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Neutronics analysis of minor actinides transmutation in a fusion-driven subcritical system

Chao Yang, Liangzhi Cao, Hongchun Wu, Youqi Zheng*, Tiejun Zu

School of Nuclear Science and Technology, Xi'an Jiaotong University, Xi'an 710049, China

HIGHLIGHTS

- A fusion fission hybrid system for MA transmutation is proposed.
- The analysis of neutronics effects on the transmutation is performed.
- The transmutation rate of MA reaches 86.5% by 25 times of recycling.

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ABSTRACT

The minor actinides (MAs) transmutation in a fusion-driven subcritical system is analyzed in this paper. The subcritical reactor is driven by a tokamak D-T fusion device with relatively easily achieved plasma parameters and tokamak technologies. The MAs discharged from the light water reactor (LWR) are loaded in transmutation zone. Sodium is used as the coolant. The mass percentage of the reprocessed plutonium (Pu) in the fuel is raised from 0 to 48% and stepped by 12% to determine its effect on the MAs transmutation. The lesser the Pu is loaded, the larger the MAs transmutation rate is, but the smaller the energy multiplication factor is. The neutronics analysis of two loading patterns is performed and compared. The loading pattern where the mass percentage of Pu in two regions is 15% and 32.9% respectively is conducive to the improvement of the transmutation fraction within the limits of burn-up. The final transmutation fraction of MAs can reach 17.8% after five years of irradiation. The multiple recycling is investigated. The transmutation fraction of MAs can reach about 61.8% after six times of recycling, and goes up to about 86.5% after 25.

1. Introduction

Fission reactors have been generating a large amount of MAs (Np, Am, Cm) and fission products (FPs). At present, approximately 10,000 t of spent fuel, containing about 100 t of Pu and 14 t of MAs, are being produced annually in the world [1]. High-level radioactive nuclear waste has become one of the most important restrictions to the development of fission power. Therefore, the transmutation of nuclear waste has become an international hotspot issue. The radio-toxicity inventory can be reduced by a factor of 10 if all of the Pu discharged from LWR can be recycled and burned. A reduction factor higher than 100 can be obtained if the MAs are burned [2]. Investigations on the transmutation of MAs in different types of reactors have been done during the past decade. Most papers claimed that fast neutron is more attractive for the transmutation of long-lived actinides [2–5]. Because the majority of MAs have a larger capture-to-fission cross section ratio in a thermal neutron spectrum, MAs are mainly transmuted by the (n, γ) reaction in the thermal reactor. But the transmutation products are still actinides, even heavier isotopes. However, the neutron capture-to-fission cross section ratio for MAs greatly decreases in a fast neutron spectrum. From neutron economy point of view, this implies that the fast neutron systems are more efficient in destroying MAs. Furthermore, the fission cross-sections of most isotopes of Am and Cm are of the threshold type, so the harder the spectra is, the better it is for the fission of these isotopes. In a critical fast neutron reactor, isotope ^{238}U needs to be loaded to provide a negative reactivity coefficient for reactor safety. The destruction of MAs would be canceled out by the neutron capture of ^{238}U. In addition, the transmutation mass of MAs is also limited by the loading mass for reactor safety. Both limits can be relaxed if the reactor is operated in subcritical mode. A neutron source is needed to continuously maintain the neutron chain reaction for a subcritical system. In this paper, the fusion neutron is selected based on the following considerations:

(1) The energy of neutrons released by fusion reaction is 14.1 MeV, which brings a very hard neutron spectrum.

* Corresponding author at: School of Nuclear Science and Technology, Xi'an Jiaotong University, 28 Xianning West Road, Xi'an 710049, China.
Tel.: +86 29 8266 3285; fax: +86 29 8266 8916.
E-mail address: yqzheng@mail.xjtu.edu.cn (Y. Zheng).

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(2) Based on the existing tokamak physics and fusion technology, a tokamak D-T fusion device could provide a strong neutron source (1 MW fusion power corresponds to $\sim 4 \times 10^{17}$ n/s [6]).

Based on these two considerations, fusion-driven subcritical system is studied in this paper. In the recent decades, a series of fusion-driven transmutation systems have been proposed.

Several conceptual designs of the transmutation reactors driven by the tokamak D-T fusion neutron source were put forward at Georgia Institute of Technology during the past years [7–11]. In these studies it was showed that one subcritical system can annually burn the transuranics (TRU) extracted from 3 to 5 1000 MWe LWRs, and one subcritical system with a smaller K_{eff} can also provide much greater fuel cycle flexibility. A fusion-driven reactor with a molten salt (Flibe) blanket studied by Ridikas can annually burn 1.1 metric tonnes of TRU with an output of 3 GW_{th} fission power [12,13]. Wu et al. proposed the conceptual design of FDS-I for the transmutation of long-live nuclear wastes, and the He-gas and liquid lithium–lead are used as coolant [14–16]. Yapici investigated the transmutation of MAs discharged from high burnup PWR-MOX spent fuel in the force free helical reactor under a neutron wall loading of 1.5 MW/m^2, and also studied the transmutation potential of TRU discharged from PWR-UO_2 spent fuel in modified PROMETHEUS fusion reactor under a neutron wall loading of 4.7 MW/m^2[17,18]. The transmutation of MAs discharged from LMFBR spent fuel in a high power density fusion reactor under a neutron wall loading of 10 MW/m^2 was studied by Ubeyli [19]. It was clearly showed that using higher neutron wall loading increased the burnup levels and decreased the effective half-lives of MAs. Most of the above-mentioned designs focused on the transmutation of TRU based on a small fusion neutron source. A large energy multiplication factor (M) can be obtained in these designs due to heavy loading of Pu. Therefore, only a relatively less neutron wall loading is required to achieve a certain relatively large output power. However, the designs with the goal of transmutation of MAs were based on a relatively high neutron wall loading, which would shorten the lifetime of the first wall and structure material due to the radiation damage limitation of material.

