Design study of a small long life fast reactor core loaded with Pu without extracting MA

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Abstract

A design study of a small long life sodium cooled fast reactor core with ternary alloy U-Pu-Zr as fuel has been completed in the paper, the purpose of which is, under the strategy of non-separation of MA from Pu, to investigate general effects on core characteristics of adding MA into the core or blanket region and to demonstrate the feasibility of loading Pu without extracting MA as drive fuel in the design. Calculation results indicate that: when MA is added into core with hard neutron spectrum the burnup reactivity swing can be reduced effectively and considerable qualities of MA can be incinerated. Meanwhile, main disadvantage in such cases is the decreasing of β_{eff}, Λ and Doppler feedback, but not markedly if the amount of MA added is small. Na void worth, which increases rapidly with the addition of MA, is always the severest problem; when MA is added into blanket, the initial k_{eff} will be reduced, burnup reactivity swing will be larger and transmutation rate of MA will be lower as the spectrum in this region is softer than in core region. However, on the other hand, MA addition into blanket brings fewer penalties of kinetic parameters (β_{eff} and Λ) and reactivity feedback (Doppler coefficient and Na void worth) compared to MA addition into core. Finally, Pu from Daya Bay reactor spent fuel without extracting MA is considered as drive fuel loaded into core. The results show that, as the MA percentage in TRU is small, impacts on core performance are insignificant (basically, variations of β_{eff}, Λ and Doppler coefficient less than 10%) except Na void worth and, at the same time, benefits of high fuel proliferation resistance and considerable amount of burned MA can be obtained simultaneously.

1. Introduction

In recent years, along with economic growth and increased energy consumption of developing countries, innovative small and medium sized reactors (SMRs) are developed in many countries to meet the requirements of some special situations or supplying electricity for a small power grid. Among these SMRs, reactors with small power level but long core life are one of the hot research areas, for example, 4S and ENHS reactor, where 4S reactor using upward movement of the peripheral reflector to actualize a long core life and ENHS reactor benefiting a large enough inner conversion ratio to sustain the core excess reactivity (IAEA, Working Material, 2005). On the other hand, non-proliferation issues become more and more important while nuclear energy is widely utilized. Therefore, for the purpose of using Pu as nuclear fuel in self-security, strategy of non-separating of MA from Pu is proposed to enhance the non-proliferation capabilities of nuclear materials. However, using Pu with a small amount of MA as drive fuel will affect the core performance and these influences, whether can be accepted or not, must be further evaluated.

By considering the strong breeding capabilities of metallic fuel, a long life core with ternary alloy

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NAT.U-Pu-10Zr (G.L. Hofman et al., 1997) as drive fuel and sodium as coolant has been designed, and the effect of a small amount of MA addition into core and blanket region on the core performance has been studied. Detailed discussions are presented in Section 3 and 4.

2. Calculation tools

The fine 171 groups NVITAMIN-C lib, used as original lib, is an updating version of VITAMIN-C lib with the same format and developed by the Nuclear Data Center of CIAE (China Institute of Atomic Energy) based on the evaluated nuclear data libraries (ENDF/B-VI, JEF-2, CENDL-2 and JENDL-3). This new lib, compared to the old VITAMIN-C lib, contains more nuclides (from 66 nuclides to 105 nuclides, two of them are one group fission product of U-235 and Pu-239, respectively) and is processed by newer data (China Experimental Fast Reactor, CIAE, 2006).

Few groups microscopic cross section lib (prepared for CITATION code), which is corresponding to nuclides of various core regions, is generated by PASC-1 code system according to the specific core layout of geometry and materials. PASC-1 code system is a program package for collapsing multi-group cross sections into few groups and is similar to AMPX. The flow chart of the process is presented in Fig.1 (Bangcheng Fang et al., 2006).

Finally, CITATION code (T. B. Fowler et al., 1971) is used for full core diffusion calculation, including steady, burnup and perturbation calculation. CITATION code is widely used in reactor core analysis and is proved sufficiently to be reliable. Monte carlo code MCNP-4C (J. F. Briesmeister, 2000) is also used in the study to check k_{eff} with the result from CITATION code.

3. Core design

3.1. Basic design parameters of the core

The cylindrical type core is 120 degrees rotation symmetric except the arrangement of RE (REGULATION) control rods. Both axial blanket and radial blanket exist. However, there is only lower blanket (40cm in height) in axial direction (no upper axial reflector and gas plenum locates directly at the top of core), which is used to decrease sodium void worth by increasing axial neutron leakage. Table 1 gives basic core characteristics and Fig. 2 shows radial geometry layout of half core.

