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A parameter study of time-varying tritium production in solid-type breeder blankets

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Abstract

Tritium production is of critical importance to prospective DT fusion power plants. Lithium ceramic and beryllium based solid-type breeder blankets are an option for supplying the tritium required to sustain the DT plasma. This research investigates the time-varying tritium production in solid breeder blankets with different compositions. The breeder fraction was varied in conjunction with the ^{6}Li enrichment. The parameter study considered 198 different blanket compositions for three blanket thicknesses. The cheapest configuration capable of meeting the tritium requirements were found. The cost of Li_4SiO_4 (including ^{6}Li enrichment) and $Be_{12}Ti$ were considered. The time-varying tritium production of each blanket configuration was simulated using the interface code, FATI, that couples the radiation transport code MCNP 6 with the inventory code FISPACT-II. Economical blanket configurations capable of self-sufficiency were found. The cost of producing excess tritium for start-up inventories was found to be between \$18,000 and \$27,000 per g. Fitting functions to predict the time-averaged tritium breeding fraction and the tritium inventory at five years, were obtained for inclusion in the PROCESS systems code. PROCESS is now able to consider different breeding blanket compositions and thicknesses when assessing the engineering, physics and economic feasibility of reactor designs.

Keywords: Fusion, tritium, TBR, neutronics, parameter, blanket

1. Introduction

Systems codes are designed to assess the engineering, physical and economic viability of future fusion reactors. Systems codes are often designed to run quickly through several iterations to find optimal solutions. This can be achieved by accessing preprocessed results and fitted functions from more computationally intense simulations. Several systems codes exist with differing approaches and objectives. PROCESS [1] is a systems code under development at CCFE with a particular focus on minimizing a user chosen figure-of-merit (e.g. the cost of electricity). The PROCESS code has been utilized effectively in the Power Plant Conceptual Study [2] and economic studies into the feasibility of fusion energy [3].

This paper reports on a new neutronics module which links high fidelity neutronics parameters into the PROCESS code. Standard neutronics tools for fusion require enhancement via scripting and linking to an inventory code to allow for nuclei burn-up and transmutation when predicting tritium production. The aim of this parameter study was to provide PROCESS with a time-averaged Tritium Breeding Ratio (TBR), the tritium inventory after 5 years of operation and material costs. Three different blanket thicknesses have been considered as well as different lithium enrichments and lithium ceramic (Li_4SiO_4) to neutron multipler ratios ($Be_{12}Ti$).

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Fitted empirical functions allow PROCESS access to this data without having to perform the full neutronics simulations. Users will now be able find the most economical blanket composition capable of tritium self-sufficiency or capable of providing a tritium surplus that could be used for subsequent reactors. Due to the small world wide reserves of tritium the rate of fusion reactor deployment will be limited by the availability of tritium [4], careful design and planning of tritium production will help alleviate this risk. The ability to minimise the cost of breeder blankets, while still achieving the required target tritium production, is of particular importance, as currently the blankets are expected to be replaced several times during the reactor's lifetime and will form a large part of the capital cost.

2. Materials and methods

2.1. MCNP model

The reactor model used in this study was adapted from a tokamak DEMO model developed at KIT [5]. The model contains no blanket penetrations for heating or diagnostics and therefore overestimate global TBR as compared to a more detailed model incorporating such penetrations. Recent research [6] has suggested that each additional penetration results in a TBR reduction of 0.35% to 0.5% depending on the penetration size and the material present within the penetration. The neutron plasma source [7] utilized in the MCNP model was represented using primary plasma parameters. The model includes a first wall with a thin layer of armour, homogenized breeder modules, a rear shielding layer and a divertor with no breeding capability. Tungsten (3mm thick) was chosen for the first wall armour and Eurofer with helium coolant (3cm thick) was chosen for the first wall [8]. The breeder blanket was split radially into 5 layers and poloidally into 19 modules. The radial segmentation of the breeder zones was based on findings from a previous study which shows radial segmentation to be necessary when simulating nuclide depletion [9].