International Thermonuclear Experimental Reactor (ITER), currently under construction in the south of France, aims to demonstrate that fusion is an energy source of the future, which has been designed to generate a fusion power of about 500 MW. This paper focuses on the analysis of MAs transmutation in a fusion-driven subcritical system based on relatively easily achieved plasma parameters and tokamak technologies. The fusion power is less than 200 MW in this study. The first neutron wall loading is less than 1 MW/m^2, which is generally accepted in designing a fusion driven hybrid reactor.

In this paper, a conceptual design of a subcritical reactor with low level first neutron wall loading is proposed. The 'D-shape' model for simulating the plasma zone of a typical tokamak D-T fusion neutron source is chosen. The fuel zone in fission blanket is loaded with 60 (MAs–Pu)–40 Zr metal fuel. Sodium is used as the coolant referring from the previous studies by Stacey et al. [10]. Li_4SiO_4 with 60% enriched ^6Li is used as the tritium breeding material. The different percentage of the reprocessed plutonium in the metal fuel is studied to determine its effect on the MAs transmutation. The MAs transmutation rate decreases with the increasing fraction of plutonium. Two loading patterns are analyzed and compared. The loading pattern which the mass percentage of Pu in two regions are 15% and 32.9% respectively is conducive to the improvement of the transmutation fraction within the limits of burnup. Multiple recycling is analyzed based on the current reprocessing technology. The fission products are partitioned from the spent fuel of each cycle by the high temperature reprocessing, and the rest of heavy nuclides are recycled. For each recycling, only new MAs are added.

Table 1
Fusion parameters and design requirements of the subcritical system.

Parameters	Values
Major radius (m)	3.0
Minor radius (m)	0.75
Plasma elongation	1.7
Fusion power (MW_{th})	<200
Thermal power (MW)	1500
First neutron wall loading (MW/m^2)	<1
Tritium breeding ratio	≥1.05
Energy amplification factor	≥10

The organization of this paper is as follows: the fusion parameters and major parameters of fission blanket are given in Section 2, together with the computational methods for evaluation. Numerical results and analysis are presented in Section 3. Finally, conclusions are provided in Section 4.

2. Calculation model

2.1. Major parameters of the fusion and fission devices

The entire system consists of a tokamak D-T fusion neutron source and two types of blankets (inboard blanket and outboard blanket). This study focuses on the neutronics analysis of the transmutation blanket. The plasma physics itself and engineering technology of fusion reactor design are referred from the previous study [7]. Some main parameters are listed as follows: the plasma current (I_p) is 7.0 MA, the magnetic field (B_0) is 6.1 T and the normalized beta (β_N) is 2.5, and so on. But the fusion power is extrapolated to 200 MW_{th} from 150 MW_{th} in this study. The fusion neutron in the "D-shape" plasma zone is simulated as a volumertric and monoenergetic 14.1 MeV neutron source, the distribution of the fusion neutron is uniform. The main parameters and design requirements of the subcritical transmutation system are shown in Table 1. Special issues are required including:

- The fusion power is less than 200 MW to ensure that the first neutron wall loading (Γ_n) is less than 1 MW/m^2 as generally accepted in designing a fusion driven hybrid reactor.
- The energy multiplication factor (M) should be larger than 10 to achieve a stable output power of 1500 MW_{th}.
- Considering the operating loss, the *TBR* must be greater than 1.05 (5% loss) to ensure that tritium is self-sustained in the entire system [18].

Around the plasma ring, 24 pairs of inboard and outboard blankets are arranged as sketched in Fig. 1(b). All results of neutronics analysis are performed based on one pair of inboard and outboard blanket in this study. The calculation model is illustrated in Fig. 1. The plasma zone is surrounded by an elliptic outboard blanket and a columned inboard blanket. The outboard blanket is divided into four regions, namely the transmutation, tritium breeding, reflector and shielding zones. The inboard blanket only contains the reflector and shielding zones. The total thickness of the outboard blanket is 1.014 m, and the inboard blanket is 0.58 m. The detailed dimensions and materials in the blanket are listed in Table 2.

