

Neutronic Research on Gas-Cooled Breeding Fast Reactor

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Abstract

In order to improve the utilization of uranium resources and alleviate nuclear waste disposal pressure, a scheme of 500MWth Gas-cooled Breeding Fast Reactor (GBFR) has been designed. The MCNPX and CINDER90 code have been used to calculate and analysis the neutronic parameters in GBFR scheme within 25 burning years. The results show that the GBFR can keep self-sustaining within 20 years without refueling using once-through fuel cycle. The system has promising neutronics performance, as it has flat power distribution, deep burnup, higher conversion ratio, and can remain stable in ultra-long period in consequence of the breeding effect.

Keywords: Gas-Cooled Fast Reactor, Breeding, Burnup, Conversion Ratio.

1. Introduction

The Gas-cooled fast reactor (GFR), classed as a Generation IV reactor, has obvious features as fast-neutron spectrum, higher conversion ratio and closed fuel cycle [1]. GFRs are different from other kinds of fast neutron reactors and breeder reactors in using helium as primary coolant direct drive turbine to generate electricity, which theoretical heat exchange higher to 48.5%, make these system have economical competitiveness with conventional commercial LWR [2]. CEA in French has devote a lot of effort on the first stage of ALLEGRO demonstrator reactor, and latter this scheme has been widely cooperated with some Europe country for further study, which thermal power is 75MWth with two main loops [4]. A gas-cooled breeding fast reactor is composed by two main effect: breeding and burnup, which can keep the reactor running in a quasi-static equilibrium mode for decades [5]. The GBFR scheme runs in once through cycle, which can reduce the process of nuclear waste disposal and improve the utilization of uranium resources [3]. Gas-cooled breeding fast reactor has several practical advantages in China, considering the uranium resources shortage and nuclear waste disposal difficulty. Besides, China has the prototype gas-cooled reactors, for example, the demonstration project HTGR in Rongcheng district, Shandong province [6]. The existing mature industrial technologies provide guidance for the conceptual design scheme. In this paper, small modular gas-cooled breeding fast reactors GBFR has been proposed, with thermal power 500MW, and helium as coolant. Meanwhile, some physical parameters have been analyzed for this scheme design.

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2. GTWFR core design

The structure of 500MWth GBFR core is shown in Figure 1, the right one shows the schematic diagram of the overall reactor core. But virtually, the calculation only uses half of the height vertically and 1/12 of the core circumferentially, in consideration of its symmetry and the parallel computation cost. Consequently, as is shown in Figure 1 (b) and (c), the boundaries represented by dash lines apply total reflection condition, and the rest boundaries apply natural boundary condition. The burning region along vertical and horizontal direction is divided into 11 and 7 regions, respectively. The specific structure design parameters are shown in Table 1.

