

# Utilization of fusion neutrons very high energy effects in the design of a fusion reactor tritium breeding blanket

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**Abstract:** Tritium needed for ITER fusion reactions can be regenerated in a blanket located in the tokamak. Such breeding has to be achieved through special interactions between very high energy (14.1 MeV) fusion neutrons and the blanket materials, like the lithium-7 tritium breeding effect and the thorium-232 neutron multiplication effect, all this while occupying the smallest possible space. Five blankets were designed and investigated; three of them were purely composed of lithium materials, while the two others were designed by adding a thorium layer before the lithium layer. A 3-D modeling was created using a Monte Carlo N-particle Code (MCNP) to simulate the fusion neutrons histories through the tritium breeding blankets, with a blanket thickness ranging from 1 cm to 200 cm. The minimum blanket thickness necessary to obtain a tritium breeding ratio (*TBR*) greater than one ranges from 20 cm to 45 cm. In particular, the Lithium Oxide Mono-Layer Blanket (LO-MLB) achieves a *TBR* greater than one while allowing blanket thickness to stay under 25 cm, thus making it the most efficient blanket in this sample. Second, the maximum *TBR* for thick blankets ranges from 1.5 to 2. In particular, the Natural Lithium Mono-Layer Blanket (NL-MLB) displays the highest maximum *TBR* thanks to its perfect combination of the lithium-7 and lithium-6 tritium breeding capacity.

**Keywords:** tritium breeding blanket; fusion power plant; fusion neutrons interactions; fusion driven system

## 1 Introduction

Accounting for advantages in terms of fuel supply, safety and environment, fusion power is regarded by the scientific community as the future of nuclear power [1]. The International Thermonuclear Experimental Reactor (ITER) project launched in 2006 with completion scheduled for 2018 is the largest research/engineering project on nuclear power.

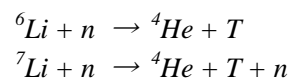
Though the deuterium deuterium fusion reaction is the long-term objective of nuclear fusion, the ITER project is experimenting nuclear power production through the deuterium tritium fusion reaction (DT reaction), for it is the least difficult reaction to initiate on earth:



On the one hand, deuterium is a non-radioactive isotope of hydrogen and extremely abundant as it can be obtained from ordinary water. On the other hand, naturally occurring tritium is extremely rare on Earth

and has to be produced before being used in a fusion reaction.

Lithium is considered by the scientific community as the best element for tritium breeding. There exists two isotopes, <sup>6</sup>Li and <sup>7</sup>Li, that occur naturally with respective proportions of 7.42% and 92.58%. Both of them can react with neutrons to produce tritium, respectively through the <sup>6</sup>Li(n, t) reaction and the <sup>7</sup>Li(n, n't) reaction:



These two tritium breeding reactions demand an external neutron source, and tritium radioactivity makes its manipulation hazardous. These two reasons motivated research of a suitable design for a tritium breeding device located inside the tokamak that would take the shape of a blanket wrapping the burn chamber [2]. Fusion reactor blankets were then designed with a certain amount of objectives.

The basic objectives of a blanket are tritium breeding and neutron shielding. Tritium breeding is necessary to feed back the fusion reaction, and neutron shielding

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allows the blanket to convert the energy of the fusion neutrons into heat and prevent them from damaging the surrounding fragile and costly equipments.

The reference <sup>[3]</sup> presents the two reference concepts in the European Breeding Blanket Programme for fusion reactor blanket design: the Helium Cooled Lithium Lead (HCLL) concept and the Helium Cooled Pebble Bed (HCPB) concept. In the HCPB concept, lithium ceramics ( $\text{Li}_4\text{SiO}_4$  or  $\text{Li}_2\text{TiO}_3$ ) breeder pebbles are associated to beryllium pebbles acting as neutron multiplier. The neutron multiplication function and the tritium breeding function are spatially separated. In the HCLL concept, the two functions are united in the PbLi eutectic which flows at low velocity inside the blanket. Neutronics calculations showed the achievement of a *TBR* of 1.14 with a breeder zone thickness of about 46 cm for the HCPB and 55 cm for the HCLL. It was noted that the feasibility of a fusion driven liquid PbLi breeder blanket has also been demonstrated in China <sup>[4]</sup>.

The secondary objectives of a fusion reactor blanket are fissile fuel breeding, power multiplication and minor-actinide transmutation. Fissile fuel can be bred in the blanket either to supply LWRs which require nuclear fuel enriched in fissile elements, or used in situ to increase the output power of the fusion reactor. Thorium-232 and uranium-238 can be used in different compounds to breed uranium-233 and plutonium-239, respectively.

Thorium-based blankets, though weaker than uranium-based blankets in terms of tritium and fissile fuel breeding, can still achieve a *TBR* higher than one while enriching thorium fuel to be loaded in LWR <sup>[5]</sup>. Amongst the thorium-based blankets, the choice of the fuel materials and of the fuel coolant can deeply influence the blanket performance in terms of tritium breeding. Concerning the choice of the fuel material, blankets fuelled with  $\text{ThO}_2$  present smaller *TBR* than blankets fueled with  $\text{ThC}$  <sup>[6]</sup>, while  $\text{ThC}_2$  and  $\text{ThF}_4$  present similar results <sup>[7]</sup>. Concerning the choice of the coolant of the fuel zone, utilization of natural lithium produces a significantly higher *TBR* than utilization of gases (He,  $\text{CO}_2$ , air) or Flibe <sup>[7]</sup>, and Flibe has higher breeding potential than Flinate and  $\text{Li}_{20}\text{Sn}_{80}$  <sup>[8]</sup>.

