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A Transition Cycle Analysis of an Advanced Sodium-cooled TRU Burner Reactor Core

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1. Introduction

The sodium-cooled fast reactor (SFR) is one of the most promising candidates to meet the Generation IV and the SFR technology has been matured as an effective way to transmute TRU due to its favorable features such as the high fission-to-capture ratio and large number of excess neutrons. In our previous studies [1,2], 400MWe SFR burner cores have been designed and analyzed for equilibrium cycle using the equilibrium cycle search option of REBUS-3 code [3]. In particular, the equilibrium cycle search method in the REBUS-3 code system provides an efficient approach for modeling fast reactor system because the feed enrichment of fresh fuel can be determined without performing the previous burn cycle analyses for an arbitrary core composed of fresh and burned fuel assemblies. However, it means that the equilibrium method in REBUS-3 code can't provide a realistic transition cycle solutions [4].

The main objective of this work is to perform the cycle-by-cycle core analysis for the transition and equilibrium cycles of the SFR burner core using the non-equilibrium mode in REBUS-3 fast reactor design code.

2. Core Design and Results

2.1 Description of the Core Design

The SFR burner core configuration considered in this work was designed to achieve high TRU burning rate and small SVR (Sodium Void Reactivity) by locating the non-fuel regions in the central region of the core in order to increase neutron leakage. The configuration is shown in Fig. 1. The innermost three rings of assemblies are occupied with the sodium ducts which are filled with sodium coolant. The next one ring of assemblies is occupied with the B_4C shield assemblies which effectively absorb the leaking neutrons from the core under sodium voiding. Table I summarizes the main design parameters used in the core. The core rates 1015.6 MWt (400MWe) and the active core height is 80cm. A four batch refueling scheme was employed and so one fourth of the fuel assemblies are discharged at the end of the every cycle. The cycle length is 332 EFPDs (Effective Full Power Days). The discharged fuels are cooled for 390 days and reprocessed with pyro-processing for 240 days in which the recoveries of 100% and 99.9% were assumed for uranium and transuranic, respectively and fission products are all removed. The reprocessed spent fuels are fabricated into new charge fuels by mixing with the external TRU feed from PWR spent fuel stocks and the depleted uranium. The composition of the TRU feed is that of PWR spent fuel TRU having 55,000MWD/tU and 10 year cooling.

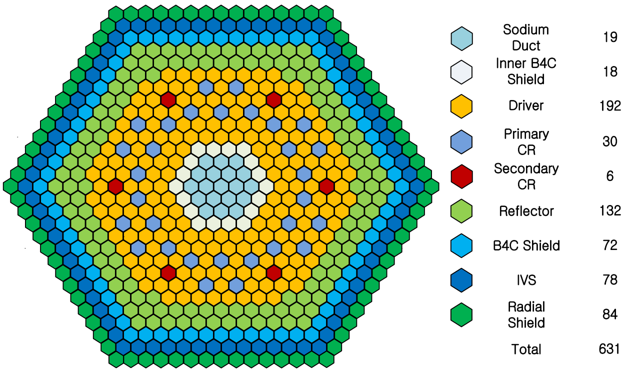

Fig. 1. Configuration of the SFR burner core having central non-fuel regions.

Table I. Main design parameters of the SFR burner core

Design parameter	Specification
Power (MWe/MWt)	400/1015.6
Fuel type	TRU-U-10Zr
Number of rods per FA	271
Smear density of fuel	75%
Duct wall thickness (mm)	3.7
Assembly pitch (cm)	16.3
Rod outer diameter (mm)	7.5
Wire wrap diameter (mm)	1.4
Clad thickness (mm)	0.53
Fuel cycle length (EFPD)	332
Number of fuel management batches	4
Active core height (cm)	80.0

The depletion analysis for the core was done with the REBUS-3 equilibrium and non-equilibrium model where the neutron diffusion equation is solved with HEX-Z nodal option and nine group cross section. The generation of multi-group cross sections for core analysis starts with 150 group cross section library that was generated by KAERI (Korea Atomic Energy Research Institute) based on ENDF/B-VII.r0. This library is MATXS format which was generated with the NJOY code for master nuclides. And, the TRANSX code is used to generate the ISOTXS format multi-group cross section from the MATXS format library where the Bell-Hansen-Sandmeier and the Bondarenko' method are used for the transport correction and resonance self-shielding treatment, respectively. Then, the core region-wise neutron spectra are obtained by DIF3D R-Z model with a 150 group cross section. Then, these core region-wise neutron spectra are used for TRANSX code to produce the condensed core region-wise cross section.

