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Preliminary study on plutonium and minor actinides utilization in thorims-nes minifuji reactor

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ABSTRACT

Molten salt reactor (MSR) design has been chosen as one of the Generation IV nuclear energy systems, since it has many merits such as proliferation resistance, resource sustainability, and safety improvement. Recently, a concept which called as thorium molten salt nuclear energy synergetic (THORIMS-NES) was being proposed for the safe and sustainable nuclear industry. THORIMS-NES miniFUJI reactor is a small power MSR which originally considers Th/^{233}U or Th/Pu as main fuel. In this study, the utilization of Pu and minor actinides (MA) in 25 MWth and 50 MWth miniFUJI reactors has been evaluated. The reactor grade plutonium and weapon grade plutonium are employed in the present study. The criticality for 25 MWth of miniFUJI can be accomplished by loading 8.76% of reactor grade Pu & MA (RGPuMA), and 3.96% of weapon grade Pu & MA (WGPuMA) in fuel, respectively. While, for that of 50 MWth, the reactor can attain its criticality with 9.16% and 4.36% of RGPuMA and WGPuMA, correspondingly. The neutron spectra become harder with the lower grade of fissile plutonium vector as well as the increasing of Pu and MA contents in loaded fuel salt.

1. Introduction

The Oak Ridge National Laboratory (ORNL) of USA has developed molten salt reactors (MSRs) in 1960s [1]. At that time, there are two types of MSR were developed in parallel, namely a *molten salt reactor experiment* (MSRE) and a *molten salt breeder reactor* (MSBR). Recently, several countries such as: US, Russia, France, Korea, Japan, and China are developing many conceptual designs of MSR.

Since it has many good points such as safety improvement, proliferation resistance, resource sustainability, ability to be used for hydrogen production due to it can operate at high temperature (>650 °C), and waste burning [2,3], MSR design has been selected as one of the six Generation IV nuclear power systems. MSR has no chance for high power surges due to online refueling and small excess reactivity, which in turn enhances the safety aspect of MSR [2]. Natural Thorium (^{232}Th) can undergo the radiative capture reaction to generate the artificial fissile nuclide ^{233}U after successive beta decays, as shown in the following process.

$$n + {}^{232}Th \rightarrow {}^{233}Th \underset{22\ \text{min}}{\rightarrow} {}^{233}Pa + \beta \underset{27d}{\rightarrow} {}^{233}U + \beta$$

Thorium–^{233}U fuel cycle will produce ^{232}U, a 2.6 MeV gamma emmiter. These later two aspects provide the resource sustainability and the proliferation resistance advantages of MSR [2].

Nowadays, a thorium molten salt nuclear energy synergetic (THORIMS-NES) concept was being proposed for the safe and sustainable nuclear industry [2]. The THORIMS-NES concept consists of three stages. The first stage is the building of the miniFUJI reactor, a small 10 MWe power reactor that may be developed during 7 years. The construction of the 100–300 MWe FUJI reactor, a thorium molten salt reactor planned to go online in 12–14 years is the second stage. The last stage is the setting up of regional breeding and chemical processing centers with production of ^{233}U by thorium spallation in AMSB (accelerator molten salt breeder) [2].

The original miniFUJI reactor design considers Th/^{233}U or Th/Pu as main fuel. In agreement with the recently suggestion to avoid the separation of Pu and minor actinides (MA), in the present study, the utilization of Pu and MA in miniFUJI reactor will be evaluated. The reactor grade plutonium and the weapon grade plutonium are employed in this study. In addition, two values of the thermal power output of miniFUJI reactor will be investigated, namely: 25 MWth and 50 MWth, respectively. These two thermal outputs may be considered as 10 MWe and 20 MWe, correspondingly, by assuming that the thermal efficiency of miniFUJI reactor is about 40%.

2. Methodology

Design parameters of miniFUJI reactor is presented in Table 1. Active core consists of several hexagonal assemblies with the reflector is made of graphite. The boron carbide is used both for

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Table 1
Specification of miniFUJI.

Physics parameters	Specification
Thermal power	25 and 50 MWt
Core geometry	
Height	2.00 m
Diameter	2.00 m
Fuel	
Types	Molten salt
Composition:	LiF, BeF_2, ThF_4, $(PuMA)F_3$
Inlet temperature	840 K
Outlet temperature	980 K
Lifetime	20 years

neutron absorber and reactor shielding [2]. The core height and diameter are 2.0 m and 2.0 m, respectively. In this preliminary study, for the thermal power of 25 MW and 50 MW the exactly same reactor size and geometry have been chosen. The power density of core are 3.98 W/cc and 7.96 W/cc for 25 MW and 50 MW thermal power output, respectively. Since this reactor operates in continuous mode with the liquid fuel, the difference of the power density can be assumed to be adjusted by changing the flow rate of the fuel salt. The detail discussion regarding the flow rate of MSR can be found in Ref. [4]. Even though, MSR can be operated continuously, the lifetime of reactor of about 20 years has been employed in this proxy study, due to the graphite lifetime. Fig. 1 shows the relation between power, lifetime of graphite and core radius of MSR, which has been taken from Refs. [5,6]. This figure is mostly match with the design parameters of 25 MWth miniFUJI. However, for 50 MWth reactor, Fig. 1 looks misleading due to the previous assumption on the reactor size and the power density. To replace the graphite, the miniFUJI reactor should be shut down when the graphite achieves its time limit due to cracking and/or swelling [6].

