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Characteristics of a gas-cooled fast reactor with minor actinide loading

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Abstract: This paper presents the neutronics characteristics of a prototype gas-cooled (supercritical CO_2-cooled) fast reactor (GCFR) with minor actinide (MA) loading in the fuel. The GCFR core is designed with a thermal output of 600 MWt as a part of a direct supercritical CO_2 (S-CO_2) gas turbine cycle. Transmutation of MAs in the GCFR has been investigated for attaining low burnup reactivity swing and reducing long-life radioactive waste. Minor actinides are loaded uniformly in the fuel regions of the core. The burnup reactivity swing is minimized to 0.11% $\Delta k/kk'$ over the cycle length of 10 years when the MA content is 6.0 wt%. The low burnup reactivity swing enables minimization of control rod operation during burnup. The MA transmutation rate is 42.2 kg/yr, which is equivalent to the production rates in 7 LWRs of the same electrical output.

Key words: *Minor actinide, fast reactor, reactivity swing, GCFR.*

I. INTRODUCTION

An LWR with an electrical output of 1000 MWe and average discharged burnup of 33 GWd/MT produces about 24 kg of minor actinides (MAs) per year. In the total MAs discharged from spent fuel of LWRs, neptunium (Np) constitutes about 50%; americium (Am) is 45% and curium (Cm) constitutes the remainder of about 5%. Minor actinides are disposed of geologically as long-lived radioactive waste (LLRW) [1].. Therefore, transmutation of MAs would contribute to the reduction of LLRW inventory. Fast reactors (FRs), also known as MA burners, can transmute MAs to short-lived nuclides and minimize higher radioactive products by taking advantage of their hard neutron spectrum. Extensive studies to transmute MAs and fission products have been undertaken [1-3].

A supercritical CO_2 (S-CO_2) gas turbine cycle at the FR temperature condition of about 530-550°C provides higher cycle efficiency than a conventional steam turbine cycle, eliminates a safety problem related to a sodium-water reaction, and simplifies the turbine system [4, 5]. Moreover, the gas turbine cycle is applicable to both a supercritical CO_2-cooled FR (GCFR), as in a direct cycle, and a sodium-cooled FR (SFR), as in an indirect cycle [6, 7]. An S-CO_2 gas turbine cycle is a promising candidate for next-generation FR systems [8-11].

One of the challenges of FR designs is a large burnup reactivity swing, which is determined as the largest difference of

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reactivity during burnup. Insertion of control rods can reduce excess reactivity, but inducing local flux depression around the control rods. Therefore, reduction of the control rod operation is desirable to simplify plant operation. Several attempts have been made to deal with the large reactivity swing in different FR designs through using MAs. A design of a modular lead-cooled FR (LFR) was proposed for a small reactivity swing [11].. Minor actinides were used to reduce burnup reactivity swing and extend the core lifetime of super long-life fast breeder reactors (FBRs) up to 30 years without refueling [12].. A feasibility of using Np in a 600 MWt GCFR was investigated for simultaneously attaining a small burnup reactivity swing and improving the neutronics performance of the core [13].. An additional Np content of 6.5 wt% was determined and loaded uniformly in the core. As a result, a nearly zero burnup reactivity loss of 0.02% has been obtained over the core lifetime of 10 years. The transmutation rate of Np is about 69 kg/yr which is equivalent to the production rate of 20 LWRs with the same electrical output [13].. Transmutation of Am in a 1500 MWt SFR and the influence of additional Am content on the core characteristics were investigated separately from Np and Cm [14].. A content of 2-3 wt% Am in the fuel, the transmutation rate of Am is equivalent with the production rate of a PWR with the same power output [14].. However, in the viewpoint of nonproliferation resistance it is also undesirable to separate these MAs.

In the present work, we aim at investigating the use of MAs in a prototype GCFR for simultaneously minimizing the burnup reactivity loss and transmuting MAs to reduce LLRW.

II. REACTOR DESCRIPTION AND CALCULATION MODEL

The prototype GCFR with a thermal output of 600 MWt has been designed as a part of a direct CO_2 gas turbine system [13].. Table I gives the detailed core parameters of the GCFR. Configuration of the GCFR is displayed in Fig. 1. The fissile plutonium enrichments of the inner and outer cores are 14.7 and 20.0 wt%, respectively. The inner and outer fuel regions contain 159 and 102 fuel assemblies, respectively. The outer blanket consists of 126 assemblies containing natural uranium. The core height and equivalent diameter are about 1.2 m and 3.15 m, respectively. The core lifetime is 10 years with one batch loading. The isotopic compositions of MAs are given in Ta II [12]..

