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Physical Scheme Study of 100MW Gas-Cooled ADS System for Thorium Breeding and Transmutation

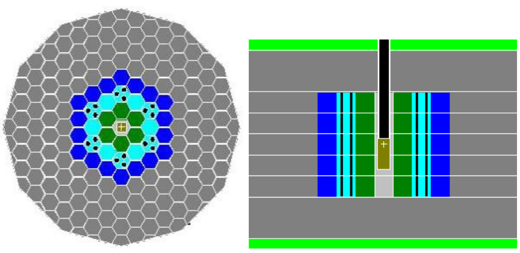
Jiang Wei[a,b], Gu Long[b,*] Li Jinyang[b] and Xu Hushan[b]
[a]*School of Nuclear Science and Technology, USTC, Hefei, Anhui 230026*
[b]*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, Gansu 730000*
[*]Corresponding author: gulong@impcas.ac.cn

1. Introduction

With explosive growth of nuclear power plant capacity in China, more and more researchers focus on the nuclear power safety, disposal of spent nuclear fuel and high-level nuclear waste, and effective utilization of nuclear resources. We can effectively deal with the above problems by developing the accelerator-driven sub-critical reactor system (ADS). According to the Chinese Academy of Sciences plan, hundreds of megawatt ADS test unit will be built in China. The extra neutrons could be provided by a particle accelerator, so the reactor can keep subcritical with high-security. In order to fully improve the utilization of neutrons in the ADS, a physical design of 100MW gas-cooled ADS transmutation system containing thorium-based fuels was studied to analyze thorium-based fuels breeding capacity and MA transmutation effect.

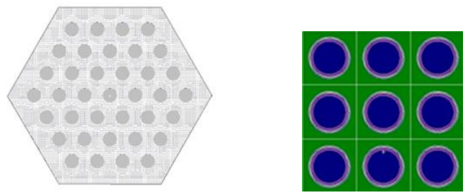
2. ADS core design

ADS core can be divided into three main regions: transmutation zone, common fuel region and breeding blanket, as shown in figure 1. TRISO fuel particles form is adopted. Fuel assemblies and TRISO fuel particles are shown in figure 2. The main core design parameters and the mass percentage of nuclides are shown in table I and table II. Helium and tungsten is respectively used as coolant and target material. Rectangular target is embedded in the middle assembly of core.



target transmutation zone common fuel region
control rod assembly breeding blanket
reflector layer shielding layer

Fig.1 Transverse sections of reactor core and fuel assembly



Helium channels coated particles matrix
nuclear fuel

Fig.2 transverse cross section of a assembly and TRISO particles

Table I. Main parameters of reactor core design

Accelerator	
Proton energy/MeV	1000
Beam radius/cm	10
Target	
Target material	tungsten
Target dimensions (length/width /height）/cm	24/24/60
Reactor	
Reactor thermal power/MW	100
Core diameter/cm	320
Number of radial divided layers	3
Coolant material	helium
Reflector material	graphite
Shield material	boron carbide
Center distance between fuel assemblies/cm	36
Gap distance between fuel assemblies/cm	0.2
Transmutation zone material	MA(20%)+PuO_2
Common fuel region material	PuO_2
Breeding blanket material	PuO_2 and ThO_2
Fuel volume share（from inside-out）/%	20.1/10.2/6.8
Matrix material（from inside-out）	SiC/ SiC /graphite

Table II. The mass percentage of nuclides in three zones of the core

Transmutation zone	
nuclide	mass percent
Pu239	14.999
Pu238	4.105
Pu240	53.367
Pu242	8.21
Np237	9.485
Am241	5.797
Am242	0.015
Am243	2.994
Cm243	0.01
Cm244	0.966
Cm245	0.05
Common fuel region	
nuclide	mass percent
Pu239	25.9375
Pu238	4.6875
Pu240	60.9375
Pu242	9.375
Breeding blanket	
nuclide	mass percent
Pu239	1
Th232	99

3. Calculating program

The physical design was established by using COUPLE 2.0 based on the nuclear data library of ENDF/B-VII which was modified with six different temperatures (300k, 600k, 900k, 1500k, 2500k). COUPLE 2.0 which is the coupled program of MCNPX and ORIGEN code systems is developed by Tsinghua University program. Core fuel temperature was set to 1200 K and other parts materials was set to 600 K. The following method is used to calculate Th-232 proliferation and minor-actinide(MA) transmutation in the system. Firstly we used mcnpx program to simulate spallation reaction caused by proton bombardment. MCNPX tally cards recorded the neutron leakage of the target surface which was as external neutron source. Spallation reaction in tungsten target and fission in the core were effectively coupled together to accurately simulate the physical processes in ADS reactor core.

