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Impact of armor materials on tritium breeding ratio in the fusion reactor blanket

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Abstract

We have studied the impact of armor materials on the tritium breeding ratio (TBR) in the fusion reactor blanket by Monte Carlo neutron transport calculations. In case a neutron multiplier is applied in the blanket, the TBR is decreased by installing the tungsten armor. On the other hand, the TBR is increased by installing the beryllium armor. The reduction of the TBR due to the installation of the tungsten armor is increased with increasing the volume ratio of the beryllium to the tritium breeder in the blanket. The blanket design without the tungsten armor is recommended from the view point of the TBR, since the design margin is very little for the TBR. On the other hand, the reduction of the TBR due to installation of the tungsten armor can be mitigated by installing the breeder region in the first layer in the multi-layered concept. By modification of the Li enrichment and the arrangement of the breeder/neutron multiplier, decreased TBR due to installation of the tungsten armor can be improved.

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Keywords: Blanket; Tungsten; Tritium breeding ratio; Armor; Beryllium; Breeder

1. Introduction

The performances of the armor material of plasma facing components have been studied so far mainly from the viewpoint of the impact on the plasma performances in the fusion reactor. The impact of the armor material on the fusion blanket performance, in particular, the tritium breeding performance is also important. The armor material such as tungsten might be installed at the surface of the blanket to protect it against heat radiation, direct plasma contact, and runaway electrons bombardment from the plasma. The tritium breeding ratio (TBR) is expected to be affected by the presence and kind of the armor materials. In a fusion reactor, the blanket is required to provide a TBR of more than unity, and to provide high local TBR in the overall region of the reactor is a critical issue in the development of the blanket and the fusion reactor design. Many design studies have been reported about the TBR [1–10], and most studies have been conducted by Sn calculation. In the study on optimization of TBR by Yanagi et al. [11], the local TBR of about 1.4 is reported for the concept without the armor material. A coverage of the breeder region is drastically reduced by the presence of the duct, divertor, gap, structure material. Taking into account the coverage, e.g. 70%, to provide the TBR of more than unity is a severe design target. Therefore, the reduction of TBR due to the armor material is a critical concern in the blanket design, and the effect of the TBR should be considered for the choice of the armor material. For the very limited design condition, the impact of the armor material on the TBR has been reported by Sagara et al. based on Sn calculations [12]. In the previous studies, however, there are no papers that studied the impact of the armor material on TBR from the view point of the ratio of the neutron multiplier to the breeder, the enrichment of the lithium isotope and the arrangement of

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the breeder and the multiplier by Monte Carlo calculation in detail. In order to evaluate the effect of the armor materials on the TBR, Monte Carlo calculations with continuous energy nuclear data libraries are required to take into account the self-shielding effect in the armor materials due to resonance reactions. In the present study, the impact of the armor material on the TBR has been studied by Monte Carlo calculations.

2. Calculation method

Neutron transport calculations were done with the Monte Carlo code MCNP-4B and the fusion evaluated nuclear data library JENDL-3.2. For the estimation of the TBR, we have used the JENDL Dosimetry File. We conducted the sensitivity analyses using a one dimensional simple calculation model shown in Fig. 1 by changing the type of the breeder, the volume ratio of the beryllium as the neutron multiplier to the breeder, and the enrichment of the ^{6}Li as the lithium isotope. In Fig. 1, the breeder region is homogenized (tritium breeder and beryllium). For the tritium breeder, we have used the solid ceramic breeder Li_2O, liquid lithium, and liquid LiPb. In addition to the sensitivity analyses, we evaluated the impact of the armor materials on the TBR for the layered concept proposed by JAERI for the DEMO reactor [11] using the one dimensional model shown in Fig. 2.

Region	Thickness (mm)	
Plasma	3000	
Armor	0 - 20	
First Wall, F82H	3	← Location A
First Wall, Water	8	
First Wall, F82H	7	
Breeder Region	700	
F82H	700	

Fig. 1. One dimensional MCNP calculation model for sensitivity analyses.