Along the radial direction, the transmutation zone is divided into two regions, and the detailed layout of the assemblies and the cross-section view of the assembly are shown in Fig. 2. The coolant flows horizontally within each assembly as shown in Fig. 1(b). The detailed dimensions and parameters of assembly are given in Table 3.

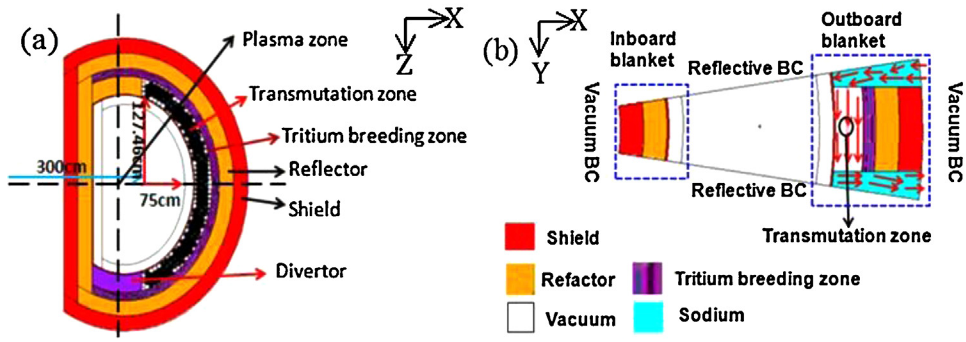

Fig. 1. Calculation model of the subcritical reactor.

Table 2
Material composition and the size of the subcritical blanket.

	Materials and volume (%)	Radial thickness (mm)
Outboard blanket		
The first wall	SS304 (80) + Na (20)	20
Transmutation zone	TRU (43.2) + Na (45.9) + SS304 (10.9)	260
Structural material	SS304 (80) + Na (20)	10
Tritium breeding zone	Li_2SiO_4 (70) + Na (30)	164
Reflector	SS304 (80) + Na (20)	60
Shielding	W-5Re (40) + B_4C (40) + Na(20)	500
Inboard blanket		
The first wall	SS304 (80) + Na (20)	20
Reflector	SS304 (80) + Na (20)	60
Shielding	W-5Re (40) + B_4C (40) + Na (20)	500

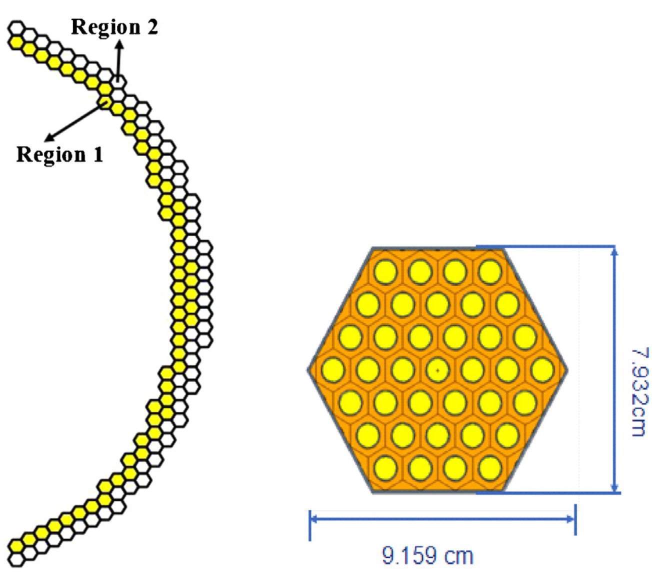

Fig. 2. Layout of fuel assemblies and the cross-section view of the assembly.

Table 3
Design parameters of fuel pin and assembly.

Parameters	Values
Assembly wall thickness (mm)	2
Material of assembly wall	SS304
Assembly pitch (mm)	79.32
Number of assemblies	119
Length of rods (m)	0.78
Fuel pin diameter (mm)	9.40
Composition (wt.%)	60 (MAs–Pu)–40 Zr
Smear density	80% TD
Thickness of cladding (mm)	0.50
Material of clad	SS304
Pitch-to-diameter ratio	1.30
Pins per assembly	37

The transmutation zone is loaded with metal fuel based on the Pu–MAs–Zr system. The metal fuel is selected due to its capability of high burnup, good compatibility with sodium and the pyro-chemical process, high thermal conductivity and low moderation capability [20–22]. In addition, the metal fuel based on the Pu–MAs–Zr system has been successfully irradiated in the experimental fast reactor [22]. In this paper, the mass percentage of zirconium is 40% in the metal fuel referring from the literature [10]. The components of MAs and Pu are given in Table 4 [23].

2.2. Computational methods

All the calculations are carried out by a code package named MCNT/ORIGEN2 [24] which couples a Monte-Carlo transport code and the depletion code ORIGEN2. The former one is used to calculate the neutron flux, cross sections, energy multiplication factor (*M*), and tritium breeding ratio (*TBR*). The latter one is used to perform the depletion calculation based on the updated cross sections,

Table 4
The component of MAs and Pu.

