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Preliminary performance analysis and optimization based on 1D neutronics model for Indian DEMO HCCB blanket

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Abstract

India, under its breeding blanket R&D program for DEMO, is focusing on the development of two tritium breeding blanket concepts; namely the lead-lithium-cooled ceramic breeder and the helium-cooled ceramic breeder (HCCB). The study presented in this paper focuses on the neutronic design analysis and optimization from the tritium breeding perspective of the HCCB blanket. The Indian concept has an edge-on configuration and is one of the variants of the helium-cooled solid breeder blanket concepts proposed by several partner countries in ITER. The Indian HCCB blanket having lithium titanate (Li_2TiO_3) as the tritium breeder and beryllium (Be) as the neutron multiplier with reduced-activation ferritic/martensitic steel structure aims at utilizing the low-energy neutrons at the rear part of the blanket. The aim of the optimization study is to minimize the radial blanket thickness while ensuring tritium self-sufficiency and provide data for further neutronic design and thermal-hydraulic layout of the HCCB blanket. It is found that inboard and outboard blanket thicknesses of 40 cm and 60 cm, respectively, can give a tritium breeding ratio (TBR) >1.3, with 60% ^{6}Li enrichment, which is assumed to be sufficient to cover potential tritium losses and associated uncertainties. The results also demonstrated that the Be packing fraction (PF) has a more profound impact on the TBR as compared to ^{6}Li enrichment and the PF of Li_2TiO_3.

Keywords: DEMO, helium-cooled ceramic breeder blanket, neutronic optimization study, tritium breeding ratio

(Some figures may appear in colour only in the online journal)

1. Introduction

India has defined the strategy for DEMO to achieve a fusion power plant by 2050 [1–3]. As per the roadmap for DEMO, the activities are expected to be spread over the next 30 years. One of the key components in DEMO will be the breeder blanket, which will generate the burnt tritium fuel and also accommodate the tritium losses through openings/penetrations inside DEMO. Therefore, the choice of breeding blanket and its tritium breeding capability plays an important role in the design of DEMO and its overall economy. India has proposed the lead-lithium-cooled ceramic breeder (LLCB) and helium-cooled ceramic breeder (HCCB) as two breeding blanket options for DEMO. A module of the LLCB blanket is planned to be tested in ITER through the Indian Test Blanket Module (TBM) program [4–6]. The engineering [7] and nuclear analyses [8] of the Indian LLCB blanket module have already been performed. The analyses reported in this paper are on the solid breeder blanket option, HCCB for DEMO. A conventional HCCB blanket concept with variance in geometrical design has been considered by India for the design and development [9, 10]. It has reduced-activation ferritic/martensitic steel (RAFMS) as a structural material [11], lithium titanate (Li_2TiO_3) as the tritium breeder and beryllium (Be) as a neutron multiplier. The main objective is to assess and optimize the tritium breeding performance of the HCCB

