A Depletion Analysis of Thorium Epithermal Reactor with Carbide Fuel

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1. Introduction

With the limited resources of uranium in the world, abundant thorium may be solution for nuclear fuel in the near future. Thorium could be used to provide an external source of fissile material to start the fuel cycle of ^{232}Th and ^{233}U [1]. For the fissile fuel ^{233}U which is produced from the neutron capture reaction of ^{232}Th, the number of neutrons produced per neutron absorbed in the fuel, that is, regeneration factor(η) is greater than 2.0 in the wide energy range. Therefore, the ^{232}Th-^{233}U fuel cycle can operate and breed with fast, epithermal or thermal spectra [2]. Many researches have been carried out the feasibility study on thorium fueled reactors which exhibit that more favorable physical and mechanical properties compared with those of uranium even though thorium has several disadvantages.[3]-[5]

There are many thorium compounds exist, such as thorium oxide, thorium carbide, thorium nitride. In this study, thorium carbide (ThC_2) ceramic fuel is chosen with the fissile material $^{233}UC_2$. [6] It is well known that the thorium carbide keeps more thorium content for longer reactor operation. Various cases of fissile content have been investigated to achieve long reactor cycle to sustainably operate the reactor without shutdown. The enrichment is varied from 2.5-4.5% $^{233}UC_2$ for the whole core, in addition to various schemes of enrichment configurations with Monte Carlo depletion analysis with MCNP6 code [7].

2. Modeling and Analysis Condition

The core design calculation has been performed on a ThO_2+$^{233}UO_2$ fuel reactor with 100 MWt with a cycle length of 1000 days and various sensitivity analyses are done to achieve enhanced thorium utilization.[5] In this study, thorium oxide fuel is replaced by thorium carvide and reduced power from 100MWt to 30MWt. The remaining reactor parameters are maintained. The thorium carbide small reactor consists of 24 fuel assemblies and one fuel assembly is composed of 236 fuel rods and 5 waterholes. And the boron carbide is adapted for the control rod. The core configuration is depicted in Fig. 1 and the core parameters are provided in Table 1.

Table 1. Design Parameters for ThUC reactor

Description	Parameters
Thermal power (MWt)	30
Fuel material	ThC_2+$^{233}UC_2$
Fuel density (g/cc)	10.61
Number of fuel assemblies	24
Number of fuel rods per FA	236
Active core height (cm)	126.72
Fuel rod diameter (cm)	0.5
Cladding material	Zircaloy-4
Coolant	H_2O
Control rod	B_4C

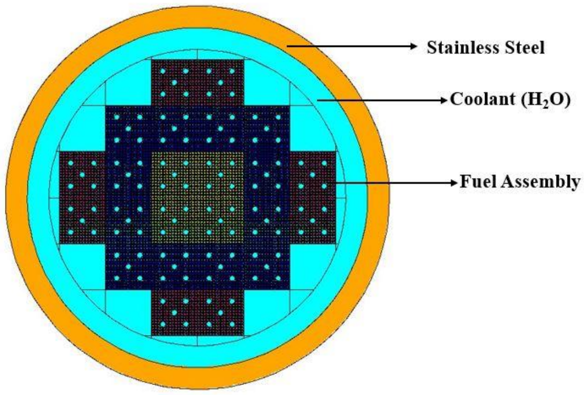

Fig. 1. Core configuration of thorium carbide small reactor

In this study, ceramic fuel composition is assumed such as the mixed fuel composed of ThC_2 as the main fuel and various content of $^{233}UC_2$ as a fissile material by following the previous study.[6] It is known that ^{233}U is difficult to separate due to high radioactivity but in this study ^{233}U is assumed to be separated by the suggested process.[1] In order to find the characteristics of thorium carbide reactor, a sensitivity study is conducted for different combinations of the fissile material $^{233}UC_2$. Three cases are chosen and the fuel compositions are provided in Table 2.

