Prediction of tritium flux in mock-up blanket using MCNP

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Abstract. The production of tritium from a lithium self-cooled blanket with a vanadium alloy structure (Li/V) was predicted using the Monte Carlo N-Particle transport code (MCNP). The mock-up blanket was set up with a lithium breeder, reflector, shielding and structure. Different types of liquid lithium, including natural lithium, FLiBe and LiPb, were considered. The LiPb was found to produce the highest tritium production rate per source neutron among the three types of liquid lithium. Additionally, the concentration of 6Li in the liquid lithium affected the tritium production rate. With 75 percent 6Li enrichment in the LiPb, the average ratio of tritium production to each neutron in the breeder zone was 1.528, which was about three times higher than when using natural lithium. Moreover, a 2 cm first wall was added in front of the model. It was also found that the first wall affected the ratio of the tritium production to each neutron in the breeder zone.

1. Introduction

Tritium is considered to be one of the main fuels for the D-T reaction in nuclear fusion reactors, which releases the energy of 17.6 MeV as:

$$D + T \rightarrow {}^{4}He\ (3.5\ MeV) + n\ (14.1\ MeV)$$

About 80 percent of the energy carried by the neutrons may escape the blanket or is absorbed by the lithium blanket. The interactions between the 14.1 MeV neutrons from the nuclear fusion reactions and the lithium from the blankets provide the tritium that is considered to be a fuel for D-T fusion [1, 2]. Since tritium is limited in natural resources and it spontaneously decays to ^{3}He, tritium production in the blanket should be studied. For the fusion nuclear technology, the blanket including the first wall provides three necessary functions for the fusion reactor: *i*) tritium production, *ii*) heat recovery and *iii*) radiation shielding. Most recent studies show tritium being produced in two isotopes of lithium. Naturally, there are two lithium isotopes, ^{6}Li and ^{7}Li with 7.42 percent and 92.58 percent abundance, respectively. Tritium (T) is produced through nuclear reactions as follows:

$$^{6}Li + n\ (slow) \rightarrow {}^{4}He + T + 4.8\ MeV \quad \text{and}$$

$$^{7}Li + n\ (fast) \rightarrow {}^{4}He + T + n - 2.5\ MeV$$

The $^{6}Li(n, \alpha)T$ reaction is the most effect for the thermal type blanket due to the high cross section of the slow neutrons, while the $^{7}Li(n, n'\alpha)T$ is not important in the tritium production in the blanket due to the low cross section and insensitivity to thermal neutrons.

Different types of Li based breeder blanket design have been proposed based on different breeder compositions and structure concepts. The first design was a ceramic breeder material, such as lithium titanate (Li_2TiO_3), Li_4SiO_4 and Li_2O, etc. [3-6] using He for cooling. This concept was proposed by all ITER parties. Moreover, Japan was interested in the water cooled

Li breeder blanket [7]. However, this kind of blanket requires beryllium (Be) as a neutron multiplier with Ferritic/Martensitic Steel (FMS) or F82H as the blanket structure. Concerning the natural resource limit and the life time of the beryllium in the second concept for the blanket, self-cooled liquid lithium was considered [2, 8-10].

For the self-cooled lithium blanket, the neutron multiplier beryllium is not required, thus the replacement frequency of the blanket is reduced. It was designed as an advanced concept for DEMO and a commercial fusion reactor. The blanket requires breeding and cooling materials, structure, reflector and shielding. The major candidates for the liquid breeder materials are ^{6}Li-enrichment, lithium-lead (LiPb) and FLiBe, etc. Vanadium alloy (V-4Cr-4Ti) has been selected for the blanket structure material due to the low activation properties and high temperature strength [8]. The self-cooled lithium blanket presents the advantages of *i*) high heat transfer capability due to the physical properties of the vanadium alloy structure, *ii*) high heat flux transfer of the liquid lithium and *iii*) low tritium leakage due to the high solubility of the tritium in the liquid lithium.

In the blanket, photons, protons, deuterium, tritium, ^{3}He and alpha can be produced through the (n,γ), (n,p), (n,d), (n,t), (n,^{3}He) and (n,α) reactions of the neutrons with the first wall structure. Here the primary particle production on the first wall, including tungsten, beryllium metal and carbon steel, will be considered. The selection of the material and optimization will provide information about and explore the design requirements of the blanket technology for ITER and DEMO. The design criteria were *i*) tritium breeding ratio $\geq$ 1.1, *ii*) permissible temperature for used material and *iii*) maximum neutron damage $\approx$ 3 displacement per atom (dpa).