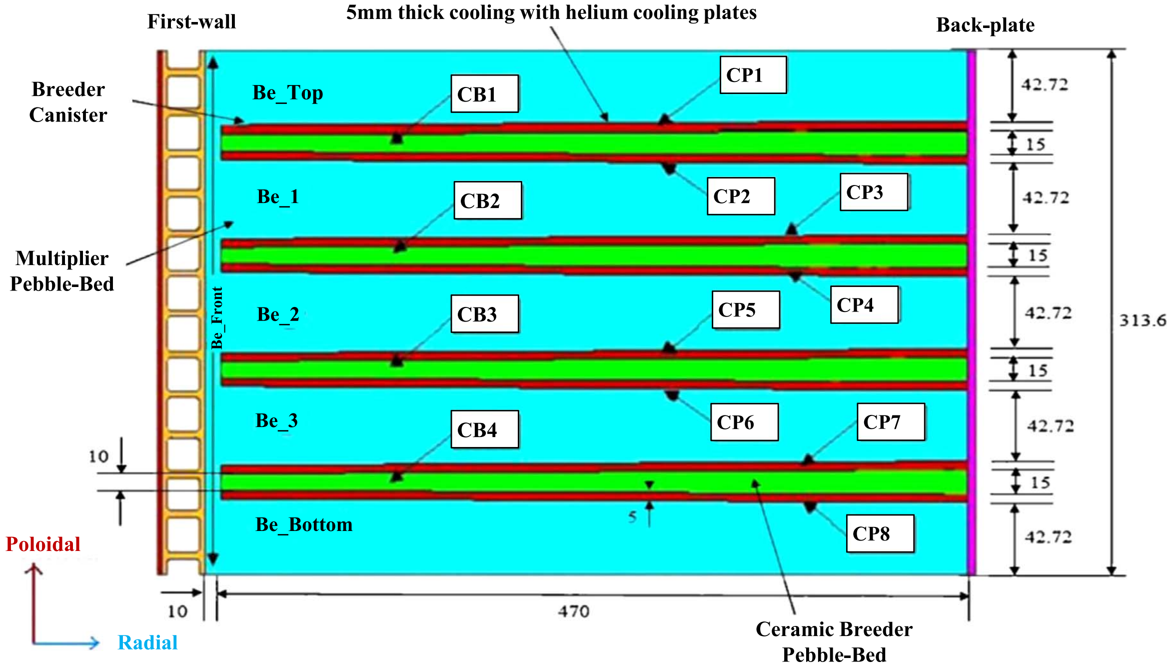


Figure 1. Radial–poloidal cut view of one breeder unit of the Indian HCCB supermodule showing different zones and their thicknesses (in mm).

blanket to ensure tritium self-sufficiency for DEMO. In order to achieve this [12], the tritium breeding ratio (TBR), which is defined as the amount of tritium produced per source neutron, should be greater than 1 [13]. The work presented in the paper explores reducing the blanket radial depth as much as possible without significantly reducing the value of the TBR. It is therefore essential to study the impact of all the HCCB design parameters and their variations on its tritium breeding performance. The impact of several parameters like ^{6}Li enrichment, the compositions of Li_2TiO_3 and Be as well as their arrangements in the breeder zone of the blanket have been studied. The parameters providing the maximum TBR value have been identified. The nuclear heating data of the blanket obtained from the study are used to calculate the temperatures of the breeder blanket materials in different blanket zones by performing 2D thermal analysis in ANSYS. Such studies need to be carried out to quantitatively compare the effect of these variations/choices on the blanket attractiveness for DEMO and to recommend priorities for focusing on the solid breeder experiments.

A brief description of the Indian HCCB blanket concept is provided in section 2. The neutronic model used in the analysis along with the simulation approach is described in section 3. The results of the study are presented and discussed in section 4. Finally, section 5 discusses the essential information obtained from the present study that will be needed in the more realistic 3D calculations to finalize the HCCB blanket design for DEMO in future studies. The paper focuses on the tritium breeding performance of the HCCB blanket, and the discussion concerning its shielding performance is outside the scope of the paper.

2. HCCB DEMO blanket concept

The Indian HCCB blanket concept is a conventional helium-cooled solid breeder concept with an ‘edge-on’ configuration having a tapering width of a breeder in the radial direction. The HCCB blanket contains Li_2TiO_3 with ^{6}Li enrichment as a ceramic breeder (CB) and Be as a neutron multiplier both in the form of packed spherical pebble beds with India-specific RAFMS used as the structural material. The plasma-facing surface of the U-shaped first wall (FW) is coated with a 2 mm Be layer that acts as high heat flux armour on the FW. The neutronic radiation coming from the fusion plasma of DEMO will be surrounded by modules of the HCCB blanket. Each HCCB blanket module has a dimension of $1.66\ \text{m} \times 0.484\ \text{m} \times 0.56\ \text{m}$ (poloidal × toroidal × radial). There are 10 breeder units in one HCCB blanket module. Each breeder unit has four CB zones surrounded by the cooling plates (CP) and five Be zones stacked alternately in the canister. Figure 1 shows a 2D representation of the radial–poloidal cross-section of one breeder unit of the HCCB blanket module with the dimensions of each zone inside it.

The neutrons coming from the plasma core of DEMO will interact with the CB and Be, which will generate heat. The high-pressure helium gas flowing through the 5 mm cooling plates extracts the nuclear heat from the CB and Be zones and is responsible for keeping the temperatures of the materials within the allowable limits. The FW of the HCCB blanket receiving the highest heat flux is cooled by the high-pressure helium gas flowing through a separate circuit. Tritium generated within the CB zones needs to be extracted and is done by low-pressure helium purge gas. The pressures of