Table 2. Thorium Carbide Fuel Composition

Cases	Fuel Composition
Case 1	97.5% ThC_2 + 2.5% $^{233}UC_2$
Case 2	96.5% ThC_2 + 3.5% $^{233}UC_2$
Case 3	95.5% ThC_2 + 4.5% $^{233}UC_2$

Considering refueling, three regions are separated as shown in Fig. 2. In addition, four cases are chosen with region-wise different compositions as shown in Table 3. Thus the homogeneous cores are composed from Case1 to Case3 and the 3 region heterogeneous reactors are from Case4 to Case7.

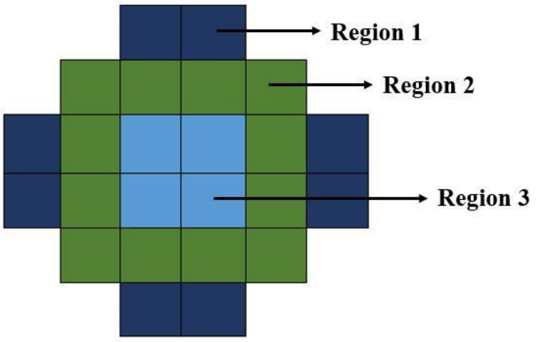

Fig. 2. Heterogeneous core configuration with 3 different regions

Table 3. Fuel compositions of various cases

Cases	Fuel Composition
Case4	Region 1: 95.5% ThC_2 + 4.5% $^{233}UC_2$ Region 2: 97.5% ThC_2 + 2.5% $^{233}UC_2$ Region 3: 95.5% ThC_2 + 4.5% $^{233}UC_2$
Case5	Region 1: 97.5% ThC_2 + 2.5% $^{233}UC_2$ Region 2: 96.5% ThC_2 + 3.5% $^{233}UC_2$ Region 3: 95.5% ThC_2 + 4.5% $^{233}UC_2$
Case6	Region 1: 97.5% ThC_2 + 3.5% $^{233}UC_2$ Region 2: 95.5% ThC_2 + 4.5% $^{233}UC_2$ Region 3: 97.5% ThC_2 + 2.5% $^{233}UC_2$
Case7	Region 1: 95.5% ThC_2 + 4.5% $^{233}UC_2$ Region 2: 96.5% ThC_2 + 3.5% $^{233}UC_2$ Region 3: 97.5% ThC_2 + 2.5% $^{233}UC_2$

All the calculations are carried out using MCNP6.1 code [7], and the kcode card and the burn card is used with 10,000 neutron histories to determine k-effective with ENDF/B-VII.1 cross sections library. 150 active cycles and 50 inactive cycles are used.

3. Results and Discussion

Fig. 3 shows the behavior of effective multiplication factor (k-eff) over the burnup. It is clearly shown that Case3 has the highest multiplication factor which shows the extended life time with enough reactivity margin. For the Case3, the estimated cycle length is about 23.4 years and the k-eff is about 1.48110 at the BOC. Table 4 shows the k-eff for all test cases and Case7 has the lowest k-eff at the beginning of cycle. It results from the large neutron leakage due outer higher fissile than other cases. And it is believed that the excess reactivity of Case3 may be controlled by implementing burnable absorbers as done in the typical commercial reactors.

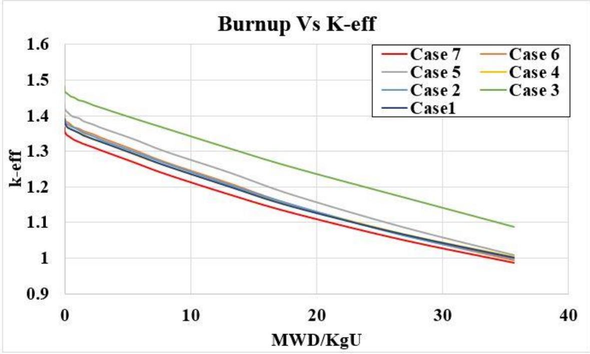

Fig. 3. k-eff change over the burnup for the various cases.

