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Original Article

HCCR breeding blankets optimization by changing neutronic constrictions

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ABSTRACT

The neutronic analysis of Helium Cooled Ceramic Reflector (HCCR) breeding blankets has been performed using the 3D Monte Carlo code MCNPX and ENDF nuclear data library. This study aims to reduce ^{6}Li percentage in the breeder zones as much as possible ensuring tritium self-sufficiency. This work is devoted to investigating the effect of ^{6}Li percentage on the HCCR breeding blanket's neutronic parameters, such as neutron flux and spectrum, Tritium Breeding Ratio (TBR), nuclear power density, and energy multiplication factor. In the ceramic breeders at the saturated thickness, increasing the enrichment of ^{6}Li reduces its share in the tritium production. Therefore, ceramic breeders typically use lower enriched Li from 30% to 60%. The investigation of neutronic analysis in the suggested geometry shows that using 60% ^{6}Li in Li_2TiO_3 can yield acceptable TBR and energy deposition results, which would be economically feasible.

1. Introduction

Using a combination of energy resources is essential to meet the growing human demands for energy and reduce many environmental issues due to greenhouse gases and radioactive waste. Indeed, the sustainable development of any country depends on its efforts to use the so-called energy basket. In the near future, nuclear fusion can be considered, along with the other energy sources, as an inexhaustible, safe, and clean energy source.

The common method to harness nuclear fusion reaction is Magnetic Confinement Fusion (MCF). The testament to this claim is the international community's effort in the ITER international project. The conceptual design of the DEMOnstration tokamak is a bridge between ITER and future fusion power plants. Deuterium-Tritium (D-T) reaction is the most probable fusion reaction as Eq. (1):

$$^{2}_{1}D + ^{4}_{2}T \rightarrow ^{4}_{2}He + n + 17.58\ MeV \tag{1}$$

Deuterium, one of the primary sources of the fusion reaction, can be extracted from seawater, and it is widely available. Tritium is the only radioactive isotope of H produced artificially by reacting neutrons with Li as following:

$$^{6}_{3}Li + n(slow) \rightarrow T + ^{4}_{2}He + 4.784MeV \tag{2}$$

$$^{7}_{3}Li + n(fast) \rightarrow T + ^{4}_{2}He + n' - 2.82MeV \tag{3}$$

Neutron carries about 80% of the fusion energy. On the other hand, the tritium required for the fusion reaction is produced through the neutron's interaction with Li. In addition to generating heat and producing tritium, the neutron interactions with materials cause atomic displacement and production of gases such as He and H, which have been the subject of research regarding radiation damages [1,2]. Due to the importance of neutron's role in the nuclear fusion reactors, neutronic analysis is essential for predicting the transport and interaction of neutrons with plasma-surrounding materials [3].

One of the fusion reactor's key components is the Breeding Blanket (BB) surrounding the plasma with Li compounds in its structure to breed tritium. In the breeding zone, neutron moderation, tritium breeding, and neutron multiplication run in parallel. Including structural materials and cooling systems, the BB thickness is about 1 m. The current approach to building this tokamak component is the Multi-Module Segmentation (MMS) scheme [4].

The main functions of BB are tritium breeding, power exhaust, and radiation shielding [5]. Optimization in selecting components

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(breeders, neutron multipliers, coolants, and structural materials) and the blanket's geometry is essential for tritium self-sustaining conditions and high-energy efficiency. The optimization of BB aims to reduce the size of the breeder zone and cost. It is crucial to consider the neutronic constraints to optimize BB [6]. Currently, various types of BB [7] are being studied, including HCLL [8], WCLL [9], DCLL [10], HCPB [11], and HCCR [12].

This study presents a neutronic analysis of the HCCR breeding blanket used in K-DEMO [13]. Three-dimensional radiation transport Monte Carlo code MCNPX and ENDF nuclear data library have been used to predict the neutronic performance of HCCR blanket [14]. This work aims to reduce ^{6}Li enrichment as much as possible without significantly decreasing the TBR and energy deposition.