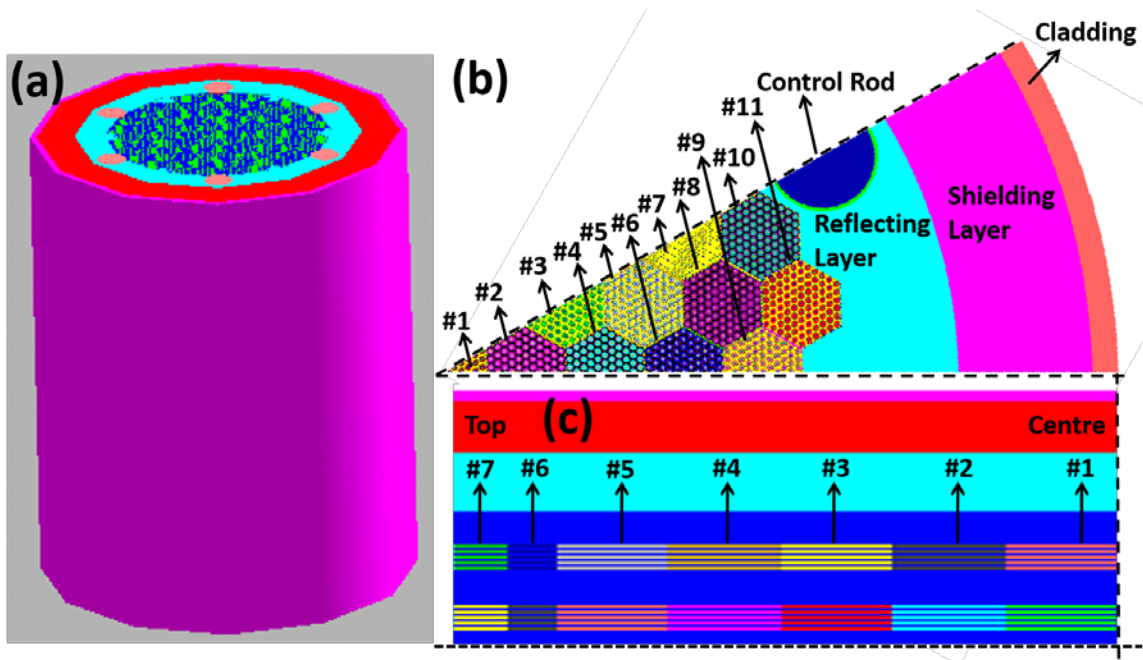


Figure 1 500MWth GBFR schematic

Table 1 The main parameters of 500MWth GBFR core design

Parameters	Value
Fuel Rod	
Fuel rod inner radius (cm)	0.5 (Material He)
Fuel rod outer radius (cm)	1.9 (Fuel)
Fuel rod cladding (cm)	0.1 (Material SiC)
Pitch radio P/D	1.22
Control Rod	
Number of control Rod	6
Material of control Rod	B4C
Control rod radius (cm)	30
Control rod cladding (cm)	1 (Material SiC)
Assembly	
Number of fuel rod in assembly	91
Distance across flats of assembly (cm)	22.2
Assembly cladding (cm)	0.1 (Material SiC)

Core

Thermal power of reactor	500MWth
Number of assembly in reactor	85
Distribution of burning region	Figure 1
Number of assembly in burning region	From inner to outer: 1/6/12/18/24/24
Enrichment of assembly (%)	From inner to outer: 11.4/12/11.4/12/10.8/0.8
Density of fuel UC (g/cm ³)	13.6
Density of Material	2.2/1.9/1.765/2.52
SiC/ Be2C/ C/ B4C(g/cm ³)	
Length of active region (cm)	200 (Material UC)
Vertical breeding region thickness (cm)	36 (Material UC)
Vertical reflecting layer thickness (cm)	32 (Material Be2C)
Vertical graphite layer thickness (cm)	64 (Material C)
Vertical shielding layer thickness (cm)	7 (Material B4C)
Horizontal reflecting layer radius (cm)	145 (Material Be2C)
Horizontal graphite layer thickness (cm)	38 (Material C)
Horizontal shielding layer thickness (cm)	7 (Material B4C)
Coolant	He
Fuel temperature in reactor core (K)	1200
Construct material temperature (K)	900
Reflecting and shielding layer temperature(K)	600

3. Calculation method and code

To make further understanding of 500MWth gas-cooled breeding fast reactor conceptual design, MCNPX and CINDER90 code package were employed in the calculation [7]. MCNPX and CINDER90 code were developed by Oak Ridge National laboratory. The data base of MCNPX is ENDF-VII. CINDER90 has neutron cross section data base of 63 energy groups, which can be coupled with MCNPX to calculate the flux and isotopes fraction change during burnup period. The whole coupling calculation process has been proved its efficiency and feasibility, as it has been used as a benchmark program to check the TP-1 concept design scheme proposed by TerraPower Company [8].

4. Results and Discussion

The effective multiplication factor changes in GBFR within 25 burnup years is shown in Figure 2. The initial k_{eff} is 1.04219, then accretes following the increase of burnup depth. It reaches the peak value of 1.04897 after 2.96 years. Then the k_{eff} gradually decrease to critical at 19.97 years. Finally, k_{eff} will get to 0.98552 after 25 years. During the whole process, the k_{eff} changes slowly, and the breeding effect and burning effect run smoothly. The fission process in GBFR does not occur throughout the entire core, but remains confined to the burning region that slowly advances through the core over time. In order to keep GBFR safe and controllable, GBFR remain certain excess reactivity within 20 years.