Though mentioned in some of the references <sup>[7]</sup>, we did not find detailed studies on the particular behavior of the fusion neutrons produced at a very high energy (14.1 MeV), *i.e.* one order of magnitude higher than the fusion neutrons. The first contribution of this study is therefore to give a detailed analysis of the special interactions occurring between high energy fusion neutrons and a selection of element commonly found in fusion reactor blankets.

It also appeared in our review that some of the studies on blankets would keep the same blanket architecture when comparing different materials. However, we believe that the spatial design of the blanket should be made according to the neutronics properties of the used materials. The second contribution of this study is therefore to propose a simplified but optimized design of a blanket with the single objective of tritium breeding. The optimization was made according to the physical properties of the considered materials.

The last specificity of the present study is the consideration of thorium as a neutron multiplier more than a fissile fuel breeder.

## 2 Description of the system

### 2.1 Geometric description

We modeled the ITER burn chamber (containing the plasma) as a perfect toroid, generated by revolving an ellipse around a central vertical axis. It was thus completely described by the three parameters *A*, *B* and *C* (see Fig. 1). We worked with *A*=621 cm, *B*=340 cm, *C*=200 cm. The three calculated parameters, volume, surface and eccentricity, are relevant with the given parameters of ITER <sup>[3]</sup>. The blanket was laid around the burn chamber, represented as a rotation-invariant object. *L* is the overall blanket thickness.

Mono-Layer Blankets (MLB) and Bi-Layer Blankets (BLB) were investigated in this research. MLB are composed of one unique and homogenous breeding layer (BL). In the BLB, the breeding layer is preceded by a neutron multiplication layer (ML).

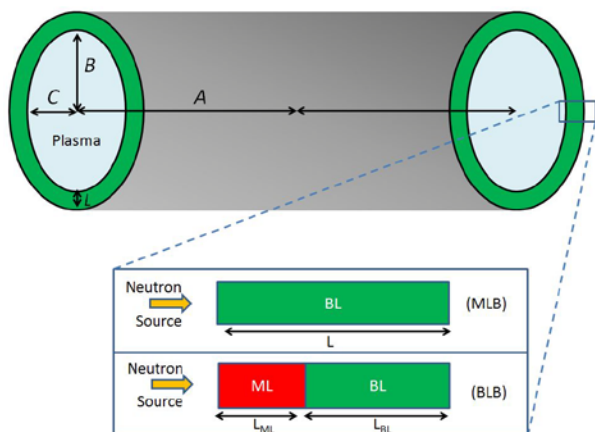


Fig.1 Transversal section of the system.

## 2.2 Physical description

The fusion neutrons are produced in the plasma with a uniform energy of 14.1 MeV. We supposed the neutron source homogenous and isotropic. As non-charged particles, fusion neutrons are not restrained in the plasma by the magnetic field and leak out in the blanket. The blanket, not loaded with any fissile material, is a sub-critical system. As a consequence, any neutron history (the account of all the events generated by a single fusion neutron) is a finite history. Therefore the two following indexes can be defined:  $TBR$ , the tritium breeding ratio, and  $m$ , the effective neutron multiplication index.  $TBR$  is the average number of tritium breeding reactions occurring per fusion neutron history.  $m$  is the ratio of neutrons leaking out of the multiplication layer per incoming fusion neutron, when the multiplication layer is considered independently.

Values of  $TBR$  and  $m$  were calculated using the Monte-Carlo N-Particle transport code <sup>[9]</sup> (MCNP). We specified the geometry and the neutron source as described in this section. Materials descriptions are discussed in section 5, and ENDF/B-VI was adopted as a cross section evaluation database. The number of histories was chosen in order to keep the fraction standard deviation (also named relative error) below 0.01 for all tallies. Note that the relative error is shown on each figure representing MCNP tallies.

## 2.3 Thermal description

The heat generated by interactions between the neutrons and the blanket materials, such as neutron collisions or  ${}^6\text{Li}(n, t)$  reactions, would have to be removed in a final design in order to keep the blanket

in a stable temperature. Heat removal would be made possible by adding coolant channels running through the blanket.

The choice of a coolant and of its specifications, depend not only on the blanket thermal parameters but also on the blanket neutronics parameters. In regions where the high energy of the neutrons plays a significant role, coolants composed of materials with high atomic mass numbers would be chosen, allowing blanket cooling without neutron moderation. Conversely, in regions where the blanket would benefit more from low energy neutrons, coolants composed of materials of small atomic mass numbers would be chosen, allowing simultaneous blanket cooling and neutron moderation.

As the purpose in this work was not a final design of a tritium breeding blanket, but rather the identification of different neutron behaviors in different blanket designs, cooling layers were not added and the focus was on the understanding of the neutrons behaviors, with the neutron multiplication materials in the first hand, and with the tritium breeding materials in the other hand. Therefore the values of  $m$  and  $TBR$  calculated for each of the blankets investigated should be taken as optimal values.

## 3 Behavior of the very high energy fusion neutrons in the blanket

Neutrons produced in DT reaction are produced with an initial energy of 14.1 MeV, which is one order of magnitude higher than the average initial energy of fission neutrons produced in thermal fission reactors (see Fig. 2).

Very high energy fusion neutrons display particular behaviors when interacting with matter that were not observed with fission neutrons. Indeed, some atoms-neutrons interactions have an energy threshold which stands between fission neutron energy level and fusion neutron energy level.

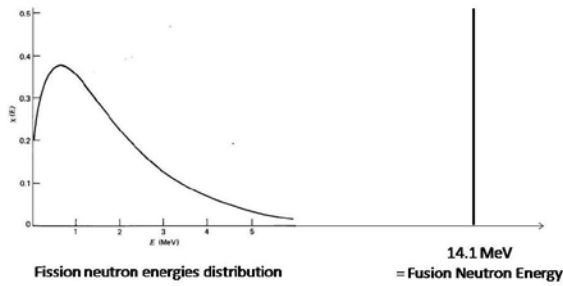


Fig.2 Fission and Fusion neutrons energies distributions.

