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A Preliminary Core Design Study of a Small Breed-and-Burn Fast Reactor using Semi-Recycling

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I. Introduction

Recently, there have been lots of interests and studies on developing ultra-long-life fast reactor cores [1][2][3] that can be operated without refueling over several tens of years. In these reactor cores, ultra-long-cycle is obtained using small driver fuel regions coupled with small blanket regions, in which the driver fuel regions initially supply fast neutrons that flow into the blanket region. The supplied neutrons from the driver fuel region breed the fissile materials in the blanket region, which causes the propagation of fission power from the driver region to the blanket region and extends the cycle length. However, there are relatively only few works of multi-cycle analysis in these ultra-long-life cores.

In this work, a small ultra-long-cycle sodium cooled reactor core is neutronically designed with multi-cycle analysis. In particular, the multi-cycling strategies are searched such that the multi-cycling is sustained only with depleted uranium makeup. That is to say, the enriched uranium is not used in the subsequent cycles after the first cycle. After the extensive trials, it was found that the partial recycling with the pyro-processing can sustain the multi-cycling only with the depleted uranium makeup for the partial recycled driver fuel. The computational methods and models are briefly given in Sec. II and Sec. III gives the detailed core design study and core performance analyses. Finally, the summary and conclusions are given in Sec. IV.

II. Computational Methods and Models

The REBUS-3 non-equilibrium model [4] with twenty five group cross sections was used to perform the core depletion analysis where the initial uranium enrichment for driver fuels at the first cycle was determined to give k_{eff} of 1.004 at BOC. The twenty five group cross sections were produced by collapsing the 150 group cross sections with the 150 group core region-wise neutron spectra that were calculated with DIF3D R-Z geometrical model [5]. The 150 group cross section library of ISOTXS format was generated using TRANSX code [6] and a MATXS format which was generated with the NJOY code and ENDF/B-VII.0 for master nuclides. The core physics parameters were evaluated with 80 group cross section and DIF3D HEX-Z nodal option. The decay chain spans the range from ^{232}Th to ^{246}Cm. The partial recycling and shuffling were performed with a small program which is written to automatically prepare the atomic number densities with partial recycling and shuffling. For the partial recycling with pyro-processing, it was assumed that all the fission products are removed and the amount of the fission products are supplemented with depleted uranium makeup.

III. Core Design and Performance Analysis

III.A. Description of Core Design

We considered small core to have improved inherent safety. The core rates 330MWt which corresponds to 130MWe electricity output. The binary metallic fuels of U-10Zr are employed to obtain high breeding ratio resulted from hard spectrum. The driver fuel uses the enriched uranium while the blanket one uses the depleted uranium. The configuration of the core for the first cycle is shown in Fig. 1. The inner most (36 assemblies) and outer most regions (42 assemblies) are occupied with the blanket fuel assemblies (they are denoted as inner and outer blankets, respectively.) while two middle regions (42 and 36 assemblies) are occupied with driver fuel assemblies. At present, 13 control assemblies are considered but they are not optimized in this preliminary work. These fuel assemblies are surrounded with two rings of the lead (Pb) reflector assemblies which are followed by the radial shield assemblies. The lead reflectors are considered to reduce the radial neutron leakage.

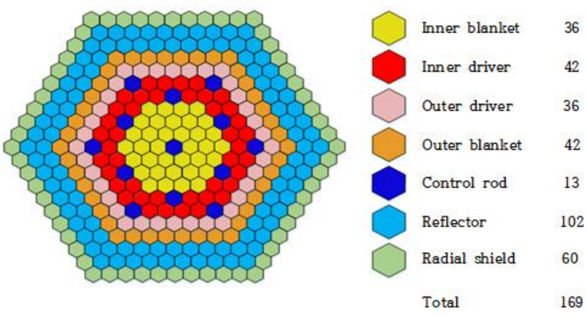


Fig. 1. Radial core configuration of the 1st cycle.