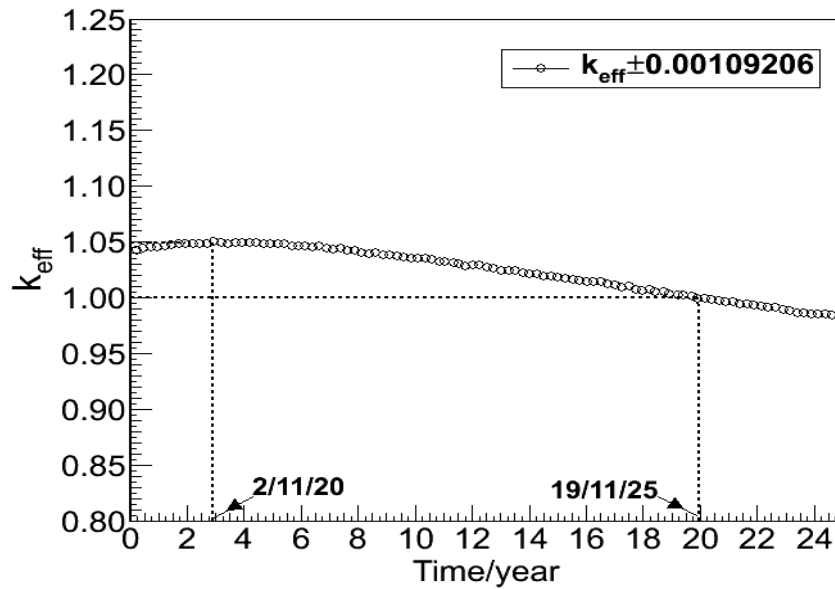


Figure 2 k_{eff} changes within 25 years burning period

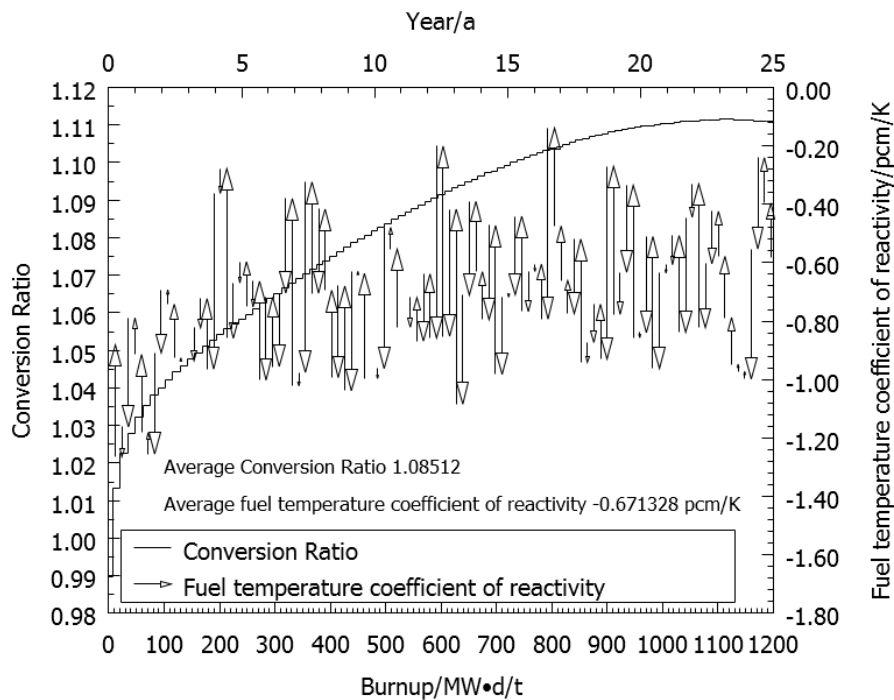


Figure 3 conversion ratio changes with burnup and reactivity coefficient

The conversion ratio represent the ratio between newly produced easy fission isotopes and the consumed ones. In GBFR this parameter is larger than 1 unit within 25 years, as shown in Figure 3, and get the peak value 1.115 at 22.5 years. The average conversion ratio within 25 years is 1.08512, which has better accordance with the breeding effect make GBFR self-sustain within decades. GBFR has higher uranium loaded nearly 51.457 ton, lower power density, and maximum depth of burnup about 1230.74 MW·d/t for the whole core within 25 years. Because of Helium is used as coolant, the effect of fuel temperature coefficient of reactivity is much more obvious, which is also shown in Figure 3. The

peak of resonance absorption in GBFR become wider when the fuel temperature gradually goes up. It can be find in Figure 3, the fuel temperature coefficient reactivity keep negative throughout the burnup procedure. The average reactivity coefficient is -0.671328 pcm/K, which demonstrate The GBFR has inherent safety for the negative temperature feedback effect. The size of arrow in Figure 3 means strength of disturbance, the direction of arrow means whether this coefficient goes up or down, the start point and end point means the end position of forward procedure and beginning of next procedure.

