Performance Analysis of Various Thorium Fuel Options for the Sodium Cooled Fast Reactor

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Abstract. Purpose of this study is to evaluate fuel performance and transuranic (TRU) transmutation performance of various fuel loaded in the core of small sodium cooled fast reactor (SFR). A comparative analysis between thorium fuel and uranium fuel was performed with comparison of various fuel material choices in uranium option. Evaluation was done for the modified core design concept based on the Prototype Gen-Ⅳ Sodium-cooled Fast Reactor (PGSFR). Calculation was done with code package, TRANSX/DANTSTS/REBUS-3. Analyses was conducted on two fuel type categories (1) Oxide fuel; UO_2, $(Th,U)O_2$, $(U,Pu)O_2$, $(Th,Pu)O_2$, $(U,TRU)O_2$, $(Th,TRU)O_2$, (2) Metal fuel; U-Zr, Th-U-Zr, U-TRU-Zr, Th-TRU-Zr. For reasonable comparison, all geometry and structure material, except smear density, had same size and same composition. Thorium and uranium fuels were compared in each fuel type. Because of the low conversion ratio, more than 20% enrichment was required in case of UO_2 core. Therefore the fuel cycle length was decreased from 290 days to 190 days. Only with fuel of UO_2 and $(Th,U)O_2$ cycle length was changed a lot. Results showed that TRU fraction charged in Th-TRU-Zr fuel was higher than U-TRU-Zr fuel resulting in higher TRU consumption rate. As more TRU was charged in the core, BOC excess reactivity was increased. This influenced safety parameters for the Unprotected Transient Over-Power (UTOP) accident. Neutron spectrum in all cores using oxide fuel was softened compared with metal fuels. In comparison of $(Th,TRU)O_2$ and $(U,TRU)O_2$, thorium oxide makes sodium void worth less positive and TRU consumption rate much larger than uranium oxide.

Key Words: SFR, Fuel, Transuranic, Thorium, Transmutation

1. Introduction

Since operation of the first Nuclear Power Plant (NPP), Kori-1 in 1978, number of NPPs is continuously increased to 25. As a result, the amount of spent fuel generation is now reaching to about 700 tons per year [1]. In addition, it has been announced that even if the storage capacity of spent fuel pool has been increased, it will be saturated soon from 2028 (Kori NPP site) to 2038 (Shin-Wolsung NPP site). Therefore, waste management plan for spent fuel becomes an urgent and hot issue to be resolved.

As an alternative option to deep geological disposal, transmutation of long-lived isotopes has been studied with fast spectrum reactor development. At this moment, Korean government selected a sodium cooled fast critical reactor(SFR) option out of many options; subcritical reactor systems, such as the Accelerator-Driven Subcritical Reactor (ADSR) and the Fusion-Fission Hybrid Reactor (FFHR), and critical reactor systems, such as the SFR, the lead cooled fast reactor (LFR).

The research on the SFR has been started since the 1950s, and the R&D expenses of 50 billion dollars has been put into practice all over the world. Currently, it has been considered as safe and practical option of GEN-Ⅳ reactor to be realized in many countries. A study on the SFR was started in Korea by Korea Atomic Energy Research Institute (KAERI) since 1997 as a part of long-term national program aiming advanced liquid metal cooled reactor for break-even core option without separate blanket. After that, in 2001, the conceptual design of 150MWe KALIMER-150 was completed, and in 2006, the concept of KALIMER-600 was completed. In addition, the design concept of the Prototype Gen-Ⅳ Sodium-cooled Fast Reactor (PGSFR) was developed in 2012 with solid plan to construct in 2028. One of the design goal of the PGSFR is to demonstrate the transmutation performance of TRU isotopes as a waste incinerator option and to test the feasibility of metal fuel for use in the commercialized SFR [2].

According to the fuel development plan of KAERI, U-Zr fuel will be loaded for the initial core, and then U-TRU-Zr fuel will be used later after completing pyro-processing technology for the extraction of whole TRU from LWR spent fuel. Self-recycling option only with SFR will be the final goal [3].

