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Comparative Study on ^{233}U and Plutonium Utilization in Molten Salt Reactor

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Abstract

A comparative study on ^{233}U and Pu utilization in a molten salt reactor (MSR) FUJI-12 has been conducted. Originally, FUJI-12 uses LiF , BeF_2 , ThF_4 and $^{233}UF_4$ as fuel. In this study, we have evaluated the use of reactor grade plutonium and weapon grade plutonium beside ^{233}U as the fuel of reactor. The need of ^{233}U concentration for criticality is about 0.34%. In contrast, the demand of the reactor grade plutonium and the weapon grade plutonium fractions for criticality is around 3.0% and 0.96%, correspondingly. The neutron flux in the thermal energy region for ^{233}U fuel case is higher than in Pu fuel cases due to larger value of the average number of neutrons produced per neutron absorbed in ^{233}U fuel than that of ^{239}Pu fuel, and may also because of the hardening of the neutron spectrum owing to plutonium utilization in thermal reactor.

Keywords: *MSR, Fuji-12, reactor grade Pu, Weapons grade Pu, Effective multiplication factor, Neutron spectrum*

1. Introduction

Recently, nuclear power plants (NPPs) produce 17% of electricity for the world. The type of current NPPs are mostly from the Generation II, III and III+. Learning from the Chernobyl and Three Mile accidents, since 1990s the studies on the Generation IV reactors have been conducted. The latest reactor types are expected be operated since 2030.

Molten Salt Reactor (MSR) is one the six concepts of the Generaton IV reactors. MSR has the following outstanding features, namely: able to burn nuclear wastes, has inherent safety system, able to be used for hydrogen production since it can operate at high temperature (>650 ^{0}C), and it has breeding capability (in the long term run).

Originally, there are two type of MSR which have been developed in US in 1960s. They are MSRE (*molten salt reactor experiment*) and MSBR (*molten salt breeder reactor*)[1] . At present, there are many conceptual design of MSR from several countries such as: US, Russia, France, Korea, and Japan.

Japan has several conceptual designs of MSR which one of them is FUJI reactor with many varieties.

FUJI-12 is one of the FUJI reactors which has simplest geometry and more economic since it has no on-site chemical processing plant and it has low rated power[2] . Study on plutonium utilization in the other type of FUJI reactors such as FUJI with 200 MWe output has been performed which called as FUJI-Pu[3].

The aim of this study is to compare the characteristic of ^{233}U and plutonium utilization in FUJI-12. Both of the plutonium types, namely: reactor grade plutonium and weapon grade plutonium are employed in the present study.

2. Methodology

Detail specification of FUJI-12 is presented in Table 1. Active core consists of several hexagonal assemblies with the pitch diameter of 0.2 meter. The reflector is made of graphite of 0.4 m thickness. The boron carbide is used both for neutron absorber and reactor shielding. Bird eye view of the reactor core can be found in the references[2,4] .

Table 1. Specification of FUJI-12

Physics Parameters	Specification
Thermal power	350 MWt
Electric power	150 MWe
Core geometry	
hight	4.00 m
diameter	4.00 m
Fuel	
Types	*molten salt*
Composition:	
- Case1	LiF, BeF_2, ThF_4, $^{233}UF_3$
- Case2	LiF, BeF_2, ThF_4, Pu*F_3
- Case3	LiF, BeF_2, ThF_4, Pu**F_3
Inlet temperature	840 K
Outlet temperature	980 K
Refueling period	5 years
Average power density	7 kWt/ liter

Pu* : Reactor grade Pu
Pu**: Weapon grade Pu

Neutronics calculation in this study was performed by using SRAC 2002 code[5], with nuclear data library is JENDL-3.2[6].

Composition of fuel for Case 1 (^{233}Ufuel), Case 2 (reactor grade Pu fuel), and Case 3 (weapon grade Pu fuel) are presented in Table 2, 3, and 4, respectively.

Table 2. Composition of fuel for Case 1

LiF	BeF_2	ThF_4	$^{233}UF_3$
71.78%	16.00%	12.00%	0.32 %
		11.80%	0.34 %
		11.60%	0.36 %

Table 3. Composition of fuel for Case 2

LiF	BeF_2	ThF_4	PuF_3
71.78%	16.00%	8.86%	3.36 %
		9.06%	3.16 %
		9.26%	2.96 %

Table 4. Composition of fuel for Case 3

LiF	BeF_2	ThF_4	PuF_3
71.78%	16.00%	10.86%	1.36%
		11.06%	1.16%
		11.26%	0.96%

The compositions of the reactor grade plutonium and weapon grade plutonium are presented in the following Table 5 and Table 6, correspondingly[7)].

