DOI: 10.15669/pnst.4.130

Progress in Nuclear Science and Technology
Volume 4 (2014) pp. 130-133

ARTICLE

An optimization study of structure materials, coolant and tritium breeding materials for nuclear fusion-fission hybrid reactor

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The blanket materials were evaluated and optimized for use in a nuclear fusion-fission hybrid reactor by calculating the tritium breeding ratio (TBR), the ratio of thermal power output to fusion power input (Q value) and the temperature distributions. The calculation of TBR and Q value was performed by Monte Carlo code (MCNP-4C) and the temperature distributions by one dimensional heat equation. First, the structure materials, coolant and tritium breeding materials were investigated in terms of the TBR and the Q value. Secondly, the layer structure was optimized by calculating the temperature distributions in the blanket where the materials were selected by considering the former results of the TBR and Q value. As a result, the highest TBR and Q value could be obtained, if vanadium alloy structure material, helium gas coolant and molten salt tritium breeding material would be used as the blanket material. In addition, by optimizing the blanket structure using these materials, it would be possible to get a high TBR of 2.0 maintaining the temperature limit of the blanket materials, and about twenty times the thermal power output could be produced compared to the fusion power input under the condition of effective multiplication factor of 0.80.

Keywords: fusion-fission hybrid reactor; blanket; structure material; coolant; tritium breeding material (TBM); Tritium Breeding Ratio (TBR); thermal power output; Q value; subcritical assembly

1. Introduction

There are some problems with high heat flux and particle loads to plasma facing components in the development of a typical fusion reactor. It could be possible that a nuclear fusion-fission hybrid reactor would obtain a high tritium breeding ratio (TBR) and ratio of thermal power output to fusion power input (Q value) because of neutron density and energy-rich-fission-neutrons from nuclear fuels placed at the blanket. Therefore, a fusion-fission hybrid reactor might solve such problems. It might also be possible to construct a fusion-assisted transmutation system for the destruction of transuranic nuclear wastes with subcritical assembly [1].

In this paper, the blanket materials and its structure were optimized for designing a fusion-fission hybrid reactor blanket. The design requirements are as follows:

- Tritium breeding ratio $\geqq$ 2.0
- Effective multiplication factor = 0.80
- Temperature in the blanket
  $\leq$ permissible temperatures for used materials
- Ratio of thermal power output to fusion power input
  Q value $\simeq$20

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2. Materials

2.1. Calculation model and methods

Figure 1 depicts the calculation model of the blanket design (1m long and 1m wide with 60 cm in thickness) with reference to ITER module. The blanket region consists of first wall (FW), nuclear fuels (subcritical assembly), coolant and tritium breeding material (TBM).

A Monte Carlo code (MCNP-4C) with nuclear data library of JENDL3.3 was used to calculate the effective multiplication factor (k_{eff}) in the subcritical assembly, neutron flux and spectrum, TBR, Q value and nuclear heat in the blanket [2, 3].

A one dimensional heat equation was adopted to calculate the temperature distributions in the designed blanket where heat flux was deduced from the nuclear heat values calculated by MCNP. The volume source of 14 MeV neutrons was assumed in the plasma region, and reflected conditions for traverse directions were adopted for MCNP calculations.

2.2. Blanket materials

The first wall (FW) materials consists of W (1mm thick) and structure material (2mm thick). F82H (Japanese reduced activation ferric/martensitic steel) and V-4Cr-4Ti (vanadium alloy) were examined for the structure materials.

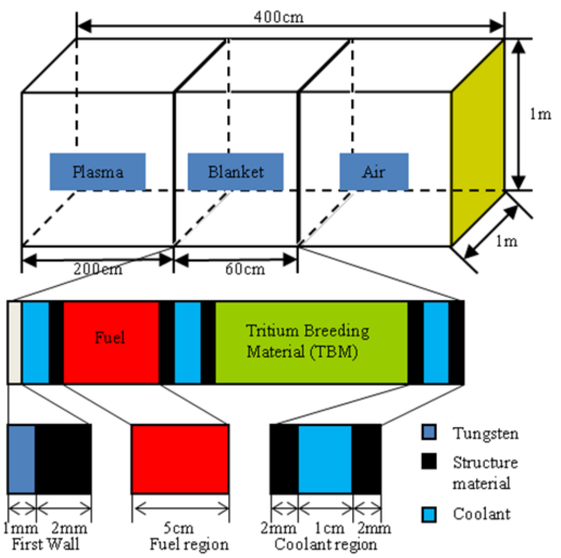

Figure 1. Calculation model for material comparison in the fusion-fission hybrid blanket.