3. Results and discussion

3.1. Sensitivity analyses

3.1.1. Dependency on the ratio of the beryllium to the breeder

Fig. 3 shows the dependency of TBR on the volume ratio of the beryllium in the blanket to the breeder for

Case I

Region	Thickness (mm)
Plasma	3000
Armor	0 - 20
First Wall, F82H	3
First Wall, Water	8
First Wall, F82H	7
Li_2O (First layer)	7.1
F82H	1.8
Water	4.2
F82H	1.8
Be	26.2
F82H	1.8
Water	4.2
F82H	1.8
Li_2O	9.2
F82H	1.8
Water	4.2
F82H	1.8
Be	26.2
F82H	1.8
Water	4.2
F82H	1.8
(to be repeated)	

Case II

Region	Thickness (mm)
Plasma	3000
Armor	0 - 20
First Wall, F82H	3
First Wall, Water	8
First Wall, F82H	7
Be (First layer)	26.2
F82H	1.8
Water	4.2
F82H	1.8
Li_2O	7.1
F82H	1.8
Water	4.2
F82H	1.8
Be	26.2
F82H	1.8
Water	4.2
F82H	1.8
Li_2O	9.2
F82H	1.8
Water	4.2
F82H	1.8
(to be repeated)	

Fig. 2. One dimensional MCNP calculation model for the layered concept.

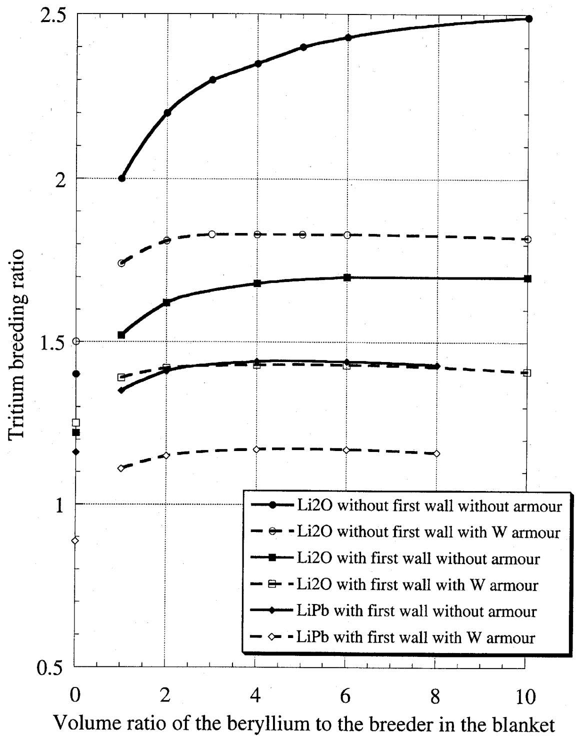

Fig. 3. Dependence of TBR on the volume ratio of beryllium to breeder in the blanket.

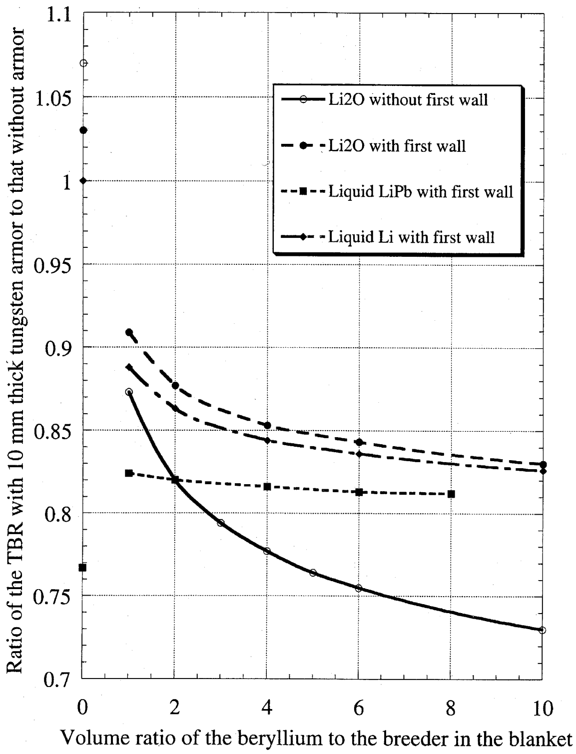

Fig. 4. Ratio of the TBR with 10 mm thick tungsten armor to that without armor on the volume ratio of the beryllium to the breeder in the blanket.

