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Reducing beryllium content in mixed bed solid-type breeder blankets

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HIGHLIGHTS

- The ratio of breeder ceramic to neutron multiplier of breeder blankets was varied linearly with depth.
- Blankets with varying composition were found to perform better than uniform composition breeder blankets.
- It was also possible to reduce the amount of beryllium required by the blanket.

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ABSTRACT

Beryllium (Be) is a precious resource with many high value uses, the low energy threshold (n,2n) reaction makes Be an excellent neutron multiplier for use in fusion breeder blankets. Estimates of Be requirements and available resources suggest that this could represent a major supply difficulty for solid-type blanket concepts. Reducing the quantity of Be required by breeder blankets would help to alleviate the problem to some extent. In addition, it is important that the reduction in the Be quantity does not diminish the blanket's performance in key aspects such as the tritium breeding ratio (TBR), energy multiplication and peak nuclear heating.

Mixed pebble bed designs allow for the multiplier fraction to be varied throughout the blanket. This neutronics study used MCNP 6 to investigate linear variations of the multiplier fraction in relation to blanket depth, in order to better utilise the important multiplying Be(n,2n) and breeding reactions. Blankets with a uniform multiplier fraction showed little scope for reduction in Be mass. Blankets with varying multiplier fractions were able to simultaneously use 10% less Be, increase the energy amplification by 1%, reduce the peak heating by 7% and maintaining a sufficient TBR when compared to the performance achievable using a uniform composition.

1. Introduction

The sustainability of resources required for deuterium tritium (DT) fusion have been previously considered [1,2]. Reported availability of Be resources is particularly concerning, although further successful prospecting could alleviate the situation. The usage of Be in fusion devices is common and is demonstrated by Be being the reference material for solid-type breeder blankets in ITER [3] and beryllides such as $Be_{12}Ti$ are considered a promising neutron multiplier for DEMOnstration power plants (DEMO) [4]. Recycling of irradiated beryllium [5] is one option that could reduce the amount of Be usage over a reactor's lifetime. Another approach that could be carried out in tandem is to reduce the amount of Be specified in breeder blanket designs. This paper aims to explore the possibility of decreasing the amount of Be required in mixed bed breeder blanket designs.

Mixed bed breeder blankets are being pursued by several research groups [6–8]. They utilise an intimate mixture of breeder ceramic and neutron multiplier pebbles. Using pure Be as the neutron multiplier has been ruled out in mixed beds due to tritium retention in the beryllium [9] and incompatible chemistry [10]. The development of advanced beryllide neutron multipliers such as $Be_{12}Ti$ has shown them to be suitable for mixed bed blankets [11]. Studies into the chemical compatibility, tritium retention and fabrication have been carried out. Studies have also shown that mixed pebble beds offer higher tritium breeding ratio (TBR) than

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separated bed breeder blankets [4]. Consequentially mixed pebble bed breeder blankets are being considered for future fusion reactors [6–8].

Neutronic optimisation studies have been carried out to ascertain the optimal multiplier fraction (see Eq. (1)) in terms of maximising TBR in mixed pebble beds [8,12] and for blankets with separated breeder and multiplier regions [13]. The traditional approach has been to find a single optimal multiplier fraction for the entire blanket. By varying the ratio of neutron multiplier and lithium ceramic the TBR can optimised (see Fig. 2). The TBR values obtained by simulation throughout this study refer to the local TBR of the DEMO model used. The DEMO model used in this study contains no penetrations for heating or diagnostics, the assumed coverage of the breeder blankets is ∼85%.

Other aspects to consider are the energy multiplication and peak heating. The heat energy produced in a blanket can be more than the sum of the neutron energies entering the blanket, due to the release of binding energy as disturbed nuclei rearrange themselves into stable configurations. The ability of the blanket to multiply the incident energy will be of interest when maximising the electricity generated. The peak heat refers to the maximum heat deposition per cm^3 in the blanket and is a criterion that may require minimising to prevent material damage.

