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Abstract

One of the primary requirements for breeder blankets in commercial DT fusion reactors is to produce sufficient tritium to sustain the plasma. Mixed bed solid-type breeder blankets are one possible design being investigated for use in power producing reactors. Current mixed bed designs tend to utilise a uniform mixture of neutron multiplier $Be_{12}Ti$ and lithium ceramic throughout the blanket. Minimizing the use of beryllium is also a priority for solid-type breeder blankets due to the scarce nature of the element. This paper investigates a method of increasing the tritium production while simultaneously reducing the quantity of beryllium required in a mixed bed breeder blanket. This is achieved by varying the multiplier to breeder ratio as a function of blanket depth. The tritium production of mixed bed blankets with an optimum uniform composition is compared to mixed bed blankets with an optimum non-uniform composition while conserving beryllium mass. The resulting increase in TBR (Tritium Breeding Ratio) when using non-uniform blankets was found to be ~1% which equates to ~1kg per year in a 3GW fusion power plant operating at 70% availability. However, the beryllium usage in non-uniform blankets is shown to be ~14% lower than uniform blankets. Hence, the benefits of achieving both reduced beryllium and increased tritium production are substantial given the associated costs of $4,500 per kg for $Be_{12}Ti$ and $30,000 per gram for tritium.

Introduction

Several breeder blanket designs have been proposed to produce the tritium required for future power producing fusion reactors. Mixed bed solid-type breeder blankets are one possible design being investigated. Solid-type breeder blankets rely on lithium ceramic to breed tritium and beryllium to multiply the number of neutrons. While lithium reserves are plentiful beryllium is a scarce material (reserves estimated at 80,000 tonnes [1]). Thus, the finite worldwide reserves of beryllium are likely to present a major supply problem and limit the number of power plants with solid-type breeder blankets that can be built [2].

This paper presents a proof of principle that non-uniform mixed bed blanket compositions can simultaneously achieve a higher TBR (Tritium Breeding Ratio) while also requiring less beryllium compared to uniform mixed bed breeder blankets. Previous research in this area has shown that linear variation in blanket compositions can result in improved blanket performance [3]. One restriction of the previous research was that only linear variations in compositions were permitted. The research presented in this paper builds upon earlier results by allowing non-linear variation in blanket compositions.

Important nuclear reactions for tritium production such as ^{9}Be(n,2n), ^{7}Li(n,n't) and ^{6}Li(n,t) are energy dependent (see Figure 1). ^{9}Be(n,Xt) reactions also occur buy are often overlooked due to the relatively small contribution the make to the total tritium production. This research is based on the premise that neutron scattering results in a softer neutron spectrum towards the rear of the breeder blanket. It is therefore possible to tailor the material composition to make better use of the local neutron spectra.