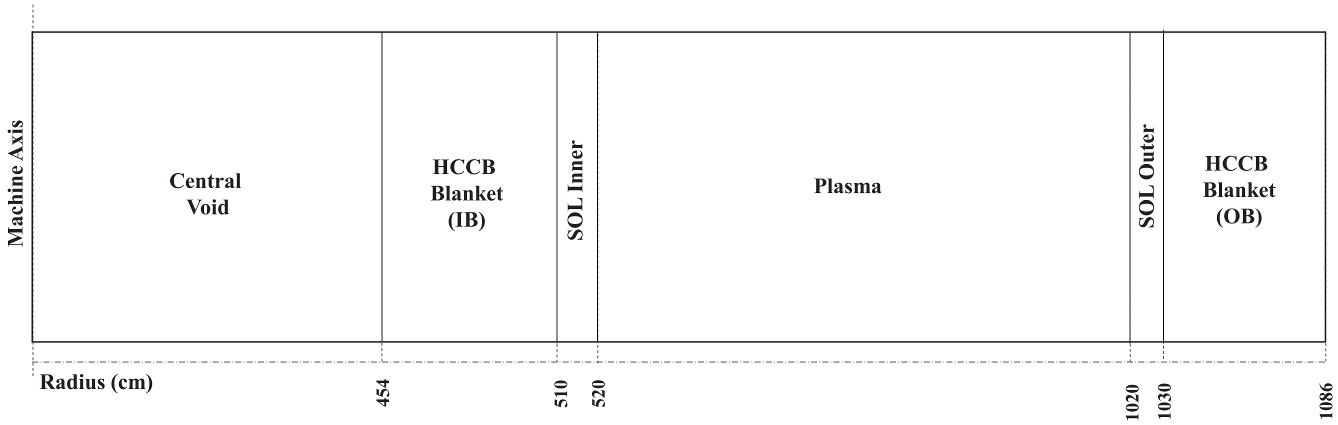


Figure 2. The radial geometric build-up of DEMO with HCCB blanket used in ANISN calculation.

the helium-cooling system and the tritium extraction system are 8 MPa and 0.1 MPa, respectively.

3. Neutronic model and calculation procedure

Radiation transport calculations have been an essential part of the reactor design process and are performed for predicting and confirming the nuclear performance of the reactor [14]. The neutronic design and optimization of the tritium breeding performance of the HCCB blanket must be carried out in a sensible progression, starting from 1D transport calculations and followed by detailed 2D and 3D analyses to effectively characterize the overall nuclear performance. The calculations reported in this paper have been performed using the 1D deterministic discrete ordinate-based code ANISN [15] using a specially prepared cross section library from FENDL-2.1 [16], consisting of 46 neutron energy groups and 21 gamma energy groups. In this study, we simulate the calculation geometry with typical dimensions of DEMO. The parameters of the Indian DEMO and the materials used in the analysis are given in tables 1 and 2, respectively.

In the simplified model used in this study, other components of DEMO like TF coils and vacuum vessels including the shielding blanket have not been considered for the purpose of assessing tritium breeding performance. The radial geometric build-up of DEMO with the HCCB blanket arranged on both the inboard (IB) and outboard (OB) sides is shown in figure 2. ANISN by default considers a height of 1 cm in the poloidal direction. The geometry is chosen to be cylindrical, i.e. the toroidal direction is infinite. The left boundary condition is reflective while the right one is a vacuum (no reflection). ANISN simulates the equatorial region of the full 3D simplified model of DEMO with the HCCB blanket placed at the IB and OB sides of it. The IB and OB have the same configuration with the plasma centre at 770 cm from the torus centre with a minor radius of 260 cm. The HCCB blanket is modelled as a homogenized mixture of blanket materials to assess its tritium breeding performance.

For ANISN calculation the geometry has to be divided into zones. The zone-wise structure of both the IB and the OB HCCB blanket is the same and is given in table 3.

Table 1. Main parameters of Indian DEMO.

Parameters	Values
Fusion power (MW)	3300
Plasma major/minor radius (m)	7.7/2.6
Plasma current (MA)	17.8
Fusion gain Q	30
Auxiliary power (MW)	110
Toroidal field B_0 (T)	6.0
Plasma heat flux (MW m^{-2})	0.5
Average neutron wall load (MW m^{-2})	2.0

Table 2. Materials used in DEMO neutronic model.

Functionality	Material
Blanket structure	RAFMS
Ceramic breeder	Lithium titanate (Li_2TiO_3)
Neutron multiplier	Beryllium (Be)
Coolant	Helium (He)
Blanket shield	SS-316 and water

The blanket zones (BZs) have been numbered with zone numbering (BZ-1 to BZ-36) in both the IB and OB, which starts from the plasma side. The blanket zones are of 1.5 cm thickness each except the few initial and back blanket zones representing the FW, FW cooling channels and back plates, respectively, on each side of the plasma. Different thicknesses of a few blanket zones have been kept to avoid over-approximation of material homogenization used in the 1D neutronic calculation geometry. The number of zones into which the HCCB blanket can be divided is up to the discretion of the nuclear analyst. The results do not change with the number of zones an analyst has decided to use but depend on the number of intervals (meshing size used in 1D geometry). We started with a large number of zones as given in table 3 for the initial calculation for the HCCB blanket but reduced the numbers in the parametric optimization calculations. The HCCB blanket module, used in the present study, has a surface area of 1.66 (poloidal) × 0.484 (toroidal) m^2. The radial extents of the blanket on the OB and IB sides are the same.