In this study, the feasibility of various fuel for the PGSFR core is evaluated. In particular, since the amount of plutonium and long-lived minor actinides produced by the low conversion effect is very small compared to uranium fuel, thorium fuel [4], which is known to be effective for TRU burning will be also compared with. A similar study has been conducted to compare uranium fuel and thorium fuel in terms of waste management [5]. Nuclear conversion and radio-toxicity studies of various types of thorium-based nuclear fuel have been also conducted [6]. It is assumed that TRU fuel is supplied from reprocessing of discharged fuel from LWR only, not from PGSFR. That is, it is assumed that all the spent fuel from PGSFR is discharged without reprocessing. In addition, the proliferation resistance is evaluated using three parameters; bare critical mass (BCM), spontaneous fission neutron source rate (SNS) and thermal generation rate (TG) relatively.

2. Core designs, Fuel options and Methodology

The PGSFR selected as the reference core is a 150MWe small size SFR developed by the KAERI. The PGSFR is designed to test the TRU transmutation performance.

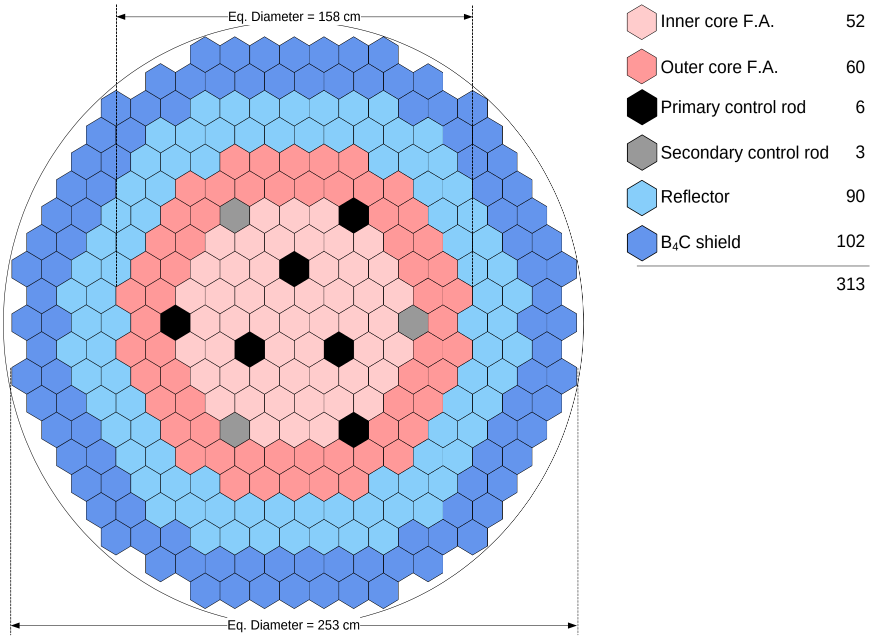

FIG. 1 PGSFR core radial layout [2]

2.1.Core designs

The PGSFR is designed as a compact core with a pitch/diameter ratio of 1.14. In addition, shielding is considered in the fuel assemblies at both upper and lower parts. Core is designed as shown in *FIG. 1* and consists of 52 inner core fuel assemblies, 60 outer core fuel assemblies, 6 primary control assemblies, 3 secondary control assemblies, 90 reflectors, and

102 B_4C shield assemblies. The effective height of fuel assembly is 217.5 cm, and detailed specifications are shown in the TABLE I. The cycle length of the PGSFR was designed as 290 EFPD with 4/5 batch.

