Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 12-13, 2016

Comparison of Core Performance with Various Oxide fuels on Sodium Cooled Fast Reactor

JinHa CHOI, Myung Hyun KIM*
Department of Nuclear Engineering, Kyung Hee University, 446-701, Rep. of Korea
mhkim@khu.ac.kr

1. Introduction

According to policy of fuel transition for SFR in Korea, the goal is conversion to transuranic fuel from uranium fuel. Prototype SFR has been developed in Korea since 2012. The system is called Prototype Gen-IV Sodium-cooled Fast Reactor (PGSFR). Ultimate goal of PGSFR is test for capability of TRU transmutation.

Purpose of this study is test for evaluation of in-core performance and TRU transmutation performance by applying various oxide fuel loaded TRU. Fuel type of reference core is changed to uranium-based oxide fuel. Oxide fuel has a lot of experience through fuel fabrication and reactor operation.

This study performed by compared and analyzed a core performance of various oxide fuels. $(U,Pu)O_2$ and $(U,TRU)O_2$ which various oxide fuel types are selected as extreme case for comparison with core performance and transmutation capability of TRU isotopes.

Thorium-based fuel is known that it has good performance for burner reactor due to low proliferation characteristic. To check the performance of TRU incineration for comparison with uranium-based fuel on prototype SFR, Thorium-based fuel, $(Th,U)O_2$, $(Th,Pu)O_2$ and $(Th,TRU)O_2$, is selected.

Calculations of core performance for various oxide fuel are performed using the fast calculation tool, TRANSX / DANTSTS / REBUS-3

2. Methods and Results

2.1 SFR Core Design

Figure 1 shown a modeled core design of SFR prototype. Basic purpose of this reactor is test for TRU metallic fuel and demonstration of TRU metallic fuel performances. Also it is designed to study the performance of nuclear waste incineration [1, 2].

The target power of the reference core is 150MWe (i.e. 392.2MWth). The fuel of the reference core is U-10Zr metallic fuel with 19.2wt% enriched uranium. The cycle length of the reference core is 290 EFPDs. The reference core consists of inner core, outer core, primary control rod, secondary control rod, reflector and B_4C shield.

2.2 Various Fuel Types

The fuel types are selected by the following reasons to compare a core performance.

First, U-10Zr metallic fuel of the reference core is changed into UO_2 fuel because oxide fuel has full experience and high usability. To compare TRU consumption rate of oxide fuel on modeled core, the fuel type is selected to mixed oxide fuel, $(U,Pu)O_2$, $(U,TRU)O_2$ and $(U,Pu)O_2$ fuel is selected to extreme case for effect of minor actinides (MA).

In accordance with research purpose, thorium fuel is also selected. Second, to compare the performance of Th-232 with U-238, UO_2 is substituted for $(Th,U)O_2$. On this time, volume fraction of thorium is 5 vol% in $(Th,U)O_2$.

Finally, $(Th,Pu)O_2$ and $(Th,TRU)O_2$ fuel are selected for compare with uranium for depletion TRU isotope. Also effect of thorium on TRU incineration can be analyzed among these fuels.

Composition ratio of plutonium and TRU respectively have same isotopic vectors about $(U,Pu)O_2$, $Th,Pu)O_2$, $(U,TRU)O_2$ and $(Th,TRU)O_2$. Isotopic vectors of plutonium and TRU are recovered from the spent fuel composition [3].

Calculation was carried out to specify the same isotopic vector as external feed on uranium and thorium fuel and all parameters of reference core were not changed except fuel composition.

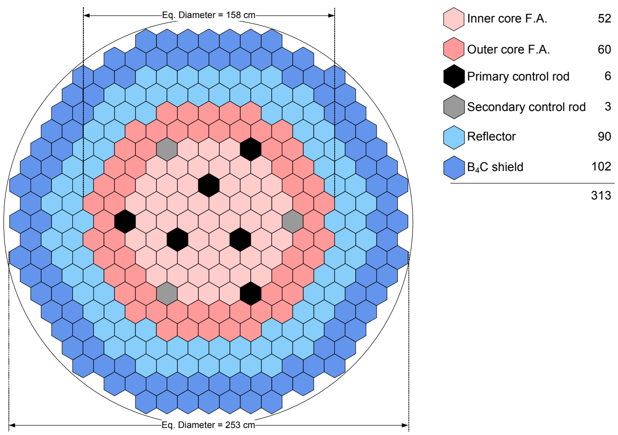

Figure 1. Design of reference core

Table Ⅰ. parameter of reference core design

	Reference core
Electric Power	150MWe
Thermal Power	392.2MWth
Fuel Type	U-10Zr metallic fuel
Uranium Enrichment	19.2wt%
Cycle Length	290 EFPDs

2.3 Results & Analyses

By changing the fuel material type from U-Zr metallic fuel to various oxide fuels, smeared density of fuels is increased to 90% theoretical density but cycle length of this core is also same with 290 EFPDs.

