Comparison of Neutronic Performance and Reactivity Parameters Between HALEU and U-TRU fuel Loaded 150-MWe SFR Cores

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1. Introduction

Recently, interest in small modular reactors (SMRs) has increased worldwide. When developing Sodium-cooled Fast Reactors (SFRs) as SMRs, three main design concepts can be considered in terms of fuel composition and cycle length. First, a long-cycle core design with a cycle length longer than 10 years utilizing the breeding characteristics of fast neutrons (e.g., ARC-100 [1], SALUS [2]), which operates without refueling and uses HALEU fuel. Second, a HALEU-loaded core design with a 12 to 18-month cycle length based on existing reactor design experiences (e.g., Natrium [3], PGSFR uranium core [4]). Third, a burner core design utilizing the fission and transmutation characteristics of long-lived radioactive nuclides in spent nuclear fuel, rather than fast neutron breeding characteristics.

Most non-light water Small Modular Reactors (SMRs) currently under development utilize HALEU fuel. However, TRU ingots obtained through pyro-processing can be used as fuel in fast reactors, which could help address HALEU supply challenges and contribute to the reduction of spent nuclear fuel from PWRs. In this study, comparative analysis of the nuclear characteristics of a HALEU-loaded core and a TRU-loaded core with similar size, power, and cycle lengths has been performed. From this study, potential safety issues from the TRU loaded SFR core can be examined. To this end, a preliminary evaluation of the equilibrium cycle nuclear characteristics for the PGSFR uranium core and TRU core designs was conducted.

2. Core Design and Analysis Methodology

The radial layout of the target cores is based on the PGSFR design, with a total of 52 fuel assemblies in the inner core and 60 fuel assemblies in the outer core. Both the uranium and TRU cores applied the same fuel reloading scheme of 4 batches for the inner core and 5 batches for the outer core. Fig.1 shows the radial configuration of the PGSFR core.

For the TRU core, two target models were selected to observe changes in core characteristics. “TRU core v.1” has the same active core height of 90 cm and a cycle length of 290 EFPDs as the uranium (HALEU) core. On the other hand, “TRU core v.2” reduced the active core height by 20 cm to 70 cm and increased the cycle length by 40 EFPDs to 330 EFPDs, taking advantage of the easier criticality achievable capability in smaller cores due to TRU loading. Table 1 summarizes the main design parameters of the target cores.

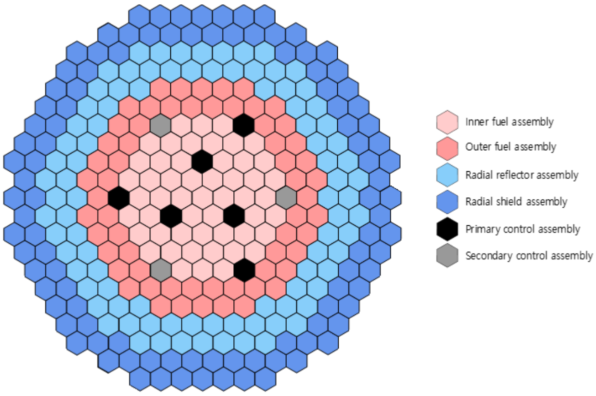

Fig. 1. Radial core configuration of the PGSFR

For the TRU cores, charged fuel is assumed to be fabricated by self-recycled TRU ingot from pyro-processing, PWR spent fuel pyro-processed TRU ingot and natural uranium. In pyro-process, small amounts of rare earth (RE) isotopes are also extracted. The extraction ratio of 6:1 for TRU:RE weight fraction is assumed in this paper.

Table 1. Design parameters of the target cores

	HALEU core	TRU core v.1	TRU core v.2
Thermal power	392.2 MWth		
Active core height	90 cm	90 cm	70 cm
Cycle length	290 EFPDs	290 EFPDs	330 EFPDs
Fuel type	U-10Zr	U-TRU-RE-10Zr	U-TRU-RE-10Zr
Fuel Inventory	7.5 ton	7.5 ton	5.8 ton
Enrichment	U-235: 19.3 wt.%	TRU: 18.7 wt.%	TRU: 23.7 wt.%
RE fraction in the fresh fuel	0.0 wt.%	3.2 wt.%	3.9 wt.%

The nuclear characteristics and equilibrium cycle analyses of the cores were performed using the MC^2-3/DIF3D/REBUS-3 code system [5, 6, 7] developed by Argonne National Laboratory (ANL) for fast reactor core and fuel cycle analysis.

3. Results and Discussion

3.1. Core Performances

Table 2 shows the performance of each core derived through the equilibrium cycle analysis. Comparing the HALEU core and TRU core v.1, the excess reactivity at the beginning of cycle (BOC) of the TRU core was reduced by about 250 pcm, but the peak fast neutron fluence was more than 15% higher. This means that a higher neutron flux is required in the TRU core to achieve the same thermal power of 392.2 MWth, indicating that in-core shielding design and cladding integrity is necessary should be looked up carefully in the TRU fueled core.