4. Calculation results and analysis

Selection of fissile nuclides, MA initial load, arrangement of nuclear fuel in the reactor core can have a big effect on the physical parameters stability of the system, minor actinide transmutation and thorium nuclide proliferation. In order to obtain good effect of thorium proliferation, U-free nuclear form is adopted in the reactor core which is divided into transmutation zone, common fuel region and breeding blanket.Pu-239 mass fraction of total heavy metals in the three regions are 15%, 25%, and 0.5% respectively. Mass fraction 20% MA which is derived from spent fuel cooled after five years is loaded in the transmutation zone, and the spent fuel is discharged from the reactor whose burnup is 35GW·d/t. MA concrete composition is shown in reference 3.

Time evolution of physical parameters in core is shown in table III and table IV. Time evolution of K_{eff} is shown in figure 3. The results show that the initial K_{eff} of the system is 0.9524, which has deep sub-criticality to ensure reactor safety. The K_{eff} volatility is small and the maximum variation of K_{eff} is 0.625%, which helps the control and operation of the reactor. When the reactor starts to run, the fission products introduce negative reactivity, but U-233 generated by Th-232(n, γ)U-233 accumulates in the thermal neutron region, which introduces positive reactivity. So K_{eff} decline slightly on the fortieth day. After 50 days K_{eff} continues to rise because neutron poison achieves balance and U-233 mass keeps accumulating. During the 350 days, maximum variation of beam intensity is about 0.12mA, which greatly reduces the performance requirements of the accelerator. The system has a higher neutron utilization and the average proton efficiency is about 70, which improves the security and economy of the system. In the hypothetical accidents, we assume there is a complete loss of coolant and the fuel temperature rises to 2500k from 1200k. So change of core reactivity is about -311pcm and the system has inherently security. The average power peaking factor in the transmutation zone and in the breeding blanket is 1.86 and 1.77, which can meet the design requirements.

Table III. Time evolution of physical parameters in core

Reactor operation time/day	i_p/mA	Proton efficiency
0	0.848833	73.5996
50	0.787232	68.9386
100	0.889269	68.6585
150	0.847245	69.9246
200	0.862057	65.6751
250	0.807347	70.4978
300	0.767691	72.3614
350	0.788121	69.2063

Table IV. Time evolution of physical parameters in core

Reactor operation time/day	K_{eff}	Doppler factor/pcm	Power peaking factor（transmutation zone/breeding blanket）
0	0.9524	-286.315	1.85/1.61
50	0.95238	-340.789	1.84/1.58

100	0.95343	-221.582	1.91/1.69
150	0.95475	-386.48	1.88/1.73
200	0.95667	-468.648	1.86/1.82
250	0.95645	-311.376	1.85/1.87
300	0.95745	-375.509	1.84/1.90
350	0.95819	-258.774	1.84/1.97

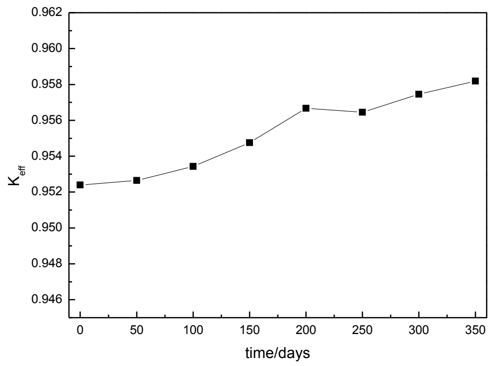


Fig. 3 Time evolution of K_{eff}

Figure 4 shows the incident neutron energy evolution of Th-232 capture cross section. In epithermal neutron zone, Th-232 capture cross section is large and has many resonance peaks. In order to increase the share of epithermal neutron, graphite is chosen as matrix material in the breeding blanket. Share of neutron which is between 10^{-5} and 10^{-2} Mev is about 34.7% and this contributes to the Th-232 proliferation.