TABLE II: PGSFR Core Design Parameters [7]

Core	
Power (MWth)	392.2
Thermal Capacity (MWe)	150
Cycle Length (Day)	290
Number of Batches Inlet/Outlet Core	4/5
Number of Inlet/Outlet Fuel Assembly	52/60
Coolant Inlet/Outlet Temperature (°C)	390/545
Active Core Height (cm)	90
Fission Gas Plenum Height (cm)	125
Fuel	
Fuel Material	U-10%Zr
Enrichment (wt. %)	19.2
Fuel Pin dia.(cm)	0.74
Assembly Pitch (cm)	13.636
P/D ratio in fuel assembly	1.14
Number of Pins per Fuel Assembly	217
Duct Material	HT-9
Cladding Material	Modified HT-9
Core Structural Material	HT-9

2.2. Fuel options

The purpose of this study is to analyze effects from various fuel options rather than analyzing the effect of the core geometry. Commonly used uranium fuel compositions are selected and corresponding thorium options are also selected. Options studied in this paper are shown in TABLE III. The composition of each fuel is adjusted to meet the same conditions specified using the REBUS-3 equilibrium cycle calculation. The smear density of metallic fuel is selected to be 75% of the theoretical density. In the case of oxide fuel, 90% of the theoretical density is selected because it can maintain higher smear density due to high porosity and small swelling phenomenon compared to other nuclear fuel type [8].

TABLE IV: Fuel Options used in calculation

Fuel Type	**Smear Density**	**Uranium Fuel**	**Thorium Fuel**	**Cycle length**
Metallic Fuel	75%	U-Zr	Th-U-Zr	290
		U-TRU-Zr	Th-TRU-Zr	
Oxide Fuel	90%	UO_2	$(Th,U)O_2$	190
		$(U,Pu)O_2$	$(Th,Pu)O_2$	290
		$(U,TRU)O_2$	$(Th,TRU)O_2$	

In all equilibrium cycle calculations, reprocessing options are not used for the spent fuel from the PGSFR and the fuel is specified to be supplied externally in sufficient quantities. Depleted uranium isotopic vector used in U-TRU-Zr, and isotopic vector of TRU are based on data from 10 years cooling, 55,000 MWD/MTU burnup of PWR UO_2 fuel with 4.5% initial enrichment [9]. Composition of plutonium in both $(U,Pu)O_2$ and $(Th,Pu)O_2$ are prepared in the same manner. Thorium is used as a fertile material in Th-TRU-Zr, $(Th,Pu)O_2$, $(Th,TRU)O_2$. For the Th-U-Zr fuel and $(Th,U)O_2$ fuel, it is assumed that only 5% of the enriched uranium fuel is replaced by thorium.

2.3. Methodology

In this study, all options are simulated with assumptions of hot full power for the same cycle length and power level. In case of UO_2 and $(Th,U)O_2$, core conditions are different from others because of fissile loading limitation. The calculation results have been obtained with the fast reactor calculation tool TRANSX / TWODANT / REBUS-3 (DIF3D). By using 24 group cross sections, the core calculation has been performed with the HEX-Z nodal diffusion option using the DIF3D module in REBUS-3. The library used for the calculation is based on ENDF/B-VII. MCNPX2.6 and ORIGEN2 are used to evaluate proliferation resistance parameters; BCM, SNS and TG.

3. Various Uranium Fuel Analysis

3.1. Core Performance

TABLE V summarizes results of core performance from various uranium fuel options. The difference between the U-Zr fuel and the UO_2 fuel, which are the same uranium-based fuel, can be seen clearly. First, since the density of oxide fuel is smaller than the density of metal fuel, the amount of heavy metal to be loaded is reduced, and the relative fissile fraction is increased. To meet the cycle length of 290 days, it exceeds 20wt%, which is the limit of uranium enrichment. Therefore, in this study, the cycle length was reduced by 100 days in order to keep the concentration of UO_2 fuel below 20wt%. In addition, the UO_2 nuclear fuel has a higher softening effect than the U-Zr nuclear fuel. The fraction of low energy neutrons in the UO_2 fuel is noted more than three times that of the U-Zr fuel b shown in TABLE VI. As a result, the neutron capture of U-238 is increased and the conversion ratio is greatly evaluated as compared with the U-Zr fuel.