Mixed bed blankets have the potential to offer different multiplier fractions throughout the blanket (see Eq. (1)). This might be achievable through careful control of the pebble mixture when filling the blanket. The objective of this work is to highlight the potential benefits of using a varying multiplier fraction in mixed pebble bed breeder blankets. This allows further optimisation of the identified performance criteria as well as a reduction in the quantity of beryllium usage. Studies that aim to reduce the beryllium usage within homogeneous blanket designs have previously be carried out. [14] considers replacing the solid Be slabs at the back of the blanket with more efficient moderator materials (ZrH), however at the time mixed bed blankets were not considered viable and mixed bed blankets were not the focus of the paper. There is a lack of studies that seek to reduce beryllium usage within mixed bed breeder blankets. This study aims to optimise the beryllium usage in a bed of equally sized $Be_{12}Ti$ and Li_4SiO_4 pebble by simulating linear variations in multiplier fraction throughout the blanket.

2. Theory

Neutron induced reactions in beryllium and lithium make them desirable materials to use in fusion breeder blankets. The cross sections of Be(n,2n) and Li(n,t) respond to different energy neutrons. The Be(n,2n) reaction is a threshold reaction requiring neutrons of at least 1.75 MeV. The Li(n,t) reaction is increasingly likely to occur as neutron energy decreases. A combination of both reactions are required to ensure a TBR of at least 1.1.

The neutron spectra varies throughout the breeder blanket mainly due to scattering and capture interactions. Due to the softer spectrum and the threshold nature of the Be(n,2n) there will be a lower proportion of neutrons capable of Be(n,2n) reactions at the rear of the blanket. The degree of spectral variation depends largely on the material composition of the blanket material and the first wall.

The two reactions of interest also differ in their Q values (energy release per reaction). The Be(n,2n) reaction is endothermic ($Q = -1.57$ MeV) whereas the Li(n,t) reaction is exothermic ($Q = 4.78$ MeV). Peak heating tends to occur at the front of the breeder blankets due to the high neutron flux. The endothermic nature of the Be(n,2n) could allow the local heating to be reduced compared to the exothermic nature of the Li(n,t) which would cause additional local heating.

The variation in spectra, the difference in cross section and the different Q values suggest that a uniform mixture of the two materials is not optimal. Preliminary calculations suggest that the optimal quantity of beryllium at the front of the blanket is expected to be higher than the optimal quantity at the rear of the blanket. As a first approximation, a linear variation in multiplier fraction, with respect to depth within the breeder blanket was decided upon.

3. Material and methods

The MCNP model used in this study was adapted from a tokamak DEMO model developed at KIT [15]. The geometry was modified to incorporate a breeder blanket with a uniform blanket thickness of 68 cm (see Fig. 1). The model includes a first wall with a thin layer of armour, homogenized breeder modules, a rear shielding layer and a divertor. Tungsten (3 mm thick) was chosen for the first wall armour and Eurofer with helium coolant (3 cm thick) was chosen for the first wall [16]. The blanket breeder zones contain a homogenised mixture of Eurofer, helium (as coolant and purge gas), $Be_{12}Ti$ and Li_4SiO_4 enriched to 40% Li (see Table 1).

The breeder zone was segmented into 40 layers of equal radial depth (1.7 cm). The study aimed to vary the multiplier fraction throughout the blanket and observe the results. Multiplier fractions were chosen for the first layer, these ranged from 0 to 1 in

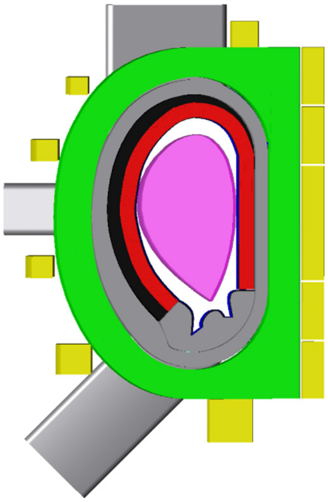

Fig. 1. The uniform thickness blanket tokamak model used. The vacuum vessel and divertor (grey), toroidal field coils (green), poloidal field coils (yellow), blanket (red), blanket rear and front casing (black) and tungsten armour (blue) are included. Image generated using [17]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

