NEUTRONICS STUDY ON TRANSMUTATION BLANKET OF FUSION-FISSION HYBRID REACTOR

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ABSTRACT

The neutronics characteristics of MA (Minor Actinides) and FP (Fission Products) transmutation in Spherical Tokamak Fusion-Fission hybrid reactor are calculated with BISON-C code on the basis of Tokmak parameter level achieved or to be achieved in the near future. Some initial results about the effect of the loading amount and pattern of MA and FP on the transmutation rate and the blanket subcritical lever which are valuable to blanket design are given.

1. INTRODUCTION

One of the most important obstacles to the development of nuclear energy is the radioactive waste from nuclear power plant. According to the investigation of the IAEA, the High-Level Wastes (HLW) of the world are increasing by 3800 m^3 per year since 1995. After disposal, the spent fuel of Light Water Reactors (LWR) still includes large amount of long-lived radioactive Minor Actinides (MA) and Fission Products (FP). Some nuclides of them have an about 10^6 years long half-life. How to transmute the large amount of MA and FP is becoming the major concern of international nuclear area. Since 1990s, two main means for transmutation have been paid more attention to. One is the Accelerator Driven System (ADS), and the other is the Tokmak fusion-fission hybrid reactor.

Several decades of research work have made the Tokmak fusion-fission hybrid reactor (especially neutron multipliers are added) show very attractive advantage in transmuting MA and FP[1-4]. In reference [5], a compact Low Aspect Ratio (LAR) Tokmak transmutation reactor was designed with a large energy multiplication M (10~100), a high transmutation efficiency and a low neutron wall loading (0.5MW/m^2). Some researchers have studied on the neutronics character of transmutation blanket by using the one-dimensional transport and burn-up calculation code BISON1.5[5-7]. But BISON1.5 can't do the FP transmutation calculation, so the FP transmutation calculation model should be encoded by researcher-self.

To meet the need of the depletion calculation of MA and FP transmutation, the code BISON-C (a modified version of the code BISON1.5) was developed by Jerzy Centnar and Piotr Gronek in 1997.[8] It is programmed specially to the transport and depletion calculation for source driven subcritical system. Compared to BISON1.5, BISON-C contains precise decay chains and data library of MA and FP and adopts fewer burn-up steps so that the error brought by BETAMEN method can be decreased. Data library of BISON-C includes P-5 Scattering Order transport cross section of 60 kinds of nuclide in 42 energy group structures. The cross section, decay chains and decay constant of 22 kinds of actinides are included too. The cross section of FP is derived from ENDFB/VI, and the others nuclide from JENDL-3.

This paper is aimed to study the neutronics character of MA and FP transmutation blanket in the Low Aspect Ration Spherical Tokmak (LAR-ST) fusion-fission hybrid reactors[9] by using BISON-C code. The impact of the loading amount and pattern of MA and FP on the transmutation rate and the blanket sub-critical lever is studied to provided some valuable results for the design of hybrid reactor blanket. The parameters of accelerator, plasma and fusion device used in this paper are taken granted by many references[5-7,10] and can be reached in the near future[11-13]. So some discusses about these parameters are not included in this paper.

The remainder of this paper is organized as follows. In Sec. 2, the model of the LAR-ST is described. In Sec. 3 and Sec. 4, the influence of the loading amount of Pu, MA and FP in transmutation blanket on the transmutation rate is calculated and analyzed. The loading pattern of the blanket is optimized to obtain a higher transmutation rate and a safety margin in Sec. 5. Then some initial conclusions which are useful to blanket design are given in Sec. 6.

2. MODEL OF THE LAR-ST

After consulting other researchers' investigation and research result, we chose the dual-cooled blanket system (liquid LiPb and He)[4] to study the neutronics characteristics of MA and FP transmutation on the base of Tokmak parameter level achieved or to be achieved in the near future. The one-dimensional blanket structure, radial dimension and material composition of volume fraction are shown in Fig.1. The neutron loading of the first wall is 1.0WM/m^2. Two kinds of coolant are included in the blanket, liquid LiPb in the MA transmutation zone and high-pressured He in the first wall and FP transmutation zone. The maximum power density is 500W/cm^3.

