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Feasibility of Long-Cycle Core Design for PGSFR

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1. Introduction

The Korean fast reactor program has been carried out for the construction of Prototype Gen-IV Sodium-cooled Fast Reactor (PGSFR) with target timeline at 2028. The purposes of the PGSFR are demonstration of the transmutation performance of TRU isotopes as a waste incinerator and feasibility test of metal fuel for use in the commercialized SFR [1].

According to the domestic R&D policy for the SFR, U-Zr metal fuel should be loaded in the initial core, and then later U-TRU-Zr metal fuel reprocessed from the PWR spent fuel discharged. Currently, active research has been done for the pyro-processing technology adapted to SFR in Korea. All benefits of SFR would be achieved when SFR and Pyro-processing are combined together commercially for sustainability with closed-cycle and waste transmutation [2].

Since PGSFR is designed as a small proto-type at 392.2 MWt, continuous operation of PGSFR with U-Zr metal fuel is not economical compared with current commercial nuclear power plant. Early introduction of TRU fuel for SFR is not easy and expected to be delayed with high possibility. This study is based on this uncomfortable assumption that alternative option be required after the completion of PGSFR.

In this study, feasibility of design change from U-Zr fuel core to alternative fuel core with fuel off the shelf, such as U-Pu MOX or U-PU-Zr. Additionally, design is aimed to achieve for long-cycle core with break-even concept for higher economics.

Technical challenges in this study is the restriction in design change, in particular, the geometry of the core should not be changed. The method done for this study is to make a new fuel assembly with fixed outer dimensions. Enrichment zoning is changed from single to three for the reduction of pin power peaking.

2. Core designs, Modification and Methodology

2.1 Reference core designs

The reference core selected in this study is PGSFR. This core is a 150MWe small size SFR developed by Korea Atomic Energy Research Institute (KAERI) since 2012. The PGSFR is designed to test the TRU transmutation performance and the feasibility of TRU metal fuel in commercial applications.

The effective radius of the active core is 158 cm and the active core height is 90 cm. It is designed to have high power density in a small core and consists of 52 inner-core fuel assemblies and 60 outer-core assemblies, 6 primary control assemblies, 3 secondary control assemblies, 90 reflectors, and 102 B_4C assemblies. Because of the small size, large neutron leakage from core outer boundary is expected and the fuel reloading scenarios are designed for 4 batchs of internal core fuel assembly and 5 batchs of external core assembly for power flattening. Detailed specifications are shown in the following table [1].

Table 1. PGSFR Core design parameters

Core Design Parameter	**Value**
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 Assembly Design Parameter	**Value**
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	Mod. HT-9
Core Structural Material	HT-9

2.2 Design Modification of Assemblies

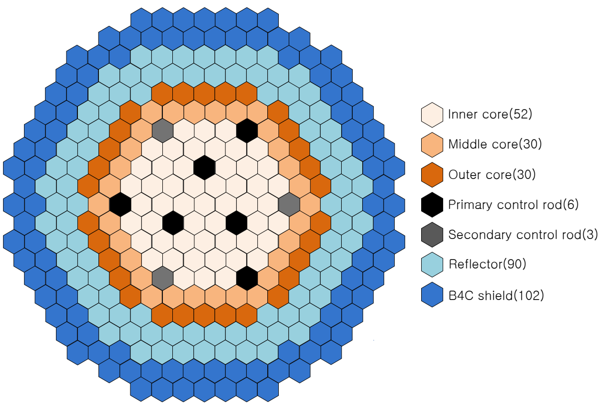

Fig. 1 Radial layout of long cycle PGSFR core

For conversion to long cycle core from original PGSFR core, addition loading of heavy metal is required. Fuel pin diameter is increased from 0.74 to 0.81. It means a fuel pitch/diameter (P/D) ratio is decreased. According to this modification, the original PGSFR fuel volume fraction of 32.35% is increased up to 41.44% in fuel assembly.