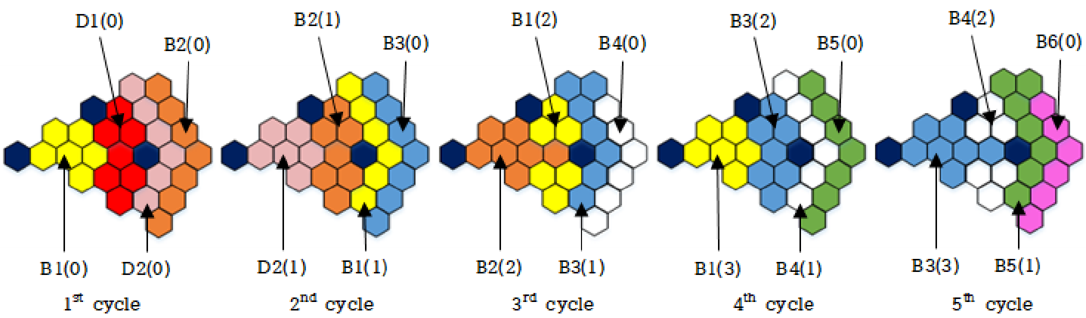
Table I summarizes the main design parameters of the reference core. The active fuel length is 100 cm and fat fuel rods of 1.5 cm outer diameter are adopted for achieving high breeding ratio both in the driver and blanket assemblies. Each fuel assembly is comprised of 169 fuel rods and 3.5 mm thick outer hexagonal duct. The average linear heat generation rate is 125 W/cm and average volumetric power density is 48.8 W/cm^3. As shown in Table I, the fuel volume fraction for the fuel assemblies is very high (i.e., 64.1%) for achieving ultra-long-cycle length for the first cycle. This fuel volume fraction includes the sodium bonding region which occupies 25% of the inner clad region of the fuel rods.

The shuffling and partial recycling scheme which is finally employed is shown in Fig. 2. As shown in Fig. 2, the once burnt D1 driver fuel assemblies are discharged and the once burnt outermost blanket B2 ones are moved into these D1 positions at EOC of the 1st cycle. On the other hand, the once burnt driver D2 assemblies are reprocessed and moved into the innermost B1 blanket positions while the once burnt B1 blankets are moved into the original D2 positions. In particular, the reprocessing of the once burnt driver D2 assemblies was considered to obtain the sufficiently long cycle length for the next cycle. At EOC of the 2nd cycle, the twice burnt D2 assemblies in the innermost region are discharged and the twice burnt B2 assemblies move into the innermost region after reprocessing but six of them are stayed in their positions, which are followed by the movements of the twice burnt B1 ones into the B2 positions and then the movements of the once burnt B3 ones into the B1 positions but six of B3 assemblies are stayed in their original positions. The fresh blanket B4 assemblies are charged into the outermost blanket region.

Table I. Main design parameters

Parameters	**Values**
Power (MWe/MWt)	130/330
Average linear heat generation (W/cm)	125
Average volumetric power density (W/cc)	48.8
Active core height (cm)	100
Number of rods for each fuel assembly	169
Fuel rod outer diameter (cm)	1.5
Cladding thickness (mm)	0.55
Fuel smear density (% of theoretical density)	75
Fuel rod pitch (cm)	1.55
Pitch-to-diameter (P/D) ratio	1.03
Wire wrap diameter (mm)	0
Duct thickness (mm)	3.5
Fuel assembly pitch (cm)	21.493
Volume fractions for fuel assemblies (%)	
Fuel/structure/coolant	64.1/22.2/13.7
Reflector composition (volume fractions (%))	
Pb/coolant/structure	93.1/3.7/3.2
Control rod assembly composition (volume fractions (%))	
[a]B_4C/coolant/structure	45.9/44.5/9.6

[a]B_4C : B-10 enrichment: 60 wt%.



B1,2(n): n-times burned blanket fuel

D1,2(n): n-times burned driver (D1: 14 w/o enriched U, D2: 16.75 w/o enriched U for the first cycle)

Fig. 2. Shuffling strategy coupled with partial recycling (Loading patterns at BOC, 1/6 core)

At EOC of the 3rd cycle, the three times burnt B2 assemblies at the innermost region are discharged, which are followed by the movements of the three times burnt B1 ones after reprocessing into the innermost region. Then, the B1 positions are occupied by the twice burnt B3 assemblies and the once burnt B4 assemblies are moved into the B3 positions. Then, the fresh blanket B5 assemblies are charged into the outermost region. At EOC of the 4th cycle, the four times burnt B1 assemblies are discharged and these positions are occupied by the three times burnt B3 assemblies after reprocessing but six of them are stayed in their original positions, which are followed by the movements of the twice burnt B4 assemblies into the B3 positions. The B4 positions are occupied by the once burnt B5 assemblies but six of them are stayed in their original positions. The outermost blanket regions are charged by the fresh blanket B6 assemblies. These shuffling and partial recycling patterns are repeated in the subsequent cycles. In all the subsequent cycles, only blanket assemblies are charged in the outermost positions, then they are shuffled into inner regions and they are discharged after four times burnt. Also, they are reprocessed after three times burning but the depleted uranium is supplemented. The main performance parameters are summarized in Table II. As shown in Table II, the cycle lengths are different for each cycle because they are adjusted such that the subsequent cycle after each cycle has the sufficiently long cycle length. The first and second cycles have 30 EFPYs and 36 EFPYs, respectively while the subsequent cycles have cycle length of 34 EFPYs. The first cycle has small burnup reactivity swing of 781 pcm but all the subsequent cycles have large burnup reactivity swings of ~6000pcm. The average burnups given in Table II are the cycle average burnup and so the discharge burnups are much larger than the cycle burnup. The initial uranium enrichments for the D1 and D2 driver fuel assemblies are 14.0 wt% and 16.75 wt%, respectively that are determined to give initial k_{eff} of 1.004 at BOC of the first cycle. The cycle average conversion ratios are larger than 1.02 for all the cycles.

