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The existing tritium resource available for future fusion power plant D-T operation is severely limited. It is essential to breed tritium to maintain the continuous consumption in the D-T plasma so as to sustain the required fusion power. A minimum criterion of calculated tritium breeding ratio (TBR)>1.1 is adopted to ensure tritium self-sufficiency, allowing a 10% safety margin to cover calculation uncertainties. In a DEMO reactor, there are various factors impacting the availability and effectiveness of fusion generated neutrons for production of tritium. In this paper, the study focused on the impact of first wall design including materials and first wall thickness, and blanket coverage aspects such as divertor geometry and the provision of equatorial heating and diagnostic ports.

Keywords: fusion, DEMO, neutronic, tritium, self-sufficiency

1. Introduction

Due to the resource limitation of the tritium availability for future fusion power plant operation in D-T, it is essential to breed tritium to maintain the continuous consumption in the D-T plasma so as to sustain the required fusion power. A minimum criterion of calculated tritium breeding ratio (TBR)>1.1 is commonly required to ensure tritium self-sufficiency, allowing a 10% safety margin to cover calculation uncertainties [1-2]. In a DEMO reactor, there are various factors [2] impacting the availability and effectiveness of fusion generated neutrons for production of tritium. They include tritium breeders, neutron multipliers, structural materials and first wall materials, coolants, first wall thickness, and the extent of blanket coverage noting the requirements for heating and diagnostic ports. Neutron transport calculations were performed based on representative neutronics models for DEMO to quantify the impact of these factors.

The impact of breeding materials including liquid and solid breeders on TBR was studied in reference [3] based on very simple geometry models to investigate the tritium breeding capability of various breeders. Reference [2] presented a comprehensive study for LiPb breeders adopted by the US ARIES advanced power plants. In this paper, the work focused on the HCPB (helium cooled pebble bed; Li_4SiO_4 is the tritium breeder and Be is the neutron multiplier) DEMO reactor design because it has been widely employed for ITER TBMs [4] and DEMO designs [5-6].

The neutronic calculation model is described in Section 2; the calculations and results are presented in Section 3; Section 4 gives the conclusions of the study.

2. Models

The basic DEMO design used in the present study has a plasma major radius of 8.768m with an aspect ratio of 3.1 and a plasma elongation of 1.552. The main components contain the first wall (FW), breeding blanket, shielding layers, vacuum vessel (VV) and the divertor with tungsten as its plasma facing target layer. The geometry parameters were created using the PROCESS code [7-8] as part of the European Fusion Development Agreement (EFDA) Power Plant Physics & Technology (PPPT) working group on DEMO [9].

The basis neutronic model was built based on a template produced within the system code HERCULES [10] to simulate the HCPB DEMO reactor using the particle transport code MCNP5 [11] with the IAEA fusion nuclear data library FENDL-2.1 [12]. The starting case model is symmetric in the toroidal direction, as shown in Figure 1, which is practically a two-dimensional (2D) geometry without any equatorial ports. The in/outboard breeding blanket radial thickness is 0.775m/0.8m.

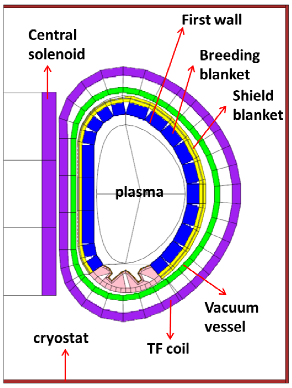


Fig. 1. Vertical view of HCPB DEMO reactor.

3. Calculation and results

HCPB is one of four breeding blanket concepts studied in Europe. In the homogenized breeding blankets, the volume fractions of Li_4SiO_4 and Beryllium are respectively 19% and 65%. The packing factor of 64% is taken into account so that the effective volume fractions are lower. There is 9.8% Eurofer included, representing the structural material as used in the PPCS study. The remaining space is filled with helium gas which has very low impact on the neutron interactions.