This work was focused on the neutron transport in the blanket mock-up module. The Monte Carlo N-Particle transport code (MCNP) version MCNPX [11] with nuclear library ENDF/B was used to study the nuclear parameters for the blanket design. The mock-up model was designed using the design criteria conditions as discussed above. The tritium production rate and the neutron distribution were investigated.

2. Design of the blanket

A lithium self-cooled blanket with vanadium alloy structure (Li/V) was designed in this work. The mock-up assembly of the breeder zone, reflector, shielding and structure is shown in FIG.1. The breeder zone consisted of five layers (10 cm thickness for each layer) of the natural lithium and lithium composition materials (FLiBe and LiPb). Each layer of the breeder material was separated into 2 cm thick sections for the neutronic calculation. The reflector was tungsten while the shielding was tenelon (Fe1518) with thicknesses of 20 cm and 50 cm, respectively. All materials were assembled in a 1 cm thick vanadium alloy structure. The overall external dimensions of the mock-up model were 128 cm × 22 cm × 22 cm.

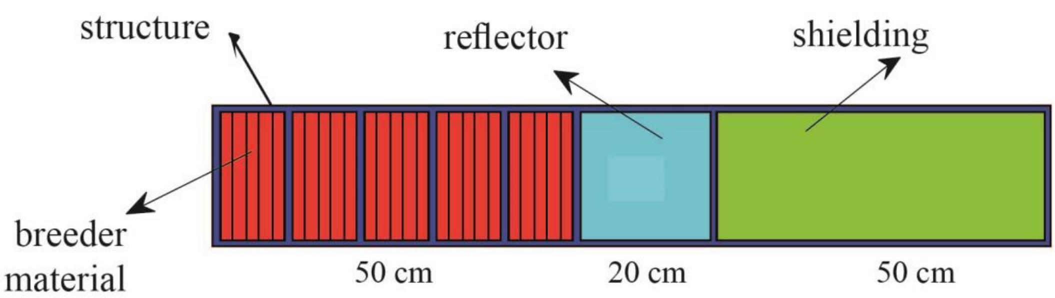

FIG. 1. Calculation model for material and structure in self-cooled liquid lithium blanket.

The 14.1 MeV neutrons source was fixed at the front of the blanket. The neutron beam radius was set as 1 cm. In addition, the 2 cm thickness of the first wall materials included tungsten, beryllium metal and carbon steel, which were added in the mock up model to study the effect on the tritium production rate and the primary particle production in the breeder zone and first wall.

3. Results

3.1.Tritium production rate in breeder materials

Three materials were selected: *i)* natural lithium, *ii)* FLiBe (natural Li composition) and *iii)* LiPb (natural Li composition). The neutron energy distributions in specific layers of the breeder zone were investigated. The neutron spectra per source neutron at the thicknesses of 2, 28 and 54 cm of the breeder zone (the origin position (0 mm) was the surface of the first structure zone) were obtained and are presented in FIG.2 and Table I. The results show that the slow neutrons (E_n < 10 keV) were generated in the layers of the breeder materials. For the natural lithium (see FIG.2(a)), the integrated slow neutrons increased through the depth layer of the breeder zone as reported in Table I. In contrast, the integrated slow neutrons decreased through the depth layers of the FLiBe (see FIG.2(b)) and LiPb (see FIG.2(c)).

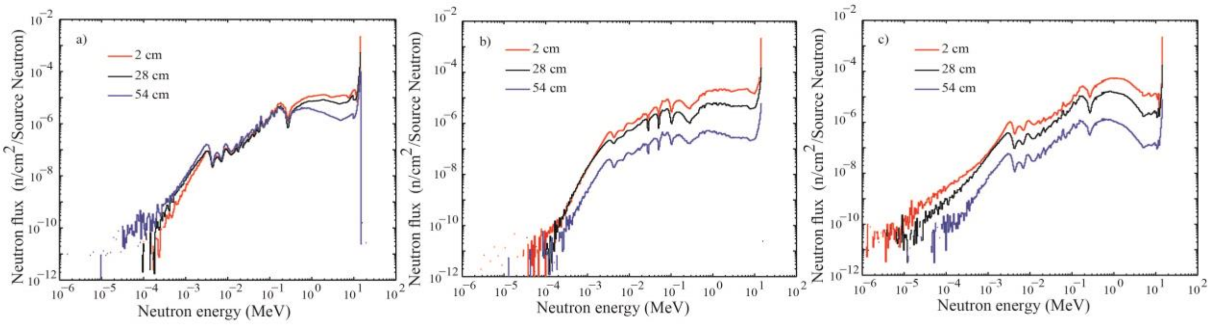

FIG. 2. Neutron energy spectra per source neutron at 2 cm, 28 cm and 54 cm (origin position was surface of first structure zone) in mock-up blanket assembly: (a) natural lithium, (b) FLiBe and (c) LiPb.