Table 5. Reactor grade plutonium composition (%)

^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu	^{241}Am
1.30	60.30	24.30	5.60	5.00	3.50

Table 6. Weapon grade plutonium composition (%)

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

3. Results and Discussion

The effective multiplication factor (*k-eff*) as a function of burnup for Case 1 (^{233}U fuel) is shown in **Figure 1**. The concentration of ^{233}U is varied from 0.32% to 0.36%. The maximum burnup is about 27 GWd/ton that corresponds to 1830 days of operation period (5 years of cycle lenght). As can be seen from this figure, the reactor can achieve its criticality with the ^{233}U concetration in the fuel of 0.34% or more.

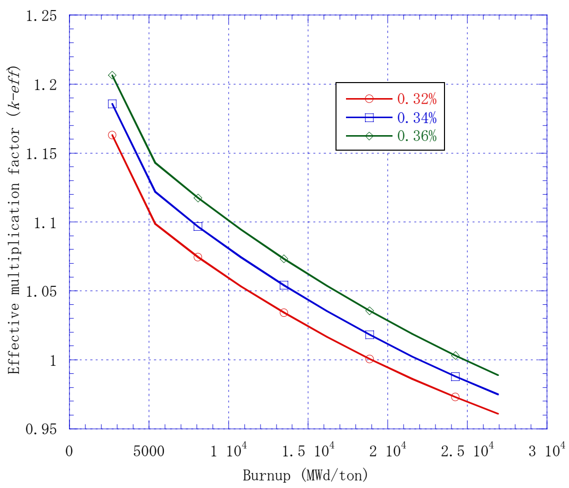

Figure 1. Effective multiplication factor as a function of burnup for Case 1

Figure 2 shows the effective multiplication factor (*k-eff*) as a function of burnup for Case 2 (reactor grade Pu fuel). The total fraction of Pu is varied from 2.96% to 3.36%. To obtain the criticality condition, the reactor grade plutonium fraction should be more than 3% since for 2.96% of total Pu fraction the k-eff is more than unity only for the first-half of the cycle lenght.

Figure 3 demonstrates the effective multiplication factor as a function of burnup for Case 3 (weapon grade Pu fuel). The total fraction of Pu is diversed from 0.96% to 1.36%. Clearly, the FUJI-12 reactor can gain its criticality for each fraction of the weapon grade plutonium.

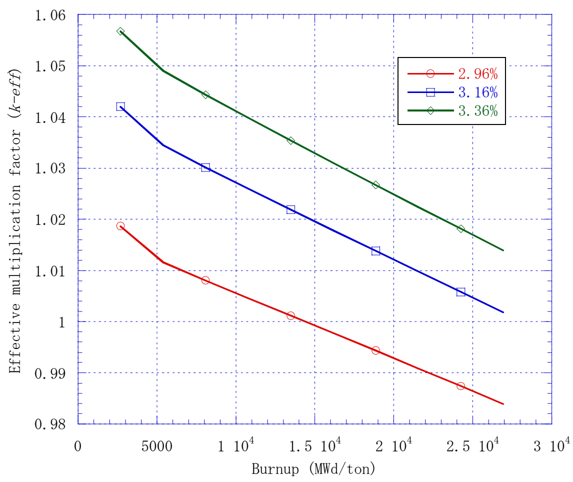

Figure 2. Effective multiplication factor as a function of burnup for Case 2

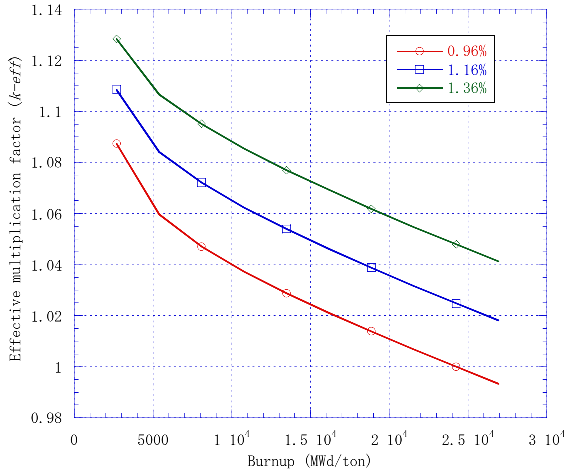

Figure 3 Effective multiplication factor as a function of burnup for Case 3

The required fraction of plutonium in Case 2 is higher than in Case 3 as a result of a huge concentration of the main fissile isotope , that is ^{239}Pu, in weapon grade plutonium in contrast with that of reactor grade plutonium.