2.2 Results of the Transition Cycle Core Analysis

For analyzing characteristics of the transition cycles to equilibrium cycle, the cycle-by-cycle calculations are performed by non-equilibrium cycle option in the REBUS-3 code system. And also, the scattered fuel reloadings are considered for every cycle. The shuffling and recycling scheme for the 1/6 core is shown in Fig. 2. As shown in Fig. 2a, the 48 once burnt fuel assemblies having high burnup are discharged at EOC of the 1st cycle. And the discharged assemblies are reprocessed and mixed with the depleted uranium and the LWR spent fuel TRU to makeup the heavy metal consumption which is the same as the amount of fission products in the discharged fuel assemblies to meet the cycle length. Then, these newly fabricated fuel assemblies are charged into some positions directed by arrows from them (see Fig. 2(a)) after the ones directed by arrows are moved into the discharged position while some of newly fabricated fuel assemblies are recharged into their original positions to reduce power peaking for the next cycle. At EOC of the 2nd cycle, 48 twice burnt fuel assemblies denoted with '(2D)' are discharged and fabricated into new fuel assemblies after reprocessing and mixing with the external feeds (i.e., PWR spent fuel TRU and depleted uranium). These newly fabricated fuel assemblies are charged into some positon in which the fuel assemblies are shuffled into the discharged positons. These shuffling and recycling patterns are repeated after the 4th cycle. In this figure, the numbers inside the parenthesis means the number of cycles during they stayed in the core. For example, the number '0' means the newly charged fuel assemblies while the number '1' the once burnt fuel assemblies.

The k_{eff} evolution curves obtained from the cycle-by-cycle non-equilibrium analysis up to the 6th cycle are shown in Fig. 3. As shown in Fig. 3, the first cycle has a high k_{eff} value of ~1.078 at BOC, which is resulted from the fact that the initial fresh fuel assemblies have 28.0% TRU contents to achieve the target fuel cycle length at the following cycles. The k_{eff} values are evaluated similarly at each cycle after the 4th cycle because the fixed shuffling patterns are used for the cycles from the 4th cycle. Especially, the amount of LWR-TRU external feeds and the TRU contents of newly charged fuel assemblies are nearly converged after the 15th cycle which is shown in Fig. 4. The inventories of TRU nuclides in the external feed for 15th ~ 19th cycles are summarized in Table II. As shown in Table II, the amount of external TRU feed is about ~174 kg which is the almost converged value. Table III compares the performance parameters for the 15th cycle and the equilibrium cycle searched with the equilibrium cycle option. The 15th cycle equilibrium core has larger burnup reactivity swing by 196 pcm and this core has smaller TRU contents by 7% than the core calculated by the REBUS-3 equilibrium mode system due to the different shuffling scheme (note that the equilibrium model does not use shuffling). The 15th cycle core has slightly more negative Doppler coefficient and smaller sodium void worth and higher power peaking factor than the core calculated by the equilibrium mode due to the low TRU contents.

Table II. Charged mass of LWR-TRU external feeds

Isotope	15 Cycle	16 Cycle	17 Cycle	18 Cycle	19 Cycle
Pu-238	4.8	4.8	4.7	4.7	4.8
Np-237	11.6	11.7	11.4	11.5	11.5
Pu-239	85.2	85.8	83.6	84.0	84.4
Pu-240	40.2	40.5	39.5	39.7	39.9
Pu-241	12.1	12.2	11.9	12.0	12.0
Pu-242	8.8	8.9	8.6	8.7	8.7
Am-241	8.1	8.2	8.0	8.0	8.1
Am-242m	0.0	0.0	0.0	0.0	0.0
Am-243	2.6	2.6	2.5	2.5	2.6
Cm-242	0.002	0.002	0.002	0.002	0.002
Cm-243	0.009	0.009	0.009	0.009	0.009
Cm-244	0.9	0.9	0.9	0.9	0.9
Cm-245	0.07	0.07	0.07	0.07	0.07
Cm-246	0.01	0.01	0.01	0.01	0.01
Total TRU (kg)	174.5	175.8	171.2	172.0	173.0