TABLE I: SLOW NEUTRON FLUXES PER SOURCE NEUTRON AT KEY POSITIONS IN MOCK-UP BLANKET.

Breeder material	**Slow neutron flux per source neutron (n/cm^2)**		
	2 cm	**28 cm**	**54 cm**
Natural lithium	0.242×10^{-5}	0.255×10^{-5}	0.402×10^{-5}
FLiBe	1.856×10^{-5}	1.053×10^{-5}	0.147×10^{-5}
LiPb	2.935×10^{-5}	1.144×10^{-5}	0.162×10^{-5}

Most of the tritium is produced due to the slow neutrons in the breeder zone, thus the tritium production rate is higher when the slow neutron flux is higher due to this high cross section of slow neutrons in the lithium. Therefore, in the tritium production procedure, the slow neutrons are needed. FIG.3(a) shows the integrated slow neutrons and FIG.3(b) shows the integrated fast neutrons in the breeder zone. For the natural lithium, the highest slow neutron production was in the last breeder layer near the reflector, while it was low in the FLiBe and LiPb. Thus, the reflector was not necessary for the FLiBe and LiPb when obtaining slow neutrons. About three and four percent of the slow neutrons were produced in the last breeder layer compared to the first layer for the FLiBe and LiPb, respectively.

The fraction between the slow neutrons to the fast neutrons is presented in FIG.3(c). The FLiBe and LiPb have an improvement to moderate for the fast neutrons to the slow neutrons due to the large cross section of beryllium and lead for the (n, 2n′) reaction. Therefore, the results show that the fraction of slow neutrons to fast neutrons was higher in the FLiBe and LiPb compositions.

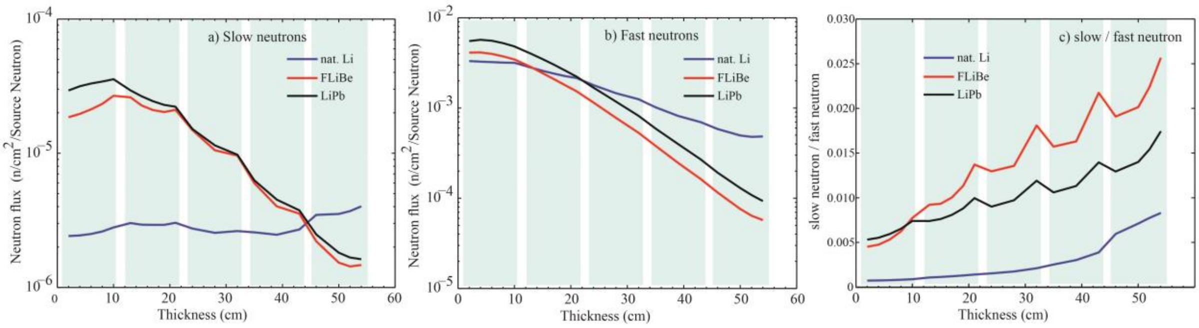

FIG. 3. Integrated (a) slow neutrons, (b) fast neutrons and (c) fraction of slow neutrons to fast neutrons in breeder zone.

The tritium production rate per source neutron in the breeding zone is presented in FIG.4(a). The highest tritium production rate was for the LiPb. The rate was reduced by about two orders of magnitude between the first layer and the last layer of the breeder zone. However, the tritium production in the LiPb was higher than in the FLiBe by a factor of about four over the breeder zone.

FIG.4(b) shows the tritium to neutron ratio in the breeder zone. In the natural lithium the ratio in the local breeding layer slightly increased from 0.005 to 0.016 from the first layer to the last layer, thereby providing an average ratio of 0.008. The FLiBe provided the ratio of tritium production to each neutron in the local breeding layer of between 0.122 and 0.301, thereby giving an average ratio of 0.200. The ratio in the local breeding layer of LiPb slightly decreased from 0.660 to 0.405 from the first layer to the last layer, thereby providing an average ratio of 0.506. From the obtained results, the LiPb composition showed a high efficiency for tritium production in the breeder zone.