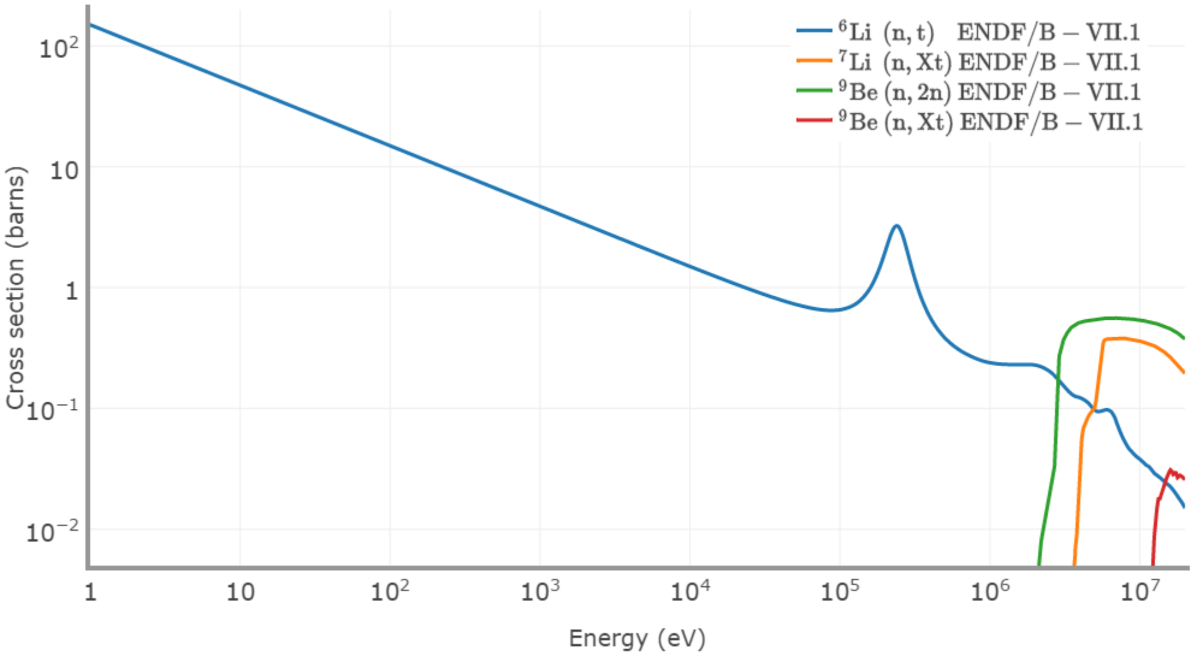

Figure 1. Important reactions for tritium production in the breeder blankets simulated. Cross section data from [4], plot produced using [5].

Current mixed bed designs tend to utilise a uniform mixture of neutron multiplier and lithium ceramic throughout the blanket [6],[7],[8]. This paper investigates a method of increasing the tritium production in a mixed bed breeder blanket by varying the multiplier to breeder ratio as a function of depth.

Method

The reactor model used in this study was adapted from a European tokamak DEMO model [9] developed within the Power Plant Physics and Technology (PPPT) programme [10]. The breeder zones within the model were segmented into eight layers of equal depth (4.9cm). Section dividers (0.9cm thick) have been added between the layers to represent structural cooling plates. The combined thickness of the breeder zones and the inter-layer cooling plates was 45.5cm for all blanket modules. Layers were filled with a homogenised mixture of $Be_{12}Ti$, Li_4SiO_4, Eurofer (3.3% volume) and helium gas (35.9% volume) used for purge gas and coolant.

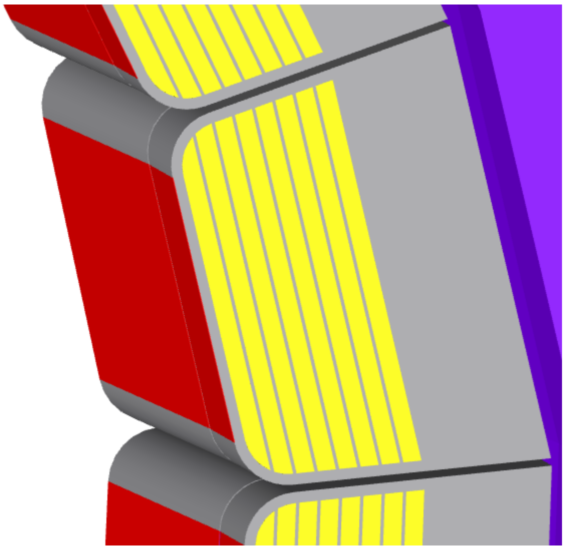

Figure 2. Part of the modified DEMO model used, showing the blanket casing (grey),vacuum vessel (blue), homogenised breeder material (orange) and tungsten armour (red) are included. Image generated using MCAM [11].

The approach taken involved two stages. Firstly the maximum TBR achievable using a uniform breeder blanket was found using MCNP6 (see Figure 3). In each simulation the material composition was kept constant in all eight layers of the breeder blanket. The multiplier fraction (see Equation 1) was varied from 0 to 1 in steps of 0.01. This was carried out with two different levels of ^{6}Li enrichment (100% and 70% ^{6}Li enrichment). Natural abundance of ^{6}Li is 7.59%, however ^{6}Li enrichment is required to achieve a sufficiently high TBR.

$$\text{multiplier fraction} = \frac{\text{volume of } Be_{12}Ti}{\text{volume of } \mathrm{Be_{12}Ti} \text{ and } Li_4SiO_4} \qquad \text{(Equation 1)}$$