Also, in this study, U-Pu-10Zr nuclear fuel is used for long cycle performance. Initial step on fast reactor development in the USA, U-Pu-Zr fuel used (e.g. EBR-1, EBR-2, Fermi). For the U-Pu-Zr fuel composition calculation, Pu isotopic vector is assumed to be the same with one from 10 years cooling, 55,000 MWD/MTU burnup of PWR UO_2 fuel with 4.5% initial enrichment [3].

As shown in Fig. 1 the fuel assemblies are grouped in to inner, middle, and outer core region with different enrichments. Three-region fuel enrichment is used to reduce the radial power peaking and to enhance internal conversion effect for cycle length efficiently. Table 2. Shows the feed Pu fraction 8.4, 13.5 and 18 wt. % for inner, middle and outer core regions, respectively. Specially, to increase the internal conversion, a relatively low enrichment fuel is loaded inner core zone [4]. The maximum relative enrichment difference is 2.143 between the inner core and the outer core.

Table 2. Enrichment zoning

Core region	Pu Content	Relative Enrichment
Inner core	8.4%	1.000
Middle core	13.5%	1.607
Outer core	18%	2.143
Avg.	12.34%	1.469

2.3 Methodology

In this study, the long cycle core is modeled with assumption that core is hot full power state. The calculation results have been obtained with the fast reactor calculation tool TRANSX [5] / TWODANT [6] / REBUS-3 (DIF3D) [7]. Fig. 2 shows the calculation process. 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. All core performance parameters has calculated by the non-equilibrium option. The kinetic parameters have been calculated by using DIF3D only. The library selected for the core calculation is based on ENDF / B-VII library. Before the core calculation, a few group ISOTXS form cross section library of global spectrum weighted has been combined with other ISOTXS that generated separately for lumped fission product materials cross section with ENDF / VI library. Also, MCNPX2.6 has been utilized for the calculation of the delayed neutron fraction at BOEC, MOEC and EOEC with each regions averaged composition from REBUS-3 depletion calculate results [8].

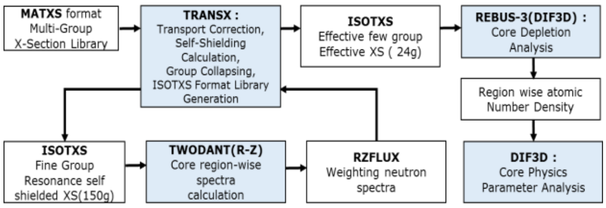

Fig. 2 Flow chart of fast reactor calculation tools

3. Result & Analyses

3.1 Core Performance

Table 3. Long cycle core performances

Core Performance Parameters	Value
Power, MWth	392.2
Cycle length (Year)	11
Pu Fraction in Inner/Middle/Outer core (Wt. %)	8.4/13.5/18
Burnup reactivity swing (pcm)	1925.61
Avg. conversion ratio	0.992
Initial Heavy metal Loading (kg)	10798.22
Initial Pu Loading (kg)	1332.82
Specific Power (KW/kg)	28.71
Average power density (w/cm3)	221.32
Average linear power density (w/cm)	166.02
Peak power density (w/cm3)	533.02
Peak linear power density (w/cm)	399.84
Power peaking factor at BOEC/MOEC/EOEC	1.82/1.66/2.41

The key long cycle core performance characteristics are summarized in table 3. The total heavy metal inventory is increased to 10798.22kg from 7350kg that is heavy metal weight of original PGSFR using U-Zr fuel. The Pu material inventory is loaded 1332.82kg. The burnup reactivity swing defined here as the difference between the maximum and minimum excess reactivity for total cycle length is 1925.61 pcm. As shown in Fig. 3, after reaching its maximum excess reactivity at 6 effective full power years (EFPY), the k-effective value is decreased monotonically because of the insufficient internal conversion effect as following the decreased total amount of fertile material. The total cycle length is evaluated more than 11 years in spite of the high power density because of the limited design modification. Also, despite the high power density, the average linear power density is estimated to be relatively low thanks to the large number of fuel rods.