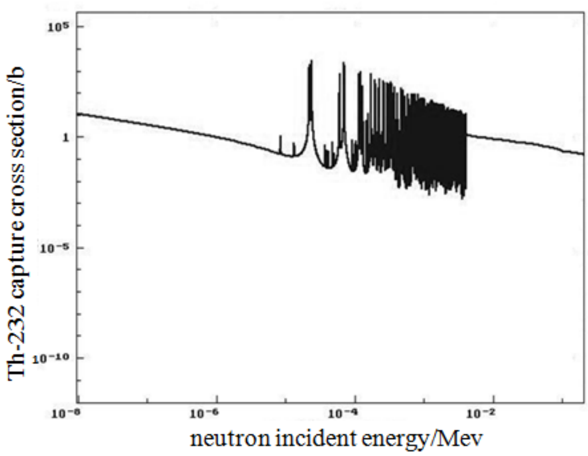


Fig. 4 The incident neutron energy evolution of Th-232 capture cross section

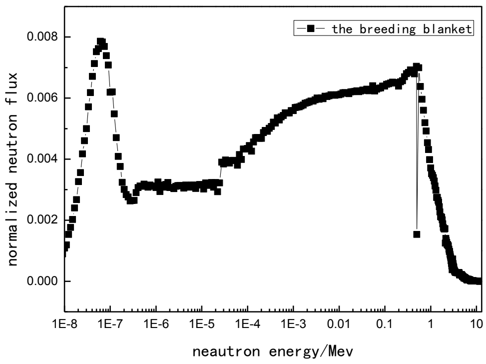


Fig. 5 Neutron energy spectrum in breeding blanket of the core

Figure 6 illustrates that during 350 days, the cumulated U-233 introduces positive reactivity which supplements the K_{eff} loss. On the 350th day, mass of U-233 accumulation is 8.575kg. Figure 7 shows that mass of U-233 grows fastest on the 100th day and after that, U-233 accumulating velocity turns down. That is because Th-232 is consumed and fission cross section of U-233 is larger than that of Pu-239.

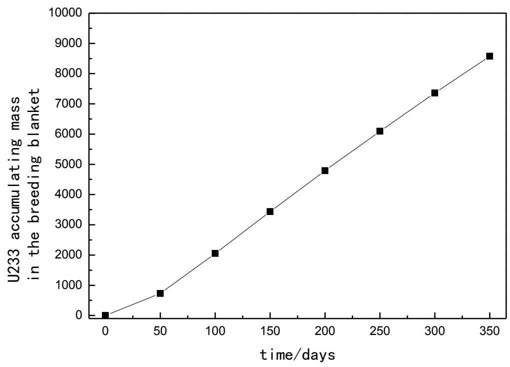


Fig.6 Time evolution of U-233 accumulating mass in breeding region

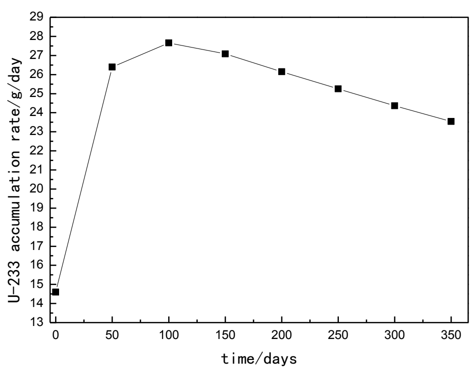


Fig.7 Time evolution of U-233 accumulation rate

in breeding zone

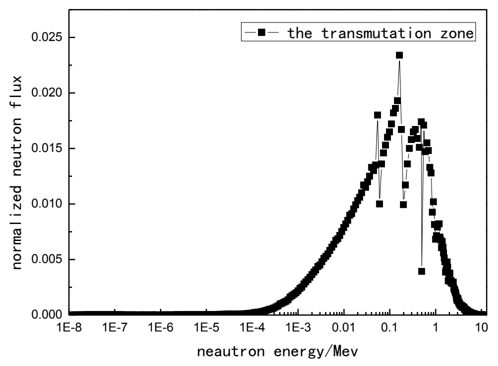


Fig.8 Neutron energy spectrum in transmutation regions of the core

Figure 8 shows that neutron spectrum is hard in transmutation zone, which helps MA transmutation. Fuel assembly in common fuel region is covered by B_4C cladding of 0.1cm thickness which makes it difficult that low energy neutrons leak from breeding blanket to transmutation zone. If we consider the spallation neutron produced in the target, average neutron energy in the transmutation zone is about 0.619Mev.
Time evolution of important nuclides mass is shown in fig 9. After 350 days, MA mass change is about 10.03kg, which means one ADS facility can transmute MA produced by 9.23 PWR the same power as ADS. So the ADS system has good transmutation effect.

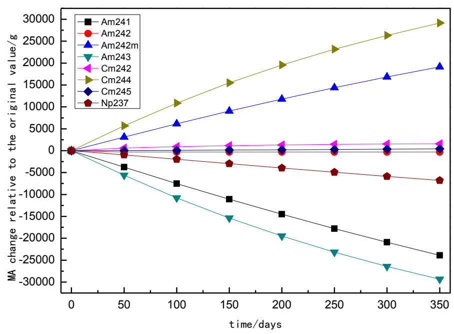


Fig.9 Time evolution of important nuclides

5. Conclusions

Physical scheme study of 100MW gas-cooled ADS system for thorium breeding and MA transmutation has been presented. The results show that during the 350 days, the swing of K_{eff}, proton efficiency, proton current density and accelerator power is relatively small，and power peaking factor can meet the design requirements and the system remains deep sub-critical status. The system has good safety feature with negative temperature coefficient in the hypothetical accident. The neutron energy spectrum was analysed and the arrangement of nuclear fuel in the core was optimized to achieve good transmutation and breeding capacity. During 350 days burnup time, about 8.575kg U-233 was produced in the thorium-based fuel assemblies and 10.03kg MA can be eliminated in the transmutation region and the transmutation support radio of the system is about 9.35. Thermodynamic calculation and analysis on ADS system will be done in future. This research may be significant and valuable to construction of ADS test facility.

6. Acknowledgement

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