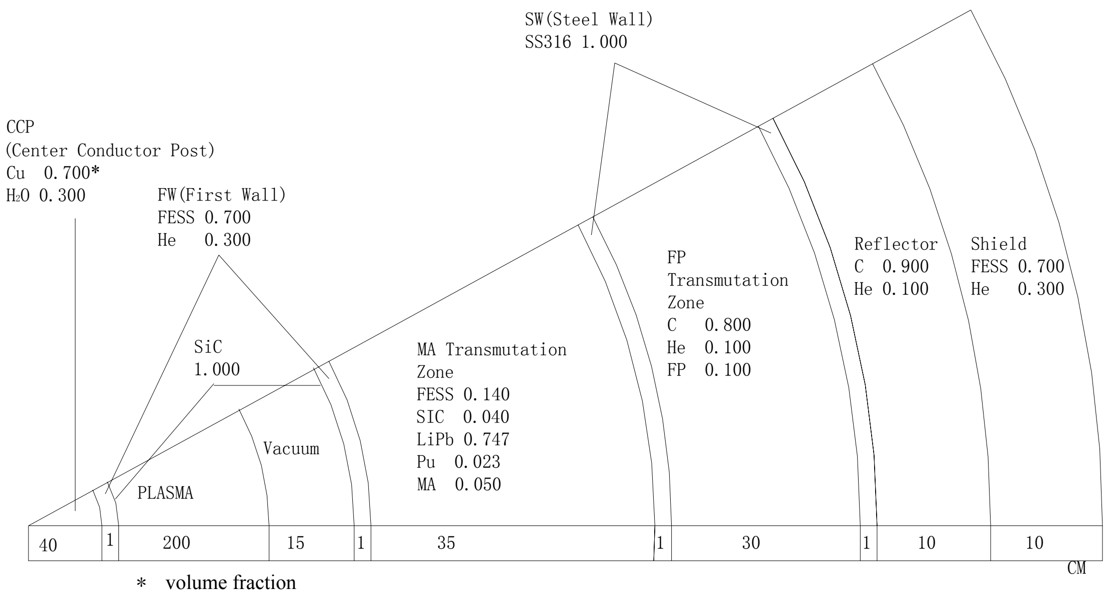


Fig. 1. Radial scheme and material composition of blanket

The composition of MA is based on the spent fuel that unloaded from PWR at 35GWd/t exposure and cooled for 5 years. The percentage of various nuclei are as follow: 49.2%Np237, 30.0%Am241, 15.5%Am243, 0.05%Cm243, 5%Cm244, 0.25%Cm245. The composition of Pu is: 56.0%Pu239, 24.4%Pu240, 12.2%Pu241, 7.4%Pu242. The composition of FP is: 8.7%Cs135, 27%Cs137, 21.8%Tc99, 5.2%I129, 11.3%Sr90, 19.8%Zr93, 6.1%Pd107.

3. MA TRANSMUTATION CALCULATION

In this section, the influence of some important parameters of the blanket to the MA transmutation is discussed. Suppose that the material composition of the MA transmutation zone showed in Fig.1 is homogeneous. Change one of the parameters while the others are kept as constant.

3.1 The influence of Pu concentration to MA transmutation

The initial loading concentration of Pu is changed by diluting, keeping the volume fraction of Pu in the blanket be fixed. So the actual loading amount of Pu is the product of Pu concentration and its volume fraction. Through calculation, the relative burnup of MA and Pu after 450 days is changed according the Pu concentration in a tendency as shown in Fig.2. We defined the relative burnup as the proportion of the amount of transmuted nuclei to total loaded nuclei here.