Light water, liquid lithium, molten salt (Li_2BeF_4) and helium (He) were investigated for typical coolant.

Lithium titanate (Li_2TiO_3), liquid lithium and molten lithium-lead alloy ($Li_{17}Pb_{83}$) were examined as generally useful TBMs [4].

2.3. Fuel and criticality

In a fusion-fission hybrid reactor, intense neutrons must be produced in the blanket. Plutonium (Pu) nitride fuels from the spent fuels cooled 3 years after 33 GWD/t burn-up in PWR mixed with thorium (Th) were used for nuclear fuel materials. A pebble bed type with He gas inside was assumed. Pu should be burned-up from view point of NPT and Th useful nuclear fertile material without producing miner actinide (MA). The effective multiplication factor was set to 0.80 safely by adjusting the proportion of Pu to Th .

3. Results and discussions

3.1. Comparison of blanket materials

3.1.1 Structure materials

Table 1 shows the calculation results of TBR and Q value obtained for the structure materials. Comparison result of structure materials shows that using V-4Cr-4Ti can obtain higher values for both TBR and Q value than using F82H. The V-4Cr-4Ti might also be superior to F82H in low activation characteristics.

Table 1. Comparison results of structure materials.

Structure material	Coolant	TBM	Ratio of Pu to Th (%)	TBR	Q value
F82H	H_2O	Li_2TiO_3	22.0	2.48	20.6
V-4Cr-4Ti			22.5	2.67	21.6

3.1.2 Coolant

Table 2 shows comparison results of TBR and Q value obtained for light water, liquid lithium, molten salt (Li_2BeF_4) and helium (He). The comparison results of coolant shows that using helium can obtain the highest values for both TBR and Q value. The reason would be that neuton absorption of helium is smaller than that of the others.

Table 2. Comparison results of several coolants.

Coolant	Structure material	TBM	Ratio of Pu to Th (%)	TBR	Q value
H_2O	F82H	Li_2TiO_3	22.0	2.48	20.6
Li-liq			33.0	2.94	21.3
Li_2BeF_4			31.5	2.72	20.7
He			31.5	3.28	22.4

3.1.3 Tritium breeding materials

Figure 2 depicts tritium production per injected neutrons at 2cm thick TBM calculated along the depth direction. The TBR was determined by summing this value over TBM region.

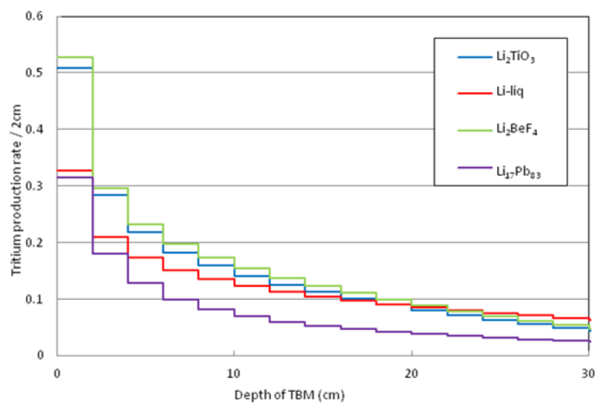

Figure 2. Tritium production rate along the depth obtained for several TBMs.

Table 3 summarizes the calculation results of TBR and Q value obtained for the TBMs. The comparison of TBMs indicates that using of Li_2BeF_4 can obtain the highest TBR. Fluorine (F) has a large elasitic cross-section around several 100keV neurton enrgy range, therfore, fast neurtons produced in the blanket would moderate and could produce tritium. Berilium (Be) also has (n,2n) cross-section in fast energy range which would be useful for neutron economy.

On the other hands, from the view point of Q values, Li-liq seems to be better than Li_2BeF_4. However, the Li_2BeF_4 is the thinnest to obtain TBR=2.0 as seen in Figure 2, therefore, Li_2BeF_4 is superior to the others to obtain higher Q value by use of thinner TBM.

Table 3. Comparison results of several TBMs.

