Burn-up Calculation of Fusion-Fission Hybrid Reactor Using Thorium Cycle

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A burn-up calculation system has been developed to estimate performance of blanket in a fusion-fission hybrid reactor which is a fusion reactor with a blanket region containing nuclear fuel. In this system, neutron flux is calculated by MCNP4B and then burn-up calculation is performed by ORIGEN2. The cross-section library for ORIGEN2 is made from the calculated neutron flux and evaluated nuclear data.

The 3-dimensional ITER model was used as a base fusion reactor. The nuclear fuel (reprocessed plutonium as the fissile materials mixed with thorium as the fertile materials), transmutation materials (minor actinides and long-lived fission products) and tritium breeder were loaded into the blanket. Performances of gas-cooled and water-cooled blankets were compared with each other. As a result, the proposed reactor can meet the requirement for TBR and power density. As far as nuclear waste incineration is concerned, the gas-cooled blanket has advantages. On the other hand, the water cooled-blanket is suited to energy production.

1. Introduction

A fusion-fission hybrid system is a fusion reactor with a blanket containing nuclear fuel. Even for a relatively lower plasma condition, neutrons can be well multiplied by fission in the nuclear fuel and tritium is thus bred so as to attain its self-sufficiency. Enough energy multiplication is then expected and moreover nuclear waste incineration is possible. A fusion-fission hybrid reactor can play an important role in seamless transition from fission energy to fusion energy.

In our group, a hybrid system with U-Pu cycle has been studied so far. However, acceptable incineration performance for minor actinide (MA) was not expected from the analysis. [1] Hence we started to investigate feasibility of a hybrid system with Th-U cycle.

In the present study, the performance of feasible fusion-fission hybrid reactor with Th-U cycle was examined by a new calculation system, in which a new procedure to prepare cross-section library for burn-up calculation is implemented in order to evaluate more accurate amount of nuclides to be produced or to be incinerated. Target parameters of the blanket of the feasible reactor are in the following;

TBR > 1.05

Keff < 0.95

Power Density < 15 W/cc (for gas cooled)

< 100 W/cc (for water cooled)

2. Calculation System

2.1 Calculation Procedure

The flow chart of this calculation system is shown in Fig. 1. The calculation was performed with the 3-D Monte Carlo code MCNP4-B [2] and point burn-up code ORIGEN2 [3]. These codes are interconnected by a shell script and some C++ codes. The cross-section library of MCNP-4B is based on JENDL-3.2 [4]. Track length data of neutron for each cell are stored in the MCNP-4B calculation. The data are fed directly to a routine for evaluation of one group cross-section library for burn-up calculation by ORIGEN2. This routine uses JENDL3.3 pointwise files at 300K [4] and JENDL Activation Cross Section File 96 [4]. The one group cross-section is made by the product of the track length data and the pointwise cross-section. Burn-up cycle was repeated for necessary times.