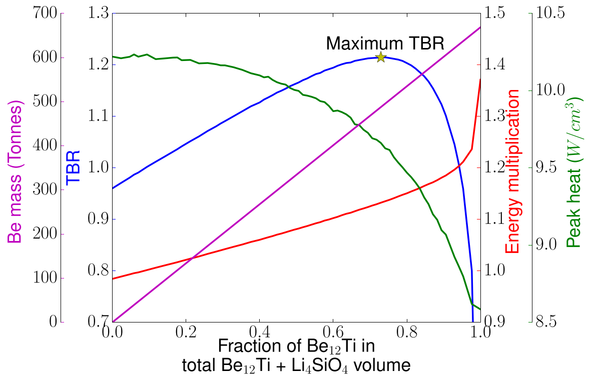

Fig. 2. Key performance criteria for different multiplier fractions in a mixed pebble bed breeder blanket utilising uniform multiplier fractions.

Table 1
Material specifications for the homogenised breeder blanket material.

Material	Component	Volume percent	Density (g/cm^3)
Homogenized breeder material	Eurofer	9.705	1.816
	He coolant	5.295	
	Li_4SiO_4	0–53.55	
	He purge gas	31.45	
	$Be_{12}Ti$	0–53.55	

increments of 0.0588. Multiplier fractions were chosen for the rear layer, these also ranged from 0 to 1 in increments of 0.0588. Every permutation of the 18 first layer and 18 rear layer composition was considered and this resulted in 324 different MCNP models. Linear interpolation between the multiplier fraction in the front layer and the rear layer was used to find multiplier fractions for the remaining 38 layers in the middle.

$$\text{Multiplier fraction} = \frac{\text{Volume of } Be_{12}Ti}{\text{Volume of } Be_{12}Ti + \text{Volume of } Li_4SiO_4} \quad (1)$$

Once the material definitions of the breeder blanket were decided upon individual MCNP 6.0 [18] simulations for each of the 324 blanket permutations were carried out. FENDL 3.0 nuclear data [19] was used for particle transport. F6 tallies were set up to ascertain the energy deposition within the individual breeder blanket and casing cells. F4 tallies were used to find the TBR. The neutron plasma source utilised in the MCNP model was based on research published by [20]. An external FORTRAN MCNP source routine provided by EUROfusion [21] required primary plasma parameters to produce a distributed neutron source. The parameters used for this study were a plasma temperature of 15.4 KeV, plasma major radius of 9 m, plasma minor radius of 2.25 m, elongation of 1.66, triangularity of 0.33 and a plasma peaking factor of 1.3. The DEMO reactor simulated was 2.7 GW fusion power.

4. Results

4.1. Performance of blankets with a uniform multiplier fraction

Fig. 2 shows the performance of breeder blankets with constant multiplier fractions throughout. Selecting the optimal composition depends on the relative importance of energy multiplication, peak heat, Be usage and TBR. The parameter which is most commonly optimised is TBR and it is widely accepted that a TBR of at least 1.1 is required [22]. The maximum TBR achievable using a uniform multiplier fraction blanket was found to be 1.2147, this was achieved with a multiplier fraction of 0.741 throughout the blanket. This TBR optimised composition results in a Be mass of 487.7 tonnes, peak heating of 9.65 W cm^{-3} and energy multiplication of 1.13. The uniform multiplier fraction blanket offers no scope to improve the overall performance while reducing the Be usage. Reducing the Be usage results in higher peak heat, lower energy multiplication and lower TBR values (see Fig. 2). To demonstrate the possible advantages of varying the multiplier fraction with blanket depth it is necessary to compare the performance of both blanket types. The performance of the TBR optimised uniform blanket has been compared with the performance of varying multiplier fraction blankets (see Fig. 7). The following Figs. 3–6 show the performance of the variable multiplier fraction blankets, certain configurations that are obtainable uniform multipler fraction blankets (e.g. configurations with equal front and rear multiplier fractions).

4.2. Performance of blankets with a varying multiplier fraction

Fig. 3 shows the $Be_{12}Ti$ required for each of the blankets simulated. As expected, blankets with high multiplier fractions at both the front and the rear of the blanket require the most Be.

