Transmutation of Minor Actinides in a Spherical Torus Tokamak Fusion Reactor, FDTR

K.M. Feng 1), G.S. Zhang 1), M.G. Deng 2)

1) Southwestern Institute of Physics, Chengdu, People's Republic of China
2) University of Electronics of Science and Technology of China, Chengdu, People's Republic of China

e-mail contact of main author: fengkm@swip.ac.cn

Abstract. In this paper, a concept for the transmutation of minor actinide (MA) nuclear wastes based on a spherical torus (ST) tokamak reactor, FDTR, is put forward. A set of plasma parameters suitable for the transmutation blanket was chosen. The 2-D neutron transport code TWODANT, the 3-D Monte Carlo code MCNP/4B, the 1-D neutron transport and burn-up calculation code BISON3.0 and their associated data libraries were used to calculate the transmutation rate, the energy multiplication factor and the tritium breeding ratio of the transmutation blanket. The calculation results for the system parameters and the actinide series isotopes for different operation times are presented. The engineering feasibility of the center-post (CP) of FDTR has been investigated and the results are also given. A preliminary neutronics calculation based on an ST transmutation blanket shows that the proposed system has a high transmutation capability for MA wastes.

1. Introduction

Fusion energy will be a long-term energy source. Great efforts have been devoted to fusion research in the past 50 years, and there is still a long way to go. Transmutation of high-level waste (HLW) utilizing D-T fusion neutrons is a good choice for an early application of fusion. The fusion transmutation concept will lead to improved pathways to fusion power as well as make competitive applications available earlier than the power application of fusion energy [1, 2]. Because of its many potential advantages, such as innovation in fusion plasma science, lower cost, and reduced time for development, the spherical torus (ST) is one of the most suitable devices for a nearer-term application of fusion [3].

This paper, reports on the calculations and analyses of the transmutation of minor actinides (MA) in FDTR, a fusion-driven transmutation reactor based on the ST configuration, with a small size, a molten salt (Flibe) transmutation blanket and a low neutron wall loading (<1 MW/m^2).

2. Model and Parameters

2.1. Reference Design

A fusion-driven waste transmutation reactor based on the ST concept, FDTR, is to be used for the transmutation of MA nuclear waste. The main design parameters for the transmutation calculation are given in Table 1. The 1-D transmutation blanket structure applied in the transmutation calculation is presented in Table 2. In the FDTR concept design, 316-type stainless steel was chosen as the first wall and blanket structure material. The Flibe molten salt was chosen as the blanket medium due to several advantages over solid blanket materials. The blanket structure is characterized by a 40 cm thick trans-

Table 1. Parameters of the FDTR reference design

Plasma major radius (m)	1.04
Plasma minor radius (m)	0.80
Aspect ratio (A)	1.30
Neutron wall loading (MW/m^2)	0.80
Fusion power (MW)	85
Transmutation zone thickness (cm)	40
Structural material	316SS
Blanket power (MW)	1942
Coolant material	Flibe
MA inventory (a% in Flibe)	0.9

Table 2. 1-D blanket model of FDTR

Zones	Thickness, cm	Materials
Plasma	80	
First wall	0.5	316SS 100%
Transmutation zone	40	316SS 10% MA (1a% in Flibe) Flibe 90%
Second wall	0.5	316SS 100%
T breeding zone	10	316SS 5% $LiAlO_2$ 90% He 5%
Third wall	0.6	316SS 100%
Reflector	20	316SS 60% He 40%
Shielding	30	316SS 30% B_4C 30% H_2O 40%

mutation zone with 1a% MA by volume and a tritium breeding zone of 10 cm thickness. In the FDTR design, the inboard blanket does not contain the MA material. The average coverage of the outboard blanket is 60%. Solid $LiAlO_2$ was chosen as the tritium breeder in the tritium-breeding zone. The geometric configuration of the FDTR is shown in Fig. 1

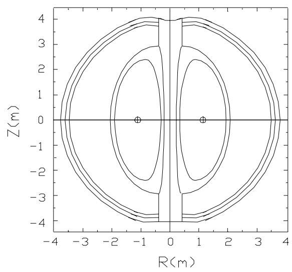

FIG. 1. Schematic of geometric configuration of FDTR

2.2. Code and Data Library

A modified version of the 1-D neutron transport and burn-up calculation code, BISON1.5 [4], was used for the neutronics calculation and depletion analyses. To match the modified BISON1.5, a new data library, BISON58, with 46n+26γ energy group structures and P-3 Legendre scattering order was compiled. Some of the neutron cross-section data required by the BISON1.5 code were prepared from the ANL-67 library. Other cross-section and decay data were derived from the evaluated cross-section actinides library based on the ENDF/B-V. In order to process the neutron cross-section data, the Total Cross-section Probability (TCP) code system was applied. The input and output formats of the main program of BISON1.5 have also been modified. The modified code is called BISON3.0.