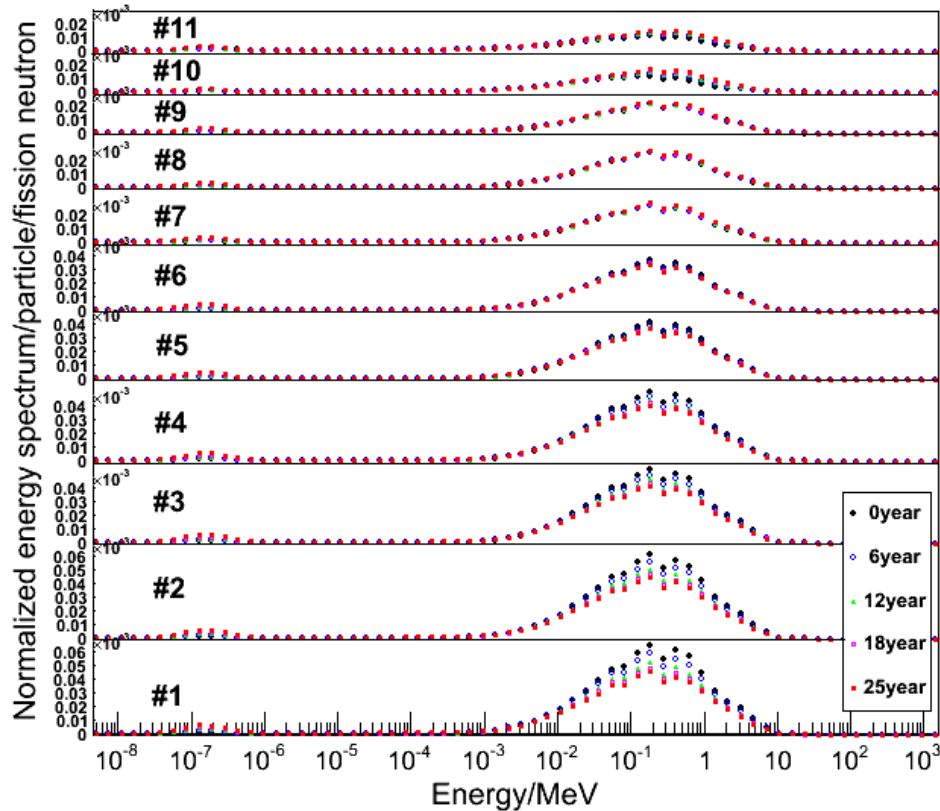


Figure 4 Each burning region energy spectrum along radius direction changes within 25 years in reactor core

Table 2 The average neutron energy changes in the core activated region within 25 years

Time/year	Average energy of neutron/MeV
0	0.550513
6	0.546796
12	0.542219
18	0.531628
25	0.519071

Energy spectrum in each burning region along radius direction changes within 25 years in reactor core is shown in Figure 4. The overall energy spectrum exhibits fast spectrum distribution forms. As the burnup depth gradually advances, the spectrums in #1-6 region slowly soften, because the burning effect is more remarkable than the breeding effect. The spectrums in #7-9 region keep stable during burning years, in that the superposition interaction of breeding effect and burning effect forms standing wave alike. The spectrums in burnup region #10-11 become harder, because the weight of breeding effect is higher than the burning effect. The average neutron energy varies in a small range in the

activated region within 25 years, as is shown in Table 2. The largest variation is 5.71%, which basically guarantees the characteristics of fast breeder reactor.