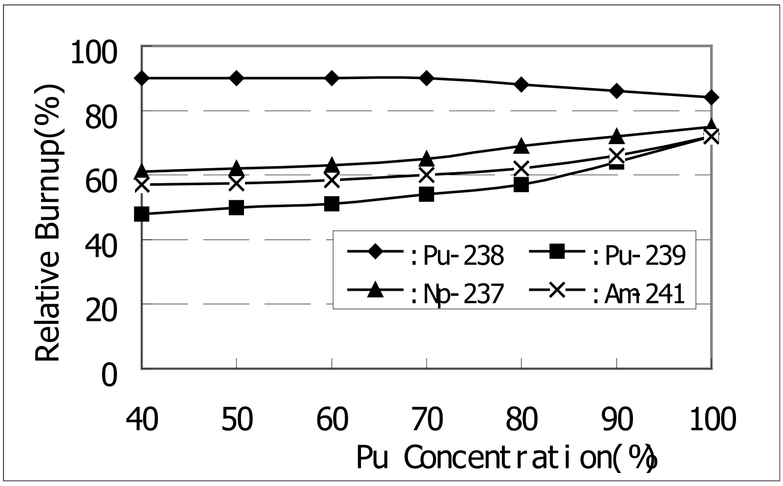


Fig.2 Relationship between Pu concentration and burnup of MA and Pu

According to Fig.2, the transmutation rate of MA increases with the increase of Pu concentration. But according to Fig.3, the initial Keff of the blanket also increases greatly because Pu includes large amount of fissile nuclei Pu^{239}. So the Pu concentration should better to be 100%, i.e. the actual fraction of Pu in the MA transmutation area should be 2.3% in this example(Fig.1), in order to ensure the blanket in this example is sub-critical while the MA transmutation rate is high.

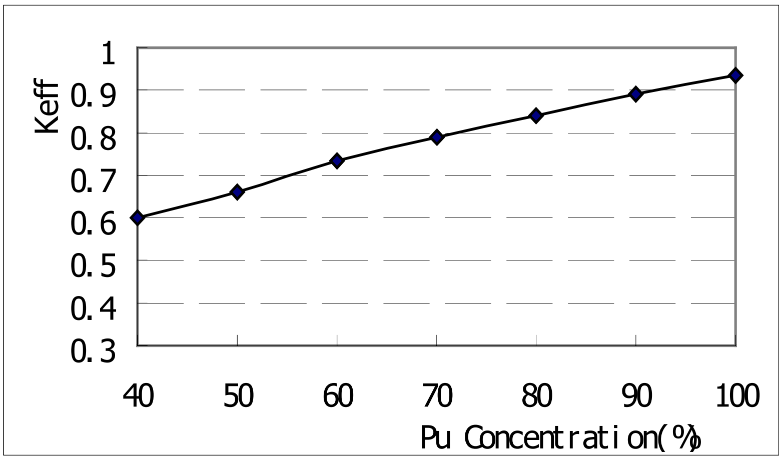


Fig.3 Influence of Pu concentration to blanket initial Keff

3.2 Influence of MA concentration to initial Keff of blanket

Keeping the concentration of Pu unchanged, we change the concentration of MA in MA transmutation zone. After calculation, we get the relationship between the concentration of MA and the initial Keff of the blanket as shown in Fig.4. From the figure, we can see that the contribution of MA to blanket reactivity varies from negative to positive. It is because some nuclei of MA are fissile. On the other hand, the concentration of MA should be high in order to achieve high transmutation efficiency. So it is advised the concentration of MA in this example is 100% to ensure the blanket is sub-critical while the MA transmutation rate is high. So the actual volume fraction of MA in blanket is chosen as 5%.