3.1 First wall

The first wall is nominally the first layer of the blanket on the plasma side. In a DEMO reactor, the erosion may be so severe that an additional plasma-facing layer is desirable for the protection at the front of the structural material (assumed to be made of Eurofer in this paper). Tungsten has been seen as a promising choice to act as the plasma-facing component (PFC) [13]. However, as a high density metal, tungsten will to some extent shield the fusion neutrons from reaching the tritium breeding blanket. To quantify the impact, the tritium breeding radio (TBR) is calculated for various materials employed by the first wall. As shown in Fig.2, when the first wall is thickened from 2mm to 2cm, the TBR decreases ~13.2% for pure Eurofer and ~16.3% for pure tungsten. With a 2mm thick tungsten layer, the TBR can be reduced ~4% comparing to directly employing structural Eurofer as the first wall. If the tungsten layer is thickened to 3cm radially, the TBR can be ~8% lower than a 3cm pure Eurofer as the first wall.

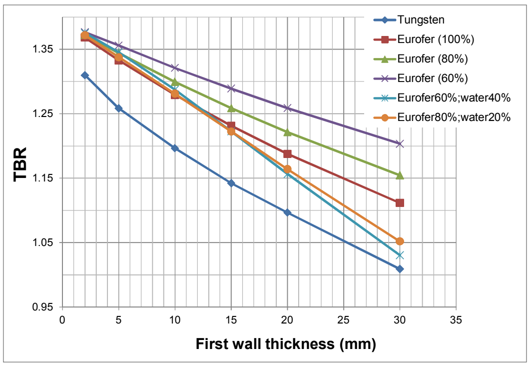


Fig. 2. TBR as function of first wall thickness.

The structural material of the blanket will need to be cooled efficiently to remove the nuclear heating, but if there is no distinctly engineered first wall to accommodate the heat load from the plasma (primarily photonic radiation and neutral particles), then that heat load will have to be removed by the blanket cooling system as well. In this work, helium and water are selected to be the alternative coolants to investigate the corresponding impact on the tritium production. The coolants have no significant impact on the tritium breeding capability in the blanket zone when the first wall is as thin as 2mm, which hardly changes the neutron spectrum beyond the layer. When the first wall is thicker, the tritium production generally decreases more with more water coolant than the helium coolant because of the higher neutron moderation capability of the water. Fig.3 shows the TBR per volume in finer layers along the radial depth of the breeding blanket. Because more neutrons are moderated after travelling through the 3cm thick first wall with the mixture of 60% Eurofer and 40% water, there is a sharp increase from Li-6 contribution to the tritium generation at the first (5cm thick) layer. It is observed that the volumetric TBR in the first 15cm blanket region (0-15cm) is significantly affected by different materials of the first wall with the same thickness, with some exception from the 60% Eurofer and 40% water mixed layer. The tritium production per volume becomes very close at the blanket depth of 35cm-40cm with the same thickness of first wall of all the materials considered. At the last 5cm layer of blanket (the location 75cm-80cm distant from the plasma edge), the tritium breeding capability decreases ~2 orders of magnitude compared with the front layer, and the impact from the first wall becomes negligible.

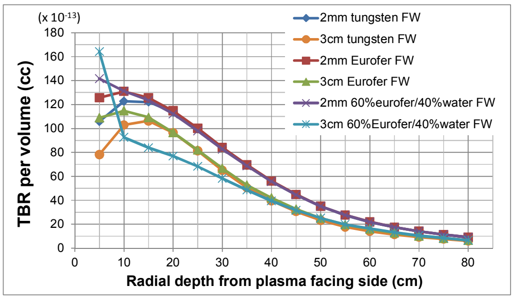


Fig. 3. TBR per volume as function of the radial depth of the breeding blanket.

3.2 Ports

It is frequently suggested that fewer ports will be needed in a fusion DEMO reaction because 1) only a minimal set of essential diagnostic systems and heating systems will be needed and 2) sufficient tritium production in the breeding blanket has to be ensured to sustain the reactor. To evaluate how the ports will affect the overall tritium production, as shown in Fig. 4, the equatorial ports have been modelled on the basis of the model described in Section 2, now using a 3D implementation of the neutronics code. In the absence of more specific information, the dimensions of each port were initially set at 2.2m (height) and 1.748m (width), the same as the equatorial ports in ITER.

