Advanced Nuclear Reactor AP1000 with ThO$_2$-UO$_2$ Fuel

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Abstract. Thorium can be used for next generation nuclear reactor fuel since it has 3-4 times more abundance and will produce less nuclear high level waste compared to uranium. In this analysis, ThO$_2$-UO$_2$ fuel is used with variation of enriched U-235 to determine the criticality condition of Westinghouse advanced nuclear reactor AP1000. Neutronic calculations have been performed using SRAC 2006 code system with JENDL 4.0 nuclear data library. AP1000 can achieve it criticality when a minimum enrichment of UO$_2$ is 4.45% with the maximum amount of the ThO$_2$ fuel rods in the fuel assembly are 1.5%. The conversion ratio for ThO$_2$-UO$_2$ fuel tends to increase and the neutron spectra became harder with the escalating of the amount of the ThO$_2$.

Keywords: AP1000, ThO$_2$, UO$_2$, SRAC 2006, JENDL 4.0

1. Introduction

Thorium is one of the nuclides that can be used for nuclear reactor fuel, which has more than triple abundance compared to uranium. Therefore the research on the use of thorium as nuclear reactor fuel is revisited. However, thorium is a fertile material so that the other fissile material is required for starting up the fission reaction within the reactor core. In thermal reactor, the absorption cross-section of thorium (Th-232) is three times larger compared to that of U-238, which leads to the more amount of fissile material produced in the reactors [1].

The researchs on the thorium fuel cycle is less intensive compared to that of uranium fuel cycle. Nevertheless, ThO$_2$ is chemically very stable and not oxidized in the operation and spent fuel management, and for this reason will provide the other advantages [1, 2].

In this study, we have performed a neutronic evaluation of advanced nuclear reactor AP1000 with ThO$_2$-UO$_2$ fuel. Here, the use of thorium is accompanied by the use of enriched U-235 as a driver fissile material. The minimum enrichment of uranium and the percentage of thorium fuel rods in each fuel assembly have been evaluated to achieve the criticality of reactor.
2. Methodology

Design parameters of studied APWR (advanced pressurized water reactor) AP1000 are presented in Table 1 [3-6]. AP1000 reactor is operated during 4.5 years of operation time to achieve the 31.4 GWd/ton burnup.

Table 1 AP1000 design parameters

| Parameter                     | Value       |
|-------------------------------|-------------|
| Thermal power output          | 3400 MWth   |
| Average linear power          | 187.66 (W/cm) |
| Diameter of active core       | 321 (cm)   |
| (pin pitch)                   | 1.26 (cm)  |
| Fuel pellet diameter          | 0.81915 (cm) |
| Fuel Type                     | Oxide      |
| Cladding                      | ZIRLO      |
| Coolant                       | H₂O        |

In this study, the cell and burnup calculations were performed by using the SRAC 2006 code with the fuel assembly configuration is IGT9 [7]. Each fuel assembly is divided into 8 equal sections, so the required input data is only for 1/8 part of the whole assembly region as presented in following Fig. 1 [3]. The JENDL 4.0 nuclear data library has been employed for these both calculation schemes [8,9].

![Fuel assembly configuration in IGT9](image)

Fig. 1. Fuel assembly configuration in IGT9

The enrichments of uranium are: 4.45 a%, 4.60 a%, 4.75 a%, 4.90 a% and 5.00 a% and then the maximum amount of ThO₂ fuel rods in each fuel assembly is determined to obtain the criticality condition of the reactor. In other words, there are two types of loaded fuels in each fuel assembly, namely: enriched UO₂ fuel rods and ThO₂ fuel rods.
To accomplish the criticality condition of AP1000, a number of UO₂ enrichment have been evaluated, those are: 4.45 a%, 4.60 a%, 4.75 a%, 4.90 a%, and 5.00 a%, respectively.

3. Results and Discussion

Fig. 3, 4, 5, 6, and 7 show the effective multiplication factor ($K_{\text{eff}}$) for 4.45 a%, 4.60 a%, 4.75 a%, 4.90 a% and 5.00 a% of UO₂ enrichments, respectively. As can be seen from these figures, for 4.45 a% of UO₂ enrichments, the criticality can be achieved when maximum amount of ThO₂ fuel rods are 1.5% in fuel assembly. However, for 4.60 a% to 5.00 a% of UO₂ enrichment, the maximum amount of ThO₂ fuel rods in fuel assembly increase to 6.0% to 14.0%, correspondingly. The amount of ThO₂ fuel rods in fuel assembly enlarge with the augmenting of enrichment of UO₂. These enhancement of enrichment of UO₂ will amplify the amount of the fissile material in fuel assembly.

Fig. 2. ThO₂ Fuel rods position in fuel assembly

Fig. 3. $K_{\text{eff}}$ for 4.45 a% UO₂ enrichment
Fig. 4. $K_{\text{eff}}$ for 4.60 a% UO$_2$ enrichment

Fig. 5. $K_{\text{eff}}$ for 4.75 a% UO$_2$ enrichment

Fig. 6. $K_{\text{eff}}$ for 4.90 a% UO$_2$ enrichment
Fig. 7. $K_{\text{eff}}$ for 5.00 a% UO$_2$ enrichment

Fig. 8. Comparison of conversion ratio

Fig. 9. Comparison of neutron spectra

Fig. 8 illustrates the comparison of conversion ratio (CR) for 4.45 a% of UO$_2$ enrichment with 1.5% of ThO$_2$ fuel rod, 4.60 a% of UO$_2$ enrichment with 6.0% of ThO$_2$ fuel rod, 4.75 a% of UO$_2$ enrichment with 8.0% of ThO$_2$ fuel rod, 4.90 a% of UO$_2$ enrichment with 12.0% of ThO$_2$ fuel rod, and 5.00 a% of UO$_2$ enrichment with 14.0% of ThO$_2$ fuel rod in fuel assembly. As can be seen from these figures, the
conversion ratio increases with the raising of ThO$_2$ fuel fraction in the fuel assembly. Conversion ratio is the ratio between the production rate and the absorption rate of fuel nuclides in the reactor.

The comparison of neutron spectra for 4.45 a% of UO$_2$ enrichment with 1.5% of ThO$_2$ fuel rod, 4.60 a% of UO$_2$ enrichment with 6.0% of ThO$_2$ fuel rod, 4.75 a% of UO$_2$ enrichment with 8.0% of ThO$_2$ fuel rod, 4.90 a% of UO$_2$ enrichment with 12.0% of ThO$_2$ fuel rod and 5.00 a% of UO$_2$ enrichment with 14.0% of ThO$_2$ fuel rod in fuel assembly is presented in Fig. 9. For all cases, in thermal energy region, the neutron spectra become harder (shifts to the high energy region) with the escalating of Th-232 nuclides in the fuel assembly. This may due to the larger cross section capture of Th-232 in thermal energy region. Similar trends can be found in the references [10-12]. Moreover, the neutron spectra also become harder with the augmenting of enrichment of UO$_2$.

4. Conclusion
Neutronics analysis of AP1000 nuclear reactor with ThO$_2$-UO$_2$ fuel has been evaluated. The reactor can obtain it criticality for as a minimum 4.45 a% of UO$_2$ enrichment with the maximum amount of ThO$_2$ fuel rod in the fuel assembly is at least 1.5%. The conversion ratio tend to increase with the raising of ThO$_2$ fuel fraction in the fuel assembly and the neutron spectra become harder with the enlarging of UO$_2$ enrichment as well as the escalating of the amount of ThO$_2$ fuel in the fuel assembly.

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