In order to obtain the spatial distribution of neutron flux, energy multiplication M and tritium breeding ratio TBR, a 2-D diffusion-accelerated neutral-particle transport code, TWODANT [5], is used to calculate the distribution of neutron wall loading at the first wall and the neutron multiplication of the transmutation blanket. The composition and half-life of MA from pressurized water reactor (PWR) spent fuel and the initial loading (IL) in the FDTR conceptual design are illustrated in Table 3. The initial inventories of MA in the transmutation zone were derived from the composition of PWR spent fuel except for ^{239}Pu. ^{239}Pu was chosen as the neutron multiplication material to obtain a higher neutron flux and transmutation rate. A reasonable Pu concentration in the transmutation zone could obviously improve the transmutation rate of the system.

Table 3. Composition of MA in spent fuel

Nuclides	Kg / GWe	Half-life, yr	IL, kg
^{237}Np	20.4	2.10+6[b]	159.8
^{241}Am	1.32	4.33+2	150.8
^{243}Am	2.48	7.38+3	27.2
^{244}Cm	0.911	1.76+1	52.1
^{238}Pu	5.99	8.60+1	487.8
^{239}Pu	144	2.40+4	1809
^{249}Pu	59.1	6.58+3	232.0
^{241}Pu	27.7	1.42+1	272.2
^{242}Pu	9.65	1.42+1	272.2
Total	271.6	-	3359.1

[a] a+b means $a\times10^b$

3. Results and Discussion

3.1. Constraints and Optimization

The key problem in neutronics design is to obtain a higher transmutation rate through an appropriate blanket arrangement. The optimization of and constraints on the relevant system parameters were investigated. These include a first wall neutron power loading of < 1 MW/m^2, a peak power density of the transmutation blanket of <200 W/cm^3, an effective neutron multiplication factor K_{eff} < 0.9 and a tritium breeding ratio of >1.10. Because of the solubility of the transuranic (TRU) actinides in the molten salt, the concentration of the MA must be considered carefully.

3.2. Neutronics Performances

The distribution of neutron wall loading on the inboard blanket (IB) and outboard blanket (OB) is presented in Fig. 2. As seen in this figure, the neutron wall loading differs greatly with the position of the first wall. It was found that the neutron multiplication, K_{eff}, is clearly reduced, from 0.83 to 0.81, in the 2-D MCNP calculation. Thus, the spatial effects must be considered in transmutation calculations. The results have taken the volume effect into account. The neutron energy spectrum of the first wall is shown in Fig. 3. The calculations of the neutron energy spectrum and the distribution of wall loading for the first wall were performed using the TWODANT code.

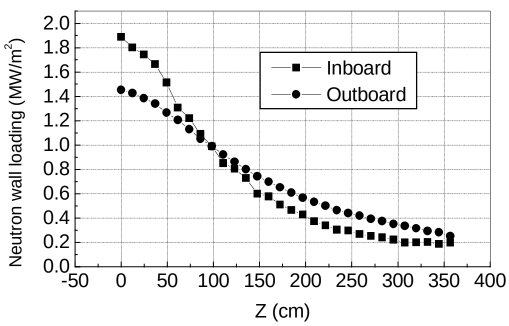

FIG. 2.Distribution of wall loading on the IB and OB

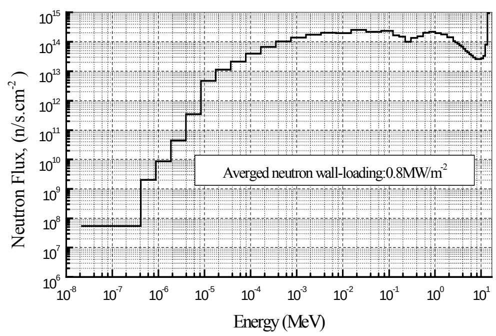

FIG. 3.The neutron spectrum on the FW

The main results of the neutronics calculation for the transmutation blanket based on the output of BISON are listed in Tables 4 and 5. It is shown that the effective transmutation rate (TR) for ^{237}Np, ^{239}Pu and ^{242}Am are 5.62%, 5.27% and 11.2%, respectively. The tritium breeding ratio (TBR), the energy multiplication (M) and the effective neutron multiplication factor (K_{eff}) have also been investigated. These calculation results as a function of the irradiation times are depicted in Fig. 4.