TABLE VII: Reactor performances for various uranium fuels

	U-Zr	U-TRU-Zr	UO_2	$(U,Pu)O_2$	$(U,TRU)O_2$
Cycle length [Day]	290	290	190	290	290
External feed fissile fraction	19.17	11.33	19.05	12.58	12.49
Burnup reactivity swing[pcm]	2028.3	1705.79	1358.5	2035.619	1668.123
Conversion ratio	0.475	0.881	0.517	0.866	0.907
TRU contents in heavy metal	-	19.68%	-	18.97%	22.12%
Peak flux [neutrons/cm2-s]	4.21E+15	5.02E+15	4.07E+15	4.94E+15	4.91E+15
Initial TRU loading [kg]	-	1454.35	-	1324.82	1535.78
Initial fissile loading [kg]	1330	804.09	1213.35	850.601	844.081
Initial HM loading [kg]	7350	7390	6860.6	6891.25	6892.07
Consumption mass of TRU [kg]	-52.89	24.09	-41.67	12.57	19.95
Consumption rate	-	1.66%	-	0.95%	1.30%

TABLE VIII: Neutron spectrum fraction below 0.01Mev for various uranium fuels

Fuel Type	U-Zr	U-TRU-Zr	UO_2	$(U,Pu)O_2$	$(U,TRU)O_2$
Neutron Fraction (Below 0.01MeV)	1.81%	2.47%	6.17%	6.44%	5.55%

Similarly, The large differences in the amount of heavy metal and fissile fraction have been shown between the U-TRU-Zr core and the $(U,TRU)O_2$ core also due to differences in density depending on the fuel type in spite of the same TRU fuel. The U-TRU-Zr nuclear fuel has been contained less heavy TRU than the heavy metal load. However, the reason for the high burnup reactivity swing is related that the neutron numbers generated per nuclear fission are increased due to the hardening effect of the spectrum in the metal nuclear fuel core. In contrast, the $(U,TRU)O_2$ core spectrum is relatively softened as shown in TABLE IX, and the burnup reactivity swing is observed lower than that of the U-TRU-Zr fuel as shown in TABLE X. In addition, due to the softening effect, the absorption rate increased in U-238, resulting in a higher conversion ratio and a larger amount of TRU, resulting in lower TRU consumption than U-TRU-Zr fuel.

The $(U,Pu)O_2$ has been consisted almost the same composition with the $(U,TRU)O_2$ fuel except the minor actinide (MA) material. However, the burnup reactivity swing of $(U,Pu)O_2$ fuel was noted much higher than that of $(U,TRU)O_2$ fuel. Because the absorption cross-section of the MAs contained in the $(U,TRU)O_2$ fuel is larger than the U-238 absorption cross-section, and thus burnup reactivity swing is evaluated lower than that of the $(U,TRU)O_2$ fuel by the high neutron capture rate in MA.

3.2. Safety aspect

The amount of neutrons in the low-energy region is increased because of the large softening effect in the oxide core. The increase of low-energy neutrons is implied an increase in the number of neutrons to be absorbed in the resonance absorption cross-section of U-238. Thus, it can be seen in TABLE XI that the nuclear fuel temperature coefficient of the oxide fuel has been obtained a larger negative value than that of the metal fuel.

As the temperature increases, the fuel is expanded and the number of nuclides in the fuel per unit volume decreases, leading to a decrease in reactivity. The expansion coefficients in axial and radial directions are increased to more negative in metal fuel with higher density as opposed to the fuel temperature coefficient.

Unlikely uranium loading core, the sodium reactivity coefficients are all positive in the TRU loading core. The main fissile material of the TRU loading core is Pu-239 which has an increase rate of η with increasing energy greater than that of U-235 [4]. As the spectrum of the TRU core is hardened, a larger amount of reactivity is inserted.

The quasi-static analysis method was developed by Wade et al. At the Argonne National Laboratory (ANL) in the 1980s [10]. This method is based on the equation of balance equilibrium, depending on the flow rate of the core, the operation power and the ratio of the three measurable integral reactivity parameters (A, B, C). It is used to predict the asymptotic core state after an unexpected transient state.

