Preliminary Study on LiF4-ThF4-PuF4 Utilization as Fuel Salt of miniFUJI Molten Salt Reactor

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Abstract. The miniFUJI reactor is molten salt reactor (MSR) which is one type of the Generation IV nuclear energy systems. The original miniFUJI reactor design uses LiF-BeF\textsubscript{2}-ThF\textsubscript{4}-\textsuperscript{233}UF\textsubscript{4} as a fuel salt. In the present study, the use of LiF\textsubscript{4}-ThF\textsubscript{4}-PuF\textsubscript{4} as fuel salt instead of LiF-BeF\textsubscript{2}-ThF\textsubscript{4}-PuF\textsubscript{4} will be discussed. The neutronics cell calculation has been performed by using PIJ (collision probability method code) routine of SRAC 2006 code, with the nuclear data library is JENDL-4.0. The results reveal that the reactor can attain the criticality condition with the plutonium concentration in the fuel salt is equal to 9.16% or more. The conversion ratio diminishes with the enlarging of plutonium concentration in the fuel. The neutron spectrum of miniFUJI MSR with plutonium fuel becomes harder compared to that of the \textsuperscript{233}U fuel.

Keywords: MSR, miniFUJI, fuel salt, lithium, thorium, plutonium

1. Introduction

Recently, thorium fuel cycle becomes an interesting issue since it more abundance than uranium and generates less nuclear high level wastes (HLW), such as plutonium and minor actinides [1]. Beside that it has high achievable conversion ratio in thermal energy region, good neutron and thermal physical properties, and the opportunity to reduce enrichment in fuel cycle [1]. One of the ways for utilizing thorium in nuclear reactors is to be used as main fuel in the molten salt reactor (MSR) [2]. MSR has the waste burning capability, small excess reactivity, and possibility to be used for hydrogen production [2-3].

Most of MSR designs consider Th-\textsuperscript{233}U or Th-Pu as main fuel with the fuel salt chemical composition is LiF-BeF\textsubscript{2}-ThF\textsubscript{4}-\textsuperscript{233}UF\textsubscript{4} or LiF-BeF\textsubscript{2}-ThF\textsubscript{4}-PuF\textsubscript{4} [2-4]. Preliminary studies on plutonium and minor actinides utilization in miniFUJI reactor has been conducted [5-6]. In these previous studies, several thermal power output and core sizes of miniFUJI reactor have been evaluated.

In the present study, plutonium utilization in miniFUJI MSR with LiF\textsubscript{4}-ThF\textsubscript{4}-PuF\textsubscript{4} as fuel salt instead of LiF-BeF\textsubscript{2}-ThF\textsubscript{4}-PuF\textsubscript{4} will be discussed.
2. Materials and method

The design parameters of studied small molten salt reactor of miniFUJI are shown Table 1. The thermal power output is 25 MWth with power density of 3.98 W/cc. Since the thermal efficiency is about about 40%, the reactor can produces 10 MW of electric power output [5]. The corresponding core diameter and height are 2.0 m, and 2.0 m, respectively. Even though, miniFUJI MSR can be operated for 20 years, in this study, the lifetime of reactor was set to 5 years.

As a matter of facts, the main consideration in this preliminary study is the neutronics aspect only. The neutronics cell calculation has been conducted by using PIJ (collision probability method code) routine of SRAC 2006 code [7], with the nuclear data library is JENDL-4.0 [8]. The volume ratio of fuel salt and graphite moderator is 30% and 70%, respectively.

| Physics Parameters | Specification |
|--------------------|---------------|
| Thermal power (MW) | 25            |
| Power density (W/cc) | 3.98         |
| Core geometry:     |               |
| Height (m)         | 2.0           |
| Diameter (m)       | 2.0           |
| Fuel types         | Molten Salt   |
| Fuel Composition   | LiF, ThF, PuF |
| Volume ratio of Fuel & Graphite (%) | 30 : 70 |
| Inlet temperature (K) | 840            |
| Outlet temperature (K) | 980           |
| Operation time (y) | 5             |

In this study we have employed the reactor grade plutonium with the isotopic vector composition is given in Table 2. These isotopic compositions of the reactor grade plutonium has 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]. The fuel salt composition is tabulated in the following Table 3.