Power distribution along radius direction in GBFR is shown in Figure 5. The figures represent 6, 12 and 25 burnup years, respectively. Peak value of the power distribution in GBFR centre region slowly decreases following the depth of burnup. The breeding effectiveness near reflecting layer gradually increase, which makes the power distribution in GTWFR more flatten. The extension velocity of active region border along radius direction is 0.94cm/a.

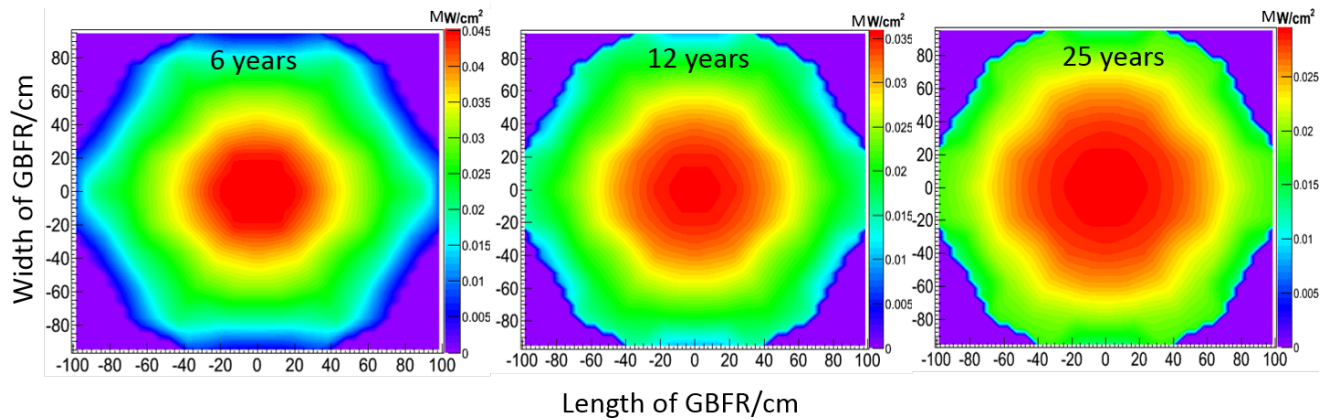


Figure 5 Power distribution along radius direction in GBFR

The average power distribution in each burning region along radius direction in GBFR is shown in Figure 6. The downward trend in in burning region #1-6 is obvious, so it can be concluded that burning is the dominating effect in these regions, while breeding is inferior. Power distribution in #7-9 region remain stable, as the burning effect and the breeding effect reach relative equilibrium. In #10-11 region the breeding effect is more remarkable, due to the significant multiplication effect of fast neutron interact with depleted uranium region.

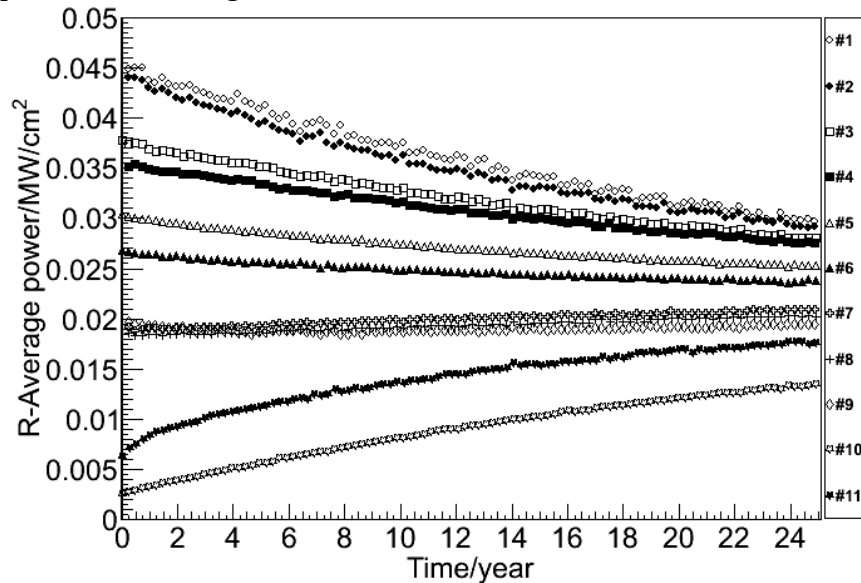


Figure 6 Each burning region average power distribution along radius direction in reactor core