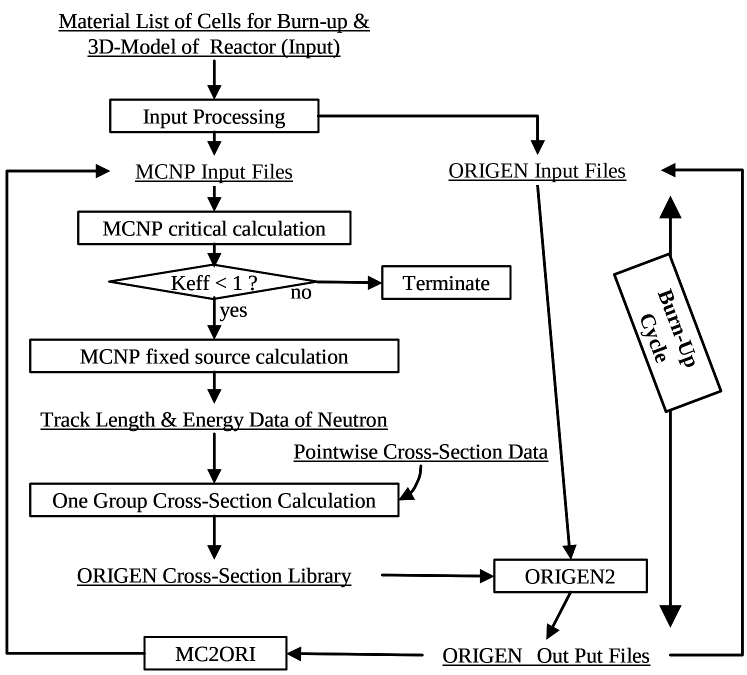

Fig. 1. Flow chart of burn-up calculation

2.2 Calculation Model

The 3-dimensional ITER model [5] was used as a base fusion reactor. The cross section of this model is shown in Fig.2. The nuclear fuel (reprocessed plutonium as the fissile materials mixed with thorium as the fertile materials), transmutation materials (minor actinides and long-lived fission products) and tritium breeder were loaded into the blanket. The blanket consists of five sections, each of which has three layers, i.e., 1^{st} one is on the plasma side, 2^{nd} one is in the middle and 3^{rd} one is in the outer layer.

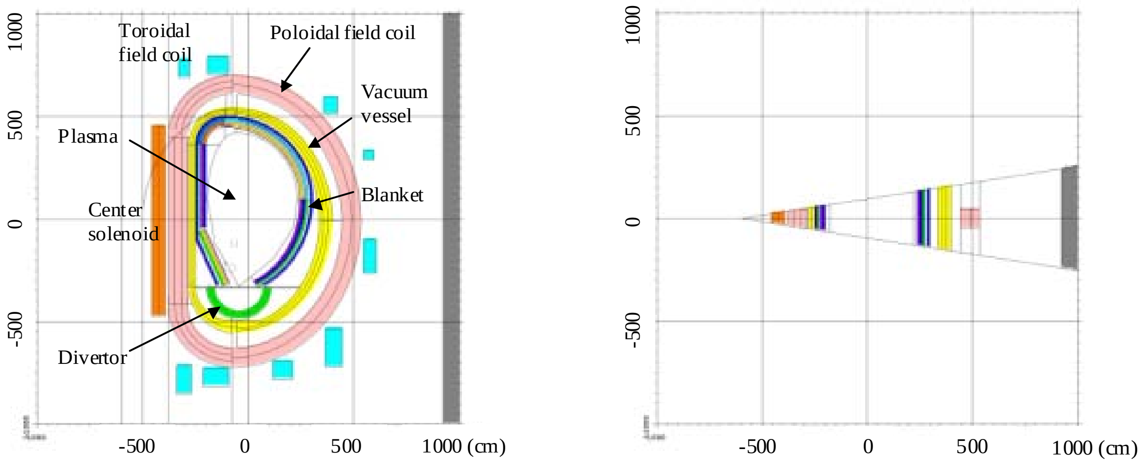

Fig. 2. Vertical (left) and horizontal (right) cross-sections of calculation model

2.3 Plasma Condition

The fusion power of the hybrid reactor was calculated by using parameters listed in Table 1, in which plasma temperature, confinement time and electron density were achieved in JT60 [6]. Other data were cited from recent ITER design.

Table 1 Calculation condition

plasma parameter	
Major radius (m)	6.2
Minor radius (m)	2.1
Plasma volume (m^3)	884
Plasma temperature (KeV)	19
Confinement time (s)	1.1
Electron density ($/m^3$)	4.80E+19
Fusion power (MW)	646
Neutron yeild (n/s)	2.20E+20
Neutron wall load (MW/m^2)	0.4

3. Results

3.1 Power density and TBR at the beginning of cycle (BOC)

The power density and TBR for gas-cooled (GC) blanket and water-cooled (WC) blanket were calculated for three cases, i.e., nuclear fuel was loaded in 1st, 2nd, or 3rd layer. In two layers other than nuclear fuel, breading materials which include Li_2ZrO_3 and Be were loaded. The ^6Li density and Be volume fraction were changed to obtain the optimized result. In the GC blanket with nuclear fuel in 1st layer, water was loaded in 3rd layer instead of Be in order to enhance production of tritium. For example, Fig. 3 shows TBR for WC blanket with the fuel in 2nd layer and Fig. 4 shows its power density.