various breeder materials with lithium of natural composition. The TBR shown in this figure are for the case without armor and with a 10 mm thick tungsten armor. The horizontal axis corresponds to the volume ratio of the beryllium in the blanket to the breeder, and the value of 0 in the axis means a blanket without beryllium. Fig. 4 shows the ratio of TBR with the 10 mm thick tungsten armor to that without the armor versus the volume ratio of the beryllium to the breeder. In the blanket without neutron multiplier such as beryllium and lead, it was found that the TBR is increased by installing the tungsten armor. Therefore, it was clarified that installation of the tungsten armor is effective for increasing the TBR in the blanket concept without neutron multiplier. This is because the neutron flux is increased by the $(n, 2n)$ reaction in the tungsten armor.

In case a neutron multiplier is added in the blanket, it was found that the TBR was decreased by installing the tungsten armor. The reduction of the TBR due to installation of the tungsten armor was increased with increasing the volume ratio of the beryllium. In the case of a blanket composed of Li_2O with an 18 mm thick first wall, the TBR is decreased by up to 17% at a beryllium/breeder ratio of 10. Fig. 5 shows incident neutron spectra at the location A, which is surface of the blanket just behind the armor, shown in Fig. 1 for the cases with 10 mm thick tungsten armor and without armor. In the Fig. 5, the incident neutron spectra is also shown for hypothetically installing the 10 mm thick beryllium armor at the surface of the blanket instead of the tungsten armor. The thermal neutron flux is increased due to the $(n, 2n)$ reaction in the tungsten armor, while the fast neutron flux with an energy of more than 2 MeV is reduced, and at 11 MeV is drastically reduced. In addition to the $(n, 2n)$ cross section, tungsten has large capture and inelastic cross sections. In case the beryllium armor is hypothetically installed, the thermal neutron flux is increased by about one order of magnitude compared with the tungsten armor as shown in Fig. 5. The beryllium has small cross sections except for the $(n, 2n)$ reaction, therefore the beryllium is more effective neutron multiplier. Neutron multiplier reactions in the beryllium in the blanket may be reduced by reduction of the incident fast neutron flux due to the installation of the tungsten armor, thus the TBR is decreased by the installation of the tungsten armor. The neutron multiplier, e.g. beryllium, in the blanket is required to increase the TBR and to satisfy the design target of the TBR. From the present study, it was clarified that the TBR was decreased by installing the tungsten armor in the blanket concept with the neutron multiplier, since the $(n, 2n)$ reaction due to the neutron multiplier in the blanket is

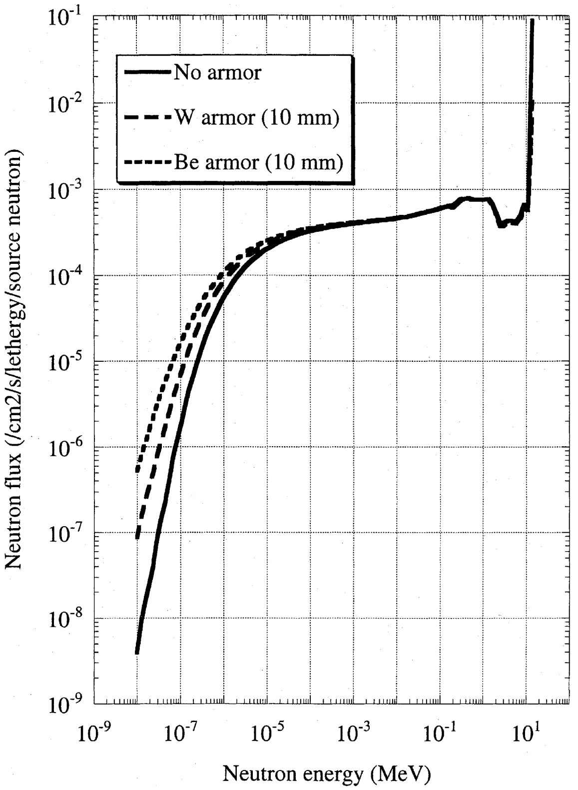

Fig. 5. Incident neutron spectra at the location A shown in Fig. 1 for the cases with 10 mm thick W, Be armor, and without armor.