2. Neutronic analysis of HCCR blankets

2.1. HCCR breeding blanket concepts

HCCR breeding blanket is used in K-DEMO, a DEMO fusion reactor established in Korea. The main machine parameters are described in Ref. [15]. The reactor nuclear power is 2200 MW corresponding to 6.26E20 n/s [12].

In this work, the neutronic model of the HCCR breeding blanket is considered using Li_2TiO_3 as a breeder, Be as a neutron multiplier, He as coolant, SS306 as a structural material, and graphite as a neutron reflector. The first wall (FW) is composed of tungsten, vanadium, and SS306 as structure material. The multiplier and breeder layers are repeated one by one. The radial thickness and the structure of the midplane modules of outboard (OB) and inboard (IB) blankets are given in Table 1 [13]. The neutronic model simulated by MCNPX is shown in Fig. 1.

2.2. Neutron flux and spectrum calculation

The neutron flux is a fundamental quantity in the neutronic consideration used to calculate the other parameters such as TBR and energy deposition by multiplying its cross-sections. Fig. 2. shows the neutron flux distribution inside the midplane module of the IB and OB blankets against radial thickness. This figure shows the neutron flux profile obtained for a boundary energy 2.5 MeV, the neutrons energy of D-D reaction. Neutron flux above 2.5 MeV decreases as the depth increases, confirming that the multiplier has no significant effect on the reproduction of the high-energy neutrons. The neutron flux increase in the neutron multiplier region is due to the ^{9}Be(n, 2n) reaction. The$^6Li(n,\alpha)T$ reaction also reduces the neutron flux in the tritium breeder region.

If neutron reflectors cover each module's outer surfaces, neutron's escape from the walls is reduced. A surface can be designated as a reflecting surface by using specular condition in the MCNP input file. Any particle hitting a reflecting surface is specularly (mirror) reflected. Fig. 3 shows a comparison of neutron flux with boundary conditions and without boundary conditions in the different cells of IB and OB blanket. If the blanket walls are covered with neutron reflectors, the neutron flux increases in the blanket and the blanket's performance improves.

Neutron flux spectrum is another fundamental quantity which is used to calculate the nuclear response in the BB of fusion reactor. The neutron energy range to obtain neutron spectra is from thermal to 14 MeV covering the energy range for tritium production by ^{6}Li and ^{7}Li, and neutron multiplication range in the Be. Fig. 4 shows the neutron spectra in the breeders, multipliers, and the reflector of IB and OB blankets. As a result of the neutron multiplication reaction, Be(n, 2n), low-energy neutrons below 1 MeV increase. These low-energy neutrons are used in tritium production because the cross-section of ^{6}Li(n, t) reaction of the low-energy neutron is much higher than the high-energy neutron.

Fig. 5 shows the neutron flux spectra in the first breeder of the OB blanket for different percentages of ^{6}Li. As the percentage of ^{6}Li increases, more thermal neutrons become involved in the tritium production reaction. So, more neutrons participate in reaction ^{6}Li(n,t) and are consumed.

Table 1
Design parameters of the IB and OB blanket.

Radial region	Density (g/cm^3)	Thickness (cm)	
		IB	OB
W	19.3	0.4	0.4
V	6.00	0.1	0.1
FW	5.92	0.5	1.0
First Breeder	1.94	4.0	3.0
Cooling Plate	5.10	1.0	1.0
First Multiplier	1.17	16.0	14.0
Cooling Plate	5.10	1.0	1.0
Second Breeder	1.94	4.0	3.5
Cooling Plate	5.10	1.0	1.0
Second Multiplier	1.17	11.0	11.0
Cooling Plate	5.10	1.0	1.0
Third Breeder	1.94	9.0	4.5
Cooling Plate	5.10		1.0
Third Multiplier	1.17		10.0
Cooling Plate	5.10		1.0
Forth Breeder	1.94		3.0
Cooling Plate	5.10		1.0
Forth Multiplier	1.17		10.0
Cooling Plate	5.10		1.0
Fifth Breeder	1.94		4.25
Cooling Plate	5.10		1.0
Reflector	1.78		7.0
Back Manifold	8.0		0.45
Total Thickness		49	81.2