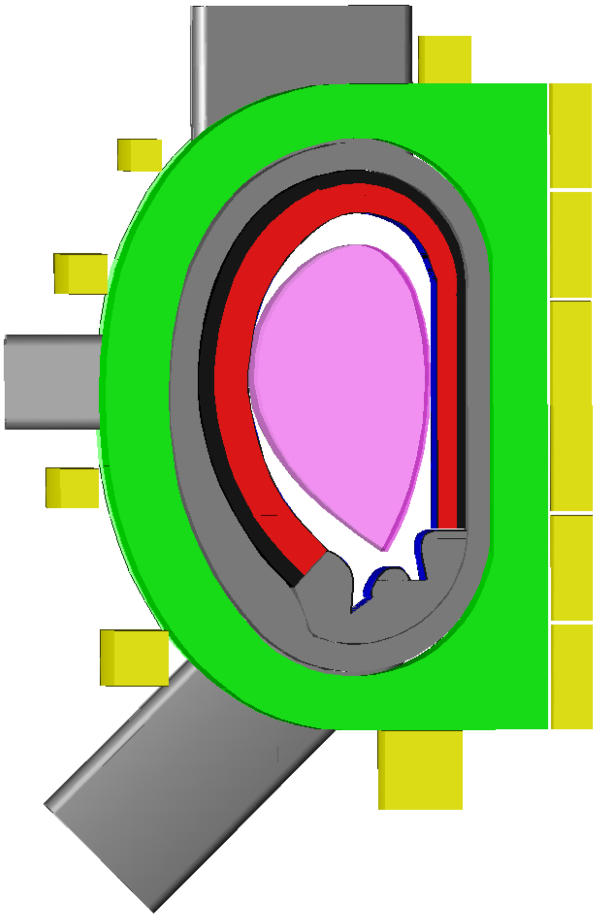

Figure 1: The thin blanket tokamak model used. The vacuum vessel and divertor (grey), toroidal field coils (green), poloidal field coils (yellow), blanket (red), blanket rear and front casing (black) and tungsten armour (blue) are included. Image generated using [10].

2.2. Materials

The homogenized breeder blanket material used was based on the HCPB design and contained fixed volumes of Eurofer [11] (9.705%) and He coolant (5.295%). The packing fraction of the $Be_{12}Ti$ and Li_4SiO_4 pebbles was assumed to be 0.63 [12] which occupies 46.45% of the available volume. Helium purge gas was used to fill the remaining voids between pebbles (31.45%). The breeder fraction (see Equation 1) was varied between 0 and 1 in 18 intervals and the ^6Li atomic fraction in the lithium was varied from 0 to 1 in 11 intervals. The breeder fraction is defined as

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

This resulted in 198 different breeder blanket compositions for each of the 3 blanket thickness scenarios (see Table 1). In models with thin and medium scenarios blanket the additional space was filled with homogenised shielding in the form of Eurofer (64.7% volume) and He coolant (35.3% volume).

Blanket description	Inboard blanket depth (m)	Outboard blanket depth (m)	Volume (m^3)
thin	0.53	0.91	891.92
medium	0.64	1.11	1104.06
thick	0.75	1.30	1322.72

Table 1: The dimensions and volumes of the three different breeder blanket scenarios simulated.

2.3. Calculation method

To calculate the time-averaged TBR and final tritium inventories a Monte Carlo approach was used for each blanket composition. The interface code FATI [13] was used to couple the radiation transport code MCNP 6.0 [14] with the inventory code FISPACT-II [15]. FENDL 3.0 nuclear data [16] was used preferentially for particle transport and TENDL 2014 data [17] was used when FENDL data was not avaliable for particular isotopes. TENDL data in 315 group format was also used for isotope burn-up calculations performed by FISPACT-II.

Burn-up was simulated in time steps of 15 days [18] for a fusion reactor with 2.4 GW of fusion power, operating at 70% [19] availability for 5 years. This resulted in 122 MCNP simulations for each blanket composition. The TBR was found at each time step with MCNP F4 tallies. The final tritium inventory was taken as the difference between the cumulative tritium production and consumption while accounting for radioactive tritium decay. Tritium retention, leakage and isotope separation efficiencies were not accounted for. Tritium losses in the cycle were therefore dominated by tritium decay. Gases (H and He) produced through transmutations within the burn cells in the blanket during irradiation were assumed to be removed from the breeder zones in the purge gas flow.