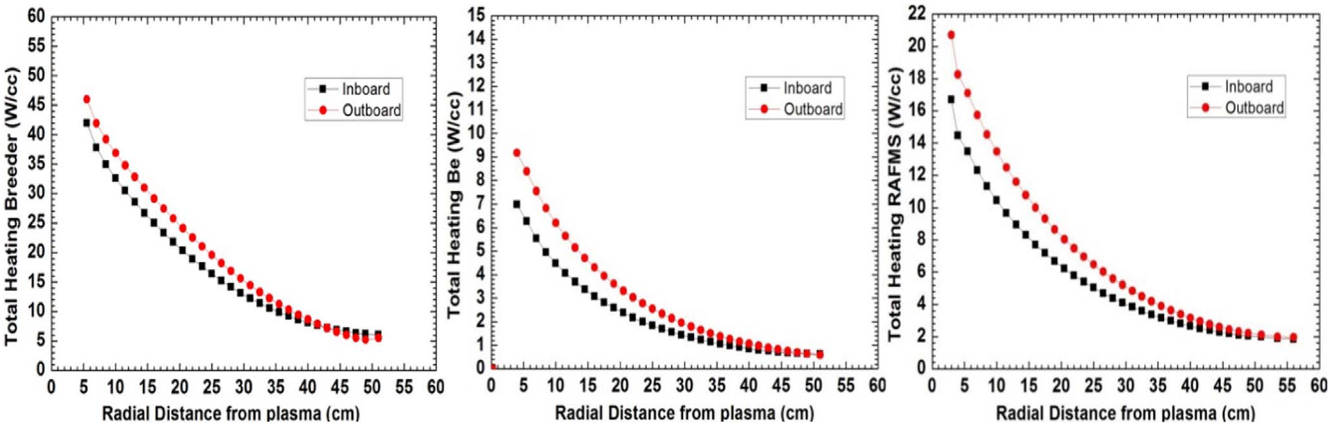
Table 3. Zone-wise structure of HCCB blanket with the material volume fractions.

Blanket zone number	Radial position from plasma (mm)	Radial depth (mm)	He	Li_2TiO_3	Be	RAFMS
1	2	2	0.00	0.00	100.00	0.00
2	30	28	54.81	0.00	0.00	45.19
3	40	10	10.76	0.00	85.30	3.94
4	55	15	16.00	10.56	62.40	11.03
5	70	15	16.00	10.73	62.20	11.07
6	85	15	16.00	10.90	61.99	11.11
7	100	15	16.00	11.06	61.78	11.16
8	115	15	16.00	11.23	61.57	11.20
9	130	15	16.00	11.40	61.36	11.24
10	145	15	16.00	11.57	61.15	11.28
11	160	15	16.00	11.73	60.94	11.32
12	175	15	16.00	11.90	60.73	11.37
13	190	15	16.00	12.07	60.52	11.41
14	205	15	16.00	12.24	60.31	11.45
15	220	15	16.00	12.40	60.10	11.49
16	235	15	16.00	12.57	59.90	11.53
17	250	15	16.00	12.74	59.69	11.57
18	265	15	16.00	12.90	59.48	11.62
19	280	15	16.00	13.07	59.27	11.66
20	295	15	16.00	13.24	59.06	11.70
21	310	15	16.00	13.41	58.85	11.74
22	325	15	16.00	13.57	58.64	11.78
23	340	15	16.00	13.74	58.43	11.83
24	355	15	16.00	13.91	58.22	11.87
25	370	15	16.00	14.07	58.01	11.91
26	385	15	16.00	14.24	57.81	11.95
27	400	15	16.00	14.41	57.60	11.99
28	415	15	16.00	14.58	57.39	12.03
29	430	15	16.00	14.74	57.18	12.08
30	445	15	16.00	14.91	56.97	12.12
31	460	15	16.00	15.08	56.76	12.16
32	475	15	16.00	15.25	56.55	12.20
33	490	15	16.00	15.41	56.34	12.24
34	510	20	16.00	15.61	56.10	12.29
35	535	25	50.00	0.00	0.00	50.00
36	560	25	50.00	0.00	0.00	50.00

The neutron source used in the calculations is a mono-energetic 14.1 MeV source placed in the plasma region.