The A parameter depends on the fuel temperature and the core power, but because it is calculated at the same power, the influence of the fuel temperature is greatest. In particular, oxide fuel has been presented a relatively low thermal conductivity, which is caused about 5 times higher than other fuel temperatures. As follows TABLE XII, the Unprotected Loss of Flow (ULOF) accident scenarios are not satisfied the safety limits in oxide fuel only.

TABLE XIII: Delayed neutron fraction, reactivity coefficient, and preliminary safety evaluation for various uranium fuels

	U-Zr	**U-TRU-Zr**	**UO_2**	**$(U,Pu)O_2$**	**$(U,TRU)O_2$**
Delayed neutron fraction	0.006561	0.003009	0.006766	0.003804	0.003837
Fuel temperature coefficient (pcm/K)	-0.303	-0.388	-0.83	-0.781	-0.653
Expansion coefficient (pcm/K)					
- Fuel axial	-0.212	-0.251	-0.181	-0.194	-0.195
- Core radial	-1.142	-1.742	-1.097	-1.112	-1.101
Sodium density coefficient (pcm/K)	-0.277	0.208	-0.253	0.158	0.22
Sodium void worth	-1200pcm	526pcm	-794pcm	593pcm	773pcm
	(-1.851$)	(1.749$)	(-1.174$)	(1.558$)	(2.016$)
A(¢)	-9.09	-19.35	-91.97	-153.96	-127.54
B(¢)	-47.68	-100.84	-39.61	-61.97	-57.16
C(¢)	-0.38	-0.72	-0.35	-0.51	-0.45
ΔT_C[℃]	155	155	155	155	155
$\Delta\rho_{TOP}$[$]	0.421	1.202	0.45	1.172	0.942
A/B < 1.0 and A&B both are negative (ULOF)	0.191	0.192	2.322	2.484	2.231
$1.0 < C\Delta T_C/B < 2.0$ C should be negative (ULOHS)	1.257	1.11	1.365	1.269	1.222
$\Delta\rho_{TOP} / \vert B \vert < 1.0$ (UTOP)	0.883	1.192	1.123	1.891	1.648

The reactivity fault value of the U-Zr fuel and the UO_2 fuel is calculated 0.421 $ and 0.45 $ respectively. However, it is confirmed that the core loaded with TRU fuel is more than 1 $ or close to 1 $. Here, reactivity fault means reactivity inserted when the strongest control rod is pulled out in the critical state. As a result, it can be confirmed that the TRU core for the UTOP accident scenario are not satisfied the safety limit.

However, all uranium nuclear fuel cores are evaluated to meet the safety limits of the Unprotected Loss of Heat Sink (ULOHS) accident scenario.

3.3. Proliferation resistance

BCM, SNS and TG are used for proliferation resistance evaluation. In the case of BCM, it means the minimum critical mass of the non-reflective body using the composition of the spent fuel at the end of cycle. In general, large BCM means that the mass required to meet the critical mass is large, meaning that it is complicated to make a nuclear weapon. The SNS means the release rate of neutrons per unit mass. Neutrons generated by spontaneous fission decline the purity of nuclear weapons and degrade their efficiency. The TG is the amount of heat generated per unit mass in the composition of spent fuel. The high amount of heat released from spent fuel means that there is a lot of heat released, which doubles the manufacturing difficulties and complicates the process [11].

The BCM of the spent fuel from the U-Zr core and the UO_2 core are evaluated to be less than the critical mass of the spent fuel from the TRU core. In particular, $(U,Pu)O_2$ showed 467 kg, which is the lowest nuclear proliferation resistance as shown in TABLE XIV.