As a matter of comparison, Figure 4 illustrates the effective multiplication factor for all evaluated cases as a function of burnup. The fraction of ^{233}U, the reactor grade Pu, and the weapon grade Pu in the fuel for this situation are same, that is 0.36%. FUJI-12 is a graphite moderated thermal reactor [3]. This figure shows the advantages of Thorium/^{233}U fuel in FUJI-12 system compared to that of Thorium/Pu fuel. This evidence may due to a larger absorption cross-section of ^{233}U compared to that of ^{239}Pu in termal energy region [8]. In addition, on the graphite moderated MSR system, the capture cross-section of ^{232}Th and ^{233}Pa and the fission cross-section of ^{233}U are in one order higher than that of solid fuel system [9].

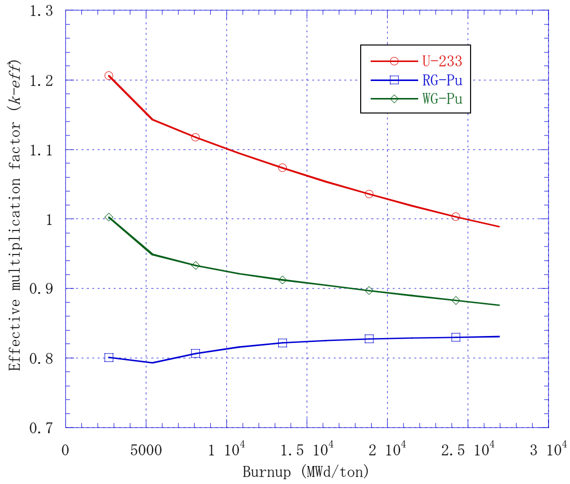

Figure 4. Comparison of the effective multiplication factor of all Cases

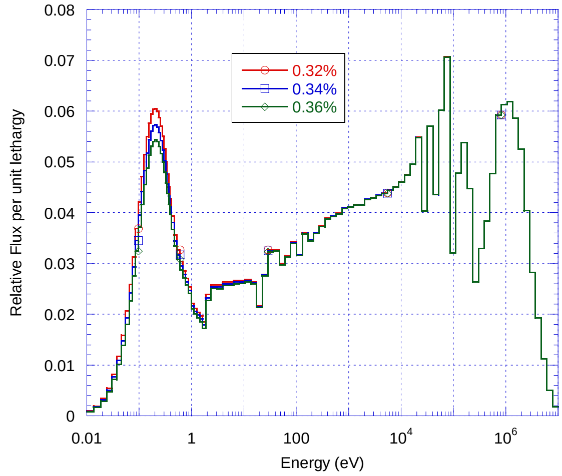

Figure 5. Neutron spectra for Case 1

The use of ^{233}U in a thermal reactor system makes it possible to achieve higher fuel conversion ratio and longer fuel burnup than with either ^{235}U or ^{239}Pu. The high conversion ratio gives possibility for significantly better utilization of natural uranium fuel resources with thorium-fueled reactors compared to the low-enrichment, light-water cooled uranium-fueled reactors.

The neutron spectra for Case 1 is presented in Figure 5. In the thermal energy region the neutron flux for the lower concentration of ^{233}U in the fuel due to smaller amount of absorption or fission reaction. The similar situation can be seen in Case 2 and Case 3. The higher fraction of either reactor grade plutonium or weapon grade plutonium in the fuel, the larger flux in the termal region, which can be observed in Figure 6 and Figure 7, respectively.