4. Results

In this section, the results of the neutronic calculations performed with the initial HCCB blanket configuration described in section 3 are presented. The breeding performance of the tritium breeder blanket depends on ^{6}Li enrichment in the CB material. Other important factors which affect the tritium breeding performance of breeder blankets are the packing fractions (PFs) and volume fractions of the CB and neutron multiplier materials used in the spherical pebble form. The optimization study of these factors on the TBR of the HCCB blanket is presented in the following section. For the initial configuration, the calculation was performed with 60% ^{6}Li enrichment in Li_2TiO_3, and 63% PFs of both Li_2TiO_3 and Be along with 10% porosity of the pebbles. The TBR and nuclear heating profiles of the breeder blanket materials were obtained. The TBR value for the HCCB blanket was found to be 1.36. This value of TBR is comfortably greater than the design target for the global TBR = 1.1. However, the 1D calculation uses a very simplified geometric configuration with no gaps in the blanket structure surrounding the plasma. It would generally result in more tritium breeding than the more precise 3D calculations using the more realistic complex geometry having all the component details. The nuclear heat deposited by neutrons in the blanket was also evaluated in order to provide heating data for the investigation of the thermal performance of the HCCB blanket. The nuclear heating results are normalized to 2 MW m^{-2} average neutron wall loading both on the IB and OB sides. The nuclear heating response was calculated per cm height of the model. The heat generation rates obtained for the materials of the HCCB blanket on both the IB and OB sides are shown in figure 3. It shows the radially distributed heat generation rates in the different materials for the edge-on configuration used in the simulation study. The OB blanket side as expected has a higher heat generation rate than the IB blanket side. The



(a) (b) (c)

Figure 3. Nuclear heating profiles in the HCCB blanket materials: (a) breeder (Li_2TiO_3), (b) multiplier (Be), and (c) structure (RAFMS) for the existing configuration of single breeder unit, normalized for an average neutron wall load of 2 MW m^{-2}.

maximum heat generation rates in CB and Be are ~46 W/cc and 9 W/cc, respectively. The maximum neutronic heat generation for the Be front layer in the FW is ~14 W/cc. The digital data of these profiles were used for the 2D thermal analysis of the HCCB blanket for estimating the temperatures of the materials, the results of which are not included in this paper.

4.1. Optimization of tritium breeding performance of HCCB blanket

Even with the constraints on the materials and the overall dimension of the HCCB blanket, the arrangement of CB and Be beds within the blanket offers a high flexibility for neutronic design optimization. The material compositions of these beds and their total radial thickness can be varied and are thus subject to optimization. In addition, the ^{6}Li enrichment can be chosen for the CB bed in an optimal way. The optimization study was carried out in four steps starting with the impact of ^{6}Li enrichment of the Li_2TiO_3 and the PFs of Li_2TiO_3 and Be. The geometrical arrangements of Li_2TiO_3 and Be in the breeder blanket were also studied. Finally, the volume percentage of Li_2TiO_3 and Be were varied to get the maximum value of TBR. For the calculations of parametric optimization, the HCCB blanket neutronic model described in section 2 was used.

4.1.1. Impact of ^{6}Li enrichment of Li_2TiO_3. Naturally abundant Li has two stable isotopes, namely ^{6}Li and ^{7}Li, with contents of 7.5% and 92.5%, respectively. Due to their different interaction probabilities with neutrons, ^{6}Li can interact with thermal energy neutrons as well as high-energy neutrons and produce tritium, but ^{7}Li can interact only with high-energy neutrons. Therefore, it is essential to know how ^{6}Li enrichment affects the TBR value. For the calculations performed here, the PFs of Li_2TiO_3 and Be are taken to be 63%. Figure 4 shows the increase in TBR due to the ^{6}Li enrichment of Li_2TiO_3. Apart from the expected increase in TBR with an increase in ^{6}Li content in Li_2TiO_3, it is also observed that the rate of increase in TBR decreases when Li_2TiO_3 contains higher ^{6}Li than ^{7}Li.