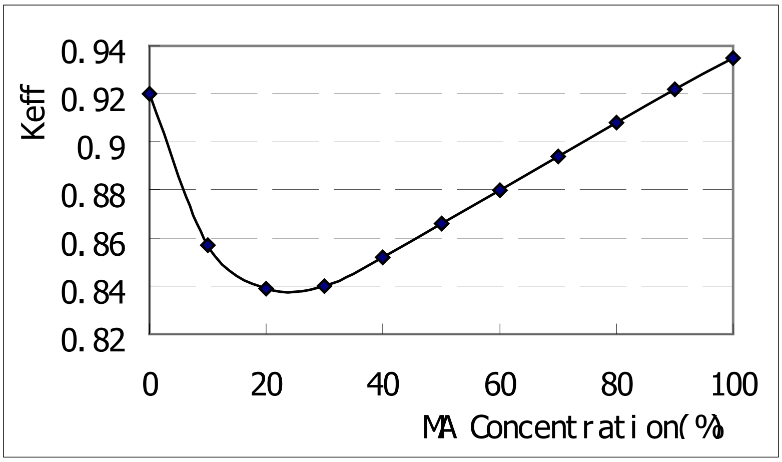


Fig.4 Influence of MA concentration to initial Keff of blanket

4. FP TRANSMUTATION CALCULATION

As the transmutation of FP mainly depends on the capture reaction of thermal neutron, the FP transmutation zone is arranged at the outside of the blanket and some graphite is applied as moderator.

In this section, we change one of the parameters in FP transmutation zone shown in Fig.1 and keep the others as constant to analysis the influence of these changed parameters to the FP transmutation.

4.1 Influence of Pu concentration to FP transmutation rate

The similar calculation as described in Sec.3.1 is performed to get the relationship between Pu concentration to FP transmutation rate. The result is showed in Fig.5. It can be seen that the FP transmutation rate increases greatly when the Pu concentration increases. This is consistent with the conclusion we get in Sec.3.1 for the influence of Pu concentration to MA transmutation rate. So the concentration of Pu should be 100% to achieve the highest FP transmutation rate while the blanket is sub-critical.

4.2 Influence of FP concentration to FP transmutation rate

By varying the volume fraction of FP in FP transmutation zone, the FP loading amount is changed. The results in Fig.6 show the FP transmutation rate and the initial Keff of blanket vary with the increasing of FP loading amount. When the FP loading amount increases, the FP transmutation rate increases firstly and then has a tendency of decrease. This is induced by the following fact. When the volume fraction of FP increases to a certain level, the volume fraction of graphite will decrease and the neutron spectrum will be harder. This will reduces the FP transmutation. So the volume fraction of FP in blanket should better to be 10%~15%. From this figure, we can also see that the negative contribution of FP to initial Keff of blanket is changed linearly. So the best volume fraction of FP should be 10% in this blanket.