| Reactor grade plutonium vector (%) |
|------------------------------------|
| $^{239}$Pu | $^{239}$Pu | $^{240}$Pu | $^{241}$Pu | $^{242}$Pu |
| 1.58       | 57.76      | 26.57      | 8.76       | 5.33       |

| Composition of evaluated fuel salts |
|-------------------------------------|
| No. | LiF (%) | ThF (%) | PuF (%) |
|-----|---------|---------|--------|
| 1   | 71      | 21.44   | 7.56   |
| 2   | 71      | 21.04   | 7.96   |
| 3   | 71      | 20.64   | 8.36   |
| 4   | 71      | 20.24   | 8.76   |
| 5   | 71      | 19.84   | 9.16   |
| 6   | 71      | 19.44   | 9.56   |
3. Results and discussion

The effective multiplication factor as a function of operation time for miniFUJI reactor with LiF$_4$-ThF$_4$-PuF$_4$ is presented in Figure 1. The effective multiplication factor (k-eff) is a parameter to evaluate the criticality condition of the nuclear reactor. The criticality means the condition where the fission reaction in the reactor can be maintained to undergo continuously along the operation time of reactor. If the k-eff is equal or larger than unity, the reactor can maintain the chain fission reaction. As given in this figure, the reactor can achieve its criticality with the plutonium concentration in the fuel salt is $\geq 9.16\%$.

![Figure 1 the effective multiplication factor](image1.png)

Figure 1 the effective multiplication factor

One of neutronics parameters that may be change in the reactor is the conversion ratio (CR). The conversion ratio is defined as a ratio between the production rate and the consumption rate of the

![Figure 2 the conversion ratio](image2.png)

Figure 2 the conversion ratio
fertile nuclides and fissile nuclides, respectively [10-11]. The conversion ratio indicates the performance of the reactor to produce more or less fissile nuclides in the reactor core. If CR is higher than unity, more fissile nuclides were produced in the reactor, and so on. Since the studied MSR utilizes thorium and plutonium, this ratio includes the contribution from intermediate nuclides such as $^{234}\text{U}$ and $^{233}\text{Pa}$. The value of the conversion ratio is calculated by using the nuclide number densities and microscopic cross-sections.

Figure 2 shows the change of the conversion ratio as a function of operation time. As can be seen in this figure, the conversion ratio reduces with the increasing of plutonium concentration in the fuel due to the enlarging of the consumption rate of the fissile nuclides such as $^{239}\text{Pu}$.

![Figure 3](image-url) Comparison of the neutron spectra

The neutron spectra of 25 MWt miniFUJI MSR with several types of fuels are presented in Figure 3. The types of fuels are LiF-BeF$_2$-ThF$_4$-$^{233}\text{UF}_4$ fuel with 0.52% $^{233}\text{U}$, LiF-BeF$_2$-ThF$_4$-$\text{PuF}_4$ fuel with 5.76% RG Pu, and LiF$_4$-ThF$_4$-$\text{PuF}_4$ fuel with 9.16% RG Pu, correspondingly. The neutron spectrum of miniFUJI MSR with RG Pu fuels become harder compared to that of the $^{233}\text{U}$ fuel. The neutron spectrum of miniFUJI MSR with LiF-BeF$_2$-ThF$_4$-$\text{PuF}_4$ is similar to that of LiF$_4$-ThF$_4$-$\text{PuF}_4$ fuel, even though the neutron spectrum of LiF$_4$-ThF$_4$-$\text{PuF}_4$ is very slightly much harder compared to that of LiF-BeF$_2$-ThF$_4$-$\text{PuF}_4$ fuel.

These evidences may be due to the presence of plutonium isotopes especially absorber isotopes (such as $^{238}\text{Pu}$ and $^{240}\text{Pu}$) in the reactor grade plutonium. Moreover, in these two cases the plutonium concentrations are high enough. This fact has also been reported in the references regarding the plutonium utilization in thermal reactor which results in the hardening of the neutron spectrum [12-13].

4. Conclusion

Proxy study on plutonium utilization in miniFUJI MSR with LiF$_4$-ThF$_4$-$\text{PuF}_4$ as fuel salt instead of LiF-BeF$_2$-ThF$_4$-$\text{PuF}_4$ has been carried out. The results show that the reactor can obtain the criticality with the plutonium concentration in the fuel salt is equal to 9.16%. The conversion ratio decreases with the increasing of plutonium concentration in the fuel due to the enlarging of the consumption rate of the fissile nuclides such as $^{239}\text{Pu}$. The neutron spectrum of miniFUJI MSR with RG Pu fuels become harder compared to that of the $^{233}\text{U}$ fuel.
Acknowledgments

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