Plutonium and Minor Actinides Utilization in FUJI-U1 Molten Salt Reactor

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Abstract. One type of standard Molten Salt Reactor (MSR) uses graphite as moderator and LiF-BeF\textsubscript{2}-ThF\textsubscript{4}-\textsuperscript{233}UF\textsubscript{4} as fuel. Recycling of spent nuclear such as plutonium and minor actinides are considered as one of the effective ways to handle the spent nuclear fuel. Plutonium and minor actinides utilization in FUJI-U1 type of MSR have been evaluated. MSR FUJI U1 is one of small MSR which was designed by Japan. Neutronic calculation was performed using PIJ modules of SRAC 2006 code with JENDL 4.0 as nuclear data library. Several neutronic parameters, such as effective multiplication factor, conversion ratio, and neutron spectrum were evaluated. Even though there are several types of plutonium, in this study, only reactor grade plutonium was taken into account.

Keywords: MSR, FUJI-U1, Plutonium, Minor Actinides, SRAC 2006, JENDL 4.0

1. Introduction

Molten Salt Reactor (MSR) is one of the six Generation IV nuclear reactor systems which is designed by several countries. The first experimental of MSR has been developed by Oak Ridge National Laboratory (ORNL) in the 1950s. They built the Molten Salt Reactor Experiment (MSRE) and Molten Salt Breeder Reactor (MSBR) with the output of 7.5 MWTh and 1000 MWTh, respectively\cite{1}. Based on these reactor designs, the MSR research had been spreading over the world. Recently, MSR has received enormous attention owing to its advantages, such as outstanding safety, easy handling of nuclear fuel spent, and can produce the hydrogen at high temperature (~650\degree C)\cite{2}\cite{3}.

FUJI-U1, a small MSR that has developed by Japan, uses graphite as a moderator which will define the reactor lifetime \cite{4}. The molten salt is used as a fuel salt which consists of thorium (\textsuperscript{232}Th)
and uranium ($^{233}$U) as fertile and fissile nuclides, respectively[4]. Several types of plutonium such as reactor grade plutonium, weapon grade plutonium, and super grade plutonium can be used as an alternative fuel salt [5]. It is worth to note that the reactor grade plutonium is a spent fuel of other reactors, especially Light Water Reactors (LWRs). Despite being a spent nuclear reactor, this plutonium still has a comparable fissile nuclide concentration with uranium. Various of minor actinides which are the spent nuclear reactor also can be used as an alternative fuel salt.

Our group has been studied the utilization of reactor grade plutonium and minor actinides as an alternative fuel salt on the MSR reactors e.g., minifuji reactor and small molten salt reactor [6][7]. To best of our knowledge, there is no report regarding the reactor grade plutonium and minor actinides as an alternative fuel salt on the MSR FUJI-U1. This scheme is worth to study since this scheme also reduces the spent nuclear fuel simultaneously.

In this paper, we used this scheme and analyzed the neutronic parameters such as multiplication factor, conversion ratio and neutron spectrum in MSR FUJI-U1 using plutonium and minor actinides as the main fuel. The neutronic calculation was performed using PIJ (the collision probability method) module in SRAC 2006 with JENDL 4.0 as a nuclear data library [8].

2. Methodology

The specification of FUJI-U1 design, Japan is shown in Table 1. The electric output and thermal output of the reactor are 200MWe and 450MWt, respectively. The lifetime of the reactor is 20 years, this based on the lifetime of graphite as a moderator [2, 9]. This reactor has homogenous molten salt as a fuel in the active core. The initial composition of molten salt in the reactor is 71.76% of LiF, 16% of BeF$_2$, 12% of ThF$_4$, and 0.24% of PuMAF$_4$. The three variations of fuel volume fraction which is presented in Table 2 were investigated. The fuel volume fraction of fuel B is less than fuel A and C, thus the moderator which used in fuel B is higher than others.

### Table 1. Specification of FUJI-U1 design [4]

| Parameters                  | Specification    |
|-----------------------------|------------------|
| Thermal Output              | 450MWt           |
| Thermal Efficiency          | 44.40%           |
| Reactor Vessel              |                  |
| - Diameter / Height (inner) | 5.40 m/5.34 m    |
| - Thickness                 | 0.05 m           |
| Core                        |                  |
| - Diameter / Height         | 4.72 m/4.66 m    |
| - Fuel volume fraction (av.)| 36%              |
| Fuel path / Duct            |                  |
| - Width                     | 0.04 m           |
| - Fuel volume fraction      | 90vol%           |
| Reflector                   |                  |
| - Thickness                 | 0.30 m           |
| - Fuel volume fraction      | 0.5 vol%         |
| Power density               | 5.5 MW/m$^3$     |
| Multiplication factor       | ca. 1.01         |
Table 2. Fuel volume fraction [10]

| Type of fuel | Fuel A | Fuel B | Fuel C |
|--------------|--------|--------|--------|
| Fuel volume fraction | 0.39   | 0.27   | 0.45   |