The power peaking factor is calculated to be 1.82 in the outer core region due to the high enrichment difference between the inner core region and the outer core region at the beginning of the effective cycle (BOEC). A high power region is shifted from the outer core region to the inner core region over the cycle length. Due to the high internal conversion effect in the inner core, the fissile material is accumulated and the peak power density is increased to 2.41 in the inner core at the end of effective cycle (EOEC). However, the peak linear power density is evaluated 399.84w/cm, which value is lower than the melting limit value of the fuel cladding material. The middle of effective cycle **(**MOEC) is defined here as the maximum excess reactivity cycle at 6year.

3.2 Safety Evaluation

As shown in Table 4, at the BOEC, due to the high leakage from outer core region which is loaded high enrichment fuel, the fuel temperature coefficient (FTC) at BOEC is evaluated to be relatively more negative reactivity compared to MOEC, EOEC. According to fissile depletion over the cycle length, amount of the fissile material in outer core region is decreased. That leads to reduce the neutron leakage from core outer boundary. The reduced neutron leakage have an effect on FTC to decrease at MOEC, EOEC.

According to depletion of fuel material, the delayed neutron fraction is decreased. There are two main reason in this core 1) reduced U-238 which isotope has the high delayed neutron fraction 2) increased Pu-239 which isotope has low delayed neutron fraction. As a result, the delayed neutron fraction is determined by the combined effect according to a change of the respective amounts of the two nuclides.

The reactivity effects of expanding core size are all negative due to reduced fuel density in active core region. Specially, radial expansion coefficient that assume the radial thermal expansion of the grid plate is the most negative among the reactivity coefficients.

The sodium voiding effect consists of two principal effects of opposite 1) a negative effect from neutron leakage and 2) a positive effect from the spectrum hardening. In this long cycle core, the fissile material increased in inner core region have an effect on spectrum to be more harden over the cycle length. Also, decreasing the amount of fissile material in the outer core leads to the neutron leakage reduction in the whole core. By overlapping the two effects, the sodium reactivity coefficient is aggravated. Specially, the sodium void worth is increased from 2.78 $ up to 4.05$.

Table 4. Delayed neutron fraction, reactivity coefficient, and preliminary safety evaluation

	BOEC	**MOEC**	**EOEC**
Delayed neutron fraction (pcm)	336.05	318.07	313.43
Fuel temperature coefficient (pcm/K)	-0.507	-0.397	-0.341
Expansion coefficient (pcm/K)			
- Fuel axial	-0.370	-0.346	-0.354
- Core radial	-1.458	-1.307	-1.321
Sodium density coefficient (pcm/K)	0.305	0.387	0.429
Sodium void worth ($)	2.78	3.62	4.05
A (₵)	-22.61	-18.70	-16.50
B (₵)	-80.46	-72.35	-71.89
C (₵)	-0.60	-0.52	-0.51
ΔT_C (℃)	155	155	155
$\Delta\rho_{TOP}$ ($)	0.249	1.160	0.148
A/B < 1.0 and A&B both are negative (ULOF)	0.281	0.259	0.227
1.0 < $C\Delta T_C/B$ <2.0, C should be negative (ULOHS)	1.164	1.120	1.091
$\Delta\rho_{TOP}$ / | B | <1.0 (UTOP)	0.310	1.604	0.206

The quasi-static analysis method was developed by Wade et al. At the Argonne National Laboratory (ANL) in the 1980s [9]. 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.