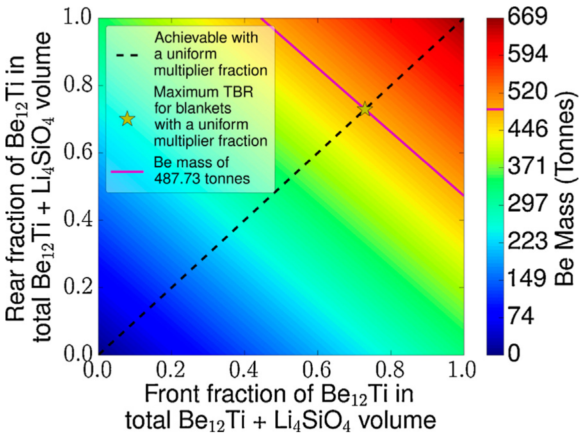

Fig. 3. Total Be requirements for each blanket composition simulated.

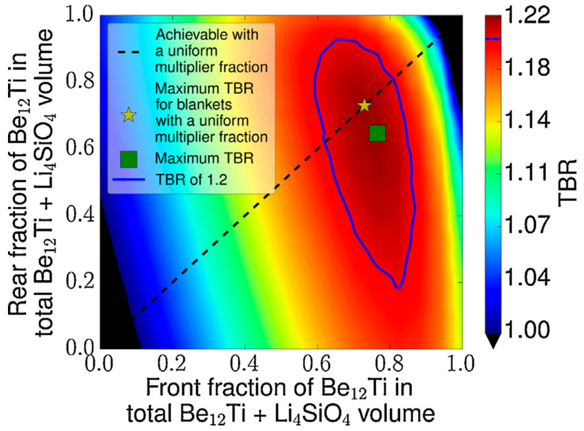

Fig. 4. The simulated TBR results for different blanket configurations.

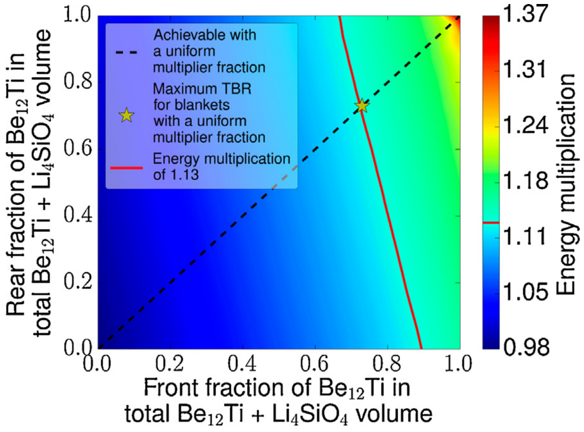

Fig. 5. Energy multiplication in the breeder blanket by neutrons and photons.

The TBR is dependant on the profile of the multiplier fraction throughout the blanket. Fig. 4 shows that TBR is very sensitive to changes in the multiplier fraction at the front of the blanket. However the TBR is relatively insensitive to variation in multiplier fraction at the rear of the blanket. Fig. 4 shows there is significant scope to reduce the rear multiplier fraction without significantly impacting the TBR. A marginal increase in TBR is achievable (TBR = 1.215) if a varying multiplier fraction is used with a front breeder fraction of 0.76471 and a rear breeder fraction of 64.706.

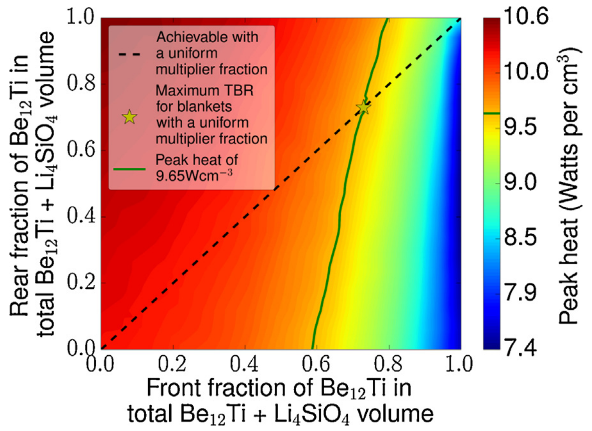

Fig. 6. Peak nuclear heating (photon and neutron) in the variable multiplier fractions blankets.