Isotopes	Mass percent (%)
MAs	
^{237}Np	52.81
^{241}Am	20.42
^{242}Am	0.16
^{243}Am	16.32
^{243}Cm	0.06
^{244}Cm	9.38
^{245}Cm	0.69
^{246}Cm	0.16
Pu	
^{238}Pu	3.26
^{239}Pu	55.95
^{240}Pu	32.49
^{241}Pu	1.15
^{242}Pu	7.15

and update the nuclide concentrations for the following transport calculation. Because spatial flux is burnup dependent, the code package uses a predictor–corrector approach to update both the neutron flux and the cross sections as functions of burnup. The computational flow is given in Ref. [25]. The code is applied to the IAEA ADS benchmark [24]. The numerical results show good agreement with those of other participants.

Several key parameters of the subcritical system are evaluated, including the energy multiplication factor (*M*), and the tritium breeding ratio (*TBR*) and the first neutron wall loading (Γ_n).

M is defined as:

$$M = \frac{E_D}{E_S} \quad (1)$$

where E_D is the energy deposition per source neutron in the subcritical blanket (MeV); E_S is the energy of the source neutron (E_S = 14.1 MeV).

TBR is calculated as:

$$TBR = \int_V \int_E \left(\Sigma(n,\alpha)^6\text{Li} + \Sigma(n,n'\alpha)^7\text{Li} \right) \cdot \phi(E)\, dEdV \quad (2)$$

where $\sum_{(n,\alpha)}^{^6\text{Li}}$ and $\sum_{(n,n'\alpha)}^{^7\text{Li}}$ are the macroscopic tritium production cross-sections of ^{6}Li and ^{7}Li, respectively (m^{-1}) [26].

Γ_n is given as:

$$\Gamma_n = \frac{E_s S}{A} \quad (3)$$

where *A* is the surface area of the first wall (m^2); *S* is the intensity of the neutron source (s^{-1}).

Some other parameters are defined to evaluate the transmutation efficiency of the outboard blanket. The MAs' transmutation ability of a subcritical system can be evaluated by using the transmutation rate (*TR*) that is defined as the ratio of the net mass of MAs transmuted to the thermal power produced in the blanket. The mathematical expression of *TR* can be written as follows:

$$TR = \frac{m_1}{P_{th}} \quad (4)$$

where m_1 is the net mass of MAs transmuted annually (kg/yr); P_{th} is the thermal power produced in the blanket (MW).

The transmutation fraction (*TF*) and the support ratio (*SR*) are defined as:

$$TF = \frac{m_N}{m_T} \quad (5)$$

$$SR = \frac{m_1}{m_0} \quad (6)$$

where m_N is the net mass of MAs transmuted during the operation (kg); m_T is the total mass of MAs loaded (kg); m_0 is the mass of MAs produced annually by a 1000 MWe LWR (m_0 = 25 kg/yr) [27].

The fission reaction rate per fusion neutron (R_f) is defined as:

$$R_{f,i} = \frac{\int_V \int_E N_i \cdot \sigma_{f,i}(E) \cdot \phi(E)\, dEdV}{S} \quad (7)$$

$$R_f = \sum_i R_{f,i} \quad (8)$$

where N_i is the density of the relevant isotope *i*; $\sigma_{f,i}$ is the fission microscopic cross section of the relevant isotope *i*; $R_{f,i}$ is the fission reaction rate per fusion neutron of the relevant isotope *i*.

Table 5
The changes of K_{eff}, *M* and *TBR* during the lifetime.

Day	Case 1			Case 2		
	K_{eff}	*M*	*TBR*	K_{eff}	*M*	*TBR*
0	0.762	13.47	1.26	0.754	12.93	1.24
365	0.751	12.77	1.22	0.745	12.33	1.20
730	0.743	12.18	1.19	0.736	11.72	1.16
1095	0.734	11.56	1.15	0.729	11.27	1.14
1460	0.724	11.00	1.12	0.721	10.76	1.11
1825	0.716	10.49	1.09	0.713	10.33	1.09

3. Numerical results and discussion

3.1. Pu mass percentage effect

A certain amount of Pu isotopes extracted from the LWR spent fuel are involved in order to increase the factor *M* and to decrease the fusion power. It is presented in Fig. 3(a) that the fission rate per fusion neutron is improved with the increasing fraction of Pu. Therefore, the value of *M* also increases with the increasing fraction of Pu and the fusion power decreases correspondingly. However, the less the Pu is loaded, the smaller the fluctuation range of fission rate per fusion neutron is, which is very beneficial to achieve a stable output power by adjusting the fusion parameters. In addition, it is shown in Fig. 3(b) that the transmutation rate of MAs decreases with the increasing fraction of Pu, because more plutonium isotopes are transmuted into MAs. In order to ensure a smaller fusion power and higher transmutation rate of MAs during irradiation, the fuel with 24% reprocessed Pu is chosen for transmutation analysis in this study.

3.2. Loading pattern effect

Two loading patterns are investigated, the first one is that the mass percentage of Pu is 24% in two regions; the second one is that the mass percentage of Pu in two regions is 15% and 32.9%, respectively. The final loading masses of MAs and Pu in the two patterns are the same. The masses of MAs and Pu are 1.40×10^4 kg and 9.31×10^3 kg, respectively.