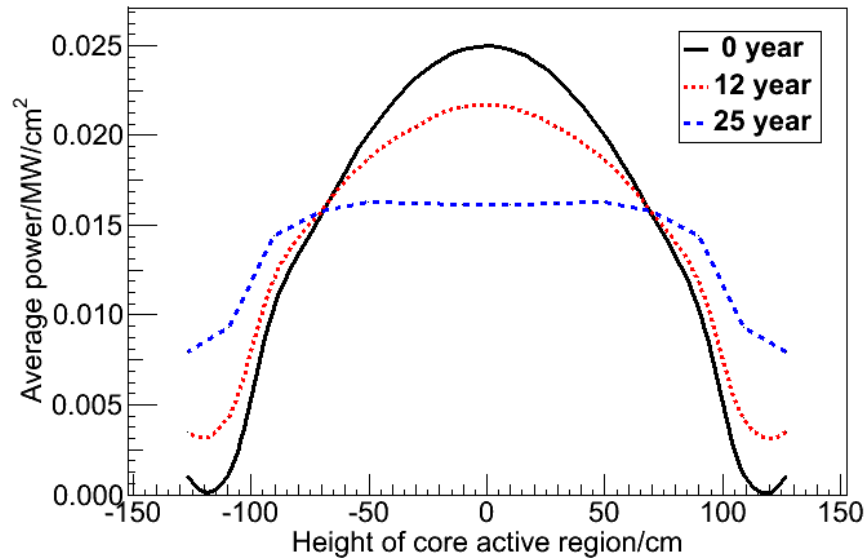


Figure 7 Power distribution along axial direction in reactor core

Power distribution in GBFR along axial direction is shown in Figure 7. It represents power distribution along axis direction at initial period, 12 burning years and 25 burning years, respectively. It can be concluded from Figure 6 that, following the interaction of breeding effect and burning effect, the power distribution become more flatten, and the breeding effectiveness gradually become more remarkable near the upper and lower reflecting layer. The average extension velocity of active region border along axis direction is 1.01cm/a.

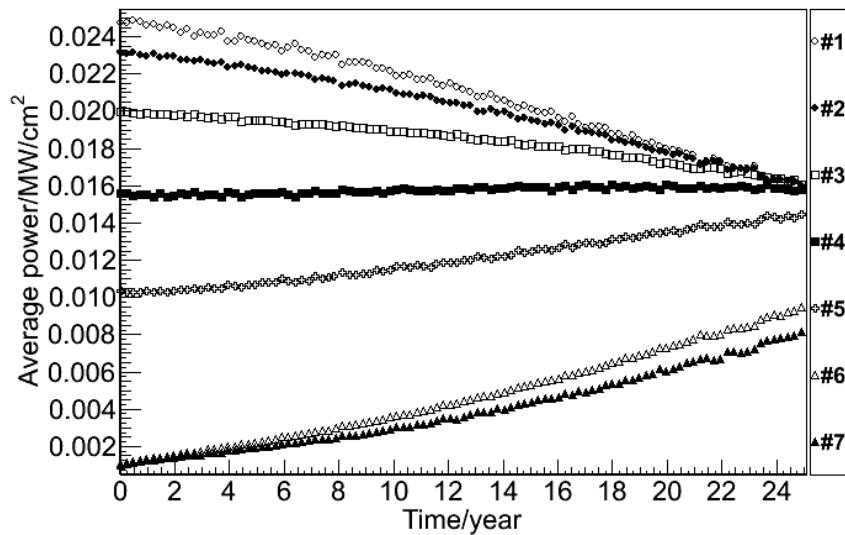


Figure 8 Each burning region average power distribution along axial direction in reactor core

The average power distribution of each burning region along axis direction is shown in Figure 7. The burning region #1 is in the center of GBFR, and #7 is next to the reflecting region. It can be concluded from Figure 8 that following the depth of burnup, the average power in burning region #1-3 gradually decrease. Because of the standing wave alike effect, which is the superposition of breeding effect and burning effect, the average power in burning region #4 generally keep stable within 25 years. The

average power along axis direction in burning region #5-7 increases during burning years in consequence of interaction of breeding and burning effect.