reduced. In the blanket design, especially the solid breeder blanket design, the TBR is a critical issue above mentioned, and a several percent decrease of the TBR may not be accepted. Therefore, installation of the tungsten armor should be carefully discussed taking into account the net TBR including the reduction of the coverage and the calculation uncertainty. From the recent experimental results [13–15], the calculation uncertainty with 10–20% may be required to be considered.

3.1.2. Dependency on the enrichment of the lithium isotope

Fig. 6 shows the dependency of the TBR on the enrichment of ^{6}Li, which is about 7% in natural lithium. It shows the example of a volume ratio of beryllium to the breeder of four. The horizontal axis corresponds to the enrichment. Fig. 7 shows the ratio of the TBR with a 10 mm thick tungsten armor to that without armor on the enrichment of ^{6}Li. It was found that the reduction of the TBR due to installation of the tungsten armor is improved with increasing enrichment. The mean free path of the tritium production reaction due to ^{6}Li is very short, and the thermal neutrons generated by the tungsten react with the ^{6}Li in the region close to the first wall. Therefore it was discussed that the TBR in the region

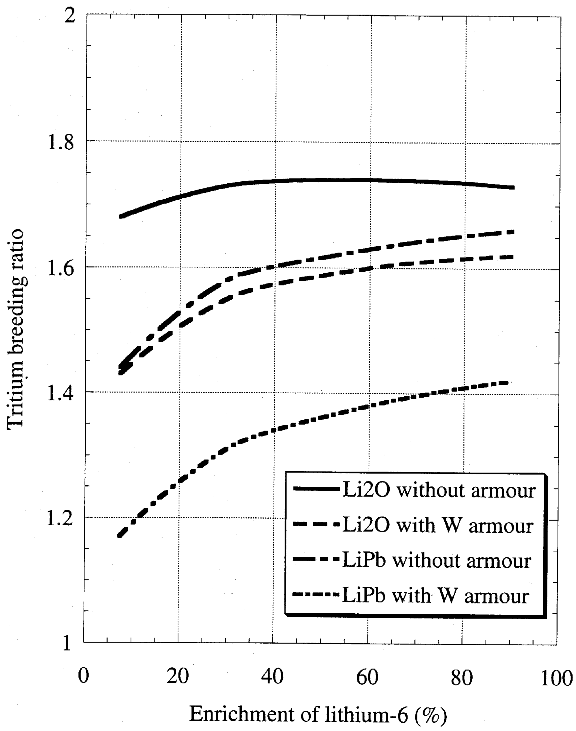

Fig. 6. The TBR versus the enrichment of lithium-6.

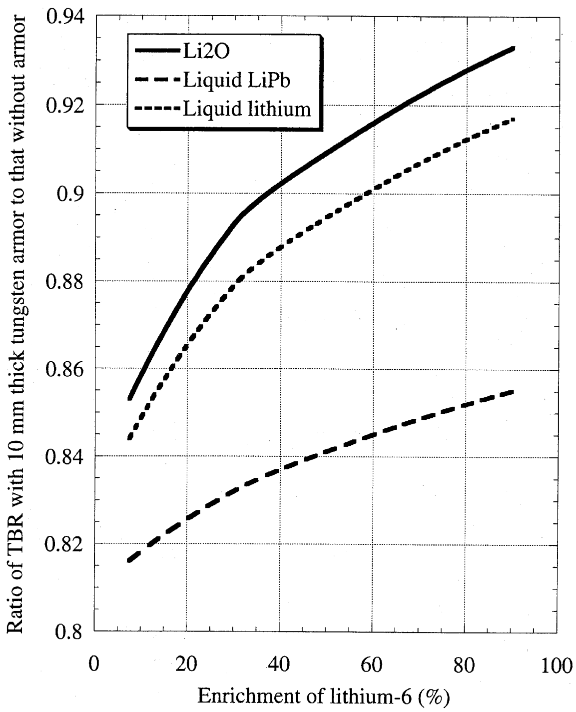

Fig. 7. Ratio of the TBR with 10 mm thick tungsten armor to that without armor versus the enrichment of lithium-6.