2.4. Cost estimates

In order to compare breeder blanket configurations in terms of their costs it was necessary to make assumptions to quantify the cost of the variable components in each breeder blanket configuration. Other costs involved such as the cost of non blanket related parts of the reactor, the structural Eurofer, He coolant and manufacturing costs were assumed to be constant for all blanket compositions and therefore were not taken into account as a variable costs. The costs associated with increased shielding required for thinner blanket geometries were assummed to be small in comparison and were also not included in this study. The cost of $Be_{12}Ti$ was estimated to be \$4,500 per kg [20], the future cost of Li_4SiO_4 (with natural Li) was estimated to be \$1000 per kg [21] and the cost of ^6Li enrichment from [22] was used. The relatively high costs of $Be_{12}Ti$ compared to Beryllium are due to additional manufacturing steps required.

The costs of the different blanket compositions (see Figure 2) are best estimates of materials bought in bulk where no significant market currently exists. The inherent uncertainty in predicting the price of future commodities means these results should be updated when better price estimates are available. The recycling value of the breeder blankets was also not considered in this preliminary study, this may be substantial due to the large quantities of beryllium and enriched lithium present in the blanket at the end of life. The separation and sale of decay products (e.g. ^3He from ^3H decay has potential uses in neutron detectors) were also not taken into account.

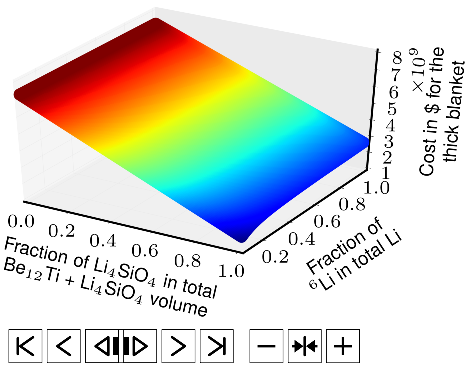

Figure 2: The combined costs of $Be_{12}Ti$, Li_4SiO_4 and $_6Li$ enrichment for different blanket compositions.

3. Theory

The breeder blanket composition affects tritium production, neutron multiplication, shielding, energy multiplication and activation. These different quantities are related, therefore changing the composition with an aim of increasing one aspect may negatively affect others. An optimal composition would take into account the relative importance of each neutronics quantity. While early fusion reactors might be more focused on producing excess tritium, later designs could be more interested in energy multiplication to maximise electricty production. This paper assumes excess tritium production is of primary importance and aims to optimise solid-type blanket compositions accordingly.

Tritium is produced predominantly via the $^6Li(n,t)^4He$ reaction but it is also produced via the $^7Li(n,n't)^4He$ threshold reaction. A small amount is produced via interactions in other nuclei (e.g. $^9Be(n,t)^7Li$). Increasing the tritium production can be achieved by:

1. Increasing the number density of tritium producing isotopes.
2. Increasing the neutron population in the blanket region through neutron multiplication.
3. Decreasing the amount of parasitic neutron absorption.
4. Modifying the neutron spectra through scattering interactions so that tritium producing reactions or neutron multiplication become more likely, or so that parasitic becomes less likely.

Enriching the lithium ceramic so that it has a higher ^6Li content increases the tritium production due to the large ^6Li thermal cross section. Increasing tritium production solely by ^6Li enrichment results in diminishing returns as higher enrichment values are reached. The corresponding reduction of ^7Li results in less $^7Li(n,nt)^4He$ reactions and consequently a reduced neutron flux. The neutron flux is also diminished due to a reduction in neutron multiplying reactions in ^9Be. The reduced neutron flux can be compensated by increasing the volume of neutron multiplier material. However, the volume not required for structural, cooling or gas extraction purposes is taken up by a combination of lithium ceramic and neutron multiplier. Therefore increasing the volume of neutron multiplier reduces the amount of lithium ceramic and the amount of ^6Li and ^7Li.