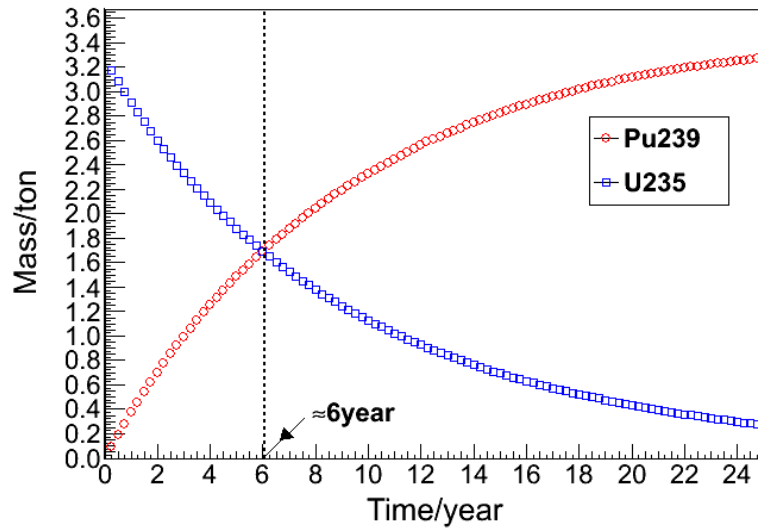


Figure 9 U and Pu mass change within 25 years in reactor core

The burning effect of U^{235} and the breeding effect of U^{238} directly relate to the stability of GBFR. The products of Pu^{239} play important roles in compensation of reactivity in GBFR, as is shown in Figure 8. It can be seen from Figure 9 that the decrease of U^{235} has the opposite trend with the accumulation accrete of Pu^{239} , and have almost the same amount of mass at about 6th year, which makes GBFR running in stability. The important isotope mass changes within 25 years in GTWFR are shown in Table 3. It can be seen that the increment of Pu^{239} is 277.99kg, which is larger than the decrement of U^{235} . A traditional 3000MWth PWR can produce 34kg/a minor actinides isotope. Converting into 500MWth running 25 years, the minor actinides isotope mass is 141.67kg, which almost equals to the amount that GBFR produces (144.63kg). But the composition of the unloaded minor actinides isotopes have large difference because of the different spectrum in GBFR and traditional PWR. The amount of Np^{237} takes 71.54% and other minor actinides isotopes take relative small portion. Whereas in traditional PWR, the amount of Np^{237} takes 49.1%. So the nuclear waste in GBFR is more appropriate to be used in accelerator driven subcritical systems for transmutation, or to be used in once-through cycle to be deep buried, which saves the complicated spent fuel reprocessing procedure.

Table 3 Important isotope mass changes within 25 years in reactor core

Importance products	Initial/kg	25 years/kg	Change $\Delta m/kg$
Fission products			
U235	3267.9	272.69	-2995.21
U238	48189.0	37007.0	-11182
Pu239	0.0	3273.2	3273.2
Pu241	0.0	110.44	110.44
Total			-10793.57
Minor actinides products			
Np237	0.0	103.46	103.46
Am241	0.0	28.736	28.736
Am242	0.0	0.00634	0.00634
Am242m	0.0	1.0378	1.0378

Am243	0.0	6.2322	6.2322
Cm242	0.0	1.2652	1.2652
Cm244	0.0	3.4113	3.4113
Cm245	0.0	0.47663	0.47663
Total			144.62547
Long-lived fission products			
Tc99	0.0	177.12	177.12
I129	0.0	25.658	25.658
Cs135	0.0	406.56	406.56
Total			609.338

5. Conclusion

A new 500MWth conceptual gas-cooled breeding fast reactor has been proposed, physical and neutronic parameters including power distribution, important isotopic mass, uranium and plutonium transformation, excess reactivity, burnup depth, conversion ratio, fuel temperature coefficient of reactivity and k_{eff} have been studied within 25 burning years. The results show that GBFR has prominent neutronic characteristics and inherent safety can be used in once-through cycle, which improves the utilization of uranium resources and alleviate the nuclear waste disposal pressure. And it could theoretically run self-sustainingly for decades without refueling or removing any spent fuel from the reactor. From neutronic point of view, GBFR has feasibility and provide a basis for further optimization design and thermal-hydraulics analysis.

6. References

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