TBM	Coolant	Structure material	Ratio of Pu to Th (%)	TBR	Q value
Li_2TiO_3	H_2O	F82H	22.0	2.48	20.6
Li-liq			34.5	2.45	21.7
Li_2BeF_4			21.0	2.65	20.8
$Li_{17}Pb_{83}$			13.5	1.40	23.2

3.2. Optimization of blanket structure

To increase the Q value, we modified the blanket structure as shown in **Figure 3** maintaining the TBR=2.0 when using the formers decided structure material, coolant and TBM, that is, V-4Cr-4Ti for structure mateial, He for coolant and Li_2BeF_4 for TBM.

Table 4 shows the results divided the blanket by sections. The Q value of 27.7 was obtained for the 11 sections maintaining TBR=2.0 which was 1.3 times larger than that of the one section blanket module.

Table 4. Calculation results of the TBR and Q value in the modified layer structure.

Structure material	Coolant	TBM	Number of fuel regions (Sum of the length of fuel regions (mm))	Ratio of Pu to Th (%)	TBR	Q value
V-4Cr-4Ti	He	Li_2BeF_4	10 (112)	17.3	2.34	27.5
			11 (129)	15.8	2.00	27.7
			12 (147)	14.7	1.69	28.6

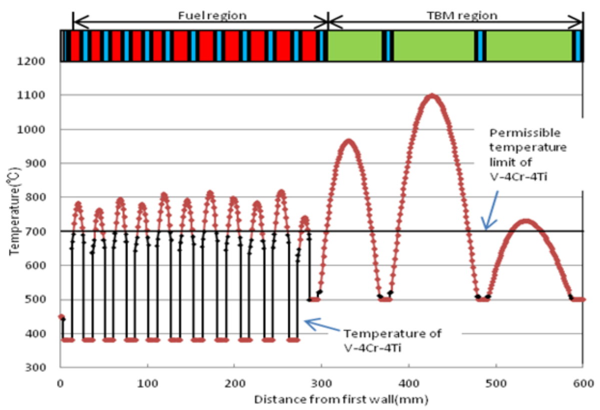

Figure 3. Temperature distributions obtained for the blanket module divided by 11 sections maintaining TBR=2.0.

The obtained optimal conditions are as follows:

Structure material: V-4Cr-4Ti < 700 ℃
Coolant :
- in the gap of FW and fuel region:
  He gas 8MPa, temperature 380 ℃
  flow velocity 35 m/s
- surrounding TBM:
  He gas 8MPa, temperature 500 ℃
  flow velocity14 m/s

TBM: 458℃ < Li_2BeF_4 < 1435 ℃

Table 5 shows the thermal power output in the blanket module divided by 11 sections, which deduced from the fusion power input of 0.088 MWt/m^2 while keeping under permissible temperature of the blanket materials as shown in Figure 3. From these results, we will expect about 1660 MWt of thermal power output could be produced if the designed blanket model would be applied to ITER having a total FW area (680 m^2).

Table 5. Calculation results of the thermal power output in the blanket module divided by 11 sections.

Module	one module	Blanket corresponding to ITER size
Input fusion power	0.088MWt/m^2	60MWt
Output thermal power	2.44 MWt/m^2	1660MWt

4. Conclusion

The blanket materials were evaluated for use in a nuclear fusion-fission hybrid reactor by calculating the tritium breeding ratio (TBR), the Q value and the temperature distributions. As a result, the highest TBR and Q value could be obtained if vanadium alloy structure material, helium gas coolant and molten salt tritium breeding material would be used as the blanket materials. In addition, by optimizing the blanket structure using these materials, a high TBR value of 2.0 would be possible while keeping under permissible temperature of the blanket materials, and about twenty times the thermal power could be produced compared to that of injected fusion power under condition of the effective multiplication factor of 0.80.

However, there are some problems with material compatibilities. To use vanadium alloy for structure materials and water or helium coolant has a problem from the viewpoint of compatibility [5]. A key issue associated with the use of Flibe is the control of tritium permeation and structure material corrosion, technologies for coating as tritium permeation barrier and reduction of impurities in the coolant or anti-corrosion coating would be required to solve the issue [6,7]. The development of materials and technologies to solve the compatibility and tritium permeation problems would be important for realization of the proposal blanket concept.

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