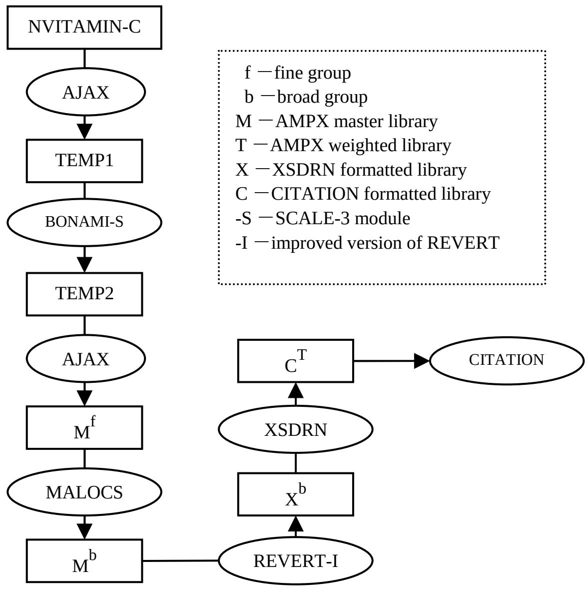


Fig.1. Flow chart of generation of few groups microscopic cross section lib

Table 1
Basic core design parameters

Parameter	Value
Thermal Power/MWt	300
Core dimensions e. q. Dia.×Height	189.181cm×80cm
FSA[a] width across flats/cm	16.6
Characteristics of FSA	
Number of fuel pins per FSA	217
Outer dia. of fuel pins/mm	10.0
P/D	1.1
Cladding thickness/mm	0.6
Fuel smear density	75%T.D.
Gas plenum/fuel volume ratio	1.0
FSA number: Inner/Outer	51/64

[a] FSA means fuel sub-assembly.

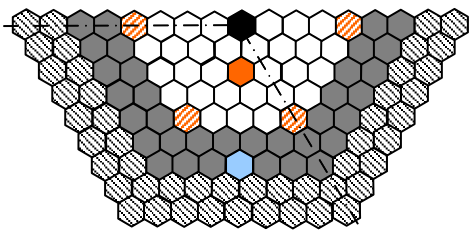


Fig. 2. Radial configuration of core.

3.2. *General impact of MA addition on the core performance*

For utilizing Pu as fuel, there are two proposition strategies: separation and non-separation of MA from Pu. The work firstly assumes MA is separated from Pu and evaluates general impact of adding a small amount of MA into the core or blanket region on core performance, and then, in the non-separating scenario, considers the feasibility of loading Pu from PWR spent fuel without extracting MA as drive fuel.

Core without MA is defined as reference core. MA is added homogeneously into the core and blanket region, respectively, and the amount is assumed to be 2.5wt% and 5.0wt%. When MA is added, Pu fraction is kept fixed and the corresponding U fraction is replaced by the adding MA. Table 2 gives the composition of MA used in the calculation, and detailed fuel and blanket material composition adopted for different cases is shown in Table 3.

Table 2
MA Composition used in the calculation

Nuclide	Weight Percentage/%
Np-237	49.1
Am-241	30.09
Am-243	15.5
Cm-243	0.05
Cm-244	5.0
Cm-245	0.26

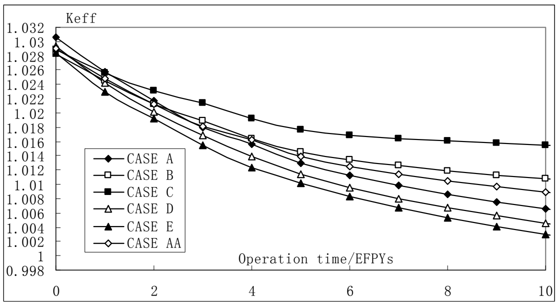
Table 3
Composition of fuel and blanket material adopted for different cases

Case	Amt. wt%	Core fuel wt%	Blan. material wt%
A	-	10.2Pu-10Zr[a] 14.28Pu-10Zr[b]	90U-10Zr
MA added into core			
B	2.5	10.2Pu-2.5MA-10Zr 14.28Pu-2.5MA-10Zr	90U-10Zr
C	5.0	10.2Pu-5.0MA-10Zr 14.28Pu-5.0MA-10Zr	90U-10Zr
MA added into blanket			
D	2.5	10.2Pu-10Zr 14.28Pu-10Zr	2.5MA-10Zr
E	5.0	10.2Pu-10Zr 14.28Pu-10Zr	5.0MA-10Zr
AA	Non-sep.	10.2Pu-1.249MA-10Zr 14.28Pu-1.749MA-10Zr	90U-10Zr

[a] Inner core. Uranium is used as supplement in all cases;

[b] Outer core.