close to the first wall is increased with increasing enrichment, thus the contribution of the neutron multiplier reaction due to the tungsten armor on the TBR may be increased, and that due to the beryllium and the lead in the blanket may be decreased with increasing enrichment. In case the tungsten armor is installed, increase of the enrichment is effective for mitigation of the reduction of the TBR due to installation of the tungsten armor. Therefore, increase of the enrichment is recommended for the blanket concept with the tungsten armor, though the fabrication cost of the breeder is drastically increased.

3.1.3. Dependency on the armor thickness

Fig. 8 shows the dependency of the TBR on the armor thickness. In this example, the blanket is composed of Li_2O and Be with an 18 mm thick first wall. The enrichment of ^6Li is 30%, and the volume ratio of beryllium to the breeder is a factor of four. The horizontal axis corresponds to the armor thickness. The TBR is decreased with increasing the tungsten armor thickness. With increasing the tungsten thickness from 1 to 20 mm, the TBR is decreased from 2% to 18%. When the tungsten armor is required in the blanket design, the thinnest possible armor should be installed from the view point of the TBR. In case the tungsten armor is less than 3 mm thickness, the decrease of the TBR is less than 4%. On the other hand, the TBR is increased by installing the beryllium armor which is not a reference material in the current DEMO blanket design. With increasing the beryllium armor thickness from 1 to 20 mm, the TBR is increased from 2% to 10%. The incident thermal neutron flux to the blanket just behind the beryllium armor is larger than that behind the tungsten armor by about one order of magnitude as shown in Fig. 5, therefore the TBR is increased by installing the beryllium armor. The beryllium armor is applied to the ITER blanket [5], therefore the reduction of the TBR is not concern in the ITER design.

3.2. Layered concept

Solid breeder blankets being developed by JAERI for the tokamak-type DEMO reactor consists of Li_2O, beryllium, F82H and water in turn [11]. Fig. 9 shows the dependency of the TBR for this layered concepts with Li of natural composition and 30% ^6Li enrichment on the armor thickness. The horizontal axis corresponds to the

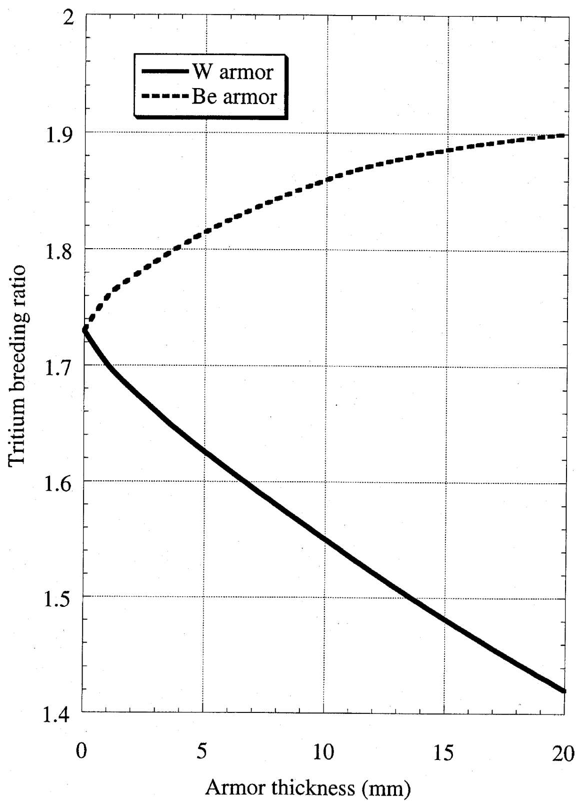

Fig. 8. Dependency of the TBR for the homogenized blanket composed of Li_2O and Be with the 18 mm thick first wall on the armor thickness.