A Very High energy Effect (VHE) was defined as an interaction occurring between materials of the blanket and DT fusion neutrons but not occurring with fission neutrons.

Fusion neutrons can cause different VHE in the blanket, depending on which materials are used. The following sections investigate the major VHE in lithium, thorium and oxygen.

### 3.1 Very high energy effect in lithium

Natural lithium is composed of two isotopes,  ${}^6\text{Li}$  and  ${}^7\text{Li}$ . Although both of them react with neutrons to produce tritium, strong differences exist between the two reactions.  ${}^6\text{Li}(n, t)$  causes the disappearance of the incident neutron, and happens more easily when the incident neutron energy is low. On the contrary the  ${}^7\text{Li}(n, n't)$  releases a neutron and occurs only with very high energy incident neutrons (see Fig. 3). The  ${}^7\text{Li}(n, n't)$  cross section is equal to zero for energies smaller than a few MeV but it becomes significantly higher than the  ${}^6\text{Li}(n, t)$  cross sections when the energy is over 3.9 MeV. There is a  ${}^7\text{Li}$  tritium breeding effect.

Without the  ${}^7\text{Li}$  tritium breeding effect, one fusion neutron would at most cause one  ${}^6\text{Li}(n, t)$  reaction. A blanket purely composed of lithium materials would therefore be limited to a *TBR* smaller or equal to one.

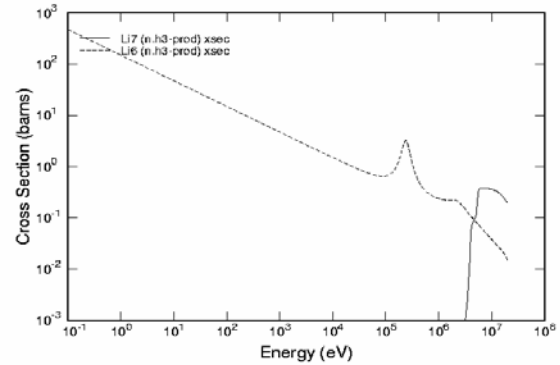


Fig.3  ${}^6\text{Li}$  and  ${}^7\text{Li}$  tritium production cross sections.

A more in depth study showed that more than 99% of the neutrons released in a  ${}^7\text{Li}(n, n't)$  induced by a 14.1 MeV incident neutron are released with an energy lower than the energy threshold of the  ${}^7\text{Li}(n, n't)$ . Therefore, it is considered that one fusion neutron is limited to a maximum of one  ${}^7\text{Li}(n, n't)$  reaction. Nevertheless, the neutron released by the  ${}^7\text{Li}(n, n't)$  reaction is still likely to react with  ${}^6\text{Li}$  in a  ${}^6\text{Li}(n, t)$  reaction. Then, in a medium where the two isotopes of lithium are present, the fusion neutron may induce both a  ${}^7\text{Li}(n, n't)$  and a  ${}^6\text{Li}(n, t)$  reaction, which would result in a theoretical maximum *TBR* of 2. That is the principle of the mono-layer blankets discussed in section 5.

A blanket uniformly composed of pure natural lithium was simulated. The total tritium breeding function and the respective contribution of  ${}^6\text{Li}$  and  ${}^7\text{Li}$  were tallied in function of the blanket thickness. Results are shown in Fig. 4.

The maximum value of *TBR* is almost reached for a thickness of 200 cm. For high thicknesses, the small excess in  ${}^6\text{Li}(n, t)$  compared to  ${}^7\text{Li}(n, n't)$  is explained by a small amount of  ${}^6\text{Li}(n, 2n)$  and  ${}^7\text{Li}(n, 2n)$  also occurring when lithium atoms are exposed to very high energy fusion neutrons flux.

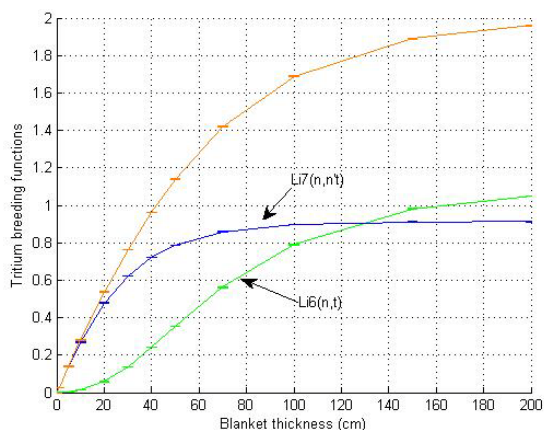


Fig. 4  ${}^6\text{Li}$ ,  ${}^7\text{Li}$  and total breeding function in Natural Lithium Mono-Layer Blanket (NL-MLB).

### 3.2 Very high energy effect in thorium

Natural thorium is solely composed of its main isotope:  ${}^{232}\text{Th}$ . Though  ${}^{232}\text{Th}$  is more commonly used in blanket as a fertile material used in the breeding of  ${}^{233}\text{U}$ , it also presents excellent neutron multiplication abilities. Indeed, when  ${}^{232}\text{Th}$  is exposed to very high energy neutrons, it not only reacts in fast fission reactions, but also in (n, 2n) and (n, 3n) reactions (see Fig. 5).