3. Conclusions

In this paper, a transition cycle core analysis for an advanced SFR burner was performed by the non-equilibrium cycle-by-cycle calculations with REBUS-3. From the analysis, it was shown that the transition cycles slowly converges to an equilibrium cycle but this equilibrium cycle core has small differences in the performance parameters from the one obtained with the REBUS-3 equilibrium model. On the other hands, the core calculated by using the non-equilibrium cycle-by-cycle mode has converged the k-effective value and the LWR-PWR external feeds after 15th Cycle. And the non-equilibrium cycle-by-cycle calculation gave a difference in the burnup reactivity swing by 6.4%, the Doppler coefficient by 12.2%, and the sodium void worth by 46.9% for the equilibrium cycle.

Acknowledgement

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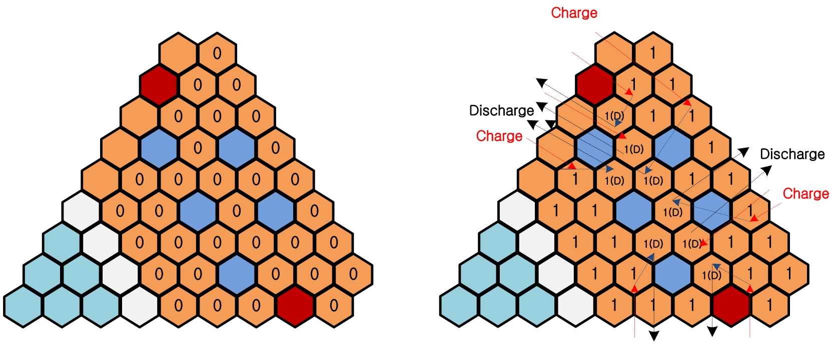
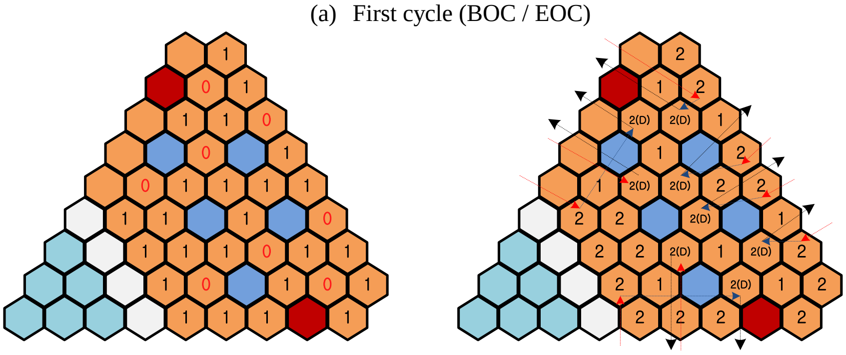
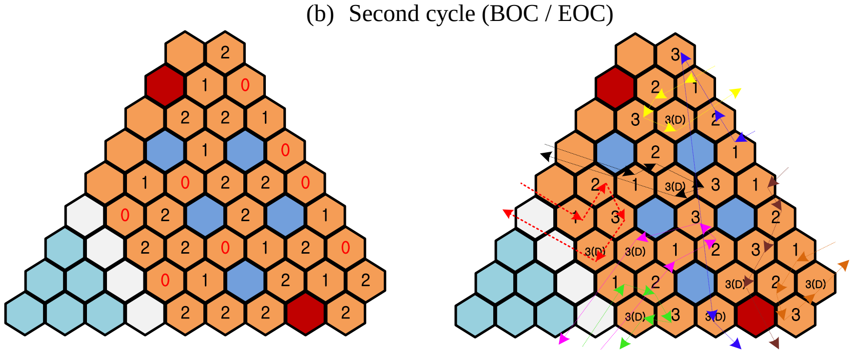


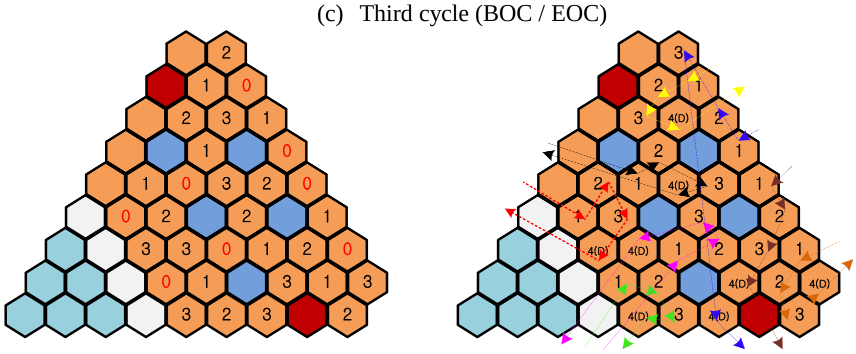
(a) First cycle (BOC / EOC)