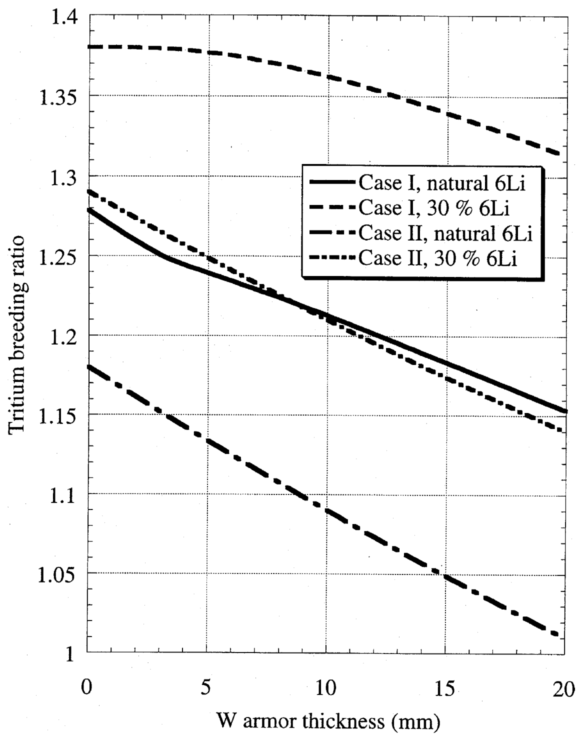

Fig. 9. Dependency of the TBR for the layered concept developed by JAERI for the tokamak-type DEMO reactor composed of Li_2O, beryllium, F82H and water on the armor thickness.

armor thickness. Case I shows the TBR for Li_2O, and Case II for beryllium in the first layer as shown in Fig. 2. By installing the 10 mm thick tungsten armor in Case I, it was found that the TBRs in the natural and 30% enriched breeders were decreased by about 5.2% and 1.3%, respectively, compared with that without armor. In Case II, they were decreased by about 7.8 and 6.2%, respectively. In case of beryllium in the first layer, it was found that the reduction of the TBR due to the tungsten armor was larger. It was discussed that the neutron multiplier reaction due to the first beryllium layer may be decreased due to reduction of the incident fast neutron flux to the blanket just behind the tungsten armor as mentioned above. Contrary, the reduction of the TBR due to installation of the tungsten armor can be mitigated by installing the breeder region in the first layer in the multi-layered concept. By modification of the arrangement of the breeder/neutron multiplier, and the Li enrichment, it can be concluded that decreased TBR due to installation of the tungsten armor can be improved.

4. Conclusions

We have studied the impact of armor materials on the TBR using sensitivity analyses. In case of a blanket without neutron multiplier, the TBR is increased by installing a tungsten armor, whereas in case of a blanket with multiplier, the TBR is decreased by installing a tungsten armor. It was found that the reduction of a TBR due to tungsten armor installation is increased with increasing the volume ratio of the beryllium to the tritium breeder. In the case of a blanket composed of Li_2O and beryllium with an 18 mm thick first wall, the TBR is decreased up to 17% for a beryllium/breeder ratio of 10. It was also found that the reduction of the TBR due to installation of the tungsten armor is mitigated with increasing enrichment of ^6Li. In the case of the layered concept proposed for the DEMO reactor by JAERI, the TBR is decreased by about 1.3–7.8% by installing the 10 mm thick tungsten armor. The reduction of the TBR due to installation of the tungsten armor can be mitigated by installing the breeder region in the first layer in the multi-layered concept. The blanket design without the tungsten armor is recommended from the view point of the TBR. On the other hand, by modification of the Li enrichment, the arrangement of the breeder/neutron multiplier, decreased TBR due to installation of the tungsten armor can be improved. These results suggest that the impact of the armor material on the TBR should be examined properly and carefully for the final blanket design. The margin is very little for the design target of the TBR in the DEMO blanket design, and the TBR is critical concern. Therefore, installation of the tungsten armor should be carefully discussed taking into account the net TBR, and it is very important to perform the blanket design taking into account the effect of the armor material on the TBR.

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