From Fig. 4, we can see that, with the accumulation of irradiation times, the system performances of TBR, M and K_{eff} are considerably reduced. In order to meet the design performances of the system, the inventories of MA in the transmutation blanket should be charged constantly. Two types of MA charging should be considered: 1) continuous charging, and 2) periodic charging (e.g. with a 300 days cycle).

Table 4. Neutronics performances of the blanket

Parameters	IB	OB
Energy multiplication, M	0.83	37.9
Tritium breeding rate. TBR	-	1.28
Max. power density, W/cm^3	12.3	133
Neutron multiplication, K_{eff}	-	0.83
Total fission rate, $F_{(n,f)}$	-	2.73
Total transmutation rate, $T_{(n,\gamma)}$	-	2.90

Table 5. Depletion rate of MA nuclides

T, yr	1	3	5	TR, %/yr
^{237}Np	2.776-5	2.238-5	1.900-5	5.62
^{239}Pu	3.227-4	2.635-4	2.261-4	5.27
^{240}Pu	1.880-4	1.934-4	1.940-4	-0.96
^{242}Pu	3.635-5	3.681-5	3.700-5	-0.38
^{241}Am	3.289-5	3.005-5	2.914-5	2.81
^{242}Am	3.352-6	2.106-6	1.550-6	11.20
^{244}Cm	1.256-5	1.115-5	1.069-5	2.31
F.P.	5.512-5	1.307-4	1.758-4	-12.59

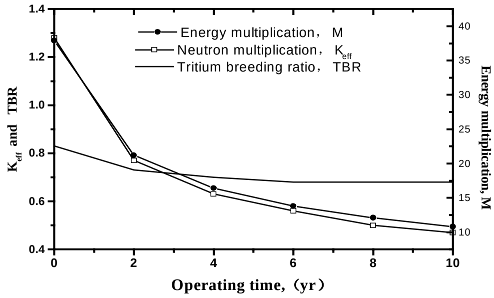

FIG. 4. TBR, M and K_{eff} as a function of the operating time

The neutron energy spectrum of the first wall is shown in Fig. 3. In order to effectively transmute the MA, a fast neutron spectrum of the blanket is required in the neutronics design. The neutronics performances of the 1-D transmutation blanket are presented in Table 4. It is found that the peak power density of the blanket zone is only 133 W/cm^3, which is not high compared with that of fission reactors, PWRs or fast breeder reactors (FBRs). The maximum peak power density of the blanket zone occurs near the first wall.

3.3. Power Density Distribution

The power density distribution as a function of the transmutation blanket thickness is shown in Fig. 5. It can be seen that the power density distribution exhibits a linear variance in the transmutation blanket zone. It was found that the specific power is proportional to the depletion rate of the MA nuclides; therefore its increment means an increment of the depletion rate. In order to obtain a uniform distribution of power density, an optimized arrangement for ^{239}Pu concentration should be considered. The inventory of ^{240}Pu and ^{242}Pu increases slowly, owing to the contribution of the ^{239}Pu (n, γ) reaction.