2.3. Tritium Breeding Ratio

Due to the scarcity of T in nature, all future fusion power plants will require to breed T in the blankets. TBR is usually used to describe the tritium breeding performance of a fusion system. It is defined as the tritium ratio produced in the blankets over the tritium consumed in the plasma. One of the most essential and challenging requirements for DEMO experimental fusion reactors is to achieve self-sufficiency conditions for tritium production. To ensure tritium self-sufficiency, net TBR >1.05 is recommended. Several parameters affect TBR, such as the percentage of ^{6}Li in natural Li, radial depth of the breeding zone, and the type of material used as the tritium breeder [16]. The reaction $^6Li(n,\alpha)T$ is exothermic, and the neutrons involved in this reaction are thermal. In contrast, the reaction $^7Li(n,n'\alpha)T$ is an endothermic reaction with 2.47 MeV threshold energy. Therefore, ^{6}Li has a larger share in tritium production than ^{7}Li and increasing the percentage of ^{6}Li increases TBR. This neutronic parameter also increases with increasing the thickness of the breeding zone. Saturated thickness is corresponding to maximum TBR [17]. In the ceramic breeders, typically lower Li-enriched is used: ^{6}Li content of 30%–60%. The total local TBR for the neutronic model presented in Fig. 1 is computed for different values of the ^{6}Li percentage, and the results of these calculations can be seen in Table 2.

The results show that even with ^{6}Li 50%, the condition of tritium self-sufficiency is met. Considering the high cost of Li enrichment, the desired results can be achieved at a lower percentage.

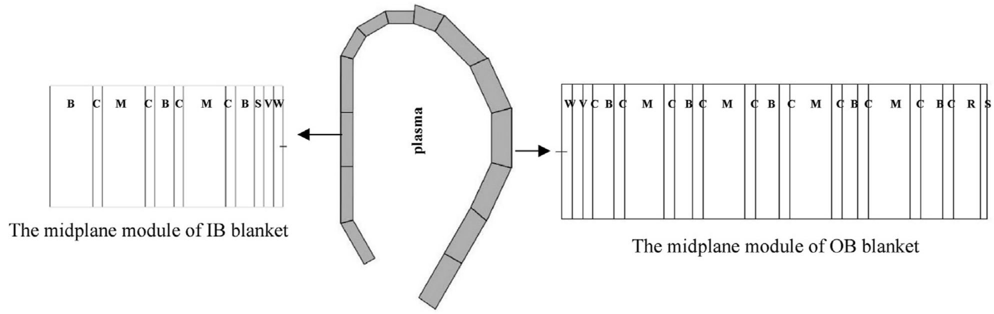

Fig. 1. Neutronic model of HCCR blanket modules, (B: Breeder; M: Multiplier; C: Coolant; R: Reflector, W: tungsten; V: Vanadium; S: Structure).