Table 4. The k-eff at BOC for various cases

Cases	k-eff ± Standard deviation
Case1	1.39036 ± 0.00065
Case2	1.39700 ± 0.00068
Case3	1.48105 ± 0.00056
Case4	1.39036 ± 0.00065
Case5	1.43148 ± 0.00063
Case6	1.40377 ± 0.00063
Case7	1.36632 ± 0.00073

When comparing with the ThO_2+$^{233}UO_2$ core of the same fissile material fraction of 4.5% $^{233}UO_2$, the thorium carbide loaded core has achieved 4 years over the thorium oxide as shown in Fig. 4. This tendency results from the neutron spectrum shift of thorium carbide loaded core in the thermal region due to more enhanced moderation of carbon than oxygen. Fig. 5 depicts the neutron spectrum for various cases of thorium carbide loaded core including the thorium oxygen loaded core. It is found that the thermal spectrum is enhanced in Case1 where the $^{233}UC_2$ content is the lowest. Table 5 shows the comparison results of thorium carbide core and thorium oxide core including actinide and non-actinide weights at the end of cycle. It is found that actinide content of thorium carbide is 5% higher than that of thorium oxide core. However, the non-actinide content of thorium carbide core is much less than that of thorium oxide core. These results also contribute to increase higher reactivity in thorium carbide core than thorium oxide core.

Table 5. Comparison of thorium carbide and thorium oxide cores

Parameter	Thorium Carbide Core	Thorium Oxide Core
Density	10.61	10.9
^{233}U content	4.5%	4.5%
k-eff at EOC	1.01751	0.99462
Actinide inventory at EOC (g)	5.089E+06	4.821E+06
Non-Actinide inventory at EOC (g)	7.464E+05	8.929E+05

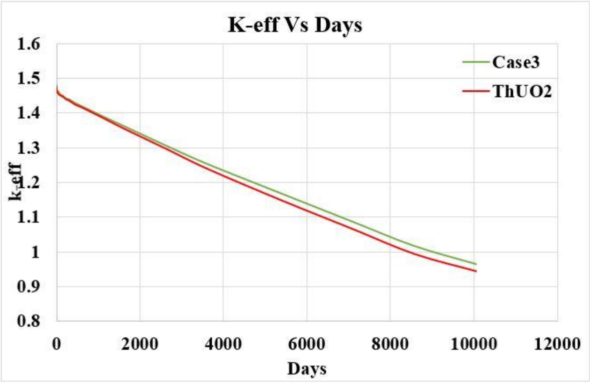

Fig. 4. Behavior of k-eff of ThUC and ThUO2 loaded core with operation time.

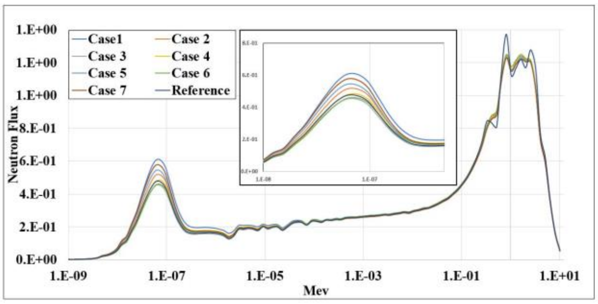

Fig. 5. Neutron Energy spectrum.

4. Conclusions

We tested an irradiation behavior of a small thorium reactor with thorium carbide fuel with several combinations of $^{233}UC_2$ contents. From the sensitivity results, the reactor cycle length is extended to about 23 years by comparing that of the thorium oxide core. It results from enhanced thermal spectrum shift due to more moderation in carbide. It is under detail investigation on the thorium carbide core safety parameters analysis such as power peaking factors, shutdown margin, and temperature feedback coefficients. And reactor power distribution will be obtained by adapting suitable burnable absorbers in the near future. As a conclusion, it is expected that thorium carbide fuel may contribute to enhance thorium-based reactor development in the future.

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