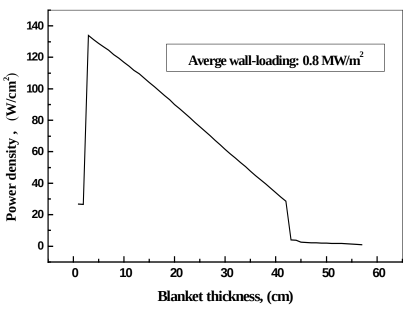

FIG 5. Power density distribution of the blanket

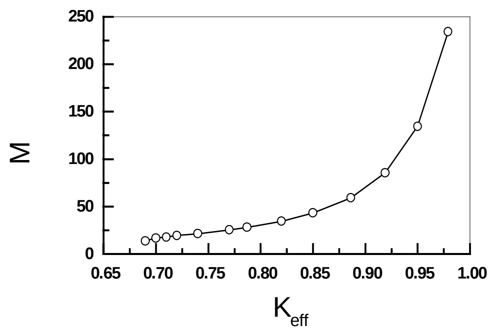

FIG. 6. M as a function of K_{eff} in the blanket

The depletion rate of the MA nuclides as a function of the operating time is displayed in Table 5. The energy multiplication M as a function of the neutron multiplication factor K_{eff} has also been investigated, and the results are given in 6. We can see that M increases quickly with the neutron multiplication factor K_{eff}. It was found that the annual transmutation amount of MA transmuted is about 110 kg with 85 MW of fusion power and an availability factor of 0.75.

3.4. Nuclear Analysis of the Center-post

The center-post (CP) is an important component in an ST tokamak device. The 2-D nuclear analysis model of the CP is shown in the Fig. 1. Preliminary neutronics calculations of the CP for the reference design have been carried out using the coupled neutron, electron and gamma 3-D time-dependent MC transport calculation code MCNP/4B [6]. It is found that the maximum neutron flux is 8.09×10^{14} n/s/sec.cm^2 at the mid-plane of the CP.

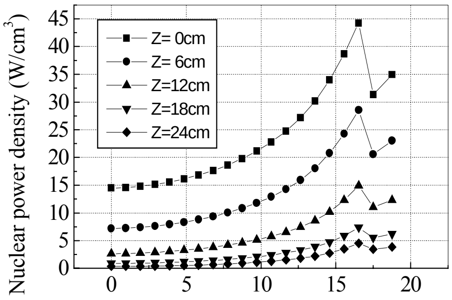

FIG. 7. Radial distribution of power density

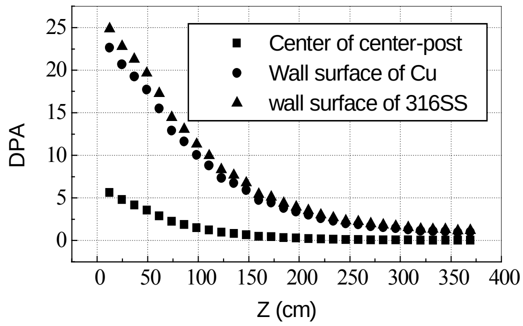

FIG. 8. Axial distribution of dpa of the CP

According to the calculation results, the maximum power density at the CP surface is 44.23 W/cm^3, which is 3.1 times the CP central power density. The axial distribution of the atomic displacement rate (dpa) of the CP at different positions is shown in Fig. 8. It is found that the maximum dpa at the axial position is 22.65 dpa (for 1 PFY). This is one fourth of the CP central atomic displacement rate. From the neutronics calculation results, the maximum radiation damage occurs at mid-plane of the CP, and the effective radiation life of the CP can meet the engineering requirements.

4. Summary

A preliminary neutronics design and analysis of a transmutation blanket based on an ST tokamak reactor, FDTR, has been completed. The engineering feasibility of the center-post of the ST waste burner has been investigated, and the results have been presented. It has been shown that the proposed system has a high transmutation capability of 390 kg for MA waste. The neutronics performances of the system can meet the design requirements. The results shown that a small-scale, compact and low fusion power tokamak, based on an ST configuration has attractive advantages if it is used as a nuclear waste burner.

References

[1] E.T. Cheng, Transmutation of nuclear waste in fusion reactors, Proc. Int. Conf. On Future Nuclear Systems: Emerging Fuel Cycles and Waste Disposal Options, Seattle, Washington, 1993.
[2] Y.-K. M. Peng, E.T. Cheng, Magnetic fusion driven transmutation of nuclear waste (FTW), J. Fusion Energy 12 (1993) 381.
[3] R.D. Stambaugh, Spherical torus pathway to fusion power, J. Fusion Energy 17,No.1, (1998).
[4] K. Furata, Y. Oka, S. Kondo, CCC-464, RSIC Computer Code Collection, Oak Ridge National Laboratory (1987).
[5] R. Odell et al., Los Alamos National Laboratory Rep. LA-10049M, Rev. 1 (1984).
[6] J. Briesmeister et al., MCNP-4B, A Monte Carlo Neutron and Photon Transport Code, Los Alamos National Laboratory Rep. LA-7396-M (1997).