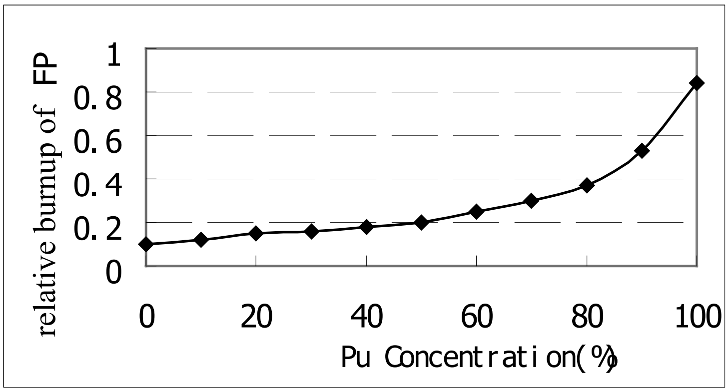


Fig.5 Influence of Pu concentration to burnup of FP

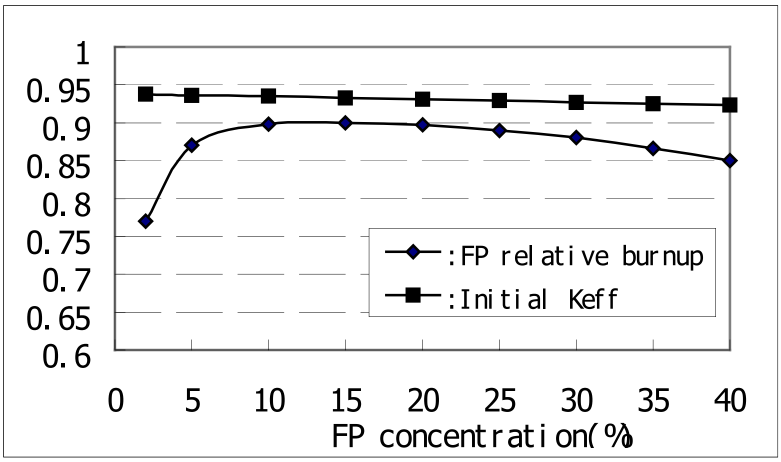
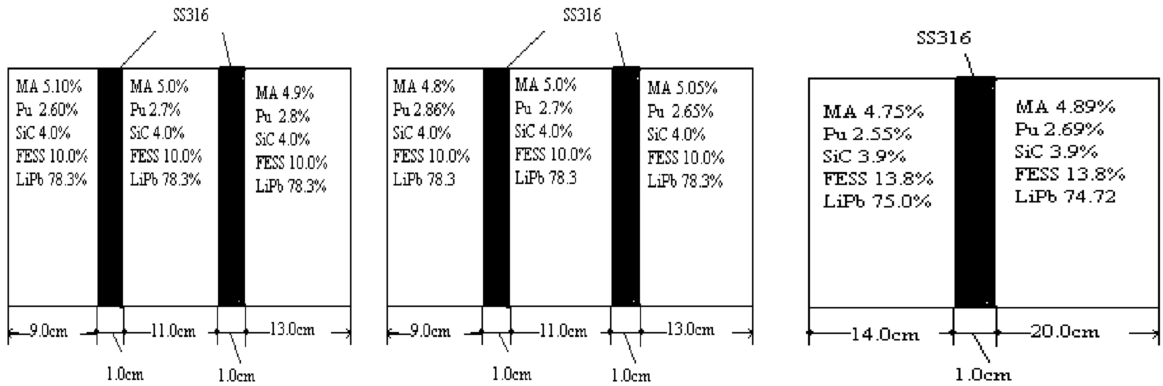


Fig.6 Influence of FP loading to Keff and Burnup of FP

5. HETEROGENEOUS LOADING OF MA TRANSMUTATION ZONE

In Sec. 3, an assumption was made that the MA transmutation zone is homogeneous. In fact, the distribution of power density can be much flatter by dividing the MA transmutation area into several sub-region. To study the influence of loading pattern to the system, four cases in different loading pattern of MA transmutation zone are designed. In order to compare with each other, the total loading amount of MA and Pu in the MA transmutation of each case are equal and the parameters of the other zones are kept constant.

The arrangement of case A, case B and case C are showed in Fig.7. Case D is the homogeneous case described in Sec.3.



Case A Case B Case C

Fig.7 the heterogeneous loading pattern of each case

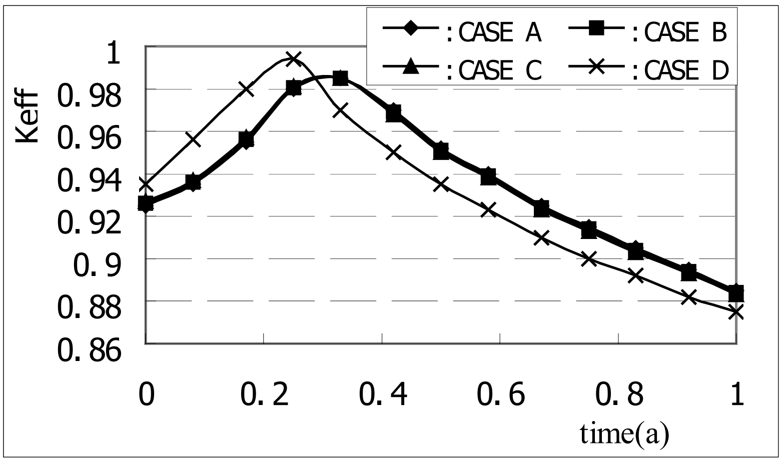


Fig.8 Keff of each case during burnup

5.1 The Keff of blanket

In order to get a steady output power, the Keff of blanket must be steady as the multiplicable factor of power $M \propto \frac{Keff}{1-Keff}$. A steady Keff can also raise the power and transmutation rate of blanket. The varieties of Keff in one year of four cases are given in Fig.8. According to the figure, the variety of Keff during one year is the smallest in heterogeneous case and the largest in homogeneous case.