The changes of K_{eff}, *M* and *TBR* during the lifetime are given in Table 5. The value of K_{eff} is significantly smaller than 1, which implies that the criticality safety issue is guaranteed. The value of K_{eff} gradually decreases during the irradiation process. The change is relatively flat, particularly in Case 2. The corresponding *M* is larger than 10 for both of the loading patterns, the value of *TBR* is bigger than 1.05, which means the tritium can be self-sustaining during the operation.

Some other performance parameters of the two loading patterns are given in Table 6. The peaking of fusion power is less than 200 MW, and its fluctuation range is small, which is very beneficial to achieve a stable output power by adjusting the fusion

Table 6
Performance parameters of the two loading patterns.

	Case 1	Case 2
Fusion power (MW)	139.2–178.7	145.0–181.5
Γ_n (MW/m^2)	0.726–0.93	0.757–0.947
Power in BOC for region 1 (MW)	35.1	30.2
Power in BOC for region 2 (MW)	27.4	32.3
Power in EOC for region 1 (MW)	35.0	31.4
Power in EOC for region 2 (MW)	27.5	31.1
Power density in BOC for region 1 (MW m^{-3})	157.9	135.9
Power density in BOC for region 2 (MW m^{-3})	125.4	147.8
Burnup for region 1 (GWd t^{-1})	130.8	117.2
Burnup for region 2 (GWd t^{-1})	104.1	118.1
TF of MAs (%)	17.2	17.8

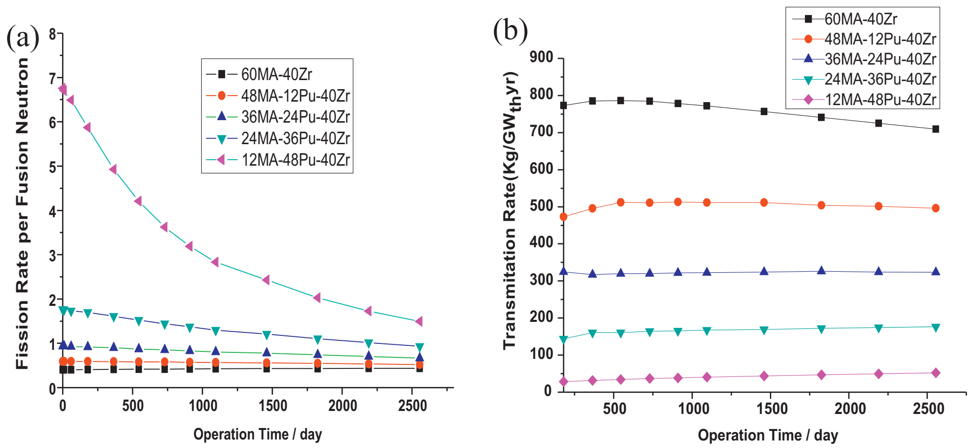

Fig. 3. Temporal variations of the R_f and MAs *TR* for the various Pu fractions.

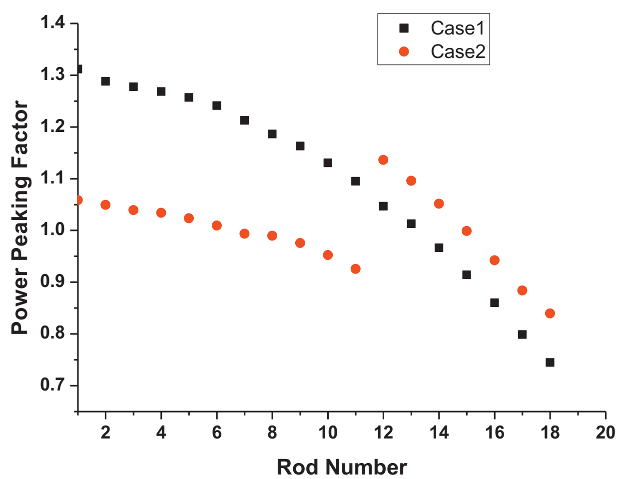

Fig. 4. The power distribution across the fission blanket.

parameters. $\Gamma_n$is less than 1 MW/m^2, which relaxes the material requirement. The power distribution across the reactor core is calculated at the equatorial plane, which is presented in Fig. 4 according to the index of fuel rods as illustrated in Fig. 5. The maximum power peaking factor for Case 1 and Case 2 is 1.31 and 1.14, respectively, arising at the rod position of No. 1 and the rod position of No. 12, respectively.

From the comparison of the two loading patterns, the Case 2 is conducive to the improvement of the MAs transmutation fraction within the limits of burnup. A higher average burnup can be obtained since the flux distribution in the blanket is flatter.

The neutron energy spectra in Case 2 at BOC are shown in Fig. 6. The first wall next to the fusion neutron source has a softer spectrum due to neutrons reflected from the inboard back into the outboard blanket. The spectrum averaged fission-to-capture ratio of different isotopes for the Case 2 at BOC is shown in Fig. 7. It is bigger than 1 for most isotopes. Therefore, MAs are efficiently transmuted by fission reaction.