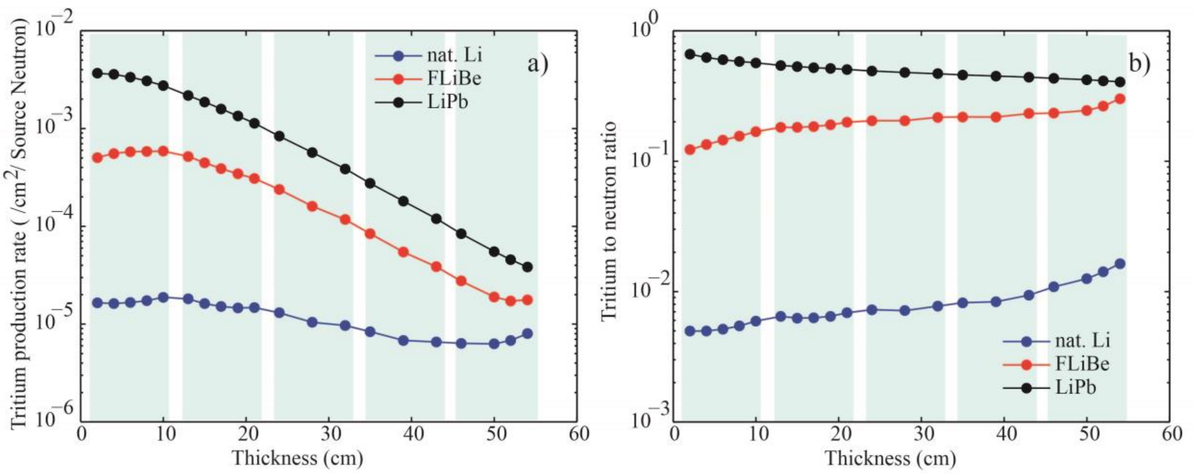

FIG. 4. (a) Tritium production per source neutron and (b) tritium to neutron ratio in breeder zone for natural lithium, FLiBe and LiPb.

3.2.Concentration of ^{6}Li in liquid lithium

Due to the highest tritium production rate per source neutron in the breeder zone, the LiPb was selected as the breeder material to study the effect of the concentration of ^{6}Li in the liquid lithium. Here, the percentage of the ^{6}Li was enriched between 0 and 100 percent in the LiPb composition.

The neutron energy distributions in the ^{6}Li enrichment LiPb were observed. The slow and fast neutrons per source neutron in the breeder zone are shown in FIG.5(a) and FIG.5(b). FIG.5(c) shows the ratio of slow neutrons to fast neutrons in the breeder zone. The obtained tritium production rate per source neutron is shown in FIG.6(a), while the ratio of tritium to each neutron is shown in FIG.6(b).

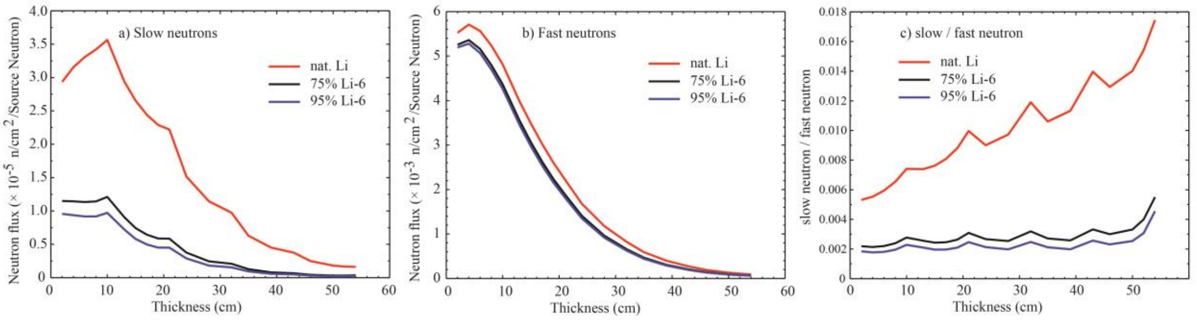

FIG. 5. Integrated (a) slow neutrons, (b) fast neutrons and (c) the fraction of slow neutrons to fast neutrons in breeder zone of different ^{6}Li concentrations in LiPb breeding material.