However, in case of the core having UO_2 and $(Th,U)O_2$ fuel, required fissile fraction of external feed is high over 20 wt.% to satisfy the target cycle lengths. Each fissile fraction of UO2 and $(Th,U)O_2$ is 25.41 wt.%, 30.37 wt.%. It is not acceptable values. Therefore the cycle length has to be decreased 190 EFPDs to satisfy the limitation of uranium enrichment less than 20 wt.%.

Parameters in the table Ⅱ and table Ⅲ are summary of core performance for 6 cases of fuel options. Each tables is shown core performance by uranium fuel and thorium fuel.

Weight fraction of external feed on fissile tends to decrease if UO_2 and $(Th,U)O_2$ fuels is changed to mixed oxide fuel with TRU. In other words, conversion to TRU mixed oxide fuel can achieve the same cycle length with small amounts of fissile material and relatively increase flux level. However, burnup reactivity swing and power peaking factor is relatively increased. In this case, the reactor size and power level are small and low because of prototype reactor. Thus, the increasing rate of parameters is small. If change of TRU fuel on demonstration plant is need to consider these parameters because the rate of increase on burnup reactivity swing and power peaking factor will be relatively higher [4].

It is because density of thorium-based fuel is slightly lower than uranium-based fuel and half-life of Pa-233 is longer than Np-239. Pa-233 is made by capture reaction of Th-232 and Pa-233 is changed to U-233 through β^- decay with 26.975days. Contrastively, Np-239 is made by capture reaction of U-238 and Np-239 is changed to Pu-239 with 2.356 days. For this reason, it is seem that conversion ratio of $(Th,PU)O_2$, and $(Th,TRU)O_2$ is low. And the power peaking factor of the thorium-based fuel is higher than uranium-based fuel. However, the conversion ratio of $(Th,U)O_2$ fuel is higher than UO_2 fuel because capture cross-section and peaking factor of Th-232 are higher than U-238.

Table Ⅱ. Performance parameters of uranium fuels

	UO_2	$(U,Pu)O_2$	$(U,TRU)O_2$
Cycle Length [Day]	190	290	290
External Feed Fissile Fraction [%]	19.05	12.58	12.49
Burnup Reactivity Swing [pcm]	1487.94	2035.62	1668.12
Conversion Ratio	0.499	0.866	0.907
Average Fuel Discharge Burnup [MWD/kg]	49.518	71.76	71.754
Peak Flux [neutrons/cm2s]	4.09E+15	4.94E+15	4.91E+15
Peak Linear Power Density [w/cm] (BOEC/EOEC)	328.36/ 321.00	340.57/ 332.84	341.51 / 333.11
Power Peaking Factor	1.98/ 1.93	2.05 / 2.00	2.06 / 2.01

Table Ⅲ. Performance parameters of thorium fuels

	$(Th,U)O_2$	$(Th,Pu)O_2$	$(Th,TRU)O_2$
Cycle Length [Day]	190	290	290
External Feed Fissile Fraction [%]	19.88	15.16	15.85
Burnup Reactivity Swing [pcm]	1341.06	1268.30	1912.83
Conversion Ratio	0.512	0.823	0.818
Average Fuel Discharge Burnup [MWD/kg]	47.879	50.526	80.270
Peak Flux [neutrons/cm2s]	4.04E+15	4.71E+15	4.61E+15
Peak Linear Power Density [w/cm] (BOEC/EOEC)	329.45/ 322.60	336.46/ 331.89	330.61/ 322.01
Power Peaking Factor	1.98/ 1.94	2.03/ 2.00	1.99 /1.94

The 24-groups normalized-neutron spectrum with 6 cases of fuel type is shown in figure 2. In fast neutron region, there are big differences. However, in thermal neutron region, the flux level of thorium-based fuel is lower than uranium-based fuel. It is because capture cross-section of Th-232 is higher than U-238 in thermal energy region. Also in thorium-based fuel, neutron flux of (Th,TRU)O_2 fuel looks like the most hardening spectrum. It can be explained with capture to fission ratio on figure3 and figure 4. Capture to fission ratio of (Th,TRU)O_2 fuel is the highest value among fuel types.