Compositions containing large volumes of lithium ceramic at the expense of neutron multipliers show low levels of tritium production due to low neutron multiplication, these blanket compositions are located on the far right hand side of Figure 3. The opposite extreme is also possible as compositions with an excessive neutron multiplier volume also produce low amounts of tritium due to the low number of Li atoms available for tritium production, these blanket compositions are located on the far left hand side of Figure 3. Compositions containing low levels of ^6Li enrichment were also not able to produce large quantities of tritium, these blanket compositions are located at the bottom of Figure 3. Finding the optimal ratio of neutron multiplier depends upon the relative benefit of increasing the neutron flux compared to increasing the lithium content and therefore different levels of ^6Li enrichment have different optimal neutron multiplier volumes. The ratio of lithium to beryllium also varies slightly with time as ^6Li burns up more rapidly than ^9Be. For this reason it is important to take isotopic-depletion into account when choosing a blanket composition to operate for sustained time periods. The task of predicting the time-varying tritium production while accounting for nuclei burn-up is well suited to a Monte Carlo approach that accounts for these neutronic effects.

4. Results

The TBR of the solid-type breeder blanket was found to decrease over time as the tritium producing isotopes were depleted in nearly all cases. Blanket compositions with no lithium fraction are not capable of high TBR values but were included in the parameter study for completeness. Reaction products such as ^{6}Li built up in blankets containing high quantities of $Be_{12}Ti$. Production of ^{6}Li occurred via ^{9}Be(n,^{3}H)^{6}He reactions and the subsequent decay of ^{6}He into ^{6}Li. This caused a small increase in TBR for blankets with no initial lithium content, but the TBR still remained below 0.1. Time-average TBR values were calculated by taking the average (mean) value of the TBR from all 122 time-steps. TBR typically decreased by 1.4% for compositions capable of achieving tritium self-sufficiency over the 5 year duration. A 1.4% reduction in TBR of 1.115 to 1.09939 equates to 13.57% decrease in the margin of TBR over 1 and this would be sufficient to drop below the common target of TBR>1.1. Blankets with low breeder fractions and low ^{6}Li enrichment showed the most rapid decrease in TBR over time.

Tritium self-sufficiency was found to be achievable with numerous blanket configurations for all blanket thicknesses (see area within red self-sufficiency line on Figure 4). However, only blankets with high ^{6}Li enrichment levels and beryllium are capable of generating a useful excess of tritium, to allow for tritium losses and to fuel subsequent reactors. Figures 3 and 4 reveal that at low ^{6}Li enrichments the optimal tritium production is insensitive to breeder fraction while at higher ^{6}Li enrichments the optimal tritium production is much more sensitive to breeder fraction.

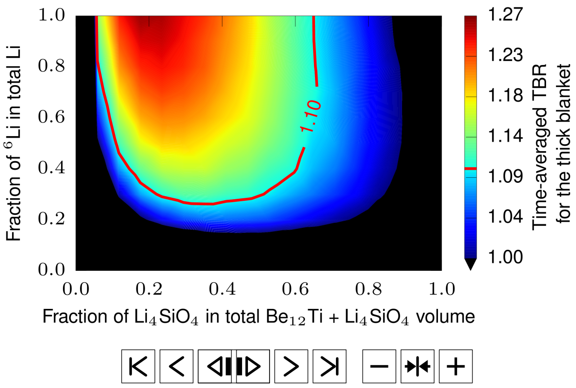

Figure 3: The time-averaged TBR values for thick, medium and thin blanket thicknesses and different blanket compositions. A TBR of 1.1 is identified by the red contour line.

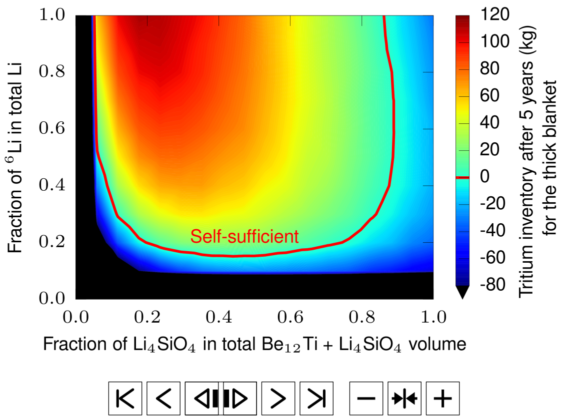

Figure 4: The tritium inventory at five years for thick, medium and thin blanket thicknesses, with self-sufficient blanket compositions identified by the red contour line.