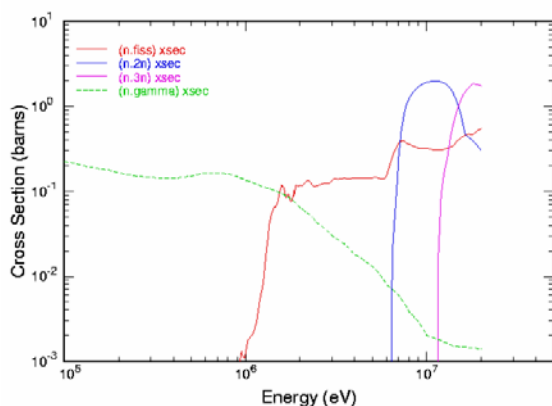


Fig.5  ${}^{232}\text{Th}$  main cross sections in high energy range.

The energy threshold of the  ${}^{232}\text{Th}(n, 2n)$  and  ${}^{232}\text{Th}(n, 3n)$  are respectively 6.5 MeV and 12 MeV.  ${}^{232}\text{Th}(n, 2n)$  and  ${}^{232}\text{Th}(n, 3n)$  are VHE and constitute the thorium neutron multiplication effect. Although the  ${}^{232}\text{Th}(n, f)$  reaction also contributes to the neutron multiplication, it is not a VHE since its energy threshold is 1.1 MeV, so it can be activated by fast fission neutrons.

A more in depth study showed that more than 99% of the neutrons released in the  ${}^{232}\text{Th}(n, 2n)$  and

${}^{232}\text{Th}(n, 3n)$  induced by a 14.1 MeV incident neutron are released with an energy below 3.9 MeV. Thus one neutron fusion cannot activate more than one  ${}^{232}\text{Th}(n, xn)$  reactions.

A pure thorium blanket was simulated and Fig. 6 represents  $m$ , the effective neutron multiplication index against the thickness of the thorium layer. The value of  $m$  is the result of the neutron gain due to fissions and (n, xn) reactions, and the neutron loss due to captures. The neutron gain due to fission and (n, xn) reactions and the neutron capture are therefore also represented in Fig. 6. The maximum value of  $m$ , 1.75, is reached for a thickness of 8 cm. In this thickness range, neutron gain is already high and capture is still rather low. For thick blankets, the effects of capture are stronger than the effects of neutron gain. Starting from 25 cm  $m$  becomes smaller than one and the thorium layer is not a multiplication layer any more.

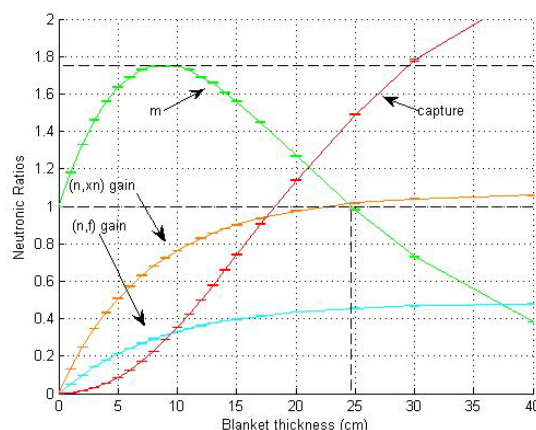


Fig.6 Effective neutron multiplication in a thorium multiplication layer.

As for the  ${}^7\text{Li}$  tritium breeding effect, neutron multiplication in thorium can occur before the  ${}^6\text{Li}(n, t)$  and therefore allows the design of blankets with  $TBR$  higher than one. That is the principle of the bi-layer blankets discussed in section 5.

### 3.3 Very high energy effect in oxygen

As long as the neutron's energy level stays in the usual range, *i.e.* less than a few MeV, the only significant cross section of oxygen is its elastic scattering cross section. But, for energy levels higher than 3.9 MeV, a strong  ${}^{16}\text{O}(n, \alpha)$  appears (see Fig. 7), resulting in an important neutron loss.

Therefore, use of lithium oxide materials as tritium breeding materials results in strong neutron absorption if these materials are located just after the burn chamber, where the fusion neutrons still have their very high initial energy.

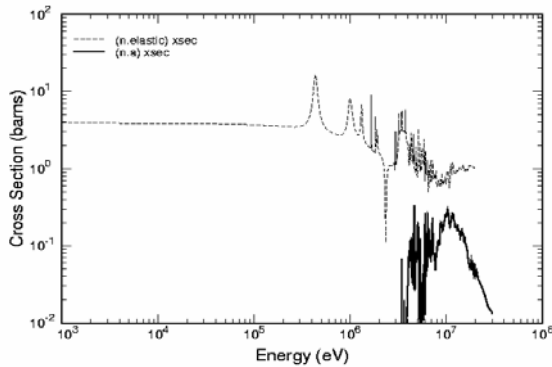


Fig.7 <sup>16</sup>O elastic and <sup>16</sup>O(n,α) cross sections.

Nevertheless, even though oxygen has a direct negative effect on *TBR* through an oxygen capture effect, the use of oxide materials must not be neglected as they are often remarkably stable. Besides, in the case of thin blankets for which escape rate is high, oxygen may be a good moderation factor, limiting the neutron escape.

## 4 Blankets structure

The neutrons produced in the <sup>232</sup>Th(n, 2n), <sup>232</sup>Th(n, 3n), and <sup>7</sup>Li(n, n't) are all produced with energies below the threshold of these three reactions. One fusion will therefore induce at most one VHE. The Lithium Mono-Layer Blankets (L-MLB) were designed to make the most of the <sup>7</sup>Li tritium breeding effect, whereas the Thorium Lithium Bi-Layer Blankets (T-L-BLB) were designed to take the most advantage of the <sup>232</sup>Th neutron multiplication effect.

### 4.1 Lithium Mono-Layer Blanket

L-MLBs are composed of a unique and homogenous layer of lithium materials. Three L-MLBs were investigated.