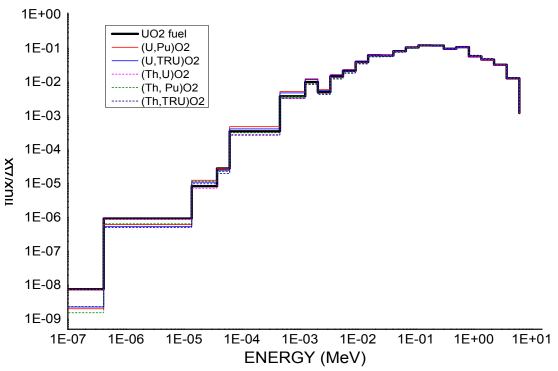

Figure 2. Neutron spectrum depending on different fuel types with uranium and thorium.

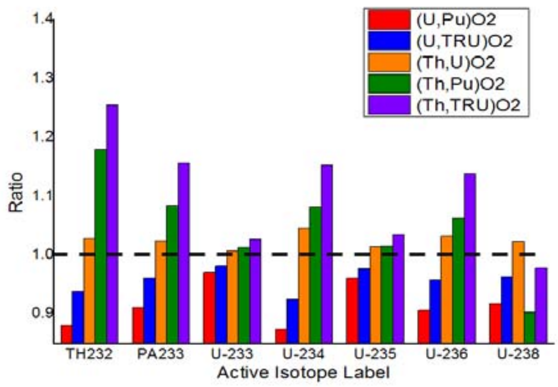

Figure 3. Relative capture to fission ratio compared UO_2 fuel on thorium and uranium isotopes.

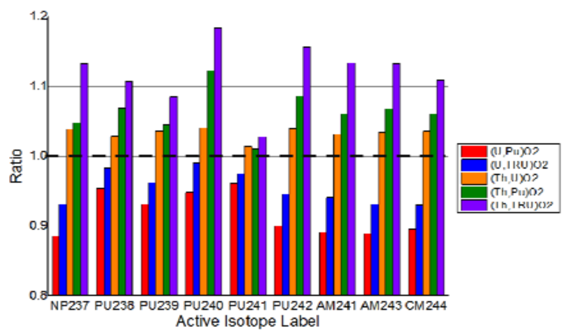

Figure 4. Relative capture to fission ratio compared UO_2 fuel on transuranic isotopes.

The largest mass of thorium in the (Th,TRU)O_2 fuel is used for transmutation but change rate is similar to (Th,U)O_2 fuel. However, (Th,U)O_2 fuel has the most value of production rate of U-233. This result was caused by higher capture cross-section of Th-232, and it means that its probability of conversion into U-233 is high Also neutron loss rate by captured to TRU isotope is closer to zero. Like the preceding, the mass of U-234 in (Th,U)O_2 is highest in same cycle length.

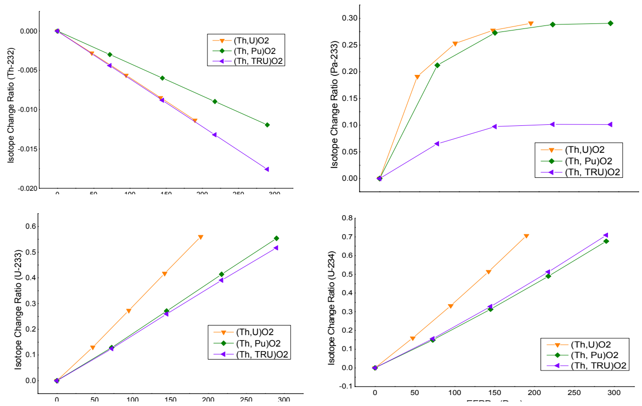

Figure 5. Relative mass change rate of Th-232, Pa-233, U-233, U-234 depending on thorium fuel types

Table Ⅳ. Consumption mass change of Th-232, Pa-233, U-233, U-234

(Th,U)O2 Fuel				
	Th232	**Pa233**	**U-233**	**U-234**
EOEC	334.23	0.58	5.08	0.2
BOEC	330.44	0.75	7.93	0.34
Mass[kg]	**-3.79**	**0.17**	**2.85**	**0.14**
(Th,Pu)O2 Fuel				
	Th232	**Pa233**	**U-233**	**U-234**
EOEC	4911.4	8.87	76.92	2.74
BOEC	4852.79	11.45	119.5	4.59
Mass[kg]	**-58.61**	**2.58**	**42.6**	**1.85**
(Th,TRU)O2 Fuel				
	Th232	**Pa233**	**U-233**	**U-234**
EOEC	4336.31	7.59	97.39	4.23
BOEC	4260.05	9.77	147.72	7.23
Mass[kg]	**-76.26**	**2.17**	**50.3**	**3**

Relative mass changes of Th-232, Pa-233, U-233 and U-234 during the cycle length are shown in Figure 5. And Table Ⅳ means consumption mass changes of Th-232, Pa-233, U-233 and U-234.