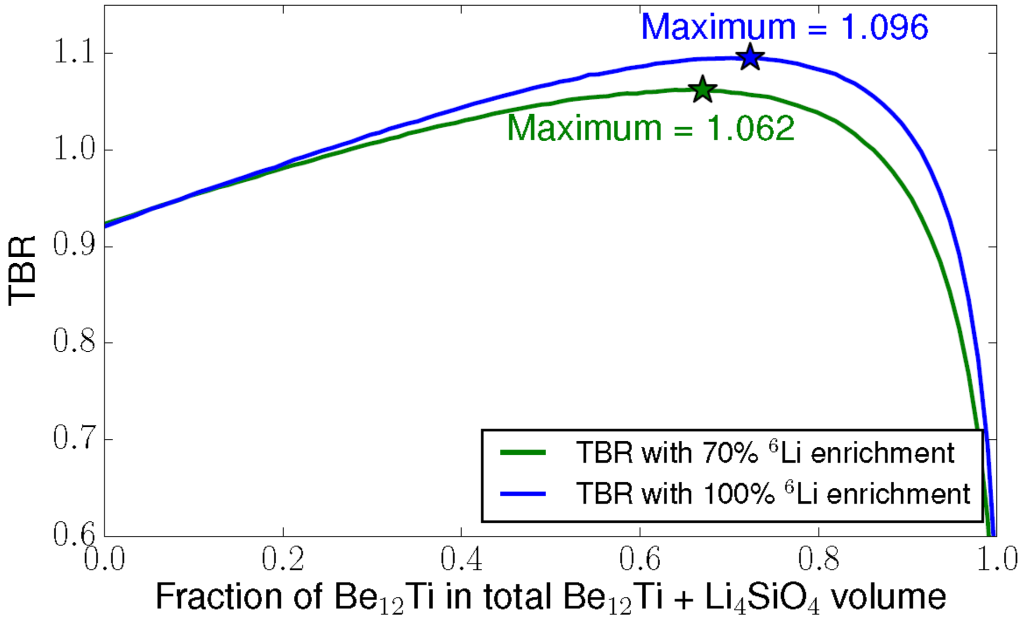

Figure 3. The result of varying the multiplier fraction on the TBR for the uniform blanket designs.

The second stage involved investigating if non-uniform compositions were capable of achieving higher TBR values than the optimal uniform blankets, while also using less beryllium. The approach taken was to use the best uniform composition as a starting design and try variations of this design to determine if the TBR could be increased. Changes to the material composition of individual layers were made and new variants of the starting design were created. Sixteen different variants of the starting design were created by varying each of the eight layers. The multiplier fraction of each layer was perturbed to make new variants. The magnitude of the perturbation was an increase or decrease of the multiplier fraction by 0.02. Simulations were performed and the TBR of each variant was obtained along with the starting design. The TBR values of all the results were compared and the highest achieving TBR was chosen as the next starting composition from which future variants would be made. Figure 4 shows typical results from one batch of variants, in this case a reduction of $Be_{12}Ti$ fraction in layer number eight was chosen as the next starting design.

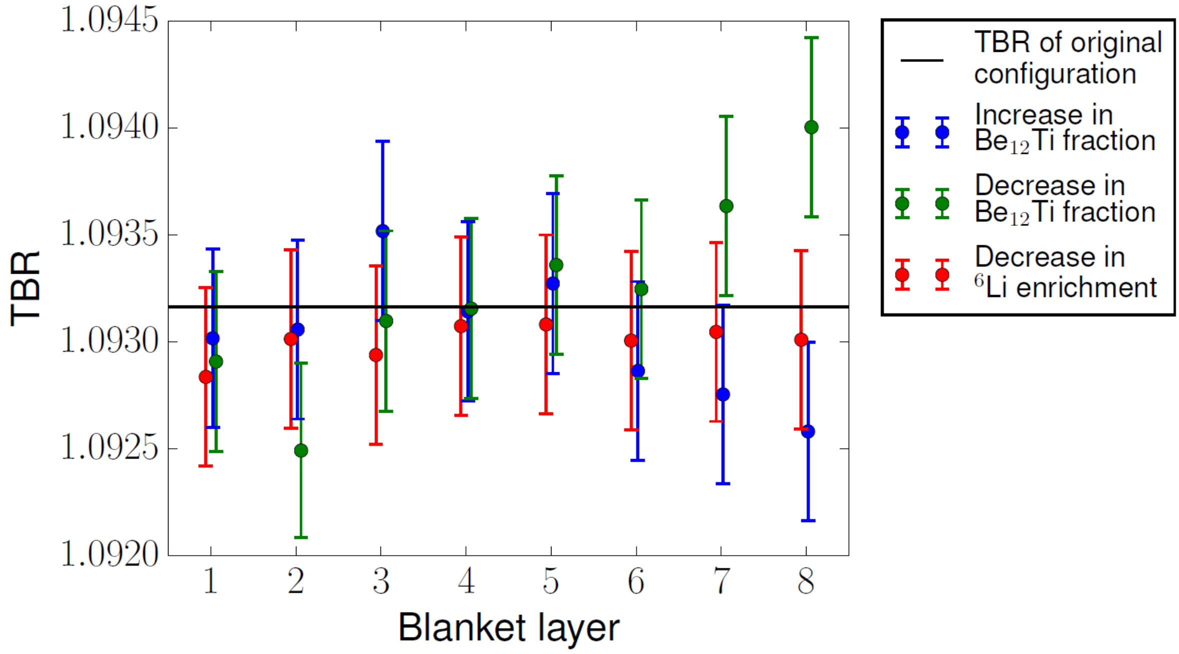

Figure 4. The TBR values obtained from different variants of the original starting design. This particular plot show the results from a typical iteration for the composition with 100% ^6Li enrichment. The error bars represent a statistical error of 1σ obtained from MCNP.