Time-averaged TBR and tritium inventory at 5 years were fitted by a surface function (see Equation 2) to produce Figures 3 and 4 respectively. The required output (either TBR or T inventory in kg) can be found by knowing the ^{6}Li atom fraction (0.1 to 1) (x), the breeder fraction (0.06 to 1) (y), blanket thickness and the values of the 19 coefficients (see Tables 2 and 3).

$$\begin{aligned} &v_1 + v_2x + v_3y + v_4yx + v_5x^2 + v_6y^2 + v_7x^2y \\ &\quad + v_8xy^2 + v_9x^2y^2 + v_{10}x^3 + v_{11}y^3 + v_{12}yx^3 \\ &\quad + v_{13}y^3x + v_{14}y^2x^3 + v_{15}y^3x^2 + v_{16}y^3x^3 \\ &\quad + v_{17}\ln(x) + v_{18}\ln(y) + v_{19}\ln(x)\ln(y) \end{aligned} \tag{2}$$

coeffi-cients	Tritium inventory after 5 years (kg)		
	Thick blanket	Medium blanket	Thin blanket
v_1	484.511177687	489.818993739	486.789982299
v_2	-415.892411688	-449.598253547	-498.345381625
v_3	-98.391561281	-110.92454506	-145.93154029
v_4	-255.859137886	-12.5050481028	159.811316367
v_5	206.691260671	313.326084789	387.491648561
v_6	30.9217399105	79.7823355573	101.954704874
v_7	-360.734499132	-1051.11973928	-1196.56045034
v_8	-134.851142496	-689.287533213	-767.97906346
v_9	1133.48706945	2463.72332805	2423.27863764
v_{10}	-96.0379800351	-169.028942532	-210.471309775
v_{11}	-4.85999133468	-32.5360882734	-37.5882110014
v_{12}	317.963200146	770.809305134	830.76354683
v_{13}	-728.498952417	-1553.57818486	-1515.66927261
v_{14}	132.262987525	428.301200541	441.537208381
v_{15}	-618.192609936	-1306.04759015	-1267.67821617
v_{16}	375.391947818	796.535412927	774.403281724
v_{17}	110.780642107	115.6823286	111.94666004
v_{18}	90.4340751694	94.8575663787	92.0566956802
v_{19}	-20.1998328509	-17.425745771	-20.0367798637
Avg. diff.	0.69421616397	0.65404320235	0.70425821661

Table 2: Coefficients for use with Equation 2 to calculate tritium inventory after 5 years. The average absolute difference between the simulated values and the fit is also included.

It is possible to achieve the same final tritium inventory with a variety of different compositions (see Figure 4) and each blanket composition has different associated costs (see Figure 2). Figure 5 uses cost values from Figure 2 and tritium inventory values from Figure 4 to show the most economical blanket composition capable of producing certain amounts of surplus tritium. The quantities of surplus tritium considered are multiples of the tritium start-up inventory required (18.1kg) for a 2.5GW fusion reactor [23]. The most economical composition capable of producing a start-up inventory can be considerably cheaper than the most expensive composition that achieves the same surplus tritium. When considering that blankets are expected to be replaced every 5 years during a reactor's life time the potential cost savings are substantial. Upon changing the blankets it might be desirable to optimise the blankets differently and not place such emphasis on tritium production.

coeffi-cients	Time-averaged TBR		
	Thick blanket	Medium blanket	Thin blanket
v_1	1.95893103797	1.96122608615	1.93920586301
v_2	-0.809792727863	-0.860855681012	-0.948494854004
v_3	0.016958778333	0.0193393390622	-0.0186700302911
v_4	-0.120230857418	0.279977226537	0.483417432982
v_5	0.461211316443	0.659918133027	0.785901227724
v_6	-0.0478789050674	0.013070435947	-0.0120169189644
v_7	-2.1978304461	-3.48450356973	-3.45723121388
v_8	-1.38785787744	-2.3360647329	-2.05212472576
v_9	4.93883798388	7.38314099334	6.45375263346
v_{10}	-0.223668963335	-0.365511595682	-0.436421277881
v_{11}	0.0178181886132	-0.0181287662329	0.0129809166177
v_{12}	1.42583418972	2.30397890094	2.26116309299
v_{13}	-2.80720698559	-4.37481611533	-3.87538808736
v_{14}	0.814691647096	1.30804004777	1.05778783291
v_{15}	-2.48568193656	-3.71450110227	-3.12644013943
v_{16}	1.37932384899	2.1588023402	1.86242247177
v_{17}	0.253355839249	0.263823845354	0.253324925437
v_{18}	0.190845918447	0.198976219881	0.18795823903
v_{19}	-0.0257699008284	-0.0192924115968	-0.0256707269253
Avg. diff.	0.0017741411512	0.0016496355171	0.0015102482817

Table 3: Coefficients for use with Equation 2 to calculate time-averaged TBR. The average absolute difference between the simulated values and the fit is also included.