The mass of main MAs isotopes for the Case 2 at BOC and EOC are shown in Table 7. The *TF* of each nuclide is given. The mass of Curium slowly grows up because of the ^{243}Am (n, γ) ^{244}Am reaction and subsequent β-decay into ^{244}Cm. The ^{238}Pu is quickly built up, because some ^{237}Np is transmuted by the ^{237}Np (n, γ) ^{238}Np reactions and subsequent β-decay into ^{238}Pu. The total mass of ^{237}Np, ^{241}Am, ^{243}Am and ^{244}Cm accounts for about 98.7% in the initial MAs loading, and they are the main objects of transmutation. Their *TF*s are 20.07%, 19.29%, 25.85%, and 1.70%, respectively.

3.3. Shielding effect

As shown in Fig. 1, the reactor is surrounded by reflector to reflect the escaping neutrons, and the shielding is arranged to protect the superconducting magnets. According to the literatures [9,10], the superconductor allows fast neutron (>0.1 MeV) fluence to be 1.0 × 10^{19} n/cm^2. The Monte Carlo code is used to perform the

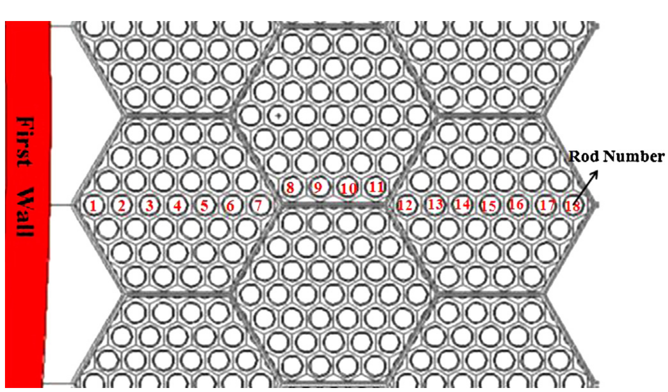

Fig. 5. Fuel rod numbers at the equatorial plane of the reactor core.

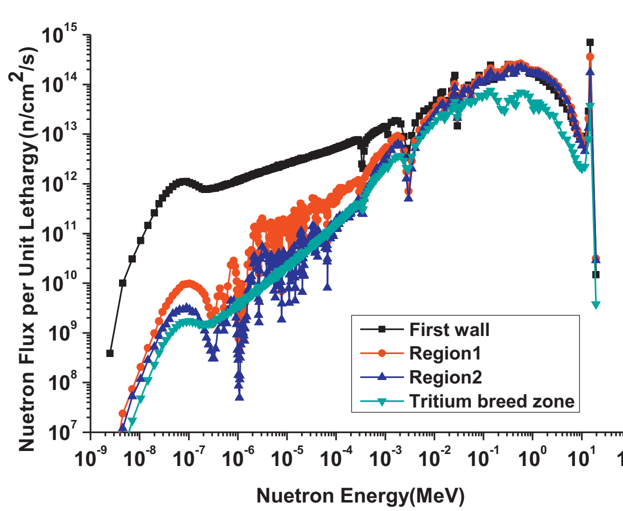

Fig. 6. Energy distribution.

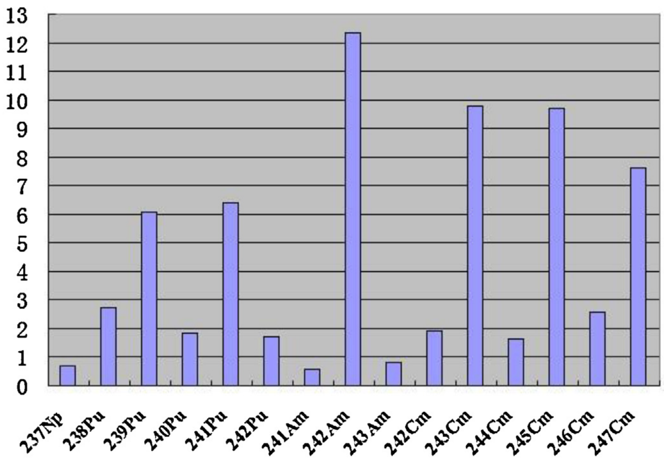

Fig. 7. Fission-to-capture ratio of different isotopes at BOC for the Case 2.