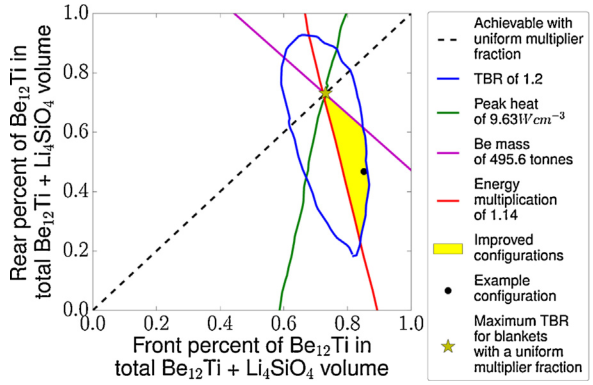

Fig. 7. The diagram shows the region of blanket configurations that offer higher energy multiplication, lower peak heat, less Be usage than the uniform multiplier fraction blanket (optimised for TBR).

Increasing the energy multiplication is desirable as it increases the quantity of electricity that can be generated by the reactor. Blankets with large quantities of Be and in particular large multiplier fractions at the front were found to produce the highest energy multiplication (see Fig. 5).

The maximum neutronic and photonic energy deposited in any one region should be kept low to minimise the chance of material failure. As the Be(n,2n) reaction is a threshold reaction and therefore endothermic, this results in lower temperatures in regions where the reaction occurs. Therefore use of Be at the front of the blanket can reduce the peak heating in the blanket. Lower peak heating could result in a reduction of cooling requirements, this could leave more space for breeding materials and subsequently increase the TBR.

4.3. Improved performance

Comparing the performance of blanket designs with uniform and varying multiplier fractions shows the additional flexibility allowed by varying the multiplier fraction. Fig. 2 shows that reduction in the Be mass for uniform multiplier fraction blankets results in detrimental performance as energy multiplication reduces and peak nuclear heating increases. Blanket designs using a varying multiplier fraction can offer reductions in Be mass without these disadvantages. Moving away from the optimal TBR configuration to improve energy multiplication and peak heating naturally involves some reduction of TBR for both blanket designs. Fig. 4 reveals that variable multiplier fraction blankets are capable of reducing the rear multiplier fraction with only minimal reduction in TBR. Fig. 7 identifies blanket configurations (yellow region) that offer higher energy multiplication, lower peak heat, less Be usage and minimal reduction to TBR when compared to the uniform multiplier fraction blanket optimised for TBR. The figure also shows one example blanket configuration that could be considered more optimal. This blanket configuration simultaneously uses 10% less Be, increasing the energy multiplication by 1%, reducing the peak heating by 7% and maintaining a sufficiently high TBR (1.2) when compared to the performance achievable using a single uniform composition. This reduction in Be usage and subsequent improvement in energy multiplication and reduction of peak heating are not accessable with a uniform multiplier fraction blanket.

5. Conclusion

Linear variations in multiplier fraction are one way to better utilise the differences in cross section and Q values of Be(n,2n) and Li(n,t) reactions. A reduction of 10% in the Be mass of blankets was achieved when using varying multiplier fractions. In addition to reducing the use of a precious resource there are potential financial advantages of using less $Be_{12}Ti$ as it is likely to be more expensive than Li_4SiO_4. The blanket's performance in key areas such as peak heating and energy multiplication were improved whilst achieving a reduction in the quantity of Be, this was not possible with a uniform multiplier fraction blanket. Additional energy amplification strengthens the economic case as this would generate additional revenue. Although the linear variation in multiplier fraction improves upon current mixed ceramic blanket designs using a uniform multiplier fraction is likely to be suboptimal. Nonlinear variations in multiplier fraction in the poloidal and toroidal directions should be considered and could potentially further improve the blanket's performance.

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