Similarly, Both SNS and TG are highly evaluated in the nuclear fuel loaded with the TRU nucleus in the initially loaded nuclear fuel. Based on the U-Zr, the spontaneous neutron generation rate per unit mass is estimated to be about 53 ~ 62 times higher for TRU fuel, and about 6 ~ 8 times higher for TG. Nuclear fuels containing TRU are highly evaluated for nuclear proliferation resistance in SNS and TG because they contained many Pu-238 and Pu-240 nuclei even when released. Because the Pu-238 and Pu-240 have a high rate of spontaneous fission and a high rate of heat generation per unit mass, the higher the amount of TRU in the released fuel, the higher the SNS and TG factors are evaluated.

TABLE XV: BCM, SNS, TG for various uranium fuels

			U-Zr	**U-TRU-Zr**	**UO_2**	**$(U,Pu)O_2$**	**$(U,TRU)O_2$**
BCM (kg)			858.544	553.197	886.72	467.861	470.814
SNS	**Total**	**#/kg•s**	9.59E-02	2.00E+04	2.82E-02	1.54E+03	2.43E+04
	Pu	**#/kg•s**	4.09E+00	2.51E+02	1.02E+00	2.19E+02	2.53E+02
		ratio	1	61.37	0.25	53.55	61.86
TG	**Total**	**W/kg**	5.63E-05	8.97E-03	3.52E-05	3.60E-03	1.07E-02
	Pu	**W/kg**	2.73E-03	2.31E-02	2.08E-03	1.69E-02	2.38E-02
		ratio	1	8.46	0.76	6.19	8.72

4. Comparison of Uranium and Thorium Fuel

4.1. Core Performance

For thorium, which has a lower density than uranium, the fuel density is lowered also. Therefore, the amount of heavy meatal in the thorium loading cores is reduced. The reduction of heavy metals lead to an increase in the amount of fissile required in the thorium core to meet the given conditions. As the amount of fissile increased, the burnup reactivity swing was expected to increase generally. However the burnup reactivity swing is decreased by thorium fuel feature. The number of neutron captured in fertile material is increased due to the large capture cross-section of the thorium and the neutron leakage rate are increased thanks to the neutron hardening effect in thorium because of the fuel density decreased. However, in the case of the Th-TRU-Zr fuel, the burnup reactivity swing is evaluated to be relatively high unlike the other core due to the hardening effect of the metal fuel characteristic and high TRU fraction 26.84% in the Th-TRU-Zr fuel.

Also, "Th can be advantageous to a burner design by allowing a reduction in the CR with respect to U-fuel while complying with safety requirements" [5]. As comparing with TABLE XVI and TABLE XVII, TRU consumption rate of thorium core is shown about 4-6 times higher than uranium fuel in both metal fuel and oxide fuel. Th-TRU-Zr fuel is considered to be the most effective fuel in terms of TRU burning. Especially, $(Th,Pu)O_2$ has the highest TRU burning rate, but it is not included long lived MA isotopes in this fuel.

For Th-U-Zr fuel and $(Th,U)O_2$ fuel, 5% volume fraction of U-238 is replaced with thorium. In terms of core performance, there is no significant difference from the existing uranium fuel composition, but the effect of thorium is confirmed slightly. The amount of fissile is slightly increased and the amount of TRU produced at the end of the cycle decreased by 5 kg as can be confirmed by comparing TABLE XVIII and TABLE XIX.

TABLE XX: Reactor performances for various thorium fuels

	Th-U-Zr	**Th-TRU-Zr**	**(Th,U)O_2**	**(Th,Pu)O_2**	**(Th,TRU)O_2**
Cycle length [Day]	290	290	190	290	290
External Feed fissile fraction [%]	19.53	15.48	19.88	15.46	15.24
Burnup reactivity swing [pcm]	1893.876	2545.08	1341.063	1954.99	1636.86
Conversion ratio	0.461	0.752	0.512	0.806	0.847
TRU contents in heavy metal	-	26.84%	-	24.46%	28.47%
Peak flux [neutrons/cm2-s]	4.08E+15	4.55E+15	4.04E+15	4.60E+15	4.58E+15
Initial TRU loading [kg]	-	1682.19	-	1462.63	1716.35
Initial fissile loading [kg]	1341.63	914.41	1240.55	960.09	943.35
Initial HM loading [kg]	7314.94	6266.54	6836.2	6466.01	6464.27
Consumption mass of TRU [kg]	-47.33	102.15	-37.96	96.52	98.83
Consumption rate of TRU[%]	-	6.07%	-	6.60%	5.76%