Looking at TRU core v.2, despite the decrease in core size and heavy metal (HM) inventory, criticality at the end of cycle could be sufficiently maintained. However, as the TRU content in the fuel increased, the excess reactivity at BOC (3,539 pcm) was observed to be about 1,300 pcm higher than that of the HALEU core. Due to the characteristics of SFRs that do not use soluble boron for reactivity control, design modifications are required to offset this, such as inserting control rod assemblies deeper at BOC or increasing the control rod worth. Furthermore, as the average and peak burnups significantly increased (peak inner 156 GWd/tHM) due to the reduced HM inventory, the necessity of extending the fission gas plenum length has emerged.

Table 2. Core performances of the target cores

	HALEU core	TRU core v.1	TRU core v.2
BOC excess reactivity (pcm)	2,222	1,975	3,539
Average burnup (GWd/tHM)	Inner: 74 Outer: 57	Inner: 76 Outer: 56	Inner: 111 Outer: 83
Peak burnup (GWd/tHM)	Inner: 105 Outer: 92	Inner: 113 Outer: 96	Inner: 156 Outer: 138
Peak fast neutron fluence ($\times 10^{23}$ n/cm^2)	Inner: 2.87 Outer: 2.45	Inner: 3.41 Outer: 2.86	Inner: 4.37 Outer: 3.75

3.2. Reactivity Coefficients

The evaluation results of reactivity feedback coefficients, which are essential for core safety, are shown in Table 3. When TRU fuel is loaded, Pu becomes the main fissile nuclide, causing the effective delayed neutron fraction to decrease significantly compared to the HALEU core (from 677 pcm to about 320~335 pcm). This indicates that the change in in-core neutron flux due to reactivity insertion becomes highly sensitive.

Additionally, the absolute value of the Doppler reactivity coefficient decreased compared to the HALEU core due to the reduction in the in-core U-238 inventory. The Doppler temperature reactivity coefficient provides an immediate negative reactivity feedback effect during accidents. Furthermore, due to the hardening of the neutron spectrum caused by TRU fuel loading, both the sodium temperature reactivity coefficient and the sodium void reactivity worth turned positive.

Interestingly, for TRU core v.2, the sodium void reactivity worth was evaluated to be 875~994 pcm, which is smaller than that of TRU core v.1 (1230~1313 pcm). This is due to the core design that maximizes neutron leakage by reducing the active core height by 20 cm. The sodium void reactivity worth is a combined effect of positive reactivity insertion from neutron spectrum hardening and negative reactivity insertion from increased neutron leakage; thus, its positive magnitude can be controlled through optimal design. Meanwhile, the axial and radial expansion reactivity coefficients—key characteristics of metallic fuel SFRs—showed negative reactivity feedback effects in all cores.

Table 3. Reactivity coefficients of the target cores

HALEU core		
	BOC	EOC
β_{eff} (pcm)	677	652
Doppler (pcm/K)	-0.339	-0.356
Sodium temperature (pcm/K)	-0.231	-0.198
Sodium void (pcm)	-1,005	-887
Axial expansion (pcm/%)	-187	-197
Radial expansion (pcm/%)	-622	-640
TRU core v.1		
	BOC	EOC
β_{eff} (pcm)	335	333
Doppler (pcm/K)	-0.255	-0.258
Sodium temperature (pcm/K)	0.368	0.391
Sodium void (pcm)	1,230	1,313
Axial expansion (pcm/%)	-223	-228
Radial expansion (pcm/%)	-587	-600
TRU core v.2		
	BOC	EOC
β_{eff} (pcm)	320	319
Doppler (pcm/K)	-0.185	-0.193
Sodium temperature (pcm/K)	0.274	0.308
Sodium void (pcm)	875	994
Axial expansion (pcm/%)	-187	-196
Radial expansion (pcm/%)	-659	-686

4. Conclusion

Through this preliminary evaluation, various nuclear characteristics resulting from loading TRU fuel into an SMR-scale fast reactor core were analyzed. While TRU loading facilitates reactor criticality achievement and enables core miniaturization, it imposes several constraints such as increased fast neutron fluence and BOC excess reactivity, a reduced effective delayed neutron fraction, and a positive sodium void reactivity coefficient.

Particularly for the sodium void reactivity, it was found that the positive effect could be partially offset by reducing the core size to maximize neutron leakage. To enhance the completeness of TRU-loaded small fast reactors in the future, further research on securing control system performance, verifying cladding integrity, and optimizing the design for an ideal neutron leakage rate must be conducted.

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