5.2 The comparison of M

The multiplicable factors M of the four cases varied with time are shown in Fig.9. It is obvious that heterogeneous loading pattern cases can decrease M greatly and raise transmutation ability. Especially, the sway of the power in blanket can be greatly reduced if the fuel is unloaded zone by zone instead of unloaded as a whole. This can improve the efficiency and make the system economic, which is very important to hybrid reactor to be run commercially.

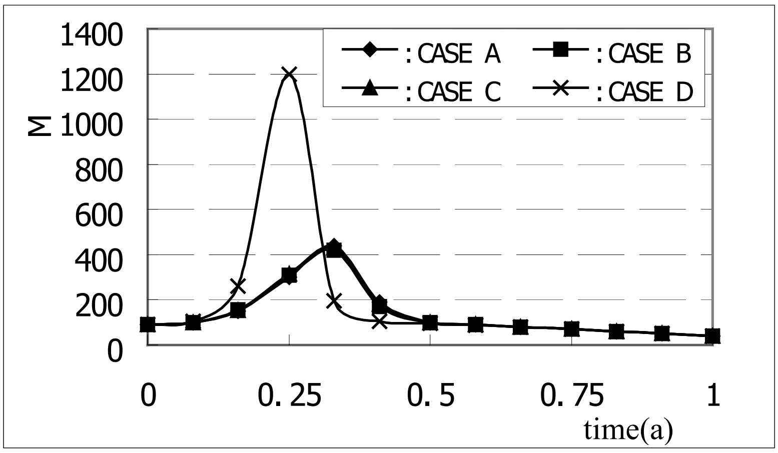


Fig.9 Multiplicable factors of each case during burnup

5.3 the comparison of transmutation ability

The transmuted quality and transmutation efficiency of each case in certain thermal power are shown in Tab.1. The result demonstrates that case A, in which the concentration of MA is arranged degressively, has the best transmutation ability to both FP and MA.

Table 1 MA and FP burnup comparison of each case

	Case A	Case B	Case C	Case D

FP:				
Transmutation rate(/GW)	4.56%	4.45	4.47%	3.72%
Transmutation quality(kg/GW)	745	727	731	608
MA:				
Transmutation rate(/GW)	3.01%	2.96%	2.96%	2.46%
Transmutation quality(kg/GW)	658	647	647	537

6. CONCLUSIONS

According to above calculation and analysis, some conclusions are gained as follows:

1. Increasing the concentration of Pu can not only adjust the initial Keff of the system, but also improve the spectra in blanket and increase the transmutation rate of MA and FP. But the volume fraction of Pu is no more than 2.3% in this system to assure that the system is subcritical.

2. With the increasing of MA loading amount, the contribution of MA to the reactivity varies from negative to positive, so an appropriate MA loading amount (volume fraction 5% in this paper) should be chosen to assure the safety of system.

3. With the increasing of FP loading amount, the transmutation rate of FP increases rapidly and then has a tendency to decrease, so there exist a best loading amount of FP to get the highest FP transmutation rate. According to the calculation, the best volume fraction of FP in FP transmutation zone is 10%~15%.

4. If the heterogeneous loading pattern is adopted and the concentration of MA is arranged degressively in MA transmutation zone, the Keff and energy multiplication can be steadier than homogeneous arrangement case and the transmutation efficiency of MA and FP can be increased by 22.36% and 22.58%.

These conclusions are based on the initial neutronics calculation of the transmutation blanket. It's useful to the design of fusion-fission hybrid reactor transmutation blanket. Some other factors, such as thermal-hydraulic, structure material and safety factor should be considered in more details in the future work.

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