Table I. Core design parameters of the GCFR.

Parameters	Value
Power output	
Electric/thermal power (MW)	243.8/600
Cycle efficiency (%)	40.6
Cycle length (year)	10
Coolant (Inlet/Outlet)	
Temperature (°C)	388/527
Pressure (MPa)	12.8/12.5
Materials	
Coolant	S-CO_2
Fuel	UO_2-PuO_2-MAO_2
Absorber (^{10}B = 90%)	B_4C
Structural material	316 SS
Core geometry (m)	
Effective core height	1.2
Equivalent diameter	3.146

Pu fissile enrichment (wt%)	
Inner/Outer core	14.7/20.0
Blanket thickness (mm)	
Axial/Radial	200/330.9
Heavy metal (ton)	
Active core	200/330.9
Blanket	
Fuel assembly	
Pitch (mm)	182
Duct thickness (mm)	3.5
Fuel pin	
Number per assembly	391
Inner/Outer diameter (mm)	5.8/6.5
Cladding thickness (mm)	0.35
Spacing	Grid spacer
Pitch (mm)	8.45
Volume ratio (%)	
Fuel	34.05
Structure	17.24
Coolant	46.74
Gap	1.96

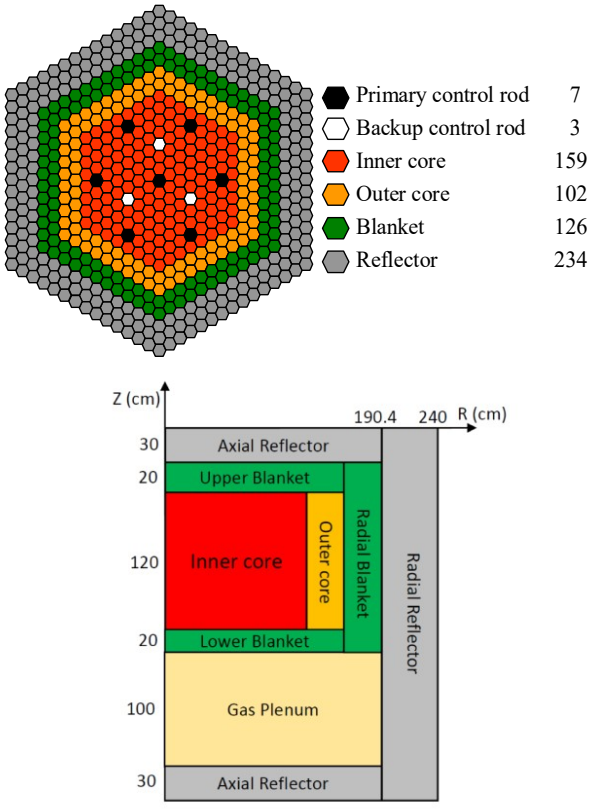

Fig. 1. Configuration of the GCFR core with the thermal output of 600 MWt.

The SLAROM-JOINT-CITATION codes were used for cross-section preparation based on the JENDL-3.3 library [15].[16].. Effective cross-sections were collapsed in each core region from a 70-group cross-section set. Burnup calculations were performed using the CITATION code [17].. A seven energy-group RZ model in the CITATION code was applied to determine optimal MA contents in the cores. Then, three-dimensional Z-triangular calculations with thirty five energy-groups were conducted for obtaining core characteristics.

Table II. Isotopic composition of minor actinides [12].

Nuclide	Compositions (wt%)
^{237}Np	49.14
^{241}Am	29.98
$^{242\,m}$Am	0.08
^{243}Am	15.50
^{242}Cm	0.0
^{243}Cm	0.05
^{244}Cm	4.99
^{245}Cm	0.26

III. RESULTS AND DISCUSSION

A. Optimization of MA loading content

In the GCFR without MAs, the effective multiplication factor, k_{eff}, decreases linearly with burnup time. The core lifetime would be about four years. A higher Pu enrichment can provide a higher k_{eff} and longer core lifetime. However, burnup reactivity swing is almost independent with Pu enrichment. The reactivity swing after 10-year burnup is about 3.9% $\Delta k/kk'$. The target lifetime of the GCFR is 10 years when one-batch refueling is applied through loading MAs homogeneously in the inner and outer cores. Fig. 2 displays the neutron capture and subsequent decay reactions of MAs. Np-237 transmutes mainly to ^{239}Pu after two neutron capture reactions via ^{238}Pu. Am-241 transmutes to ^{239}Pu and ^{243}Am after several capture and decay reactions. Whereas, ^{243}Am transmutes to ^{244}Cm, which has a larger fission cross section than the other MA nuclides. Thus, the addition of MAs in the fuel will compensate for reduction of k_{eff} at EOC and lengthen the core lifetime.