4.2. Safety aspect

As with the uranium fuel, the fuel temperature coefficient in the oxide fuel is evaluated to be relatively more negative reactivity compared to the metal fuel because of the softening effect of the oxide fuel. Due to the characteristics of thorium with small resonance absorption cross section, the fuel temperature coefficient of all thorium cores is evaluated to be less negative than that of uranium core.

Due to the hardening effect of thorium fuel, the mean free path of the neutron is became longer, resulting in the high leakage effect. As a result, the expansion coefficient is evaluated to be more negative reactivity than that of the uranium fuel.

TABLE XXI: Delayed neutron fraction, reactivity coefficient, and preliminary safety evaluation for various thorium fuels

	Th-U-Zr	**Th-TRU-Zr**	**(Th,U)O_2**	**(Th,Pu)O_2**	**(Th,TRU)O_2**
Delayed neutron fraction	0.006874	0.003094	0.006947	0.003238	0.002951
Fuel temperature coefficient, (pcm/K)	-0.276	-0.297	-0.703	-0.681	-0.536
Expansion coefficient (pcm/K)					
- Fuel axial	-0.22	-0.26	-0.185	-0.199	-0.199
- Core radial	-1.333	-1.994	-1.118	-1.156	-1.143
Sodium density coefficient (pcm/K)	-0.412	-0.041	-0.255	0.053	0.133
Sodium void worth	-1449pcm	106pcm	-863pcm	243pcm	477pcm
	(-2.108$)	(0.343$)	(-1.357$)	(0.752$)	(1.324$)
A(₵)	-6.03	-13.91	-75.86	-157.65	-111.557
B(₵/)	-40.32	-112.58	-37.69	-75.06	-62.141
C(₵)	-0.33	-0.81	-0.33	-0.61	-0.484
ΔT_C[℃]	155	155	155	155	155
$\Delta\rho_{TOP}$[$]	0.35	1.715	0.41	1.32	0.981
A/B < 1.0 and A&B both are negative (ULOF)	0.149	0.124	2.013	2.1	1.795
1.0 < C$\Delta T_C/B$ <2.0 C should be negative (ULOHS)	1.254	1.113	1.338	1.263	1.208
$\Delta\rho_{TOP}$ / ∣ **B** ∣ **<1.0 (UTOP)**	0.868	1.523	1.093	1.759	1.579

The effect of sodium voiding is attenuated by the use of thorium. As follow the previous research, “Void reactivity reduction in Th is mainly related to the higher energy threshold an lower value of the fission cross-section of Th compared to U-238, which helps limiting the increase in neutron production following a spectrum hardening”[5]. Therefore positive reactivity insertion due to sodium voiding in core is decreased on all thorium fuel core (TABLE XXII and TABLE XXIII). Specially, in Th-TRU-Zr fuel, reactivity insertion is drastically reduced.

In the case of metal fuel, almost safety limits are satisfied. But the reactivity fault value is high due to the small delayed neutron fraction Th-TRU-Zr fuel. Especially in case of Th-TRU-Zr, therefore, the limit is not satisfied for UTOP accident scenario. As mentioned, the oxide fuel has a high fuel temperature. As a result, the ULOF accident scenario is evaluated to be weak in thorium oxide fuel as well. The core with thorium is evaluated closer to the limit than the core with uranium. This is because the use of thorium fuel makes the sodium density coefficient a less positive value or has a negative value. As a result, the difference between the A parameter and the B parameter is reduced to have a value closer to the limit of ULOF accidents scenario.