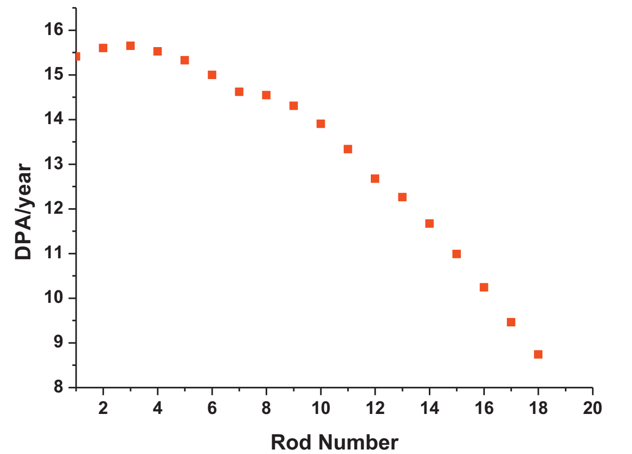

Fig. 8. Radiation damage to the cladding of fuel rod at BOC for the Case 2.

shielding calculation based on the above loading pattern 2. The first layer around the fission core is a reflector region (60 mm) composed of SS304 stainless steel, which is used to reflect neutrons. Tungsten metal alloy (W-5Re) [19] with thickness of 250 mm is used to prevent gamma photons and fusion neutrons, and a layer of boron carbide is used as neutron absorber, where its thickness is 250 mm. The result shows that the fast neutron (>0.1 MeV) fluence to the superconductor is 9.42×10^{18} n/cm^2 for 15 years of operation.

3.4. Radiation damage of first wall and cladding

Radiation damage is a critical factor in determining the service lifetime of the first wall (FW) and fuel pin cladding. The life-limiting criterion is generally the displacement of atoms (dpa), ranging between 100 and 200 dpa. The average damage rate of the first wall for Case 2 is 13.4 dpa/yr. The damage rate of cladding is calculated at the equatorial plane of reactor core. The index of fuel rods is shown in Fig. 5. The results of calculation are displayed in Fig. 8. The maximum damage rate of cladding is 15.6 dpa/yr. Therefore, the maximum radiation damage of cladding is 78 dpa when the fuels are removed for reprocessing.

3.5. Multiple recycling calculations

After one cycle, all the fuel assemblies in the blanket are unloaded. The fission products are partitioned by the high temperature reprocessing from the spent fuel and the rest of these heavy isotopes are recovered. ^{238}Pu and ^{242}Am are quickly built up during this cycle, and their fission cross sections are relatively large in a harder neutron spectrum. Therefore, only new MAs are added to meet the design requirements for the following recycling. The composition of new MAs is the same as the first cycle. Six times of recycling are calculated based on the above Case 2. The mass of MAs added to the recycling fuel is 3.1 t in cycles from 2 to 4, and the mass is reduced to 2.9 t in cycles from 5 to 7. All the parameters of the subcritical system are similar to the first cycle and meet the design requirements. K_{eff} of each recycling varies linearly between 0.745 at BOC and 0.710 at EOC; the fusion power varies linearly between 155 MW at BOC and 185 MW at EOC; and the *TBR* varied linearly between 1.17 at BOC and 1.07 at EOC. Likewise, the mass change of the major MAs (^{237}Np, ^{241}Am, ^{243}Am and ^{244}Cm) for different recycling is also similar to the first cycle.

The performances of the subcritical system for each recycling are given in Table 8. The *TF* of MAs reaches about 19.4% in each recycling and the *SR* reaches about 23. After six times of recycling, the total *TF* of MAs reaches about 61.8%. Fig. 9 shows that the *TF* of MAs can reach 86.5% by recycling 25 times when the transmutation reactor is operated in the same manner beyond the 7 cycles tested. A higher *TF* can be achieved if more recycling is performed.

Table 7
The transmutation fraction and mass of major nuclides.

Nuclide	Mass at BOL (kg)	Mass at EOL (kg)	*TF* (%)
^{237}Np	7.37E+03	5.89E+03	20.07
^{238}Pu	3.96E+02	1.30E+03	−228.64
^{239}Pu	4.78E+03	3.69E+03	22.77
^{240}Pu	2.68E+03	2.71E+03	−1.22
^{241}Pu	8.53E+02	5.75E+02	32.64
^{242}Pu	6.09E+02	6.32E+02	−3.80
^{241}Am	2.85E+03	2.30E+03	19.29
^{242}Am	2.20E+01	9.32E+01	−324.4
^{243}Am	1.68E+03	1.68E+03	25.85
^{243}Cm	9.08E+00	7.26E+00	20.06
^{244}Cm	1.31E+03	1.29E+03	1.70
^{245}Cm	9.60E+01	1.52E+02	−58.02
^{246}Cm	2.17E+01	2.29E+01	−5.62
MAs	1.40E+04	1.15E+04	17.8
Total Pu	9.31E+03	8.91E+03	4.37

3.6. Transmutation MAs effectiveness

The purpose of transmutation is to transmute long-lived actinides into short-lived fission products. To do a comparison of

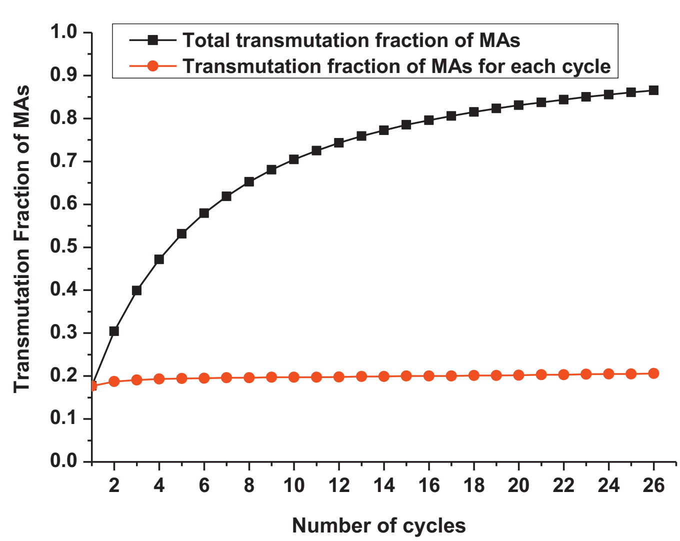

Fig. 9. The change in the *TF* of MAs with the number of cycles.