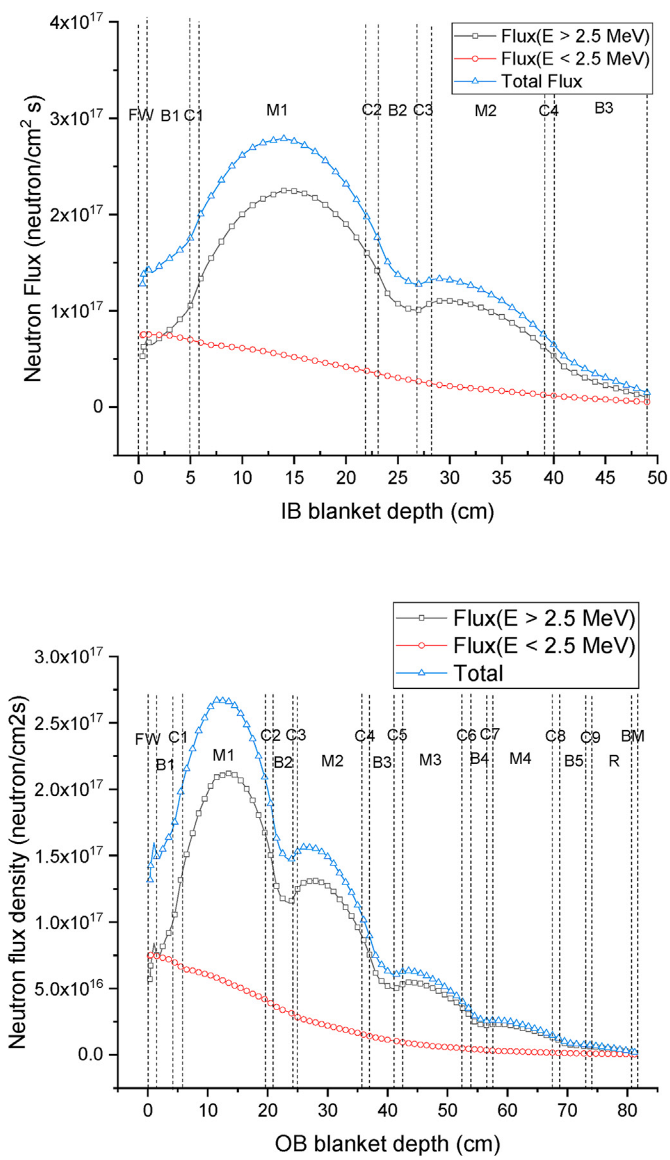

Fig. 2. Neutron flux distribution in IB and OB blanket.

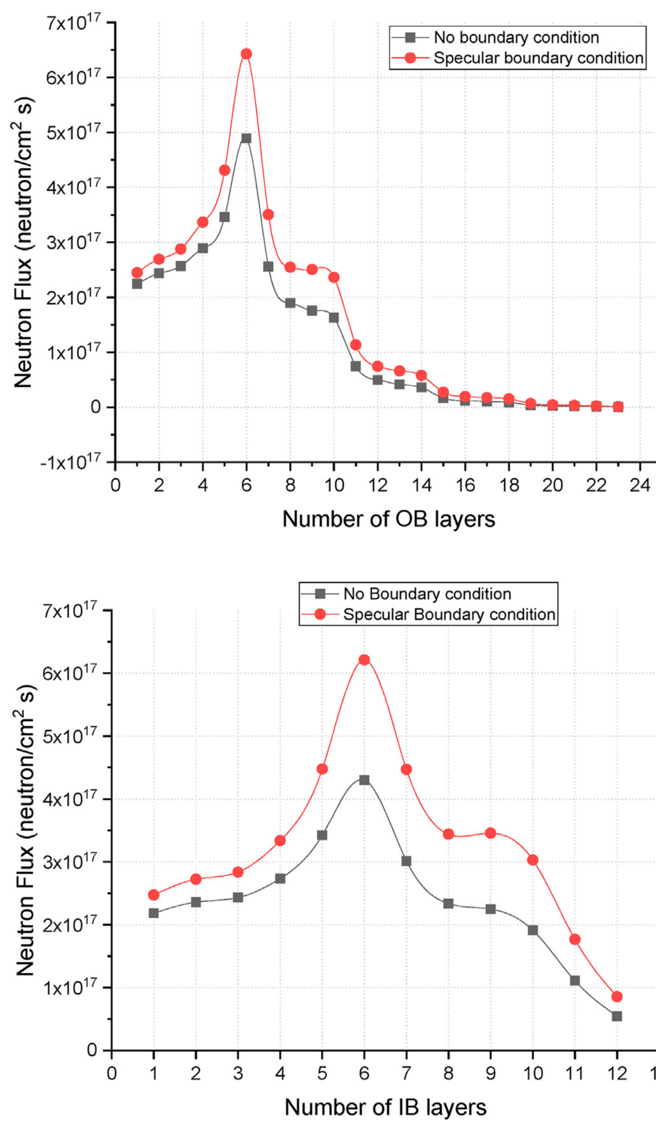

Fig. 3. Neutron flux in the cells of IB and OB blankets.