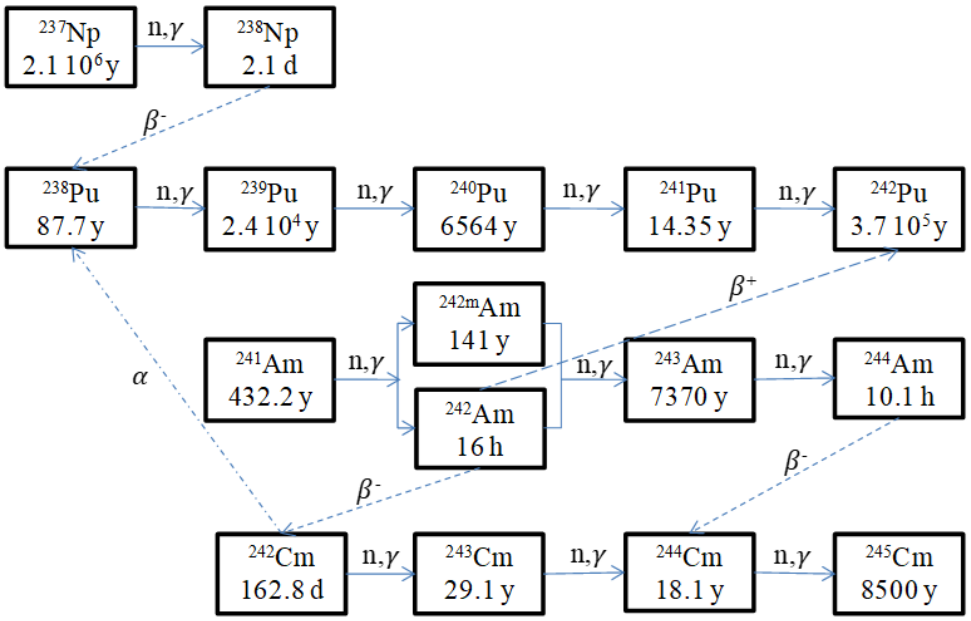

Fig. 2 Neutron capture and subsequent decay reactions of minor actinides

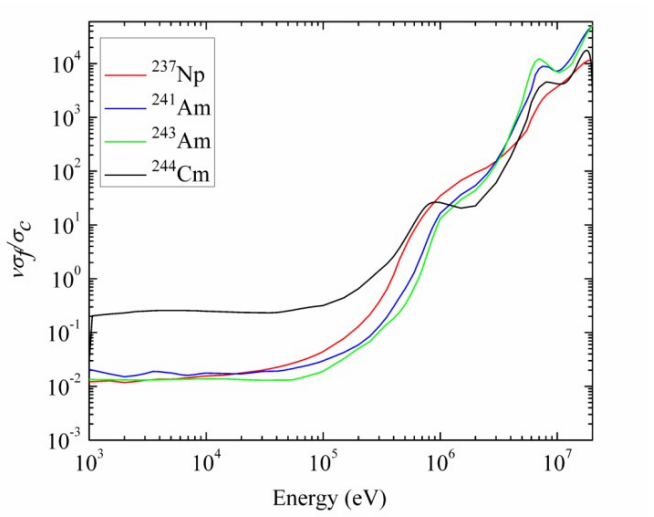

Fig. 3 Production per capture cross section ratios of minor actinides in fast neutron energy

Since the production to capture cross section ratios of most MAs increase significantly at neutron energy greater than 0.1 MeV as shown in Fig. 3, positive reactivity is inserted mostly due to neutron spectral hardening when coolant is voided. The considerable increase of void reactivity is a salient difficulty in using substantial quantities of MAs. Fortunately the positive void reactivity of the GCFR would be less restrictive compared to that of a SFR. The MA composition is determined to attain the objective function of minimum burnup reactivity swing and almost zero burnup reactivity loss. The burnup reactivity swing is defined as the difference between the maximum k_{eff} and the minimum k_{eff} over the burnup cycle, although the burnup reactivity loss is defined as the k_{eff} difference between EOC and BOC.