To simulate different port numbers of 18, 16, 8 and 4, the reflecting boundaries are adjusted in the toroidal direction to represent the model in 20°, 22.5°, 45° and 90°, respectively. Fig.5 presents the results of TBR with various numbers of equatorial ports. It is observed that each empty port decreases the TBR by around 0.5% so that the total reduction from 18 ports is up to 10% compared to the case without any equatorial ports. If the equatorial ports are filled with the homogenised materials of 50% Eurofer and 50% void, the neutron scattering effect significantly alleviates the TBR loss caused by the ports. Each half-filled equatorial port decreases the TBR by only up to 0.35% and the tritium breeding ratio is reduced ~6% with 18 equatorial ports filled with the homogeneous material (50% Eurofer with 50% void). This decrease of TBR is more coherent with the breeding blanket coverage reduction from the ports (18 ports area up to ~5.6% of the blanket area with no ports). It is worth noting that only the design with a 2cm thick first wall has a tritium self-sufficiency issue (in comparison with requirement of TBR>1.1) with more than 8 equatorial ports installed. There is a possibility to compensate the tritium shortage in such a case by increasing the Li-6 percentage in the breeding materials. Preliminary investigation shows this to be a saturating effect of limited value in a blanket design with a fairly high lithium-6 enrichment already, but a definitive analysis requires more study..

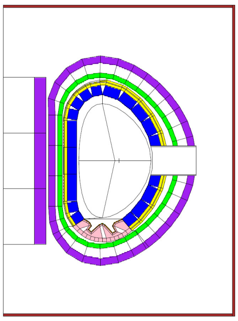


Fig. 4. Vertical view of HCPB DEMO reactor with equatorial port.

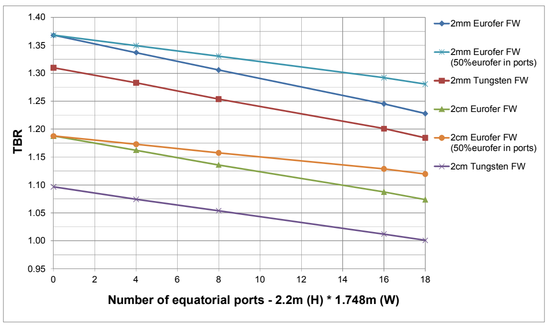


Fig. 5. TBR variation with the number of equatorial ports.

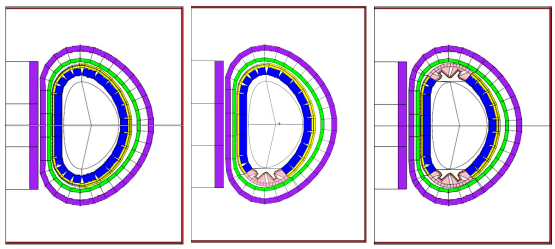
To estimate the effect of the equatorial port dimensions on tritium production, the port sizes were varied in the height and width to calculate the effect on TBR. The results are listed in Table 1. It is observed that, 1) the TBR is increased more by halving the port in height than in width; 2) the case of a smaller number of ports with larger port dimensions – but the same port area - causes a slightly higher decrease of TBR than the case of more port numbers with smaller port dimensions. For example, the TBR is higher for 16 equatorial ports with dimensions of 1.1m (H) x 0.874m (W) than 4 ports with double the height and width to maintain the same total port area.

Table 1. TBR with varying port dimensions.