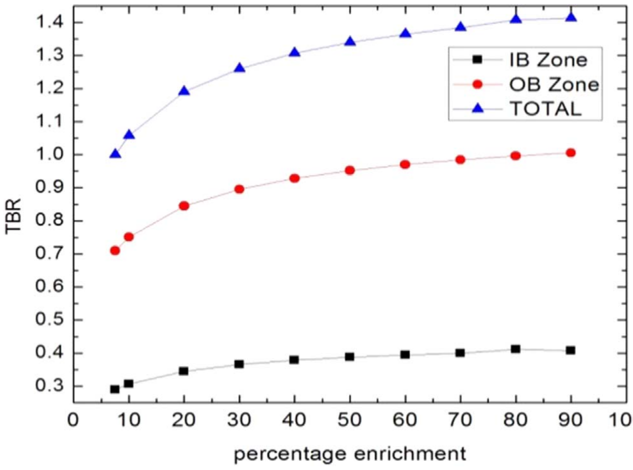
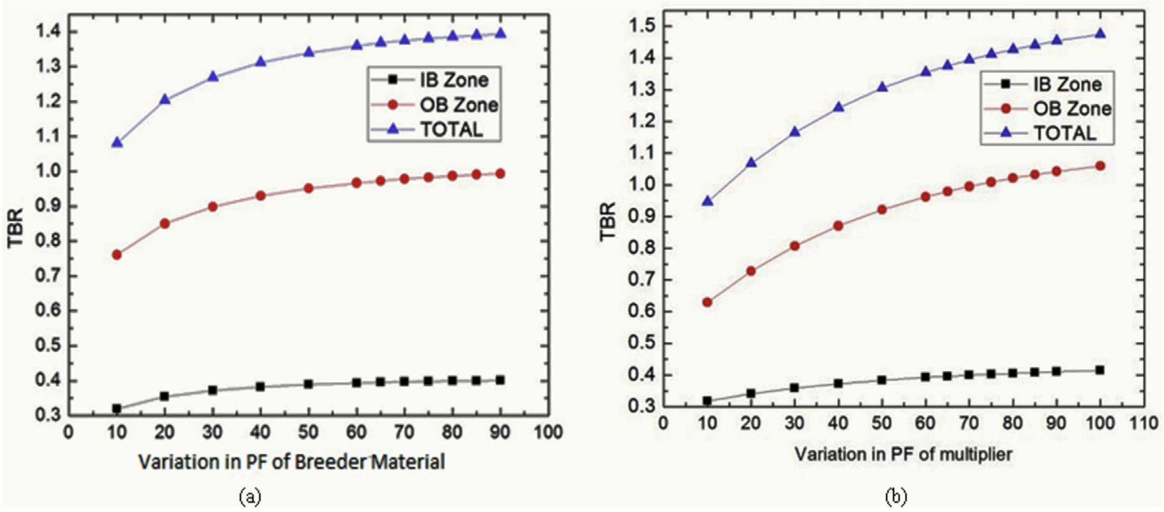


Figure 4. TBR variation due to ^{6}Li enrichment of Li_2TiO_3 in HCCB blanket for both IB and OB sides of DEMO.

4.1.2. Impact of PFs of Li_2TiO_3 and Be. The HCCB blanket contains Li_2TiO_3 and Be in the form of packed spherical pebble beds. The porosity of the pebble beds is defined in terms of their PF, which is the percentage of total filled space and is calculated as

$$\text{Packing fraction} = \frac{\text{Volume occupied by all the spherical pebbles in unit cell}}{\text{Total volume of the unit cell}} \times 100.$$

Single-size spherical pebbles placed in a container can theoretically achieve a PF of up to 0.7405 (74%). In practice, the random ordering of pebbles suggests a PF between 0.625 and 0.645. This was achieved by computer simulations and verified with experimental measurements. For the neutronic



(a) (b)

Figure 5. Dependence of TBR on PFs of (a) breeder material (Li_2TiO_3) keeping Be PF of 63%, and (b) multiplier material (Be) keeping breeder PF of 63%.