This process was repeated 50 times and each time the highest performing TBR value was found. While this is not an exhaustive search of all possible variants the results serve as proof of principle that changing the multiplier fraction as a function of depth can raise the achievable TBR and reduce the beryllium requirements of a mixed bed blanket design.

Results

The resulting increase in TBR by using non-uniform blankets was found to be ~0.01 for the blanket simulations carried out (see Figure 5). This equates to over 1kg of additional tritium produced per year or $\$3x10^9$ worth of tritium per year, assuming a market value of $30,000 per g (for a 3GW fusion power plant with 70% availability). The absolute increase in TBR for the blanket design used in this research is marginal. The absolute change in TBR is dependent upon assumptions made in the model. Different models with thicker blankets are likely to show a larger increase in TBR than the thin blankets (45.5cm) used in this research. This would be due to an increased difference between neutron spectra at the front and rear of the blanket which this method relies upon. Detailed studies would be required to ascertain the error associated with the simulated TBR value however as all simulations used the same geometry, nuclear data and number of simulated neutrons it is assumed that the error effects all the simulated TBR values in a similar manner.

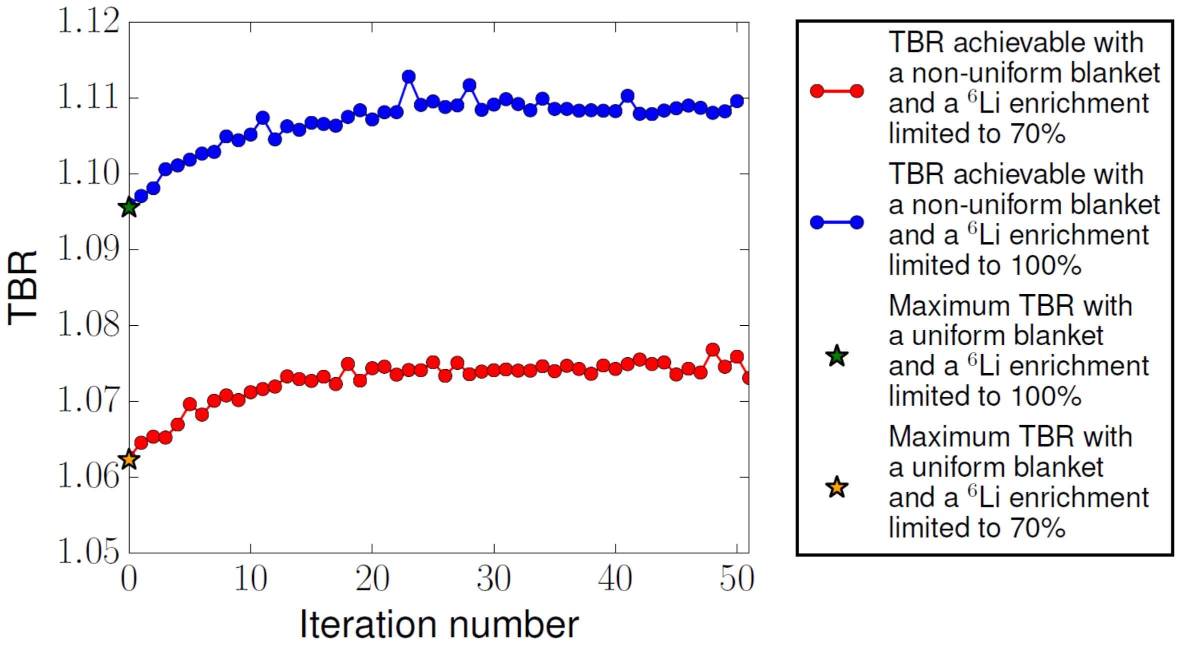

Figure 5. The additional increase in TBR achievable with the non-uniform mixed pebble bed blanket