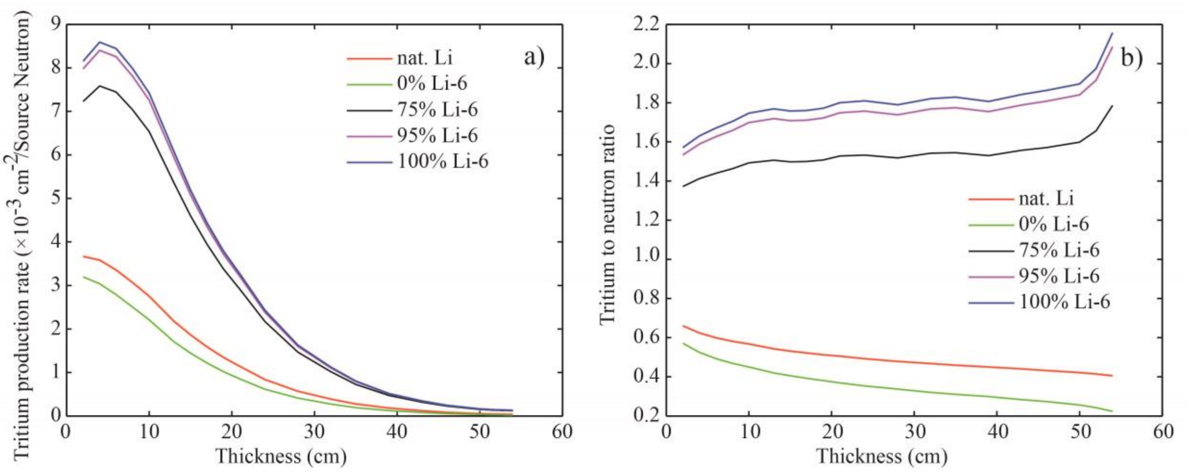

FIG. 6. (a) Tritium production rate per source neutron and (b) tritium to neutron ratio in breeder zone of different 6Li concentrations in LiPb breeding material composition.

The amount of slow neutrons was high in the natural lithium due to the large cross section of the ^{7}Li(n, n′α)T in the natural lithium, but the tritium production in FIG.6(a) is low due to the abundance of the ^{6}Li in the breeder composition. The tritium production increased with the increasing percent ^{6}Li enrichment and decreased due to the increasing breeder layer. The ratios of tritium production to each neutron in the local breeder layer are presented in Table II. The high ^{6}Li concentration in the LiPb produced the highest tritium to neutron ratio. With 75 percent ^{6}Li enrichment in the LiPb, the ratios of tritium production to each neutron in the local breeding layer were between 1.372 and 1.787 with an average ratio of 1.528.

However, due to the fast decay of tritium and leakage in the tritium recovery system, 75 percent ^{6}Li enrichment was sufficient for the LiPb to achieve the design criteria.

TABLE II: MINIMUM AND MAXIMUM RATIO OF TRITIUM PRODUCTION TO NEUTRON IN LOCAL BREEDER ZONE AND AVERAGE VALUE.

Percent of ^{6}Li enrichment	Tritium to neutron ratio		
	Minimum	**Maximum**	**Average**
0 %	0.224	0.572	0.369
Natural lithium	0.406	0.661	0.506
75%	1.372	1.787	1.528
95%	1.533	2.087	1.747
100%	1.571	2.158	1.798

3.3.First wall effect

First wall materials including tungsten, beryllium metal and carbon steel were considered and added to the model to study the effect on the tritium production rate in the breeder zone. In this work, the 75 percent ^{6}Li enrichment of LiPb was used as the breeder material. The tritium production rates per source neutron in the breeder zone were obtained. FIG.7(a) shows the tritium production rate per source neutron in the breeder zone when the first wall materials were modelled on the blanket model. The results showed a high tritium production rate in the breeder zone near the first wall for the tungsten and beryllium metal due to the multiplier reaction chain in the first wall material. For the other area of the breeder zone (thickness > 10 cm), the effect of the first wall material on the tritium production rate was not significant.

FIG.7(b) shows the ratio of tritium to neutrons in the breeder zone. For the tungsten and beryllium metal, the ratios were almost constant in the breeder zone at thickness between 0 cm and 45 cm. The model with the carbon steel had a slight improvement in the ratio in the breeder zone at a thickness < 10 cm compared to the model without the first wall structure.