Port height * width * port numbers	TBR	Total port area (cm^2)
2.2m*1.748m * 16	1.087±0.001	615296
1.1m*1.748m * 16	1.136±0.001	307648
2.2m*0.874m * 16	1.141±0.001	307648
1.1m*0.874m * 16	1.164±0.001	153824
2.2m*1.748m * 8	1.136±0.001	307648
1.1m*1.748m * 8	1.161±0.001	153824
2.2m*0.874m * 8	1.163±0.001	153824
2.2m*1.748m * 4	1.162±0.001	153824

3.3 Divertor

The function of the divertor is to extract helium ash and other impurities from the plasma as well as convected heat from the fusion reactions. Therefore it is an essential exhaust system in a fusion reactor and necessarily a component directly adjacent to the plasma chamber which effectively reduces the breeding blanket coverage, reducing the tritium breeding capability of the reactor. To quantify the impact of the divertor on the overall TBR, three models were built to represent the extreme cases of no divertor and two divertors, as well as the usual single divertor topology, as illustrated in Fig. 6. In this work, the divertor is composed of 4 layers. The first plasma-facing layer is 6mm thick and made of tungsten; the second layer is 4.4cm thick and a mixture of Eurofer, tungsten and a small amount of copper; the third and fourth layers are mainly the structural base of the divertor, comprising a mixture of Eurofer and helium coolant. [14]



a) no divertor b) 1 divertor c) 2 divertors

Fig. 6. DEMO model with 0/1/2 divertors.

The results presented in Fig.7 shows that the TBR reduction by one divertor is ~10.9% for the 2mm first wall made of Eurofer and ~9.9% for the tungsten clad variant. Both effects are slightly smaller than the effective decrease in blanket coverage area, which is ~11.5% for one divertor. If there are two divertors in the reactor, the TBR falls by nearly twice the reduction caused by one divertor, i.e. TBR drops ~21.5% and ~19.7% for 2mm first wall of Eurofer and tungsten respectively. If the first wall is thicker, the effect of the divertor on TBR is slightly lower because of the competition of the higher losses caused by the two effects.

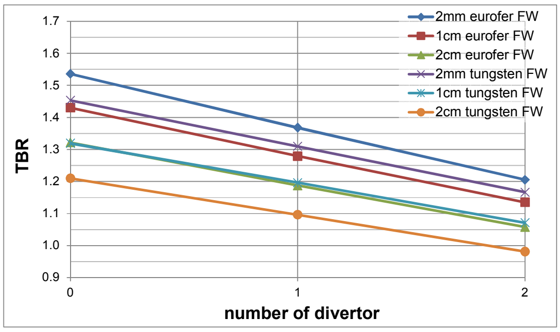


Fig. 7. The impact of number of divertors on TBR

4. Conclusion

Tritium self-sufficiency is a mandatory requirement for future DEMO reactors and fusion power plants. There are many aspects affecting the tritium breeding ratio in a reactor apart from determining optimal material compositions of tritium breeders and neutron multipliers for different blanket concepts. This paper focused on the impact study for a HCPB DEMO reactor design and the factors considered included first wall aspects such as the choice of thickness and materials, equatorial ports such as numbers, individual areas and plugging materials, and the number of divertors. It is found that:

- Thickening the first wall made of solid tungsten decreases TBR more rapidly than if it is made of Eurofer. Unless the first wall is as thin as 2mm, the use of water as the coolant results in lower tritium breeding with the same breeding materials than helium coolant.
- With the same effective total area of equatorial ports, there is essentially no statistically significant change in TBR by providing fewer ports with larger port dimensions than more ports with smaller port dimensions.
- In the model adopted in this paper, the tritium breeding ratio reduces about 10% for each divertor incorporated in the design, largely due to a similar fractional loss of the breeding blanket modules.

Although the TBR is reduced by thickening the first wall, increasing the density of the first wall materials, installing more ports or introducing a second divertor (a concept often re-introduced in discussions focused on divertor power loading problems but which may not seem realistic from the viewpoints of maintaining tritium self-sufficiency), the possible compensation is to further optimize the materials volume fraction of the tritium breeder and neutron multiplier, as well as enriching the Li-6 fraction and/or the thickness of the blanket. In this paper, only the TBR at the initial time has been calculated and no time dependence is taken into account. When the reactor starts operating, the breeding materials, especially Li-6 and Li-7, will be depleted which will affect the neutron spectrum in the region so as to result in a different profile and overall magnitude of tritium production [15-16]. This requires further study in the future.

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