Effect of Rare Earth Element Recycling on Sodium Cooled Fast Reactor Core Performance

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1. Introduction

Korea Atomic Energy Research Institute (KAERI) has been developing a sodium cooled fast reactor (SFR) for enhancing the natural resource utilization and effectively managing the spent nuclear fuel (SNF) discharged from light water reactor (LWR) in Korea. The metal fuel recycled through a pyrometallurgical process of LWR SNF is loaded into the SFR. The charged fuel contains recycled transuranic elements and rare earth (RE) elements.

RE element was classified as a lanthanum group in periodic table and included in the fission products as about 20 %. Since the chemical behavior of RE element is very similar to that of transuranics, the RE elements could not be completely separated from TRU elements through pyrometallurgical process. RE elements play as a neutron poison in the reactor core while inclusion of those to charged fuel makes the SFR-pyroprocessing system more resistant against a proliferation. Therefore, a quantification of maximum RE recovery fraction and clarification of its effect on the core performance and safety is crucial for the design of a pyrometallurgical process.

2. Methods and Results

2.1 Reference Core Model

The reference core model used in this study is a single enrichment SFR core by varying the thickness of sodium bonding thickness [1]. This core concept was selected as most promising TRU burner concept for long term deployment. The reference core showed better performance in terms of sodium void reactivity and TRU burning capability. The core design parameters of the reference core were listed in Table I.

Table I: Core design parameters of reference core model

Core design parameters	
Core power [MWe/MWt]	600/1500
Core inlet/outlet temperature [°C]	390/545
Cycle length [EFPD]	332
Number of fuel batch	5
Fuel pin outer diameter [mm]	7
Active core height [cm]	89
Smear density (inner/outer) [%TD]	60/69.5
Charged fuel composition	LWR recycled TRU

In order to evaluate the core performance in more severe condition, the charged TRU composition and RE inventory were changed to those of a reference LWR spent nuclear fuel (SNF) which implies anticipated spent fuel discharged from LWR when the pyroprocessing facility and SFR plant are ready to be deployed. The reference SNF corresponds to 4.5 wt.% enriched UO_2 fuel loading, 55 MWd/kg discharge burnup and 10 year cooling period [2]. The composition of the reference SNF is shown in Table II. Since the reference SNF contains more minor actinides and RE elements (1.72 wt.% of SNF) than in the original core model (33 MWd/kg discharge burnup), it makes the analysis more conservative.

Table II: Composition of reference LWR spent fuel (unit: wt.%)

U	Pu	MA	FP	
			RE	Other
92.95	1.20	0.21	1.72	3.23

2.2 Calculation Methods

All the calculations were carried out by using equilibrium core analysis of REBUS-3 code. In order to reflect the RE element recycled from LWR, a lumped cross section of RE element in LWR was made separately from that of self recycled RE element.

The RE element recovery fraction in the reference core model has been assumed to be 5 %. The recovery fraction was increased until a critical state at EOEC could be achieved. The recovery fraction of TRU was assumed as 99.9 % for all cases.

2.3 Results and Discussions

The variation of the core performance with respect to the RE element recycling option was listed in Table III. Maximum recovery fraction was found to be about 70 % above which the criticality at EOEC could not be achieved. The charged TRU enrichment and loading are increased as increasing RE recovery fraction because a neutron absorption by RE elements is increased. Because of this, the TRU consumption by cycle was increased while heavy metal inventory was decreased. The increased discharge burnup is due to smaller heavy metal loading.

The burnup reactivity swing at recovery fraction of 70 % gets twice of reference case due to very low TRU conversion ratio.