Firstly, the k_{eff} at BOL and burnup reactivity swing during the core life are compared for different cases. Under the core spectrum of the design, fission/absorption cross section ratios of all MA nuclides are larger than that of U-238, but the absolute capture cross sections of these nuclides are also lager. Therefore, when MA is added into core, BOL reactivity does not change significantly for some reasons of U fraction is replaced partly by MA and the amount of MA is really small. But, burnup reactivity loss can be reduced observably, as shown in Fig. 3. The reason about that may be that the offspring of main MA nuclides after capture reaction have larger fission/absorption cross section ratio compared to their parent nuclides. These offspring can provide reserve reactivity under hard neutron spectrum. However, as the neutron spectrum in blanket is softer than in core, adding MA into blanket region shows the opposite results, where core reactivity at BOL decreases slightly and core burnup reactivity loss increases almost linearly with the amount of adding MA.



CASE	A	B	C	D	E	AA
$\triangle\rho^{a}$ %△K/KK'	-2.22	-1.63	-2.30	-1.26	-2.36	-1.86

[a] Burnup reactivity swing. The core life time is limited to 9~10 EFPYs due to the irradiation damage effect, although from reactivity point of view the core can be operated for a longer time.

Fig. 3. k_{eff} of different cases changes with operation time.

It can be concluded that neutronic characteristics of MA nuclides relate closely to neutron spectrum of where they have been added. Under soft spectrum (for example, in blanket), MA nuclides, including most of their descendants, are thorough neutron absorbers for their fission/absorption cross section ratios are as small as U-238 and their capture cross sections are larger than U-238. Under hard spectrum, however, only from viewpoint of reactivity and burnup reactivity swing, some favorable consequences can be obtained, as mentioned above. Fig. 4 shows the neutron spectrum of core and blanket region. It is worth to note that there is basically no significant spectrum difference between core (and blanket) with or without MA.

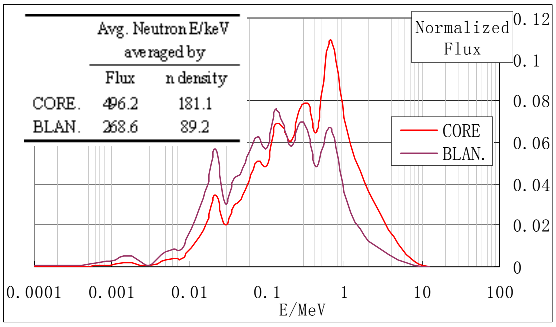


Fig. 4. Core and blanket neutron spectrum of CASE A.

Adding MA into blanket region brings fewer penalties of kinetic parameter and reactivity feedback compared to adding MA into core region, as shown in Table 4, which gives kinetic parameters and reactivity feedback of different cases.

Table 4
Kinetic parameters and reactivity feedback of different cases

CASE	β_{eff} [*a] pcm	Λ 10^{-7}s	Dop. Effect [*b] ¢/K	Na void worth [*c]/$
A	381.934	3.261	-0.112	3.408
B	359.158	2.821	-0.093	4.747
C	337.680	2.475	-0.078	6.178
D	380.799	3.205	-0.112	3.581
E	379.660	3.163	-0.112	3.473
AA	368.221	2.992	-0.101	4.192

[*a] The newest ENDF/B-VII.0 delayed neutron data is used in the calculation;

[*b] This Doppler coefficient is the linearized average value between fuel temperatures 940K and 1100K;

[*c] Assumption of voiding the whole core and core upper region in uniform is made.

When MA is added into core, β_{eff} decreases with the amount of MA addition. However that, as fast fission of U-238 contributes more than half value of β_{eff}, this decrease is not significantly. Prompt neutron lifetime Λ is similar to β_{eff}, but decreases more quickly with the amount of MA added. Besides β_{eff} and Λ, Doppler effect, mainly caused by resonance absorption of nuclide U-238, is 30% smaller in CASE C than in CASE A. On the other hand, Na void worth, which is the most sensitive parameter, increases remarkably after MA added into core. For example, compared to reference core (Case A, without MA), Na void worth of CASE B (2.5wt% MA addition) and CASE C (5.0wt% MA addition) increases by 39.4% and 81.3%, respectively. Actually, only from neutronic view of point, this unfavorable feedback, which is positive and will be a potential problem for reactor core safety, is the main limitation for MA adding into a fast reactor core, especially for a sodium cooled reactor. On the contrary, as we have mentioned above, adding MA into blanket region brings fewer penalties of kinetic parameter and reactivity feedback.

Another benefit of MA addition is incineration of these MA nuclides. Table 5 gives results of MA transmutation rate of different cases.