4.3. Proliferation resistance.

TABLE XXIV: BCM, SNS, TG for various thorium fuels

			Th-U-Zr	**Th-TRU-Zr**	**$(Th,U)O_2$**	**$(Th,Pu)O_2$**	**$(Th,TRU)O_2$**
BCM (kg)			891.338	828.494	913.974	959.671	809.505
SNS	**Total**	**#/kg•s**	4.24E-02	2.80E+04	2.60E-02	1.45E+03	2.95E+04
	Pu	**#/kg•s**	1.76E+00	2.86E+02	1.02E+00	1.70E+02	2.89E+02
		ratio	0.43	69.93	0.25	41.56	70.66
TG	**Total**	**W/kg**	4.07E-05	1.26E-02	3.22E-05	6.28E-03	1.31E-02
	Pu	**W/kg**	2.24E-03	2.58E-02	2.08E-03	1.20E-03	2.65E-02
		ratio	0.82	9.45	0.76	0.44	9.71

The use of thorium in all cores lead to an increase BCM due to a decrease in the amount of fissile plutonium and low fuel density, resulting in a significant increase in nuclear proliferation resistance over uranium core. However, SNS and TG is showed different trends depending on the fuel composition. Especially, TRU nuclear fuel is highly evaluated for SNS and TG. This is due to the generation of Pu-238 nuclei, which have the greatest effect on SNS and TG due to the radiation collapse of MAs within the TRU composition. Th-TRU-Zr nuclear fuel and (Th, TRU)O_2 nuclear fuel have lower conversion rate than uranium core; the production of Pu-238 in thorium is more difficult than that of uranium, but they have higher number of Pu-238 isotope due to large amount of TRU loaded in initial core. SNS and TG values of thorium fuel without TRU isotopes in new fuel are lower than those of uranium fuel. In the case of BCM, the proliferation resistance is increased when thorium is used, but in case of SNS and TG, it is influenced by the amount of Pu-238.

5. Conclusions

This study selected various types of uranium based fuel and its corresponding thorium based fuel for the PGSFR core in order to evaluate the feasibility of alternative fuels by comparison only from the nuclear design aspects.

Among the used uranium fuel options, U-Zr fuel and U-TRU-Zr fuel, previously included in the PGSFR fuel plan, are evaluated as fuel optimized for each core purpose. U-Zr fuel is a fuel that focuses on safety because it is a fuel designed to evaluate uncertainty before using TRU fuel [3]. The calculation results are also confirmed to have the highest safety in U-Zr fuel.

The U-TRU-Zr fuel is also identified as the most optimized fuel for TRU transmutation in the PGSFR core. The transmutation performance of U-TRU-Zr fuel is evaluated to be the best thanks to the relatively low conversion ratio and the hardening effect of the metal fuel. The highest proliferation resistance and safety among uranium fuels except for U-Zr fuel is observed. However, it is necessary to change the design of the core to complement the positive value of sodium voiding effect.

The advantages of thorium, as confirmed in previous studies using thorium in fast reactor, were also confirmed in the PGSFR core. Due to the low density of thorium, the amount of TRU in the fuel can be increased, and thorium fuel is found to be more effective for TRU transmutation than the uranium fuel because the conversion process of TRU nuclide is longer than that of uranium. TRU consumption rate of thorium core is shown about 4-6 times higher than uranium fuel in both metal fuel and oxide fuel. In particular, Th-U-Zr fuel is considered to be the most effective fuel for TRU transmutation among thorium fuel used in this study.

Thorium fuels is also effectively evaluated in terms of safety as well as transmutation performance. In particular, it is once again confirmed that the reactivity insertion effect of sodium voiding in the core, which is the most sensitive accident in the sodium-cooled fast reactor, is greatly reduced by the use of thorium. In the preliminary safety evaluation, it has been confirmed that the use of thorium is closer to the limit value.

As potential nuclear fuel, thorium fuel is considered significantly improve transmutation and safety over uranium fuel at the PGSFR core. However, there are some problems to be solved in order to use thorium fuel, especially the positive sodium void worth and UTOP accident.

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