The first blanket, the Natural Lithium Mono-layer Blanket (NL-MLB), is composed of pure lithium with natural isotopic composition: 7.42% of <sup>6</sup>Li and 92.42% of <sup>7</sup>Li. This blanket does not require isotope enrichment, but has a strong reactivity with of oxygen. Furthermore, as the exothermic <sup>6</sup>Li(n, t)

reaction heats the blanket's material, an efficient cooling would be required to prevent lithium to reach its melting point of 180.54 °C. Figure 8 summarizes neutron utilizations in the NL-MLB in a zero-escape scenario.

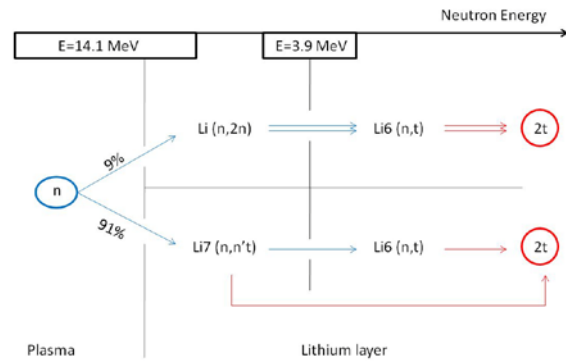


Fig.8 Neutron utilization in a NL-MLB

The second blanket, the Optimized Isotopic Composition Lithium Mono-Layer Blanket (OICL-MLB), is composed of lithium whose isotopic composition has been optimized to maximize the *TBR*. It is an upgrade of the NL-MLB. This blanket, whose limitations are the same as the NL-MLB, requires <sup>6</sup>Li enrichment. As the optimized <sup>6</sup>Li enrichment ( $\beta_{max}$ ) is function of the blanket thickness, series of simulations had to be made for each given blanket thickness to determine the optimized <sup>6</sup>Li enrichment and calculate the corresponding *TBR*.  $\beta_{max}$  ranges from 0% to 20% depending on the thickness of the blanket. Experimental results of  $\beta_{max}$  are given in Table 1.

In the thinnest blankets, fusion neutrons leak out of the blanket before being moderated below the VHE energy range. In the VHE energy range, the <sup>7</sup>Li tritium breeding cross section is larger than the <sup>6</sup>Li tritium breeding cross section. Then optimal isotopic composition of the blanket is 100% of <sup>7</sup>Li.

In larger blankets, a part of the fusion neutrons is moderated below the VHE energy range before leaking out of the blanket. High <sup>7</sup>Li proportion increases the probability of the first breeding, and the potentiality of a double-breeding, whereas high <sup>6</sup>Li proportion increases the probability of the second breeding before escape. The optimal composition of

the lithium maximizes the number of breeding in one fusion neutron history.

**Table 1 Optimized  ${}^6\text{Li}$  enrichment in a L-MLB**

Blanket Thickness (cm)	$\beta_{max}$ (%)
1	0
10	0
30	20
50	20
70	20
100	14
150	10

The third blanket, the Lithium Oxide Mono-Layer Blanket (LO-MLB), is composed of lithium oxide  $\text{Li}_2\text{O}$  whose lithium isotopic composition is the same as natural lithium. Lithium oxide is a stable material whose melting point is  $1570\text{ }^\circ\text{C}$ . The presence of the oxygen atom has a double effect on the blanket  $TBR$ : a negative effect as its absorption cross section is high for fusion neutrons and a positive effect as it moderates the neutrons, therefore increasing the probability of reaction before they leak out of the blanket.

#### 4.2 Tritium Lithium Bi-Layer Blanket

T-L-BLBs are composed of two homogenous layers. The first layer is a pure thorium-232 layer which fosters neutron multiplication. The second layer is composed of tritium breeding materials. For a given total blanket thickness, the respective thicknesses of the two layers were chosen to optimize the  $TBR$ .

Three T-L-BLBs, differing only in the materials chosen to breed the tritium were designed. They are the equivalents of the three L-MLB to which we added a pure thorium layer. For each of them, series of simulations were made to determine the optimal thickness of the neutron multiplication layer in function of the blanket thickness ( $L_{ML,max}(L)$ ) and calculate the corresponding  $TBR$ . Experimental results of  $L_{ML,max}(L)$  are given in Table 2.

The blanket obtained when adding a thorium layer before a breeding layer composed of natural lithium is the Thorium Natural Lithium Bi-Layer Blanket (T-NL-BLB). In the T-NL-BLB both  ${}^7\text{Li}$  breeding effect and  ${}^{232}\text{Th}$  multiplication effects may occur,

depending on the thickness of each layer. The optimal thickness of the thorium layer, maximizing the  $TBR$  in the lithium layer, appeared to be zero, and so whatever the total thickness of the blanket. Hence T-NL-BLB is in fact mono-layer and identical to the NL-MLB. It shows that when using natural lithium as tritium breeding material, the  ${}^7\text{Li}$  tritium breeding effect is stronger than the  ${}^{232}\text{Th}$  neutron multiplication effect. This is coherent with the results presented in Figs. 4 and Fig. 6 which shows that the maximum  $TBR$  obtained using the  ${}^{232}\text{Th}$  neutron multiplication effect is 1.75, when the maximum  $TBR$  obtained using the  ${}^7\text{Li}$  tritium breeding effect is 2.0.

The blanket obtained when adding a thorium layer before a breeding layer composed of lithium with variable isotopic composition would have to be optimized in function of two variables: the neutron multiplication layer thickness and the lithium enrichment in  ${}^6\text{Li}$ . The lithium enrichment parameter was fixed to a constant value to facilitate the optimization of the second parameter. It was fixed to the value of 100% to avoid a competition between the  ${}^7\text{Li}$  tritium breeding effect and the  ${}^{232}\text{Th}$  neutron multiplication effect, and then exploit the neutron multiplication effect to its maximum. Therefore the Thorium  ${}^6\text{Li}$  Bi-Layer Blanket (T-6L-BLB) was investigated. Neutron utilization in T-6L-BLB is presented in Fig.9.