Table 8
Performances of the subcritical system for six times of recycling.

Parameter	Fuel cycle number					
	2	3	4	5	6	7
Thermal power (MW)	1500	1500	1500	1500	1500	1500
Burn cycle time (a)	5	5	5	5	5	5
Mass of MAs added (t)	3.1	3.1	3.1	2.9	2.9	2.9
Mass of MAs burned (t)	2.72	2.85	2.92	2.94	2.93	2.93
TF of MAs (%)	18.7	19.1	19.3	19.4	19.5	19.6
SR	21.8	22.8	23.4	23.5	23.5	23.5
Average burnup (GWd t^{-1})	116.80	117.05	117.20	117.2	117.20	117.3

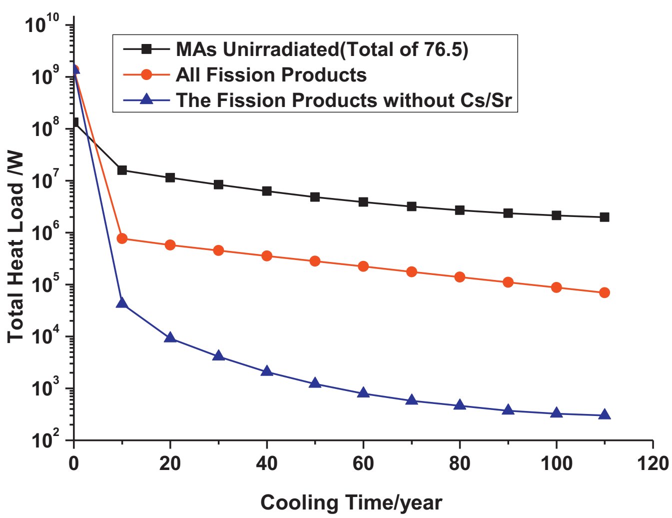

Fig. 10. The change in total heat load for unirradiated MAs and fission products with cooling time.

the effectiveness, the total heat load of MAs in spent fuels is compared to the one of the fission products that is produced due to the transmutation of MAs. The heat production of 76.5 t of unirradiated MAs is presented in Fig. 10. The value 76.5 t is the total amount of MAs that is transmuted after recycling 25 times in the transmutation reactor. The comparisons between MAs with and without transmutation are made. A further comparison considering the partition of Cs/Sr from the fission products is also illustrated. The removal of Cs/Sr from the fission product waste makes a significant difference. After just 10 years of cooling, the heat load of the fission products decreases by a factor of 20, and by a factor of 300 without Cs and Sr.

4. Conclusions

The transmutation analysis based on a fusion-driven subcritical system is analyzed in this paper. The subcritical system is driven by a tokamak D-T fusion neutron source based on relatively easily achieved plasma parameters and tokamak technologies. Such design requires: the fusion power is less than 200 MW; the first neutron wall loading (Γ_n) is less than 1 MW/m^2; the energy multiplication factor (M) is larger than 10; the value of *TBR* is bigger than 1.05. The metallic fuel (60 (MAs–Pu)–40 Zr) is applied and the sodium is selected as the coolant. The fuel assemblies are loaded in subcritical blanket with a modular type structure.

To increase the M and decrease the fusion power, the reprocessed plutonium is loaded in the blanket. The reprocessed plutonium improves the fission rate per fusion neutron and the M, but reduces the transmutation rate of MAs. The fuel with 24% reprocessed Pu is loaded to make sure that Γ_n is less than 1 MW/m^2.

Two loading patterns are calculated in this paper, and the results prove that the design meets all the requirements. The pattern with different mass percentage of Pu loaded in the fuel is conducive to improve the *TF* of MAs for its flat flux distribution. The final *TF* of MAs is 17.8% in five years of irradiation. After the first cycle, the spent fuel is reprocessed and reloaded. New MAs are added to make up the burned fuel. The multiple recycling is calculated, the *TF* of MAs can reach about 19.4% and the *SR* can reach about 23 in five years of irradiation for each recycling. After six times of recycling and reloading, the *TF* of MAs is about 61.8%. It can be increased up to 86.5% by 25 times of recycling.

This paper gives the MAs transmutation ability evaluation of the fusion-driven subcritical system. The results demonstrate the feasibility. The subcritical system is operated with a very low K_{eff}, which can provide much greater fuel cycle flexibility. Further multiple recycling investigations will be performed based on the conclusions in the future.

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