The change of reactivity coefficients with respect to the RE recycling option was summarized in Table IV. Because RE elements have higher absorption cross

Table III: Variation of core performance with respect to the rare earth recycling option

Rare earth element recovery (%)	5 (Ref.)	20	50	70
Charged TRU enrichment (wt.%)	29.9	31.6	40.6	87.4
Charged Pu fissile enrichment (wt.%)	13.3	13.8	16.2	28.3
Burnup reactivity swing (pcm)	3701	3977	4915	6988
Conversion ratio (fissile/TRU)	0.769/0.565	0.745/0.529	0.637/0.379	0.308/0.039
Mass inventory at BOEC (kg)				
Heavy metal	17007.6	16571.4	14692.0	8685.3
TRU	4966.8	5105.9	5762.8	7500.8
MA	624.1	669.7	877.0	1439.6
Charged TRU amount at BOEC (kg)	1080.6	1116.8	1283.2	1718.8
Total TRU consumption per cycle (kg)	203.1	221.6	299.5	497.8
Average discharge burnup (MWd/kg)	133.9	137.3	154.1	249.8
Peak discharge burnup (MWd/kg)	213.5	221.8	259.6	464.0

Table IV: Effect of rare earth recycling option on reactivity coefficients

RE recovery (%)	5 (Ref.)	20	50	70
Effective delayed neutron fraction	0.00322	0.00318	0.00301	0.00250
SVR (pcm/$)	2316/7.20	2473/7.78	3064/10.18	4113/16.45
Sodium density coefficient (pcm/°C)	0.800	0.853	1.045	1.369
FTC at 900K (pcm/°C)	-0.279	-0.239	-0.106	0.027
Axial expansion coefficient (pcm/°C)	-0.244	-0.248	-0.269	-0.319
Radial expansion coefficient (pcm/°C)	-1.001	-1.008	-1.036	-1.091

section in low neutron energy range, the neutron spectrum gets harder when the amount of RE elements gets larger in the core. This is the reason why the expansion reactivity coefficients gets more negative when the RE recovery is increased with same geometrical configuration.

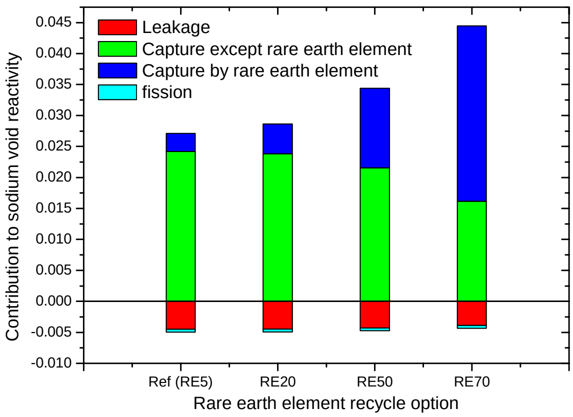

Fig. 1. Neutron balance change at sodium void for rare earth recycling option

The sodium void reactivity gets more positive due to decrease of RE capture at void. Fig. 1 shows breakdown of neutron balance at void. As shown in the figure the change of neutron leakage and fission reaction is similar throughout all the cases. However, the neutron capture of RE element is significantly decreased at void when the RE recovery is increased. The reactivity at normal condition is held by a large neutron capture reaction of RE in the low energy range and it was significantly decreased by spectrum hardening effect at void.

The fuel temperature coefficient gets less negative as increasing RE recovery and even yields positive fuel temperature coefficient when RE recovery is 70 %.

As stated above, the maximum RE recovery for the criticality of EOEC is about 70 %. This only implies a possibility of construction of a critical reactor. Based on the past experience on the SFR core design, the maximum RE recovery fraction could be around 20 % considering the core performance and safety aspect of the SFR.

3. Conclusions

The effect of RE element recycling option on the core performance and safety was evaluated by equilibrium core analysis. The maximum RE recovery fraction that could make the critical state at EOEC was evaluated to be 70 %. If the core performance and safety was considered, it should be reduced to 20 % because increased amount of RE in the core makes the sodium void reactivity more positive.

Acknowledgement

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REFERENCES

[1] Dohee Hahn, et al., "Establishment of Advanced SFR Concepts," KAERI/TR-4063/2010, KAERI, 2010
[2] Result of technical discussion with Department of Nuclear Fuel Cycle Technology Division of KAERI.