Table 4 shows that only the unprotected transient over-power (UTOP) accident scenario at MOEC is not satisfied the safety limits due to the high excess reactivity. The safety parameter of UTOP is calculated with $\Delta\rho_{TOP}$ that is the reactivity worth of the strongest primary control rod assembly. In case of the core having high excess reactivity, $\Delta\rho_{TOP}$ becomes high value, whcih leading the risky condition even if reactivity coefficients are highly negative. At EOEC, the unprotected loss of heat sink (ULOHS) accident scenario is closed the safety limit value because of the positively increased coolant density coefficient. The unprotected loss of flow (ULOF) accident scenario is satisfied the safety limits all case.

3.3 Cycle length Evaluation according to Power level

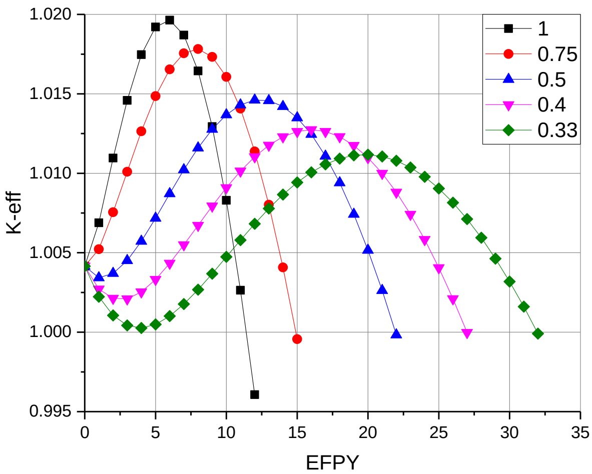

Fig. 3 K-eff of long cycle PGSFR for different powers

The general small long-cycle fast reactors is required to have a low power density designed to maximize the conversion efficiency and to have fewer fuel rods for maximize the amount of heavy metal.

In this study, the long cycle core with high power density is designed by maintaining the original PGSFR power density. Thus, the cycle length is calculated as 11 years. The variation of the cycle length with the decrease of the power level is evaluated. As shown in Table 5, according to reduction of the power level, the total cycle length is increased inversely and the burnup reactivity swing is decreased. The low burnup reactivity swing reduces the burden of required control rod worth. The cycle length of 0.5 relative power is 22 years. That is more than twice as long as the reference power.

As shown in Fig. 3, in case of low power, k-effective is decreased slightly early stage because of the insufficient internal conversion and increased until maximum excess reactivity. After reaching its maximum excess reactivity, it decreases monotonically due to the decreased conversion.

Table 5. Relative power and cycle length

Relative power	Power level	Power density	EFPY
1(ref)	3.922E+08 W	221.32 W/cm3	11
0.75	2.942E+08 W	165.99 W/cm3	15
0.5	1.961E+08 W	110.66 W/cm3	22
0.4	1.569E+08 W	88.53 W/cm3	27
0.33	1.307E+08 W	73.77 W/cm3	32

4. Conclusions

In this study, an economical long cycle core using U-Pu-Zr metal fuel is proposed as the alternative utilization method of PGSFR. The core design is changed to be a long cycle core with high conversion rate for power production. The cycle length of modified long cycle core is evaluated more than 11 years due to high conversion ratio in spite of the high power density.

At the EOEC, the power peaking factor is highly evaluated, but the linear peak power density is satisfied to be lower than the fuel cladding melting limit value. As the fissile amount generated in the inner core region is increased steadily until EOEC, it make high power peaking factor at EOEC. The excess reactivity value increased rapidly until the MOEC. Only the UTOP accident scenario at MOEC is not satisfied the safety limit due to high excess reactivity. Therefore additional design modification for preventing UTOP accidents is required. Also, it is confirmed that the cycle length can be increased with the low burnup reactivity swing as a result of decrease the power level. The decreased burnup reactivity swing can help that the safety value of UTOP accident scenario satisfies safety limit without core design parameter modification.

As a conclusion for feasibility test for core conversion, the use of U-Pu-Zr is O.K. for the long cycle operation of PGSFR with fuel assembly design changes. However this is possible only if U-Pu-Zr is available from outside by consigned reprocessing.

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