Table 5
MA transmutation rate of different cases

CASE	MA mass/kg		$\triangle m_{MA}$/kg	Trans. Rate
	BOL	EOL[a]	EOL-BOL	%
A	0	44	-[b]	-
B	359	276	83	23.120
C	718	517	202	28.134
D	609	579	30	4.926
E	1218	1123	96	7.882
AA	219	186	33	15.068

[a] Assumes core life of about 9EFPYs, which is constrained by irradiation damage;

[b] No MA is added into reference core, therefore, this core is a net MA producer.

On the one hand, transmutation rate increases with the amount of adding MA and is much higher in core region than in blanket; on the other hand, although the influence to core performance caused by MA addition into blanket is relatively small, which means more MA can be added into blanket and the absolute amount of burned MA is comparable to the case when MA is added into core region, we must notice that the transmutation rate in blanket is so small that we have to increase the recycle times to burn a specific amount of MA. Therefore, adding MA into blanket is not recommended.

3.3. Non-separation scenario

The content described above is under the precondition of separating MA from Pu except CASE AA; however, the strategy of non-separation of MA from Pu when Pu is utilized as nuclear fuel is proposed to enhance proliferation resistance, where MA is used as a strong barrier for its large radiotoxicity and decay heat release. In CASE AA drive fuel used in the core is non-purified Pu (containing MA) from PWR Daya Bay reactor spent fuel with burnup of 33.3MWd/kg and cooling time of 5 years (weight percentage: Pu/MA =87.754/12.246 wt%).

When Pu without extracting MA is loaded as drive fuel (CASE AA), as MA weight percentage is smaller in this case than in CASE B or C, the corresponding impacts on core performance are also relatively smaller, which can be shown in Fig. 3, Table 4 and Table 5. In CASE AA, compared to CASE A (reference core), the burnup reactivity swing decreases by 16.135%; β_{eff}、Λ and Doppler feedback is also reduced, but not significantly (basically, variations less than 10%); Na void reactivity effect increases by 23%; MA transmutation rate (about 15%) is smaller than CASE B or C as the initial loading MA mass is decreased.

It has to admit, the severest problem in CASE AA is still Na void worth, which increases from 3.408$ to 4.192$. Although this value is less than 5$, it is still an unsatisfactory hidden trouble. Positive Na density reactivity effect is a prevalent problem in Na cooled fast reactor, especially in the core fueled with metallic fuel. In the study core, the reactivity effect induced by Na void can be compensated partly by Doppler feedback (about -0.1¢/K) and fuel expansion feedback (about -0.512¢/K, axial plus radial), however that, if we want to reduce Na void reactivity effect to zero or even a negative value, some special improved designs are required, or some engineering measures should be introduced, e. g. passive shutdown system.

Table 6
BOL and EOL TRU composition of CASE A and AA

Mass/kg	CASE A		CASE AA	
	BOL	EOL	BOL	EOL
Pu	1790	1697	1790	1706
MA	0	43	219	185
MA/TRU	0	2.471%	10.901%	9.783%

Table 6 exhibits composition of TRU at BOL and EOL in CASE A and CASE AA. It is obvious that the proliferation resistance of BOL initial loading fuel and EOL discharged fuel is increased when MA is loaded together with Pu as drive fuel, because a significant amount of MA is contained in TRU.

Finally, it is worth to note that Np and Am are burned after depletion, but Cm (Cm-244 and Cm-245, especially Cm-245, of which the mass is about 3.5 times compared to the initial loading) mass increases contrarily, which would bring problems to fuel reprocessing and fabricating in fuel cycle.

4. Conclusions

The general results of adding MA into the core or blanket region can be described as follows:

I. Adding MA into core region can significantly reduce the burnup reactivity loss and the transmutation rate is relatively high, both depended on the amount of MA added; on the other hand, along with the addition of MA, β_{eff}, Λ and Doppler feedback will decrease by a certain extent, but not markedly if the amount of adding MA is small, while Na void reactivity effect is found to increase significantly after MA addition and, from neutronic viewpoint, is the main limitation for adding MA into fast reactor core.

II. Adding MA into blanket region will bring fewer penalties towards some kinetic parameters and reactivity feedback, including: β_{eff}, Λ, Doppler coefficient and Na void reactivity effect. The transmutation rate in this case, however, is really small and, furthermore, k_{eff} at BOL and burnup reactivity loss are both degraded.

In the scenario of non-separation of MA from Pu, advantages or disadvantages mentioned above are both not obvious except Na void worth, which is still the severest problem, but can be compensated partly by Doppler feedback and reactivity feedback caused by fuel thermal expansion. The most important benefit of non-separating strategy is the increasing proliferation resistance; simultaneously, during the long core life, considerable qualities of MA can be burned out. It is also worth to notice that composition of MA is changed and Cm content is increased, which would bring problems to fuel recycling.

5. Acknowledgement

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