Fig. 4 shows the dependence of burnup reactivity loss as a function of MA content in the fuel of the GCFR. Burnup reactivity loss is about -0.04% $\Delta k/kk'$ when MAs are loaded with a content of 6.0 wt%. Fig. 5 shows the change of k_{eff} as a function of burnup in the case of 6.0 wt% MA loading. Burnup reactivity swing is reduced from 3.9% $\Delta k/kk'$ to about 0.11% $\Delta k/kk'$. In comparison to the Np loaded core described in [13]., although the burnup reactivity swings are approximately equal, the k_{eff} in the MA loaded core is greater by a factor of about 1.007, mainly because of the appearance of ^{244}Cm in the total MA compositions. Since ^{244}Cm has a higher fission cross-section than those of ^{237}Np and ^{241,243}Am in the fast neutron energy range of 1 keV – 1 MeV, addition of ^{244}Cm provides a greater k_{eff}.

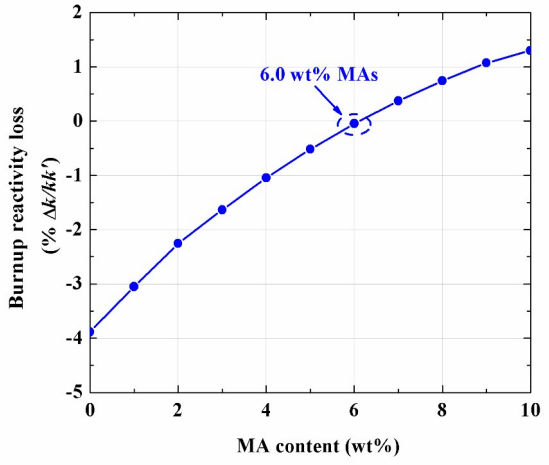

Fig. 4. Burnup reactivity loss as a function of the MA content in the GCFR. The burnup reactivity loss is nearly zero when 6.0 wt% of MAs are loaded

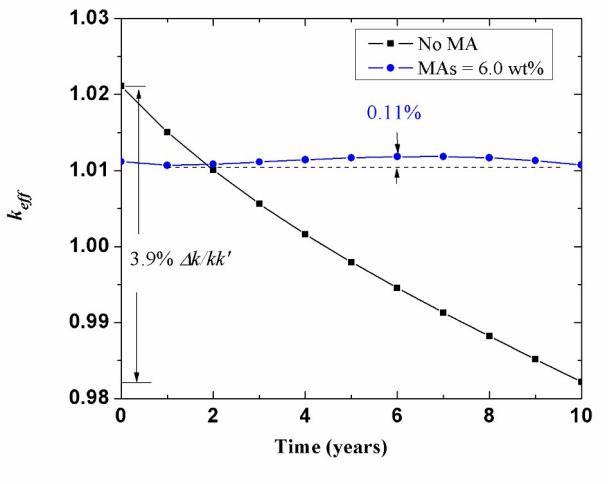

Fig. 5 Change of the k_{eff} during burnup in the GCFR core with 6.0 wt% MA loading

B. MA transmutation rate

Fig. 6 shows the transmutation products at EOC of the initial MA compositions in the GCFR. It can be seen that after 10 years operation, about 23.40% and 1.77% of the initial ^{237}Np amount are transferred to ^{238}Pu and ^{239}Pu, respectively. 12.95% of the initial ^{237}Np amount is fissioned, while 61.8% remains at EOC. Among the four nuclides, ^{243}Am has the smallest fission rate (7.6%). However, about 25.3% of the initial amount to ^{244}Cm at EOC. Cm-244 has the greatest fission rate (15.66%) compared to other actinides. Consequently, a smaller amount of MAs (6.0 wt%) loaded into the core achieves approximately the same burnup reactivity swing compared to the ^{237}Np amount (6.5 wt%). Table III presents the change of heavy metal inventories in the GCFR at BOC and EOC. The MA transmutation rate is about 42.2 kg/yr, which is equivalent to the generation rate in 7 LWRs with the same electrical power. It is noticed that while the total MA amount decreases, the amount of Cm increasing in the GCFR is about 7.3 kg/yr.