Change rates of Th-232 on thorium based fuel are between 1 % and 2 %. U-233 is mostly produced from (Th,TRU)O2 fuel but production rate of U-233 is the highest on (Th,Pu)O2 fuel. It is related to high conversion ratio of (Th,Pu)O2 and flux level. Also, production rate of U-233 is the smallest on (Th,Pu)O2 fuel because capture to fission ratio is high.

The mass change of TRU during the cycle length is shown in Figure 6. Table Ⅴ and table Ⅵ summarize transmutation performance parameters of uranium-based fuel and thorium-based fuel. The Table Ⅳ and table Ⅴ compare the some information of initial TRU loading mass and consumption mass of TRU.

The Initial loaded TRU mass is decreased in four cases of fuel except UO_2 fuel and $(Th,U)O_2$. Above all, in the thorium-based fuel, the production and loss of TRU mass are the highest. Because $(Th,U)O_2$ fuel was substituted from 5 vol.% U-238 of UO_2 fuel to Th-232. It is because of not only small amount of U-238 mass, but also capture cross-section of U-238 in $(Th,U)O_2$ fuel. The conversion from Th-232 to TRU isotopes is difficult due to complex transmutation. And the number of TRU isotopes per unit volume in thorium-based fuels is more than uranium-based fuels in accordance with slight density difference.

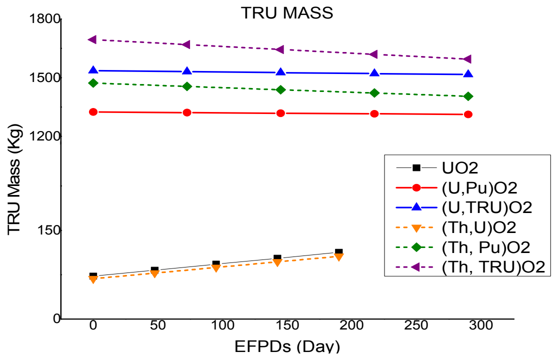

Figure 6. Mass change of TRU depending on various fuel types

Table Ⅴ. Transmutation performance parameters of uranium fuel

	UO_2	$(U,Pu)O_2$	$(U,TRU)O_2$
TRU contents in heavy metal	-	18.97%	22.12%
Initial TRU loading [kg]	-	1324.82	1535.78
Initial fissile loading [kg]	1204.98	850.60	844.08
Initial HM loading [kg]	6604.98	6891.25	6892.07
Consumption mass of TRU [kg]	40.30	-12.57	-19.95
Consumption rate	-	-0.95%	-1.30%

Table Ⅵ. Transmutation performance parameters of thorium fuel

	$(Th,U)O_2$	$(Th,Pu)O_2$	$(Th,TRU)O_2$
TRU contents in heavy metal	-	24.14%	29.61%
Initial TRU loading [kg]		1472.60	1694.53
Initial fissile loading [kg]	1240.55	951.82	930.552
Initial HM loading [kg]	6836.2	6472.27	6139.9
Consumption mass of TRU [kg]	37.96	-67.18	-99.57
Consumption rate	-	-4.56%	-5.88%

3. Conclusions

In this study, comparison of core performance and transmutation performance is conducted with various fuel types in a sodium-cooled fast reactor. Mixed oxide fuel with TRU can produce the energy with small amount of fissile material. However, the TRU fuel is confirmed to bring a potential decline of the safety parameters. In case of $(Th,U)O_2$ fuel, the flux level in thermal neutron region becomes lower because of higher capture cross-section of Th-232 than U-238. However, Th-232 has difficulty in converting to TRU isotopes. Therefore, the TRU consumption mass is relatively high in mixed oxide fuel with thorium and TRU.

In the next study, evaluation of safety should be conducted about six cases of oxide fuels to support the conclusions of this study.

REFERENCES

[1] Y. I. Kim et al., "Status of SFR Development in Korea", Proceedings of International Conference on Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios (FR13)", IAEA, Paris, France, March 4-7 (2013)

[2] J. H. Lee, "Preliminary Conceptual Design Report of Gen-IV Prototype SFR", SFR-010-DA-307-001, KAERI, Daejeon, Korea (2013)

[3] Yongkyo Lee, "Sensitivity of Transmutation Capability to Recycling Scenarios in KALIMER-600 TRU Burner", Transactions of the Korean Nuclear Society Autumn Meeting (2013)

[4] Taeyang Noh, "Alternative Cores for a Multipurpose Experimental Sodium-cooled Fast Reactor with U-Zr Fuel" PHYSOR(201)