2.4. Nuclear heating

Nuclear heating measures the energy deposited by neutrons, photons, and alpha particles in the various components surrounding the plasma. Energy deposition in the material due to nuclear interactions of neutrons and atomic nuclei described by energy-dependent Kerma (Kinetic energy release in materials) factors. The amount of energy deposition in each layer depends on

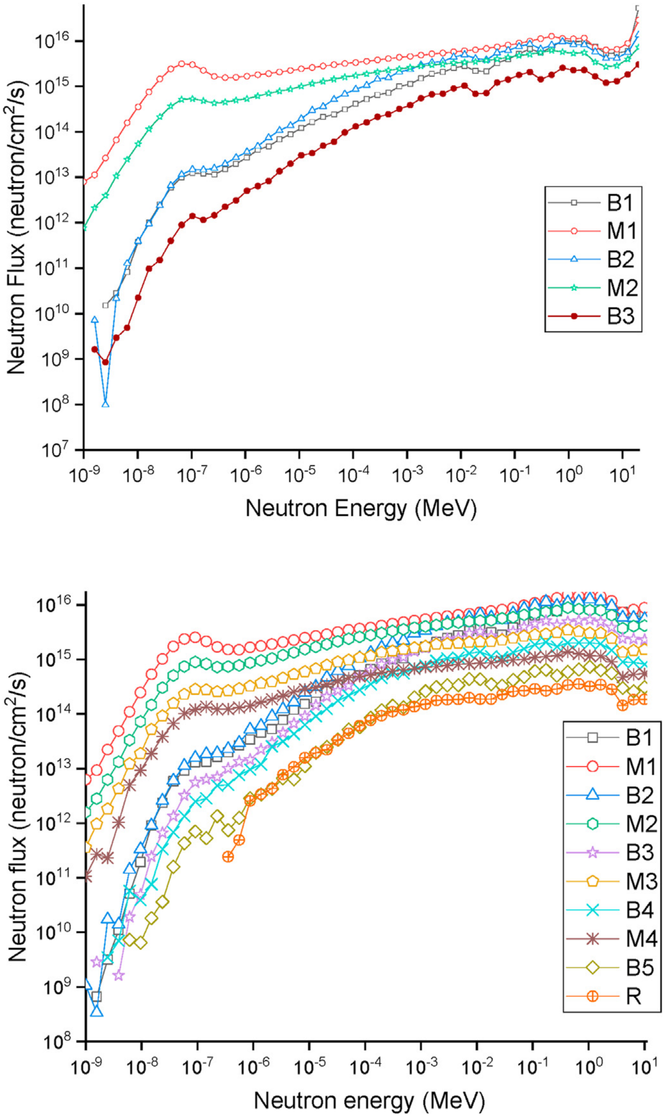

Fig. 4. Neutron spectra in each component of IB and OB midplane blankets.

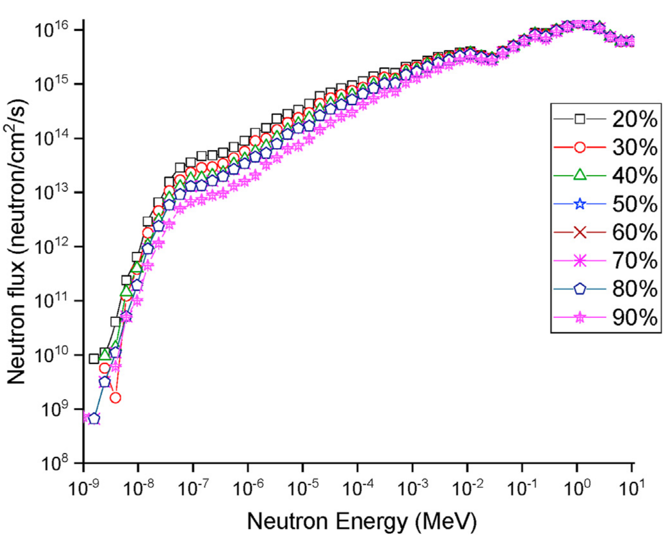

Fig. 5. Neutron spectra in the first breeder of OB blanket.