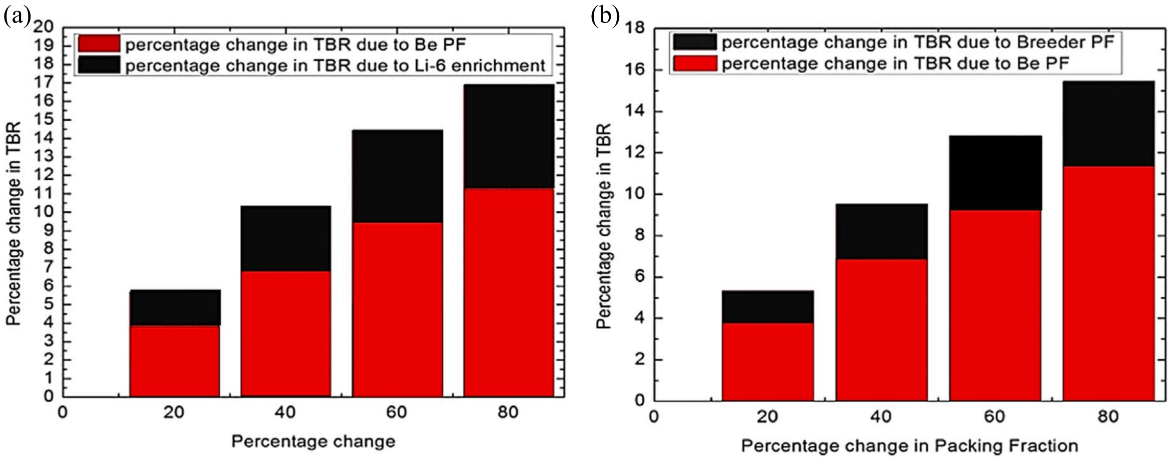


Figure 6. Impact on TBR due to (a) percentage change in ^{6}Li enrichment and PF of Be, and (b) percentage change in PF of the Li_2TiO_3 (breeder) and Be materials.

Table 4. Comparison of the impact of Li_2TiO_3 and Be layer thicknesses and their order of arrangement on TBR.

Parameters	Homogeneous arrangement		Heterogeneous arrangement		Heterogeneous sandwich arrangement	
Thickness of layer behind FW	10 mm	20 mm	10 mm Be	10 mm Li_2TiO_3	5 mm Be and 5 mm Li_2TiO_3	10 mm Li_2TiO_3 and 10 mm Be
TBR	1.388	1.396	1.366	1.379	1.385	1.395

calculations, 60% ^{6}Li enrichment is taken, and the results are shown in figure 5.

From figure 5, it is seen that the TBR value increases significantly up to 60% PF of Li_2TiO_3, and thereafter it starts to saturate, whereas there is no such saturation with Be. The relative impact of the Be PF on TBR as compared to ^{6}Li enrichment and the PF of Li_2TiO_3 is shown in figure 6. The study shows that the percentage variation in the PF of Be has a more profound impact on the percentage variation in TBR compared to the same percentage variations in the PF of the breeder material and in ^{6}Li enrichment.

4.1.3. Geometrical arrangements of Li_2TiO_3 and Be layers. The thickness of the Li_2TiO_3 and Be layers and their placing order just behind the FW have an impact on the overall TBR value of the HCCB blanket. The results are summarized in table 4 for calculations performed with different arrangements. In terms of the tritium breeding capability, it is evident that the homogeneous mixture of Li_2TiO_3 and Be is superior to a heterogeneous configuration. A thickness of Be layer more than 10 mm just behind the FW is not desirable for the present HCCB blanket configuration as shown in figure 7. The increased thickness of Be layer leads to a decrease in the

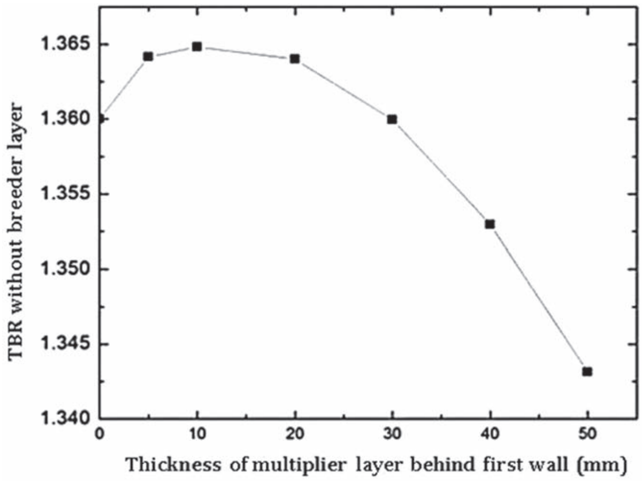


Figure 7. Impact on TBR of multiplier material (Be) thickness.

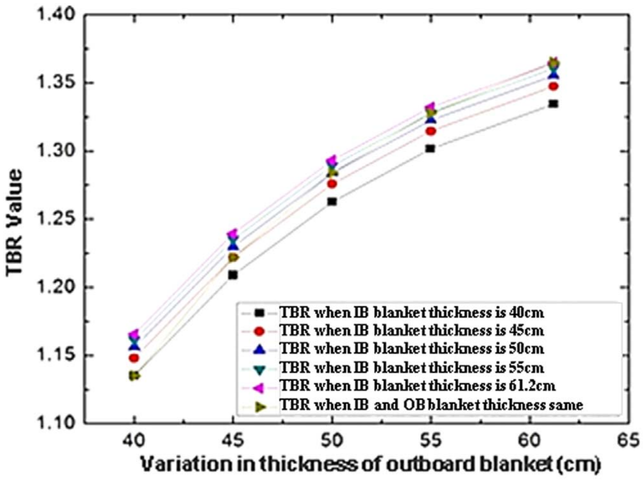


Figure 8. TBR as a function of IB and OB thicknesses.