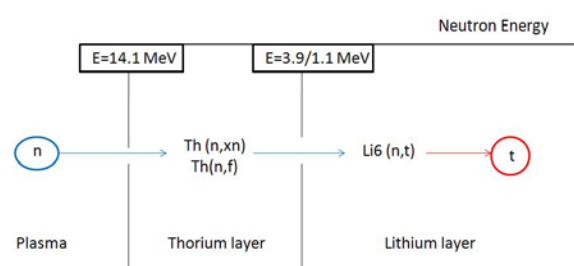


Fig.9 Neutron history in a T-6L-BLB.

Optimal thickness of the neutron multiplication layer in T-6L-BLB (shown in Table 2) increases with the total thickness of the blanket until it reaches the limit value of  $8\text{ cm}$ . In the thin blankets, there is a competition between a larger neutron multiplication provided by a larger thorium layer, and a better moderation of the neutrons provided by a larger lithium layer. A better moderation means lower

escape, and larger cross section for the  ${}^6\text{Li}(n, t)$  reaction. The optimal thickness of the thorium layer is the balance of the two effects which produces the highest  $TBR$ . In the thick blankets,  $L_{ML,max}$  is constant to 8 cm when L increases and escape ratio tends to zero. We conclude that 8 cm is the thickness of the thorium layer which produces the highest neutron multiplication in a thick T-6L-BLB. It is noted that it equals the thickness of the thorium layer which produces the highest neutron multiplication in an independent thorium layer (see Fig. 6). This shows that neutrons which fly back to the thorium layer from the lithium layer have no effect on the neutron multiplication, because they have been moderated below the threshold of the various reactions of neutron multiplication in the thorium.

The last T-L-BLB investigated uses lithium dioxide with natural enrichment of lithium as tritium breeding material: the Thorium Lithium Oxide Bi-Layer Blanket (T-LO-BLB). Optimal thickness of the neutron multiplication layer in T-LO-BLB is shown in Table 2.

It was observed in the optimization of the T-NL-BLB that the  ${}^7\text{Li}$  breeding effect was stronger than the  ${}^{232}\text{Th}$  multiplication effect. In the T-LO-BLB, the  ${}^7\text{Li}$  breeding effect is weaker because it is associated to the  ${}^{16}\text{O}$  capture effect. In these conditions, the addition of a thorium multiplication layer can contribute to a higher  $TBR$  in the T-LO-BLB.

Like in the T-6L-BLB,  $L_{ML,max}$  increases with L until it reaches its limit value. But the increase is slower,  $L_{ML,max}$  reaches its limit value for a higher L, and the limit value is smaller. The existence of the  ${}^7\text{Li}$  breeding effect in the T-LO-BLB can explain the observed differences.

The thorium layer is useful to  $TBR$  only if the neutrons produced in the  ${}^{232}\text{Th}(n,xn)$  and  ${}^{232}\text{Th}(n,f)$  reactions are then used to breed tritium. This can only occur through  ${}^6\text{Li}(n,t)$  reactions (See sections 3.1 and 3.2). In thin blankets where neutron moderation is not effective  ${}^6\text{Li}(n,t)$  are rare (see Fig. 4), so the  ${}^7\text{Li}$  breeding effect is preferred to the  ${}^{232}\text{Th}$  multiplication effect, though weakened by the  ${}^{16}\text{O}$  capture effect. It results in a mono-layer blanket, without thorium layer.

In thicker blankets, moderation is more effective,  ${}^6\text{Li}(n, t)$  reactions occur more often, and a thorium layer which delivers more neutrons to the  ${}^6\text{Li}(n, t)$  improves the  $TBR$ . In the thickest blankets,  $L_{ML,max}$  never reaches the value of 8 cm, because the  ${}^7\text{Li}$  breeding effect still balances the  ${}^{232}\text{Th}$  multiplication effect.

**Table 2 Optimized thickness of the neutron multiplication layer in T-L-BLB**

Blanket Thickness (cm)	$L_{ML,max}$ in T-NL-BLB	$L_{ML,max}$ in T-6L-BLB	$L_{ML,max}$ in T-LO-BLB
10	0	4	0
20	0	7	0.7
30	0	8	1.75
50	0	8	2
70	0	8	3.1
100	0	8	3.1
150	0	8	3.1

### 4.3 Summary

The five blankets investigated in this study are summarized in Table 3.

**Table 3 Blankets Composition**

Blanket	Neutron Multiplication Layer	Tritium Breeding Layer
NL-MLB	X	Li, $\theta = \theta_{nat} = 6.42\%$
OICL-MLB	X	Li, $\theta = \theta_{max}$
LO-MLB	X	$\text{Li}_2\text{O}$ , $\theta = \theta_{nat}$
T-LO-BLB	${}^{232}\text{Th}$	${}^6\text{Li}$ , $\theta = 100\%$
T-6L-BLB	${}^{232}\text{Th}$	$\text{Li}_2\text{O}$ , $\theta = \theta_{nat}$

## 5 Results and analysis

In Figs. 10 to 14, we give for each blanket the  $TBR$  as a function of the blanket thickness. The critical thickness was defined as the minimum blanket thickness necessary to get a  $TBR$  greater than one. We also define  $TBR_{lim}$  as the limit of the  $TBR$  for thick blankets. Both critical thickness and  $TBR_{lim}$  are emphasized on each figure and gathered in Table 4.