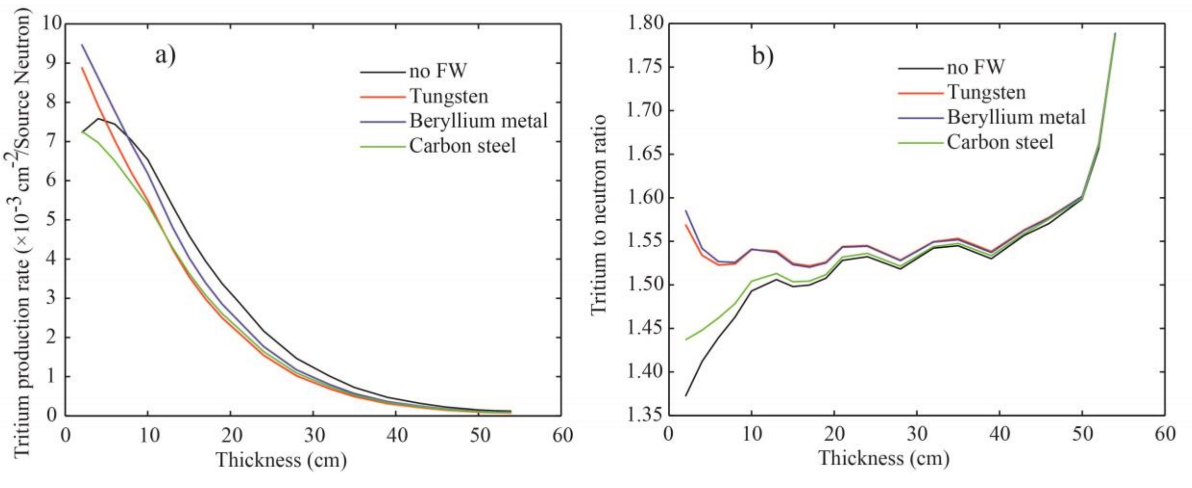

FIG. 7. (a) Tritium production rate per source neutron and (b) tritium to neutron ratio in breeder zone for different first wall materials.

TABLE III: PRIMARY PARTICLE PRODUCTION IN FIRST WALL MATERIAL.

Particle type	Primary particle production (/cm²/source neutron)		
	Tungsten	Beryllium metal	Carbon steel
Gamma	2.317×10^{-3}	3.231×10^{-7}	4.299×10^{-5}
Proton	9.602×10^{-7}	n/a	8.876×10^{-5}
Deuterium	n/a	n/a	1.270×10^{-6}
Tritium	n/a	1.085×10^{-6}	1.009×10^{-9}
^{3}He	n/a	n/a	5.864×10^{-11}
Alpha	2.765×10^{-7}	5.067×10^{-5}	2.220×10^{-5}

4. Conclusion

The simulations of the breeder blanket based on a lithium self-cooled blanket with a vanadium alloy structure (Li/V) model were carried out using the Monte Carlo N-Particle transport code. The tritium production rate was high in the FLiBe and LiPb due to the high multiplier reaction chain of the fast neutron with beryllium in the FLiBe and with lead in the LiPb. However, it was found that the tritium yields from the breeding blanket with LiPb were the highest among the three types of liquid lithium considered in this work. The concentration of ^{6}Li in the LiPb was studied. In the compositions with 75 and 95 percent ^{6}Li enrichment, the number of slow neutrons produced in the breeder zone was low. Therefore, the multiplier reaction chain was high in the breeder zone, thus the thermal reaction of the ^{6}Li(n, α)T was high. The tritium production rate significantly increased over the thickness of the breeder layer in the ^{6}Li enrichment of LiPb. The 75 percent ^{6}Li enrichment was sufficient for the LiPb to achieve the design criteria of the blanket for the fusion device. Moreover, the simple design of the mock-up blanket in this work could easily allow for the extension of the first wall structure. First walls, including tungsten, beryllium metal and carbon steel, were found to affect the tritium production rate in the first layer of the breeder zone. For the tungsten and beryllium metal the tritium production increased in the first layer compared to the structure without the first wall. Finally, the extension of the first wall structure in the blanket model was used to study the primary particle productions, which were produced through the neutron reaction in the first wall structure. The number of primary particles per source neutron through the (n,γ), (n,p), (n,d), (n,t), (n,^{3}He) and (n,α) reactions were observed as shown in Table III. To achieve the blanket design criteria, the displacement per atom needs to be calculated using the information about the primary particle production in the blanket.

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