Table 5. TBR as a function of Be to Li_2TiO_3 ratio.

Front thickness of breeder (mm)	End thickness of breeder (mm)	Multiplier to breeder ratio	TBR value
7	7	8.6:1	1.342
7	12	6:1	1.356
7	19.5	4:1	1.364
7	25	3.2:1	1.365
7	37	2:1	1.358
5	25	3.48:1	1.355

tritium breeding capability of the blanket due to the slowing down of high-energetic neutrons and therefore making ^{7}Li ineffective in the deep part of the breeder blanket.

4.1.4. Impact of volume fractions of Li_2TiO_3 and Be. The evidence for the requirement of a large amount of Be as compared to Li_2TiO_3 to have increased tritium breeding in the HCCB blanket has been investigated. The results are shown in table 5 for several volume fraction ratios of Be and Li_2TiO_3. The volume fractions of RAFMS and He coolant are kept constant. Finding the optimal ratio of Be to Li_2TiO_3 depends upon the relative benefit of increasing the number of neutrons to the Li content.

The values in table 5 indicate that there is an optimum ratio that gives the largest TBR and that ratio requires the amount of Be to be almost three times that of Li_2TiO_3. It is also observed that the TBR is very sensitive to change in the Be fraction at the front of the blanket and relatively insensitive to variation in the Be fraction at the end of the blanket.

4.1.5. Impact of IB and OB blanket thicknesses. The TBR value of a blanket depends directly on the amount of tritium breeder material present in it. For the HCCB blanket, a TBR value of 1.36 has been obtained by considering the same radial extents of the blanket on the OB and IB sides as discussed in the section 4. Therefore, it is necessary to have enough space for the blanket to maximize the TBR. The radial thickness of the blanket on both the IB and OB sides has to be optimized. Figure 8 shows the TBR as a function of the thickness of the tritium breeder zone in the IB and OB blankets of DEMO.

Owing to space constraints which are generally more stringent on the IB side, figure 8 reveals that a TBR value >1.3 is obtained with IB and OB blanket thicknesses of 40 cm and 60 cm, respectively. This should be sufficient to account for the 1D approximations of the 1D neutronic model and at the same time would provide sufficient space to accommodate other components on the IB side.

5. Summary and future work

We have performed the 1D neutronics calculations for the assessment and optimization of the tritium breeding performance of the Indian HCCB blanket with typical DEMO dimensions. A TBR value in excess of unity can be claimed for the HCCB blanket as predicted by the calculations reported in the paper. The impact on the tritium breeding performance has been studied by varying the different design parameters of the HCCB blanket. The following are the conclusions drawn based on the results obtained:

- It is found that 60% ^{6}Li enrichment gives a TBR value >1.3, which will be sufficient for DEMO considering the 1D optimization and neutron losses.
- The PF of Be has a more profound impact on the TBR as compared to ^{6}Li enrichment.
- The PF of Be has a more profound impact on the TBR as compared to the PF of Li_2TiO_3.
- A 10 mm Be layer behind the FW gives the optimal value of TBR. This TBR value can be increased further in the heterogeneous sandwich-type arrangement by introducing a 10 mm Li_2TiO_3 layer before the multiplier layer behind the FW.
- The optimal multiplier to breeder volume fraction ratio obtained is $\sim$3:1.
- IB and OB blanket thicknesses of 40 cm and 60 cm, respectively, can give a TBR >1.3.

These quite encouraging results show that the Indian HCCB blanket concept is attractive, considering its features from the tritium breeding point of view. The presented calculations show that the most crucial requirement of the breeder blankets, namely tritium self-sufficiency, can be achieved in DEMO by using an HCCB blanket on both its IB and OB sides. However, the conclusions cannot be made solely on the basis of the 1D neutronics calculations performed here. 1D simulations are very useful in the preliminary studies, being computationally inexpensive and less time-consuming. On the other hand, if we desire precise results, 3D simulations are needed. 3D calculations for the same will be performed next for more realistic or precise results. In addition, the feasibility of optimized neutronic parameters will be checked through thermal hydraulics calculations to check that the temperature profiles of blanket materials are within the allowable material temperature limits.

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