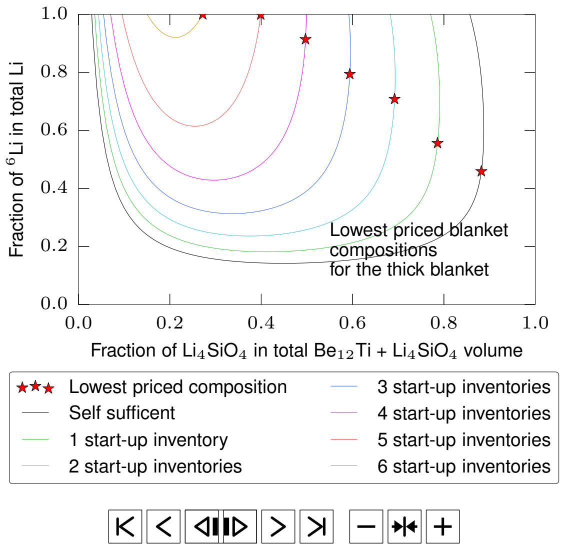

Figure 5: Cost effective blanket compositions capable of producing different sized start up inventories.

The thickness of the blanket does not appear to make a significant impact on the total quantity of tritium produced over the five year irradiation time, however the thickness certainly affects the material costs (see Figure 6). The additional tritium production in the rear of the blanket is marginal compared to the tritium production at the front of the blanket. In terms of their tritium production, the additional costs inherent with thicker blankets make them economically unattractive. Figure 6 shows that it is often possible to produce the same quantities of tritium with the thin blanket at approximately $^2/_3$ of the cost of the thick blanket. However thicker blanket designs may show greater merit if the irradiation time or fusion power was increased. The shielding of sensitive components such the toroidal field (TF) coils should also be considered when deciding on blanket thickness. While thicker blankets would attenuate neutrons and gammas more effectively compared to thinner blankets they would leave less space for shielding material. The resulting protection offered by different blankets is beyond the scope of this study.

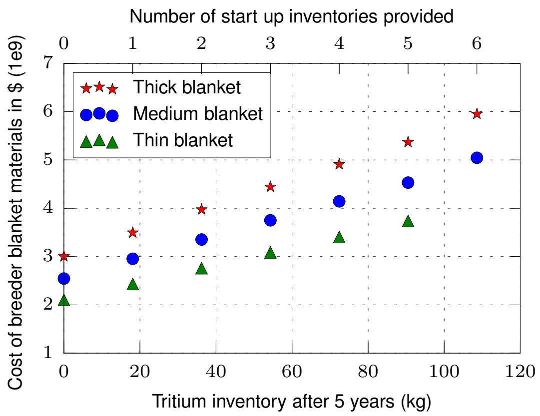

Figure 6: A comparison between costs required for the three blanket thicknesses to produce different sized tritium inventories.

The cost per gram of producing excess tritium can be calculated by finding the additional costs incurred in the breeder blanket composition and divided this by the quantity of tritium produced. This gives costs in the range of $18,000 to $27,000 per g depending on the quantity of tritium required and blanket thickness used. This is comparable to production from CANDU reactors ($30,000 per g) and cheaper then proposed methods ($84,000 to $134,000 per g) of tritium production [23]. The maximum tritium production hardly varied with blanket thickness and the thicker blankets were found to generate only marginally more tritium (see Table 4). The maximum tritium production assumed a lithium enrichment of 100% which is not practically feasible. The minimum level of ^{6}Li enrichment required to achieve self-sufficiency varied slightly with blanket thickness and thicker blankets were found to require marginally less ^{6}Li enrichment (see Table 4).

Blanket thickness	Maximum tritium surplus (kg)	Maximum TBR	Minimum ^{6}Li enrichment required for self-sufficiency
Thin	105.0	1.247	16.4
Medium	110.9	1.261	14.9
Thick	112.4	1.264	14.2

Table 4: The relative performance of the different blanket thicknesses.