It should be noted that the neutronics aspect is the main consideration in the present study. The neutronics cell calculation [4] was performed by using PIJ (collision probability method code) routine of SRAC 2002 code [7], with nuclear data library is JENDL-3.2 [8]. The SRAC code with JENDL-3.2 library consists of 107 energy groups, where 48 thermal groups and 74 fast groups with 15 overlapping groups.

The composition of fuel salt is tabulated in Tables 2 and 3. The total fraction of LiF and BeF_2 in the fuel salt is fixed at 87.78%, while the total fraction of ThF_4 and $PuMAF_3$ is 12.22%. In the present paper, the fraction of $PuMAF_3$ to the total fraction of ThF_4 and $PuMAF_3$ is varied to evaluate the criticality of miniFUJI reactor. The composition of fuel for the reactor grade Pu with MA, and the weapon grade Pu with MA are also presented in Tables 2 and 3, correspondingly.

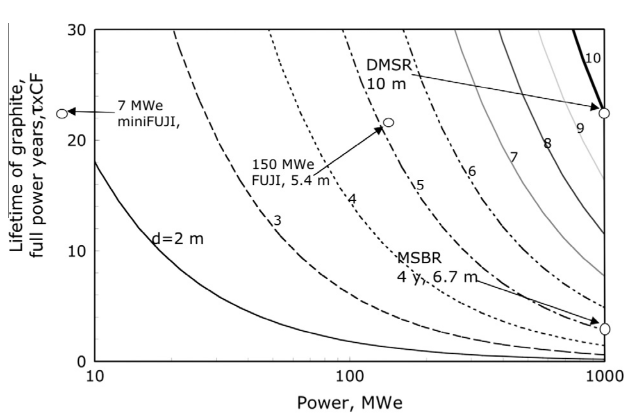

Fig. 1. Relation between power, lifetime of graphite and core radius of MSR [5,6].

Table 2
Composition of fuel for reactor grade plutonium.

LiF (%)	BeF_2 (%)	ThF_4 (%)	$PuMAF_3$ (%)
71.78	16.00	3.06–6.26	5.96–9.16

Table 3
Composition of fuel for weapon grade plutonium.

LiF (%)	BeF_2 (%)	ThF_4 (%)	$PuMAF_3$ (%)
71.78	16.00	7.86–11.06	1.16–4.36

Table 4
Reactor grade plutonium vector (%).

^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
1.58	57.76	26.57	8.76	5.33

Table 5
Minor actinides vector (%).

^{237}Np	^{241}Am	^{243}Am	^{242}Cm	^{243}Cm	^{244}Cm	^{245}Cm	^{246}Cm
42.25	47.57	8.50	0.32	0.01	1.26	0.07	0.01

Table 6
Weapon grade plutonium vector (%).

^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu	^{241}Am
0.01	93.80	5.80	0.13	0.02	0.22

The isotopic vector compositions of the reactor grade plutonium, and the minor actinides are listed in the following Tables 4 and 5, respectively. These isotopic compositions have been taken from the spent fuel composition of the 3 GWth of pressurized water reactor (PWR) with 33 tons of annual loaded uranium oxide fuel, 33 GWd/t burnup, and 10 years cooling [9]. Since the Ref. [9] offers only two data for curium isotopes, namely ^{243}Cm and ^{244}Cm, the detail isotopic composition of Curium isotopes have been derived from the other Ref. [10], based on the fact that the mass ratio of MA and Pu in the PWR spent fuel is 1:9 [11].

In case of the reactor grade plutonium, the idea for not separating Pu and MA can be accomplished practically. However, since the weapon grade plutonium is separated from the spent fuel interim storage site, this scenario can be adopted only theoretically. The isotopic vector compositions of the weapon grade plutonium is presented in Table 6 [12]. As can be seen from this table, ^{241}Am is also included in WGPu. The isotopic composition of MA in the weapon grade Pu with MA fuel is exactly same as in Table 5, so that the total fraction of isotopic composition of ^{241}Am for this case is slightly different compared to the that of the reactor grade Pu with MA case.

3. Results and discussion

Fig. 2 shows the effective multiplication factor (*k-eff*) as a function of burnup for 25 MWth of miniFUJI, where (a) for the reactor grade Pu with MA (RGPuMA), and (b) for the weapon grade Pu with MA (WGPuMA), respectively. As can be seen from the figures, the criticality condition of miniFUJI reactor can be obtained for 8.76% of RGPuMA, and 3.96% of WGPuMA, correspondingly. This fact means that 25 MWth of miniFUJI reactor can be loaded with at least 8.76% of RGPuMA, and 3.96% of WGPuMA in loaded fuel.