The resulting reduction in the amount of beryllium required was ~14%. The multiplier fraction at the rear of the high TBR achieving non-uniform blanket compositions was lower than the multiplier fraction at the rear of uniform breeder blankets (see Figure 6). This is particularly beneficial as beryllium is a scarce resource and a major contributor to the blanket cost [12]. Another point of interest is that the multiplier fraction at the very front of the non-uniform blanket was also lower than uniform blanket. This is due to the capability of beryllium to act as a neutron reflector. Therefore an optimal beryllium fraction at the front of the blanket exists. Beryllium fractions above this would result in neutrons being reflected back out of the blanket and increase the chance of parasitic absorption in the first wall. In the second layer the multiplier fraction of the non-uniform blanket is higher than the uniform blanket. The second layer appears to be the position where additional neutron multiple is most beneficial. The results presented in Table 1 summarise the main results of this research.

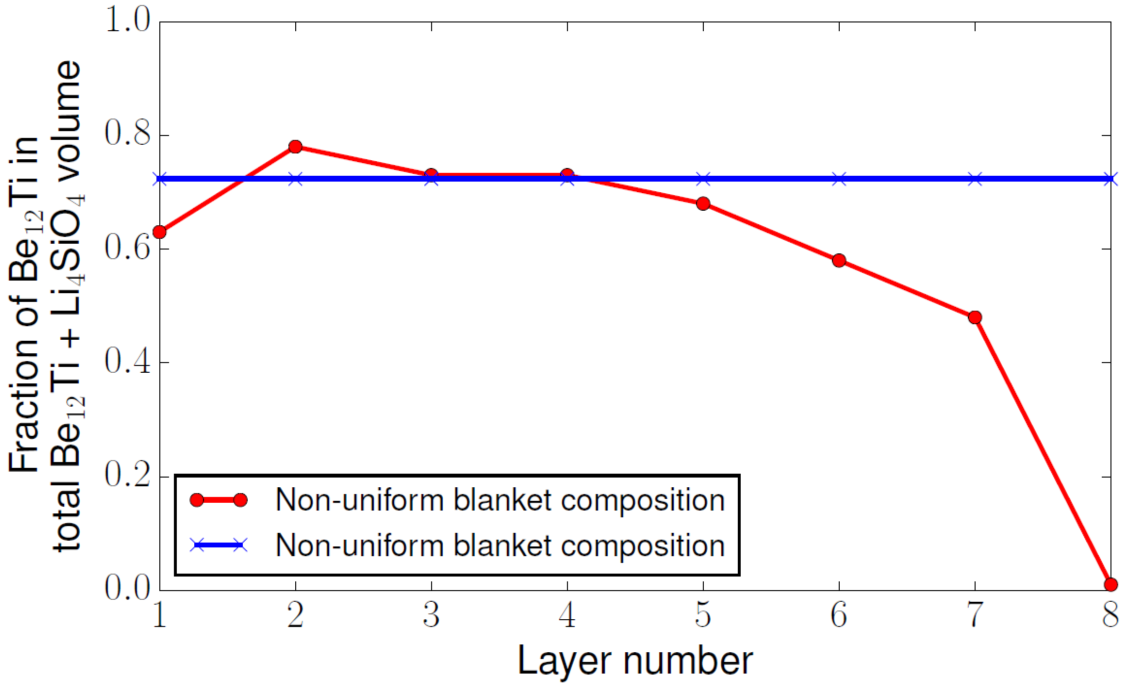

Figure 6. The difference in multiplier fraction required for maximum TBR in a uniform and non-uniform blanket.

	TBR achievable		Tonnes of $Be_{12}Ti$ required	
	^{6}Li enrichment of 70%	^{6}Li enrichment of 100%	^{6}Li enrichment of 70%	^{6}Li enrichment of 100%
Uniform mixed bed	1.062	1.096	325.7	357.2
Non-uniform mixed bed	1.073	1.109	285.1	300.2
Improvement	0.011 higher TBR	0.013 higher TBR	12.5% reduction in $Be_{12}Ti$	15.9% reduction in $Be_{12}Ti$

Table 1. Summary of maximum TBR values achieved with uniform and non-uniform blankets.

Conclusion

The approach aimed to capitalise on the variations in the neutron spectra throughout the blanket by varying the breeder to multiplier ratio as a function of depth. The layered blanket method explored by this research offers a method of reducing the beryllium requirements of a solid-type mixed bed breeder blanket while also increasing the TBR. The modest increase in TBR offers a supplementary method of improving the TBR once other techniques have been exhausted. This could be particularly useful when reactor designs offer little scope to increase the blanket coverage and further ^{6}Li enrichment is not desirable. For example designs with double null divertors or no breeder blankets on the central column.

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