The criticality of the reactor was calculated in varying the concentration of fuel salt that shown in Table 3 with output the effective multiplication factor, conversion ratio, and neutron spectrum. The effective multiplication factor ($k_{eff}$) is one of critical parameter of the reactor. If the value of $k_{eff}$ is less than one the reactor in subcritical condition, more than one the reactor in supercritical condition, and equal to one the reactor in critical condition [11].

Table 3. Variation of fuel salt concentration

| Fuel A | Fuel B | Fuel C |
|--------|--------|--------|
| LiF | BeF$_2$ | ThF$_4$ | PuMAF$_4$ |
| 6.64% - 12.00% | 0.24% - 5.6% |
| 71.76% | 16% | 6.24% - 12.00% | 0.24% - 6.0% |
| 6.84% - 12.00% | 0.24% - 5.4% |

Table 4. Reactor grade plutonium [5]

| Isootope | Fuel A | Fuel B | Fuel C |
|---------|--------|--------|--------|
| $^{238}$Pu | $^{239}$Pu | $^{240}$Pu | $^{241}$Pu | $^{242}$Pu |
| 1.58% | 57.76% | 26.57% | 8.76% | 5.33% |

Table 5. Minor actinides [12]

| Isootope | Fuel A | Fuel B | Fuel C |
|---------|--------|--------|--------|
| $^{237}$Np | $^{241}$Am | $^{243}$Am | $^{242}$Cm | $^{244}$Cm | $^{245}$Cm | $^{246}$Cm |
| 42.25% | 47.57% | 8.50% | 0.32% | 0.01% | 1.26% | 0.07% | 0.01% |

Based on the fact, the mass ratio both of plutonium and minor actinides in the spent nuclear fuel is 9:1 [13]. The reactor grade plutonium composition is shown in Table 4 which consists of $^{239}$Pu and $^{241}$Pu as fissile nuclides that can lead fission reaction and others as fertile nuclides that can decay to fissile nuclides. The minor actinides composition is shown in Table 5 which will be burned in the homogenous fuel salt.

3. Results and Discussion

Figure 1 shows the effective multiplication factor as a function of burnup for (a) fuel A, (b) fuel B, and (c) fuel C, respectively. As shown on the graph, if the concentration of plutonium and minor actinides is increased in the fuel salt, the value of effective multiplication factor will increase as well. This is due to the total fissile in the fuel salt. The reactor achieved its criticality condition with burn up $2.5 \times 10^8$MWday/Ton, if we loaded plutonium and minor actinides in fuel salt (PuMAF$_4$) of 5.6%, 6%, and 5.4% for fuel A, fuel B, and fuel C, respectively.
Conversion ratio in the neutronic calculation is a comparison between the total fissile which is converted from fertile nuclides and the total fissile nuclide which is burned on the active core. Figure 2 shows the conversion ratio as a function of burnup for (a) fuel A, (b) fuel B, and (c) fuel C, respectively. If the concentration of plutonium and minor actinides in fuel salt is increased, the value of conversion ratio will decrease. This trend is similar for fuel A, fuel B, and fuel C.
Figure 2. Conversion ratio vs burnup for (a) fuel A, (b) fuel B, and (c) fuel C.

Figure 3. Neutron spectrum vs log energy for (a) fuel A, (b) fuel B, and (c) fuel C.

The comparison of the spectrum neutron as a function of log energy is described in Figure 3 for (a) fuel A, (b) fuel B, and (c) fuel C, respectively. In the thermal energy range \((10^3 \text{ eV} - 10^6 \text{ eV})\), the neutron spectrum becomes harder if the concentration of plutonium and minor actinides in the fuel salt is increased. The trend of the neutron spectrum is similar for these three cases but the spectrum
neutron for fuel B is higher than other. This is due to the higher contain of plutonium and minor actinides, which also have mention in the references [7, 14].

4. Conclusion
Utilization of plutonium and minor actinides in FUJI-U1 Molten Salt Reactor has been investigated. The reactor can achieve the criticality condition with loading plutonium and minor actinides of 5.6%, 6.0%, and 5.4% for fuel A, fuel B, and fuel C, respectively. If the concentration of plutonium and minor actinides in the fuel salt is increased, the conversion ratio will decrease and the neutron spectrum becomes harder.

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