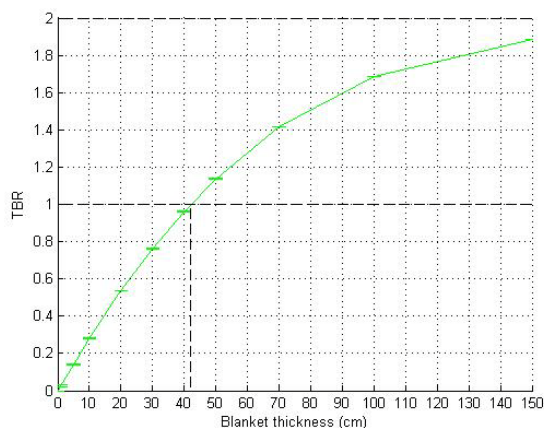


Fig.10 TBR in NL-MLB.

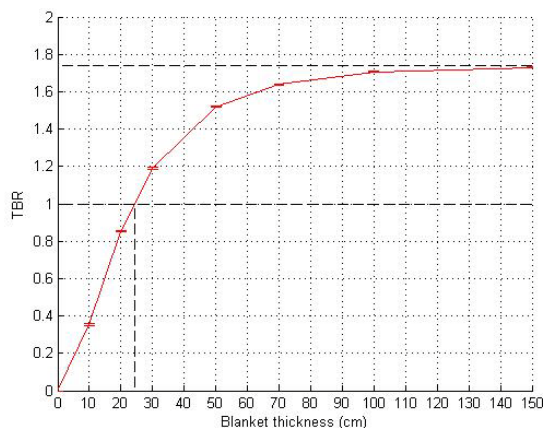


Fig.13 TBR in T6L-BLB

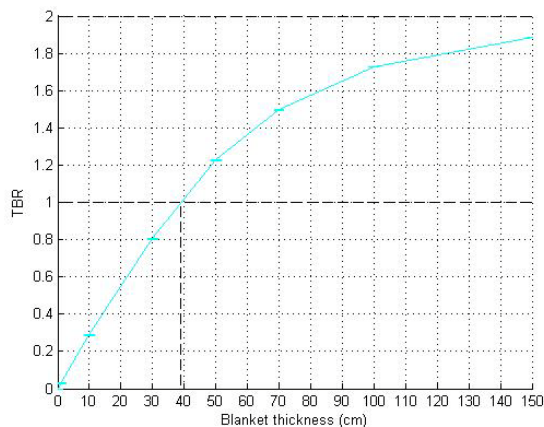


Fig.11 TBR in OICL-MLB

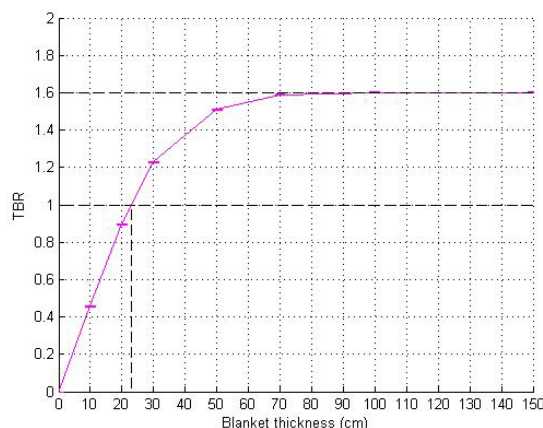


Fig.14 TBR in TLO-BLB

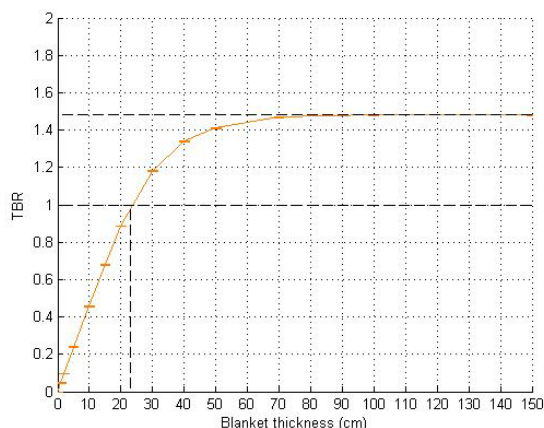


Fig.12 TBR in LO-MLB

Table 4 Blankets Results

Blanket	Critical thickness (cm)	Limit TBR
NL-MLB	42	2.00
OICL-MLB	39	2.00
LO-MLB	24	1.48
T-6L-BLB	24	1.74
T-LO-BLB	23	1.60

Figure 15 gives a general overview of the different blankets' behaviors, making it clear that the best blanket in terms of TBR is not the same for all thicknesses. Figure 16 synthesizes the results of the five blankets and focuses on the section of critical thickness.

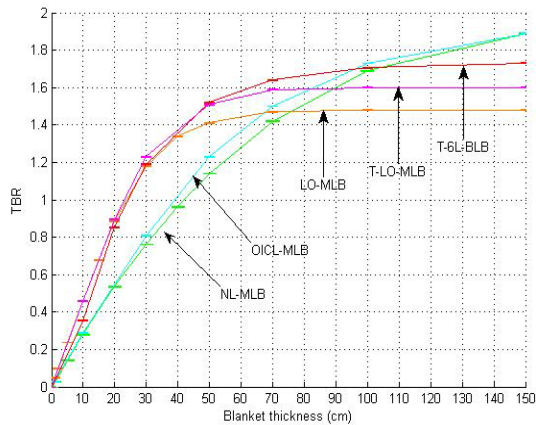
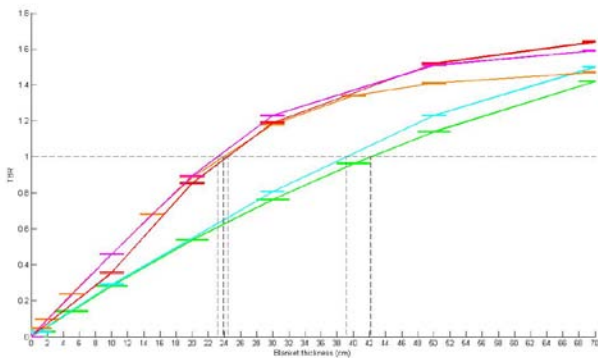


Fig.15 TBR Comparative.