Table 2
The values of local TBR in a various amount of ^{6}Li percentage.

^{6}Li enrichment (%)	TBR
20	0.96
30	0.95
40	1.06
50	1.10
60	1.12
70	1.14
80	1.16
90	1.18

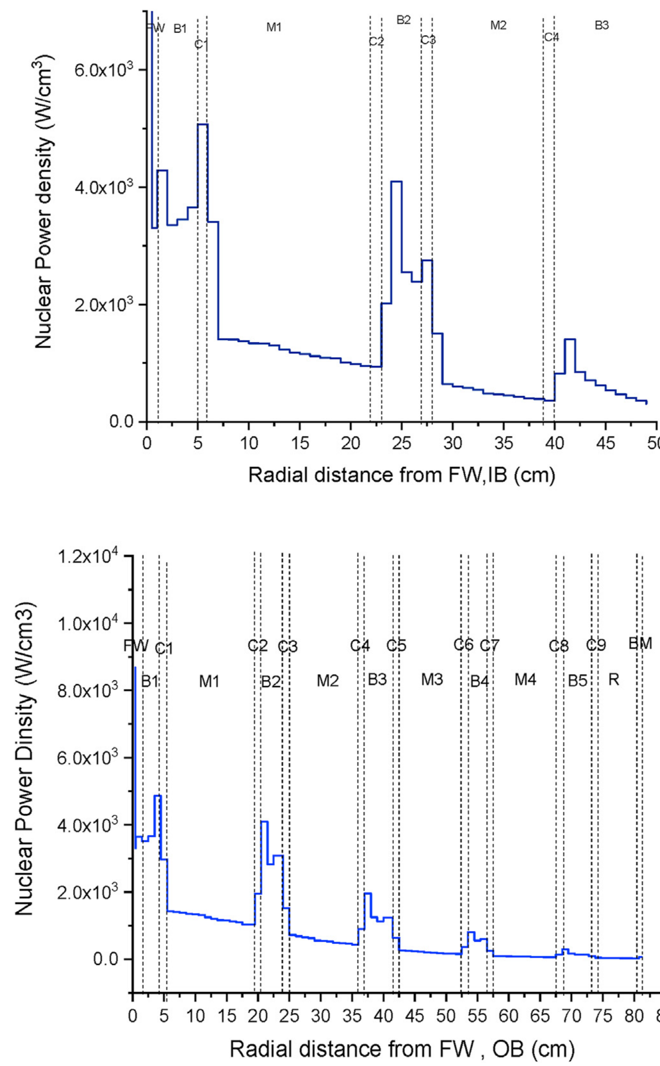

Fig. 6. Nuclear power density against radial distance from FW.

the type of materials through which the particles and photons pass. The highest peaks are at the layers where the neutrons have a high rate of elastic collisions with the small nuclei, which means a vital energy deposition. Nuclear power density in IB and OB blanket is shown in Fig. 6.

The sum of energy deposition and energy multiplication factor

(EMF) in the midplane modules of IB and OB blanket were calculated in different percentages ^{6}Li. The results of this study are shown in Table 3. The required energy multiplication factor of the fusion reaction is the total energy deposition per source neutron ratio to the neutron's energy generated by the fusion reaction, which is a number between 1.1 and 1.3. The energy multiplication factor for the studied geometry is 1.1.

Nuclear power density is computed in various cells of IB midplane blanket. As shown in Fig. 7, the FW′ nuclear power density is maximum and in the multiplier layers is minimum. In neutron multipliers, alpha particles' energy deposition is significant due to reaction ^{9}Be(n,2n)2α.

Table 3
The values of energy deposition in a various amount of ^{6}Li percentage.

