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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.

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 minimising a user chosen figure-of-merit (e.g. the cost of electricity). The PROCESS code has been utilised effectively in the Power Plant Conceptual Study [2] and economic studies into the feasibility of fusion energy [3].

The objective of this paper is to report on a new neutronics module which links high fidelity neutronics parameters into the PROCESS code. Additionally this paper makes recommendations for blanket design in terms of how the material composition of the blanket effects the tritium production. 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.

A European DEMO with solid-type breeder blankets based on the Helium Cooled Pebble Bed (HCPB) design [4] and a fusion power of 2.4 GW was considered for this study. Three different blanket thicknesses have been considered as well as different lithium enrichments and lithium ceramic (Li_4SiO_4) to neutron multipler ratios ($Be_{12}Ti$).

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 [5], careful design and planning of tritium production will help alleviate this

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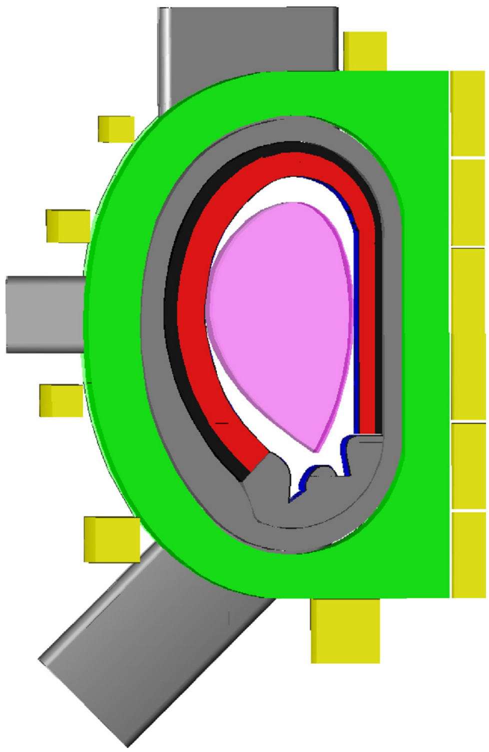

Fig. 1. The thin blanket tokamak model used. This model was adapted from a tokamak DEMO model developed within the PPPT programme [7]. The vacuum vessel and divertor (grey), toroidal field coils (green), poloidal field coils (yellow), homogenised breeder blanket material (red), blanket rear and front casing (black) and tungsten armour (blue) are included. Image generated using [13]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

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

[6] The reactor model used in this study was adapted from a European tokamak DEMO model [7] developed within the Power Plant Physics and Technology (PPPT) programme [8]. The model is compatible with MCNP 6 [6] and makes use of constructive solid geometry (CSG) to represent fusion reactor components. 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 [9] has suggested that each additional penetration results in a TBR reduction of 0.35–0.5% depending on the penetration size and the material present within the penetration. The neutron plasma source [10] utilised in the MCNP model was represented using primary plasma parameters. The model includes a first wall with a thin layer of armour, homogenised breeder modules, a rear shielding layer and a divertor with no breeding capability. 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 [11]. 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 [12] (Fig. 1).

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

Blanket description	Maximum inboard blanket depth (m)	Maximum 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

2.2. Materials

The homogenised breeder blanket material used was based on the Helium Cooled Pebble Bed (HCPB) design and contained fixed volumes of Eurofer [14] (9.705%) and He coolant (5.295%). The homogenised volume fractions used are similar to previous studies [15]. The packing fraction of the $Be_{12}Ti$ and Li_4SiO_4 pebbles was assumed to be 0.63 [16] which occupies 53.55% of the available volume. Helium purge gas was used to fill the remaining voids between pebbles (31.45%). The volume fractions of the Eurofer and helium were kept constant in all simulations. The assumption that volume fractions remain constant in different thickness of blankets may be oversimplifying the situation. It may be more realistic to increase the Eurofer and helium fraction with respect to blanket thickness. The breeder fraction (see Eq. (1)) was varied between 0 and 1 in 18 intervals and the ^{6}Li atomic fraction in the lithium was varied from 0 to 1 in 11 intervals. The breeder fraction is defined as

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

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

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 [17] was used to couple the radiation transport code MCNP 6.0 [6] with the inventory code FISPACT-II [18]. FENDL 3.0 nuclear data [19] was used preferentially for particle transport and TENDL 2014 data [20] was used when FENDL data was not available 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 [21] for a fusion reactor with 2.4 GW of fusion power, operating at 70% [22] 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