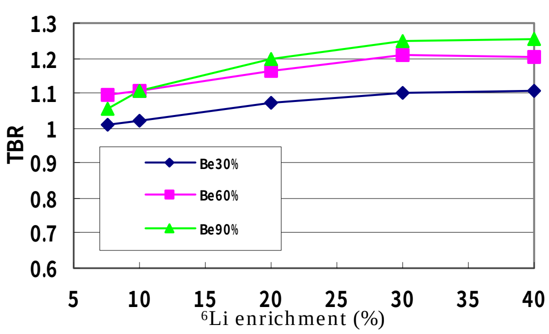

Fig. 3 TBR for WC blanket at BOC

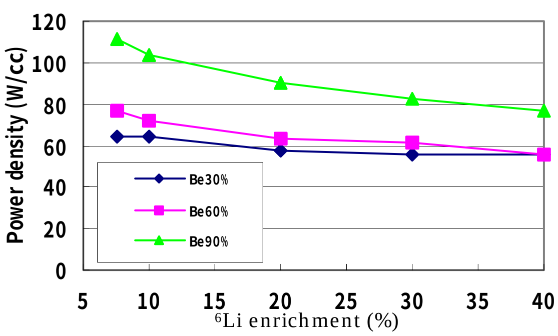

Fig. 4 Power density of WC blanket at BOC

3.2 Burn-up calculation

In the case of GC blanket, two blankets with nuclear fuel loaded in 1st layer (GC1) and 3rd layer (GC3) were feasible. In 5 year burn-up calculation, GC1 was employed because the case doesn't need much plutonium in the fuel layer.

In the case of WC blanket, two blankets with nuclear fuel loaded in 2nd layer (WC2) and 3rd layer (WC3) were feasible. These data are summarized in Table 2. WC2 was employed for 5 year burn up calculation because of its high power density and neutron flux. In all cases, blanket has a transmutation zone that contains long-lived fission products (LLFP). In the present calculation, the period of burn-up is 5 years, in which each year has five burn-up cycles. The plant factor is 70%.

3.2.1 TBR

As shown in Fig.5, GC1 blanket shows a slight increase of TBR over the 5 years burn-up calculation. WC2 blanket shows a decrease of TBR, but the rate of the decrease becomes smaller and TBR >1.05 is achieved in 5 years later, as shown in Fig. 6.

Table 2. Condition of calculation

case	TBR	Power Density W/cc	Fuel material fraction (%)			Breeder (Li_2ZrO_3 +Be)	
			Pu	Th	Be	Li6 enrichment(%)	Be fraction (%)
GC1*	1.06	15.4	0.25	6	63.75	40	90
GC3	1.04	8.8	3	77	0	40	90
WC2	1.25	82.7	8	52	0	30	90
WC3	1.09	31.5	8	52	0	10	60

* Water was employed instead of Be in the 3rd layer. The volume fraction of water and Li_2ZrO_3 are 80% and 20%, respectively.

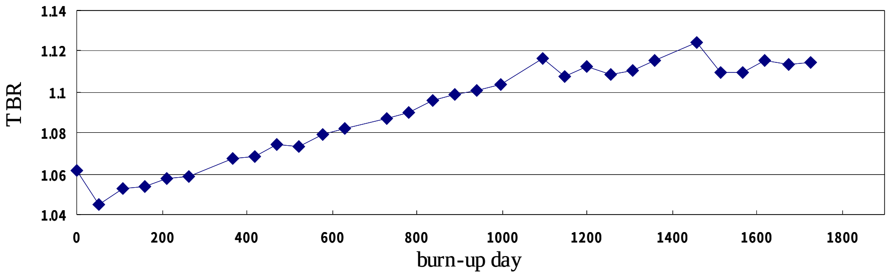

Fig. 5 TBR for GC1

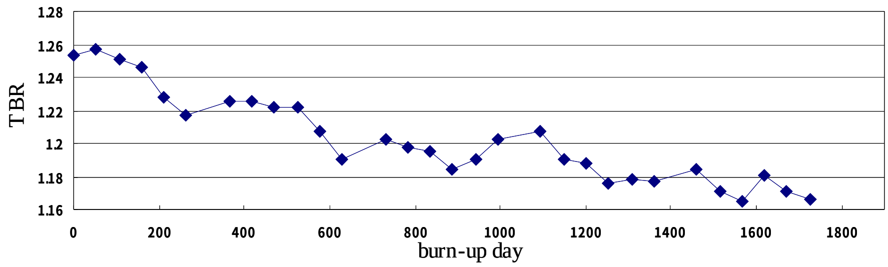

Fig. 6 TBR for WC2

3.2.2 Transmutation of FP

^{93}Zr, ^{99}Tc, ^{107}Pd, ^{129}I and ^{135}Cs were loaded as the LLFP mixed with Be or water in the transmutation zone (FP cell) in the 1st layer of the blanket in the case of WC2 and in the 2nd layer in the case of GC1. The calculation result is shown in Table 3.