Legend: Green: NL-MLB, Cyan: OICLMLB,

Orange: LO-MLB, Red: T-6L-BLB, Magenta: T-LO-BLB,

Fig.16 TBR comparative around the critical thickness region.

Blankets can be classified in two groups. The first group of blankets is constituted by the NL-MLB and the OICL-MLB. Blankets in this group are characterized by a  $TBR$  increasing slowly for thin blankets, reaching a value of one for blanket thickness around 40 **cm**, and finally reaching the maximum value of 2 for really high thicknesses. The results of the OICL-MLB, though somewhat better than the results of the NL-MLB, are not worth the costly  $^6\text{Li}$  enrichment. Moreover, they display the exact same results on the section where they are more competitive than the blankets of the second group, which is over 100 **cm** of thickness.

The second group is constituted by the LO-MLB, the T-6L-BLB and the T-LO-BLB. Blankets in this group are characterized by a  $TBR$  increasing sharply in the section of thin blankets, reaching a value of one for blanket thickness around 24 **cm**, and displaying relatively low  $TBR_{lim}$ . We observe significant differences between these three blankets when

thickness exceeds 40 **cm**. LO-MLB has the lowest  $TBR_{lim}$  due to the  $^{16}\text{O}$  neutron capture effect. For the T-LO-BLB, a part of the neutron loss due to the  $^{16}\text{O}$  neutron capture effect is offset by the neutron gain due to the  $^{232}\text{Th}$  neutron multiplication effect, thus slightly improving the  $TBR_{lim}$ . Yet, the best  $TBR_{lim}$  in the second group is obtained by the T-6L-BLB, reaching the highest value of the effective neutron multiplication of the thorium layer discussed in the section 3.2, making it the best blanket of this second group. However, the production of this blanket is extremely costly as it demands a 100% enrichment in  $^6\text{Li}$ .

Accounting for blankets results in terms of  $TBR$  as well as their conditions of production and manipulation, we make some recommendations, depending on the space available for the blanket.

When little space is available and total blanket thickness is limited to 50 **cm**, the LO-MLB, T-LO-BLB and T-6L-BLB showed excellent and similar results. The LO-MLB being the easiest to manufacture and to manipulate should therefore be adopted. The condition of self-sufficient fuelling is achieved for a blanket thickness of 24 **cm**.

For an available space ranging from 50 **cm** to 85 **cm**, the T-LO-BLB and T-6Li-BLB displayed the highest  $TBR$ . As there is only a small difference between these two blankets, and considering the price and difficulty to enrich the lithium materials in  $^6\text{Li}$ , the best blanket in this range is the T-LO-BLB.

Finally, in the case of thick blankets, when maximum tritium breeding is sought without consideration of thickness limitations, the NL-MLB obtains the best results.

## 6 Conclusion

The design of a nuclear fusion tritium breeding blanket can only be achieved by taking into account the special interactions between the very high energy neutrons produced in the plasma and the nuclei making up the first layer of the blanket. In order to take advantage either of the  $^7\text{Li}$  tritium breeding effect, or of the  $^{232}\text{Th}$  neutron multiplication effect, several types of tritium breeding blankets were investigated.

The calculations of *TBR* as a function of the blanket thickness led to the following recommendation: a Lithium Oxide Mono-Layer Blanket (LO-MLB) should be used when blanket thickness is limited to less than 50 **cm**, a Thorium Lithium Oxide Bi-Layer Blanket (T-LO-BLB) should be used when the blanket thickness ranges from 50 to 85 **cm** and a Natural Lithium Mono-Layer Blanket (NL-MLB) should be used when a blanket thickness larger than 85 **cm** is allowed.

Although adding a coolant would negatively affect the neutronics results of the blanket, it is a necessary step towards a more realistic model of a nuclear reactor blanket. However, the design of a cooling system should not cancel out the high energy neutrons effects emphasized in this study. Therefore, future research proposals should investigate a final design that would fulfill the thermal restrictions imposed by the materials properties, while simultaneously optimizing the neutron utilization in order to approach the optimal results calculated in this study.

## Nomenclature

L-MLB	Lithium Mono-Layer Blanket
NL-MLB	Natural Lithium Mono-Layer Blanket
OICL-MLB	Optimized Isotopic Composition Mono-Layer Blanket
LO-MLB	Lithium Oxide Mono-Layer Blanket
T-L-BLB	Thorium Lithium Bi-Layer Blanket
T-NL-BLB	Thorium Natural Lithium Bi-Layer Blanket
T-6L-BLB	Thorium <sup>6</sup> Li Bi-Layer Blanket
T-LO-BLB	Thorium Lithium Oxide Bi-Layer Blanket
<i>TBR</i>	Tritium Breeding Ratio
<i>TBR<sub>im</sub></i>	<i>TBR</i> without escape
$\beta$	the lithium enrichment in <sup>6</sup> Li
$\beta_{max}$	the lithium enrichment in <sup>6</sup> Li which maximizes the <i>TBR</i> in a blanket composed of lithium material with variable isotopic composition

<i>L</i>	the total blanket thickness
<i>L<sub>ML</sub></i>	the thickness of the thorium layer in a T-L-BLB
<i>L<sub>ML,max</sub></i>	the thickness of the thorium layer which maximizes the <i>TBR</i> in a T-L-BLB
<i>m</i>	neutron multiplication index

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