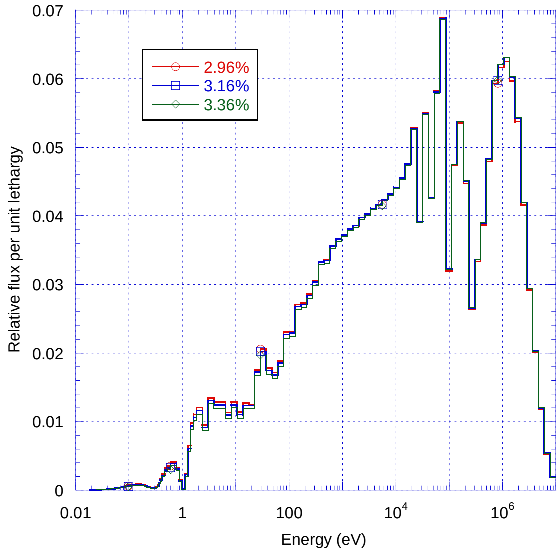

Figure 6. Neutron spectra for Case 2

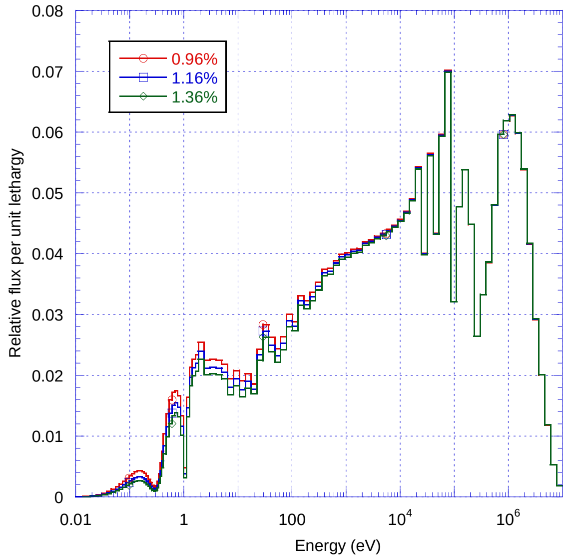

Figure 7. Neutron spectra for Case 3

As a matter of assessment, Figure 8 shows the neutron spactra for all evaluated cases. Again, the fraction of ^{233}U, the reactor grade Pu, and the weapon grade Pu in the fuel for this condition is similar, that is 0.36%. In the thermal energy region the neutron flux for Case 1 is higher than in Case 2 and Case 3 may owing to larger value of η, the average number of neutrons produced per neutron absorbed, in ^{233}U fuel than ^{239}Pu fuel[10]. In addition to this, plutonium utilization in thermal reactor may result in the hardening of the neutron spectrum [11-13].

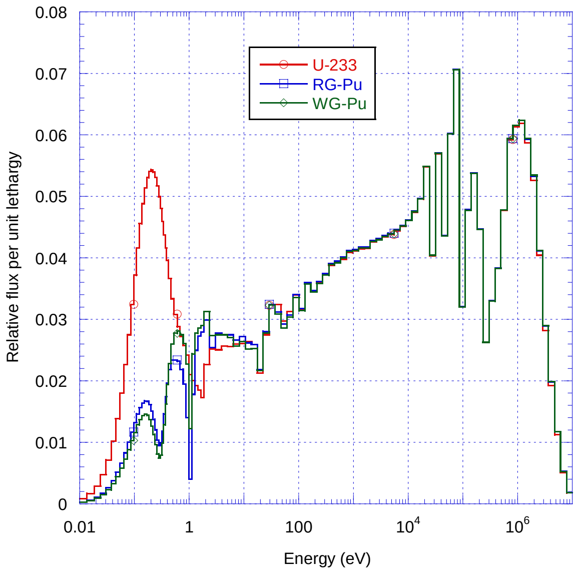

Figure 8. Comparison of the neutron spectra of all Cases

4. Conclusion

The comparative study on ^{233}U and Pu utilization in MSR FUJI-12 has been carried out. The required ^{233}U concentration for criticality is about 0.34%. On the other hand, the required fraction of the reactor grade plutonium and the weapon grade plutonium fractions for criticality is about 3.0% and 0.96%, respectively.

The required fraction of plutonium in the weapon grade type is higher than in the reactor grade type by reason of a enormous concentration of ^{239}Pu in the weapon grade type of plutonium.

The neutron flux in the thermal energy region for ^{233}U fuel case is higher than in Pu fuel cases may in concequence of higher value of the average number of neutrons produced per neutron absorbed in ^{233}U fuel than ^{239}Pu fuel and the hardening of the neutron spectrum due to plutonium utilization in thermal reactor.

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