Table 3 Performance of incineration

Gwty-PWR 5years	Gas Cooled (GC1)		Water Cooled (WC2)	
	in FP cell	Total	in FP cell	Total
Zr 93	2.8	-3.6	4.0	-16.5
Tc 99	52.1	47.3	76.9	51.7
Pd 107	140.7	133.3	165.5	106.9
I 129	43.4	37.9	66.3	28.6
Cs 135	12.8	-0.7	16.6	-84.6

Because of its high neutron flux, WC2 blanket has a better transmutation performance of FP cell than GC1 blanket. But WC2 blanket contains much more plutonium and generates more FPs, then ^{93}Zr and ^{135}Cs are totally built up. Compared with WC2, ^{135}Cs production was decreased for GC1 blanket because of less plutonium contained. It is necessary to load more ^{93}Zr and ^{135}Cs in FP cell if they should be incinerated effectively.

3.2.3 Production of MA

As shown in Table 4, the production rate of MA (^{237}Np, ^{241}Am, ^{243}Am) is compared with the calculation result of U-cycle blanket in which only thorium is replaced by uranium in the fuel cell. In the Th-cycle, production of ^{237}Np is much smaller, but production of ^{243}Am is the same as U-cycle because using Pu as nuclear fuel caused generation of ^{243}Am. Pu composition was drastically different from U-cycle because Pu isotopes are produced from a fertile material of ^{238}U in the U-cycle. Subsequent Long-term burn-up calculation will show difference in Am production.

Table 4 MA & Pu production (5 years burn-up)

Production Rate (kg / 5years) 0 - 5 year		MA			Pu		
case		Np237	Am241	Am243	Pu239	Pu240	Pu241
GC1	Th-cycle	0.3	11.7	41.2	-643.1	-268.7	44.6
	U-cycle	79.7	30.5	37.0	829.8	-61.9	254.5
WC2	Th-cycle	5.4	659.7	395.5	-8036.1	-810.0	591.3
	U-cycle	257.2	670.6	369.5	-3307.8	-483.2	585.3

4. Long-term Burn-up Calculation

Additional 5 years burn-up calculation without refueling or shuffling was performed to estimate the long-term burn-up characteristics of 10 years. The result of the calculation for MA and Pu is shown in Table 5. In Th-cycle of GC1, Pu and MA except for ^{237}Np are reduced compared to the first 5 years. TBR is stabilized over 1.05 and the FP transmutation performance is almost the same as the first 5 years burn-up calculation. Gas-cooled blanket is suited to incineration of nuclear waste.

Table 5 MA & Pu production (10 years burn-up)

Production Rate (kg / 5years)			5 - 10 year				
		MA			Pu		
case		Np237	Am241	Am243	Pu239	Pu240	Pu241
GC1	Th-cycle	2.2	-12.1	3.4	-73.5	-21.2	-111.1
	U-cycle	38.2	28.8	23.6	400.9	73.5	89.0
WC2	Th-cycle	8.7	488.5	211.2	-5365.2	-946.1	-89.6
	U-cycle	208.7	534.0	198.7	-2161.7	-450.0	33.6

5. Conclusion

A burn-up calculation system with more accurate estimation procedure of one-group cross section for point burn-up calculation has been developed to estimate the performance of blanket in a fusion-fission hybrid reactor using thorium cycle. In the calculation, reprocessed plutonium and thorium oxide were loaded in the blanket. A 3-D ITER model was used as a base reactor, and the plasma condition achieved in JT60 was used. As a result, it was shown that the proposed reactor can meet the requirement for TBR and power density in both gas-cooled and water-cooled blankets. And Th-cycle has advantages in FP and Pu transmutation compared to U-cycle. As far as nuclear waste incineration is concerned, gas-cooled blanket has advantages. On the other hand, water cooled-blanket is suited to energy production.

References

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[5]http://www.naka.jaeri.go.jp/ITER/FDR/

[6]http://www-jt60.naka.jaea.go.jp/HOME-J.html (in Japanese)