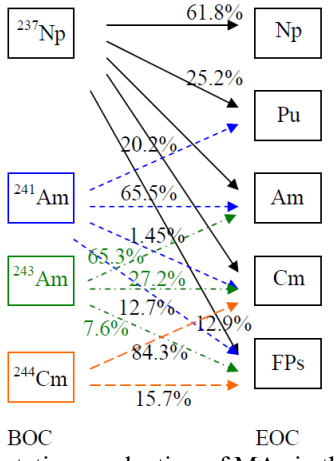

Fig. 6. Transmutation production of MAs in the GCFR core

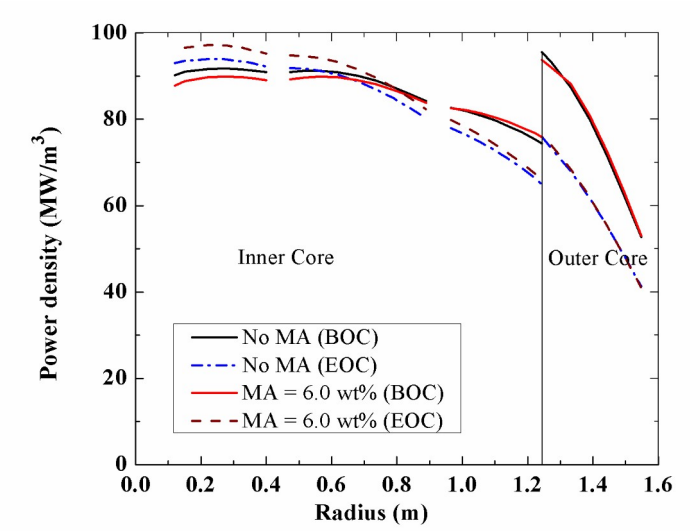

Fig. 7. Radial power distribution at the midplane of the GCFR core

Table III. Change of the heavy metal nuclide inventory.

Core region	Nuclide	Inventory of heavy metal nuclides (ton)		
		BOC	EOC	Inventory Change
Blanket	^{235}U	0.0820	0.0636	-0.0183
	^{238}U	27.2120	26.3820	-0.8300
	Total U	27.2940	26.4460	-0.8483
Active core	^{235}U	0.0652	0.0358	-0.0294
	^{238}U	21.6680	19.9370	-1.7310
	Total U	21.7330	19.9730	-1.7604
	^{237}Np	0.8820	0.5530	-0.3290
	Total Np	0.8820	0.5530	-0.3290
	^{238}Pu	0.0800	0.3874	0.3071
	^{239}Pu	2.7450	2.6732	-0.0717
	^{240}Pu	1.1810	1.1955	0.0144
	^{241}Pu	0.4350	0.2203	-0.2143
	^{242}Pu	0.2220	0.2140	-0.0081
	Total Pu	4.6630	4.6904	0.0274
	^{241}Am	0.6025	0.4849	-0.1176
	$^{242\,m}$Am	0.0014	0.0285	0.0271
	^{243}Am	0.2798	0.2042	-0.0756
	Total Am	0.8837	0.7176	-0.1661
	^{242}Cm	0.0000	0.0099	0.0099
	^{243}Cm	0.0009	0.0013	0.0004
	^{244}Cm	0.0948	0.1462	0.0514
	^{245}Cm	0.0049	0.0167	0.0118
	Total Cm	0.1006	0.1741	0.0735

C. Power distribution and void reactivity

Fissile plutonium enrichment in the inner and outer cores has been determined so that the maximum power density in the inner core at EOC matches that in the outer core at BOC. That is true because that determined plutonium enrichment is known empirically to maximize the core average power density in a two-region core. The radial power distributions at the core midplane at BOC and EOC of the GCFR are portrayed in . The maximum power density in the inner core increases from BOC to EOC by about 10% for the MA loaded core and by 3% for the core with no loaded MA, whereas that in the outer core decreases by about 20% for the GCFR. Difference of the maximum power density in the inner core and the outer core is a few percent. When the maximum power densities in the inner and outer core are approximately equal, the power peaking might be lower. Therefore, the coolant efficiency is expected to be increased.

Evaluation of void reactivity of the GCFR has been conducted by assuming that coolant pressure in the core was reduced from the rated value of 12.5 MPa to atmospheric value. Void reactivity is about 1.53 $ at BOC and 0.72 $ at EOC. The smaller void reactivity at EOC relative to that at BOC is ascribed to the decrease of MAs from BOC to EOC.

IV. CONCLUSIONS

The neutronics characteristics of a prototype 600 MWt GCFR with MA loading have been investigated and presented. Minor actinide content was determined to minimize the burnup reactivity swing. The results show that the burnup reactivity swing is minimized to 0.11% $\Delta k/kk'$ at 6.0 wt% MA loading. Once the nearly zero burnup reactivity swing is obtained, the control rod operation is minimized and the required number of control rods is reduced (10 rods compared to 19 rods of MONJU reactor). The MA transmutation rate is about 42.2 kg/yr in the GCFR, which is equivalent to the MA production rate in 7 LWRs with the same electrical power. Discrepancy of the maximum power densities in the inner and outer cores is a few percent which allows a high efficiency of the coolant. The void reactivity is 1.53 $ at BOC and 0.72 $ at EOC, respectively, which is calculated when the coolant pressure in the core was reduced from 12.5 MPa to atmospheric value

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