(b) Second cycle (BOC / EOC)



(c) Third cycle (BOC / EOC)



(d) Fourth cycle (BOC / EOC)

Fig. 2. Scattered fuel reloading strategy (BOC/EOC)

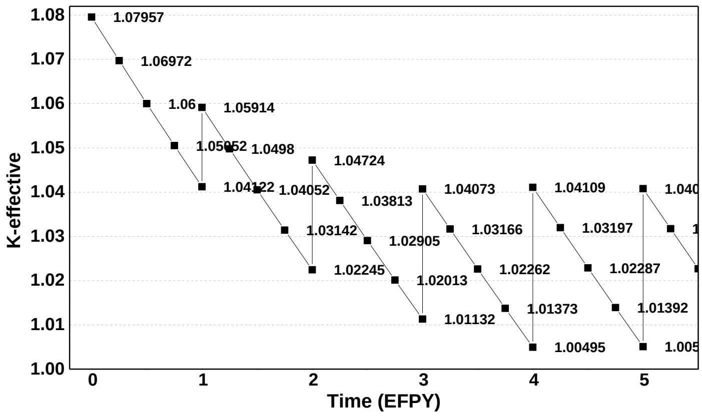


Fig. 3. Evolution of k-effective value curves during the first five years of the closed cycles for the core calculated by using non-equilibrium mode in REBUS-3.

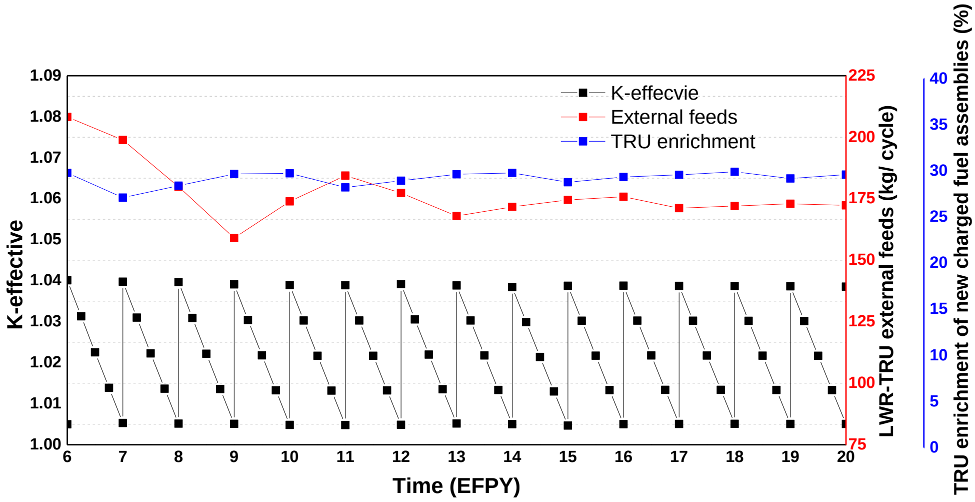


Fig. 4. Evolution of k-effective value curves, external LWR-TRU feeds, and TRU contents in the new charged fuel assemblies for the core calculated by using non-equilibrium mode in REBUS-3.

Table III. Performance parameters of the SFR burner core for equilibrium cycle

Parameters	REBUS-3 Equilibrium-mode	REBUS-3 Non-equilibrium mode 15^{th} cycle
Burnup reactivity swing (pcm)	3041	3237
TRU wt% in HM (BOEC/EOEC)	30.69 / 30.24	28.55 / 28.09
TRU consumption rate (kg/cycle)	171.0	174.5
3D power peaking factor (BOEC)	1.42	1.55
Peaking LPD(W/cm, BOEC)	335	365
Doppler coefficient (pcm/K , 900K, BOEC)	-0.237	-0.266
Sodium void worth (pcm, BOEC)	573	304