^{6}Li (%)	Energy deposition(MeV)	EMF
20%	14.5	1.0
30%	14.4	1.0
40%	14.7	1.0
50%	14.8	1.1
60%	14.9	1.1
70%	14.9	1.1
80%	15.0	1.1
90%	15.1	1.1

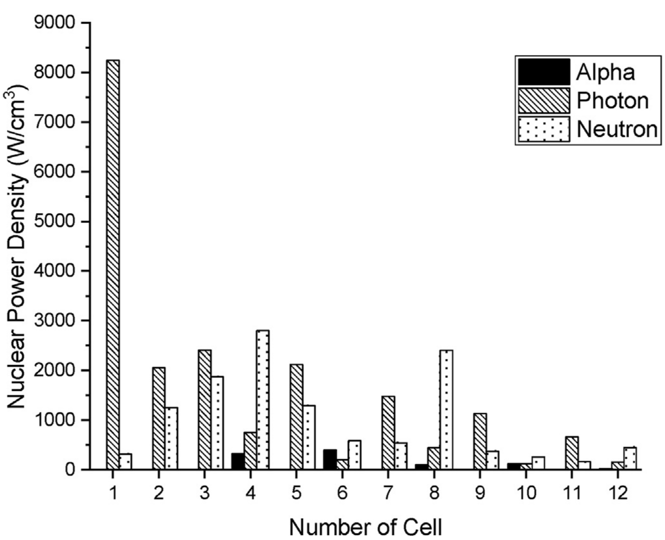

Fig. 7. Nuclear power density in the cells of IB blanket.

2.5. Neutron Multiplication Factor

It should be noted that in the reactions of T breeding, one T is bred by consuming one neutron. Since one T is burned in a D-T fusion reaction to produce one neutron, the fuel self-sufficiency is not attained. Therefore, the multiplication of neutrons is required. Be is used as a neutron multiplier in this ceramic breeder: ^{9}Be(n,2n)2α. Furthermore, reaction neutrons with more than 10 MeV energy induce another reaction with ^{7}Li referred to as a neutron multiplication reaction (n, 2n): ^{7}Li(n,2n)T. In most realistic, engineered blanket designs, a value of 1.5 is required for Neutron Multiplication Factor (NMF) to establish tritium breeding self-sufficiency [18]. Given the low cross-section of reaction ^{7}Li(n,2n)T compared to reaction ^{9}Be(n,2n)2α, it is clear that the percentage of Li enrichment has little effect on this coefficient. In the IB blanket of the proposed model, NMF is about 1.64 for ^{9}Be(n,2n)2α and 0.12 for ^{7}Li(n,2n)T. In the OB blanket, NMF is 1.67 and 0.13 for Be and ^{7}Li reaction with the neutrons, respectively.

3. The amount of economic saving

HCCR breeding blankets are divided into 32 inboard and 48 outboards modules toroidally and into 6 inboard and 8 outboard modules poloidally. Li' mass used in the HCCR blanket is about 8064 kg for IB blanket and 17,280 kg for OB blanket. Since the cost of 60% and 90% enriched ^{6}Li has been estimated to be \$1333 kg^{-1} and \$1600 kg^{-1}, respectively [19], using 60% enriched Li instead of 90% will save about \$7.0 million. Table 4 summarizes the results of this study.

4. Conclusion

In this work, the neutronic analysis of the HCCR breeding blanket has been performed using MCNPX. This study shows the effect of ^{6}Li percentage on various neutronic parameters, such as TBR and nuclear power density. This study indicates that acceptable results of TBR are obtained with a lower enrichment of ^{6}Li in the ceramic BB in such a way the self-sustaining condition is maintained. Also, increasing the percentage of ^{6}Li from 60% to 90% does not cause a significant change in energy deposition. As far as Li enrichment's high cost, the acceptable results are achieved at a lower price.

The neutron flux in the blanket increases by using reflector material in each module's outer surfaces, and as a result, the blanket's performance improves.

Nuclear power density in the IB and OB midplane modules of BB was performed by measuring the energy deposited by neutrons, photons, and alpha particles in the various components. The Energy multiplication factor, EMF, for the studied geometry is about 1.2.

Table 4
The cost of ^{6}Li enrichment.

	The cost of ^{6}Li enriched (\$kg^{-1})	Li mass used (kg)		cost
		IB	OB	
60% Li enriched	1333	8064	17,280	\$33 million
90% Li enriched	1600			\$40 million

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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