Figure 7 shows how the optimal breeder to multiplier ratio required to achieve maximum tritium production varies with lithium enrichment. During the life of the breeder blanket ^{6}Li is burnt-up more rapidly than ^{9}Be, this means the final ratio breeder fraction will be lower than the initial ratio. By modelling the blanket burn-up it is possible to compensate for this and find the optimal breeder to multiplier ratio taking into consideration uneven burn-up. Figure 7 reveals that blanket thickness makes negligible difference to the optimal breeder fraction at different enrichment levels.

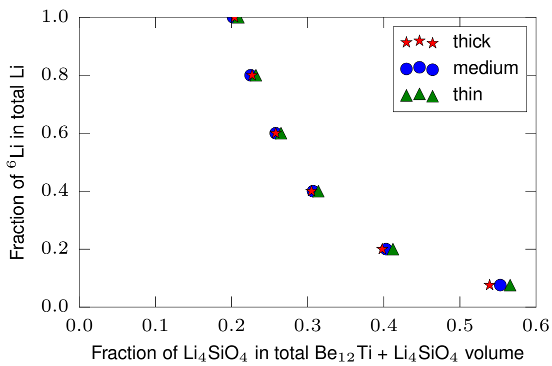

Figure 7: Optimal ratio of breeder to multiplier in terms of maximising the TBR as a function of ^{6}Li enrichment.

5. Conclusion

It has been commonly assumed that the availability of tritium will be one of the limiting factors for future DT fusion reactor deployment. The findings of this study suggest that it is possible to optimise the production of tritium for solid-type breeder blankets by varying the breeder fraction, the lithium enrichment and the blanket thickness. The calculated decrease in TBR values over time shows that it is desirable to take account of nuclide depletion when accurately studying time-varying tritium production in solid-type breeder blankets. The additional computational time (122 MCNP runs instead of 1) and complexity required to simulate nuclide burn-up can be avoided in cases where burn-up is negligible (high breeder fraction and high ^{6}Li enrichment). This study shows there is scope to reduce the cost of breeder blankets by changing the composition and thickness of the blankets. Thinner blankets were found to be capable of achieving the same amount of tritium production for reduced costs For example the thin blanket is capable of producing up to 105kg of excess tritium and is typically \$$1.5\times10^9$ cheaper than the thick blanket. Excess tritium can be produced by at an additional cost of \$18,000 to \$27,000 per g depending on the quantity required, this is comparable to limited production from CANDU reactors (\$30,000 per g) and cheaper then proposed methods (\$84,000 to \$134,000 per g) [23]. The cost analysis focuses on the costs of breeder and multiplier materials and does not take into account all the associated costs in breeder blanket construction, operation and decommissioning. The cost of the solid-type breeder blankets in this study is dominated by the cost of $Be_{12}Ti$ which is estimated to be \$4,500 per kg. Reducing the cost of $Be_{12}Ti$ would have a substantial impact on the cost predictions made in this study. A further study will look at the possibility of reducing the quantity of $Be_{12}Ti$ used in the blanket by varying the breeder fraction with blanket depth. A single composition of breeder material for the entire blanket is not likely to be the most optimal solution in terms of tritium production. It would be advantageous to optimise separate blanket modules for their position within the reactor, however this would incur additional design and manufacturing costs. The approach used in this study makes several assumptions inorder to achieve the goal of demonstrating a methodology for producing parameterised neutronic inputs into the PROCESS systems codes. Ideally the study would be carried out on a more refined breeder blanket design and less homogenised blanket structure. Accounting for burn-up as well as multiple dimensions resulted in large comptational expense and this is perhaps the main limitation of the study. Before incorporating further dimensions or realism into such a study further development of the coupling code FATI that links FISPACT II and MCNP 6 should be carried out. Helium Cooled Lead Lithium (HCLL) breeder blankets are likely to have different costs involved due to the different neutron multiplier used, lack of pebble manufacturing costs and higher ^{6}Li enrichments required. Further studies involving optimisation of multiple criteria (e.g. energy multiplication) and different blanket designs (e.g. HCLL) would also be of interest to reactor designers.

6. Acknowledgements

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