheme for cooling and thermal catching.

In other cases, for WCLL and WCCB, both modules applied water as a coolant. The neutron cross-section of water is lower than helium-cooled [12,13], exhibited by the trend of the neutron flux distribution. It represented that the neutron cross-section of helium is higher than water.

### 4.2 Radiation damage

The material behavior might be happened cause of transmutation due to the neutron irradiation. These lead to material damage initiated either swelling or corrosion. One of the vital measurements of the radiation damage parameter is displacement per atom (dpa). This calculation will consider material affected to belong to the first wall in four blanket modules—tungsten as FW material used for any blanket module configuration as divertor material.
Figure 3. Poloidal-tungsten first wall of radiation damage (unit: dpa/fpy) in each port of four blanket modules.

The radiation damage mechanism is supposed to address the displacement per atomic (DPA). Figure 3 depicts the DPA in four modules with the same first wall material. It shows the DPA of HCPB and WCCB is lower than HCLL and WCLL, and the neutron energy causes it in lithium lead by Li-7 moderation weakening coolant, it respected to increase the damage of DPA.

The HCLL concept results from the highest radiation damage rates, maximum ~22.85 dpa/fpy followed by the WCLL with a maximum damage rate around 18.75 dpa/fpy. It means, on average. There are 22 for every reaction. Next, the rest of the modules of WCCB and HCPB are following with maximum rates, 15.94 and 13.72.

5. Conclusions

Neutron flux distribution has the highest measurement on equatorial port (Port-D and port-N), which means if these ports are closed to the plasma reaction that shoots out neutron into the first wall and blanket. Moreover, the highest total neutron flux is the helium-cooled lithium lead (HCLL) module caused by lithium-6 required to counter-balance the reduced FW. Furthermore, the coolant used at the HCLL module being moderator effectively to enhance the effectiveness of lithium-6 isotope performance; this also happened to WCLL. Meanwhile, for HCPB and WCPB, using lithiated solid ceramic as Li2O in the form of a pebble bed made up the high of neutron absorption due to the lithium used for the breeder is not higher lithium lead did. For radiation damage, a HCLL produced the most significant neutron irradiation estimated dpa/fpy, about 22.8. The rest of the atomic displacement is 18.75 DPA/fpy, 15.94 dpa/fpy, and 13.72 dpa/fpy, following in WCLL, WCCB, and HCPB modules. HCLL and WCLL are the worst modules taken irradiation damage due to the Li-7 isotopes that can cause a reduction of the cooling capability inside the blanket. Furthermore, in radiation damage, the WCCB module is taken into a requirement of material endurance under high neutron irradiation. Finally, many suggestions closed to the statement to use the benefits of water coolant and lithium lead as a material component in the blanket.
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