Table II Comparison of the core performances

Parameters	1st cycle	2nd cycle	3rd cycle	4th cycle	5th cycle
Cycle length (EFPY)	30	36	34	34	34
Burnup Reactivity swing (pcm)	781	6104	6192	5820	5880
Average burnup (MWD/kg)					
Total core	82.8	101	96.5	95.3	95.7
Driver	136.4	134.9	129.2	128.1	128.1
Blanket	29.1	11.2	10.5	8.5	9.9
Cycle average conversion ratio	1.02085	1.10848	1.1008	1.1255	1.1183
Heavy metal inventories (kg)	[a]7111/[b]6493	7003/6257	6917/6211	7001/6295	6977/6272
Fast neutron fluence (n/cm^2)	6.93E + 23	1.52E + 24	1.48E + 24	1.53E + 24	1.52E + 24

[a]Values at BOEC.
[b]Values at EOEC.

The evolutions of k_{eff} are compared in Fig. 3. The initial k_{eff} for the second cycle is quite high because the driver fuel assemblies are moved into the innermost region after reprocessing but it decreases as time. For all the cycles after the second one, the evolutions of k_{eff} are quite similar to each other. That is to say, the effective multiplication factors for these cycles are initially much smaller than that of the second cycle but higher than that of the first cycle and then they rapidly increase as time up to their maximum values. Their maximum values of the effective multiplication factors occur at ~7.5 EFPYs and then the effective multiplication factors monotonically decrease as time. The trends of the evolution of the effective multiplication factors can be understood from the evolution of the conversion ratios that are given in Fig. 4. As shown in Fig. 4, the conversion ratio for the first cycle slowly increases as time but they are still less than 1.0 up to 17.5 EFPYs and then increases further. For the second cycle, the conversion ratio is slightly larger than 1.1 and then slowly increases and decreases after its maximum value.

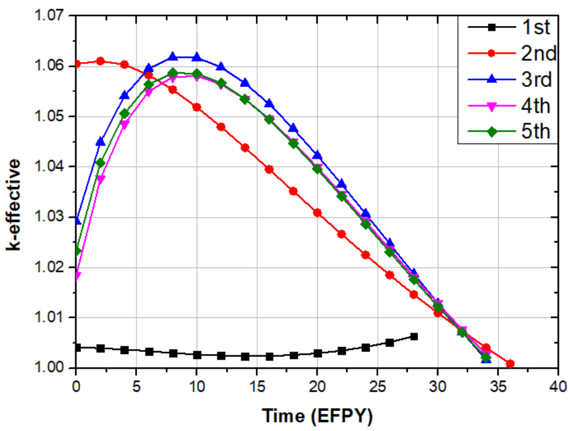


Fig. 3. Comparison of the eigenvalue evolutions.

For the cycles after the second cycle, the initial conversion ratios are much higher than 1.0 and they monotonically decrease as time, which explains the trend of the eigenvalue evolution that the effective multiplication factor initially rapidly increase and decrease after their maximum values.

Table III summarizes the reactivity coefficients including sodium void reactivity worth. As shown in Table III, all the reactivity coefficients for all the cycles are negative except for the reactivity coefficient for sodium coolant expansion. The core has negative sodium void reactivity worth at BOC of the first and second cycles while it is slightly positive a BOC of the fifth cycle and the sodium void reactivity worth at EOC of all the cycles are positive but they are quite small.

Finally, we analyzed the power distributions of the core at BOC, MOC, and EOC for the first and fifth cycles. They are shown in Fig. 5(a) and (b), respectively. As shown in Fig. 5, for the first cycle, the power density is initially high in the outer driver regions and the power distribution moves into the inner and outer blanket regions while the power distribution for the fifth cycle is initially concentrated in the inner where three times burnt fuels are loaded and then it propagates into the middle and outer regions. These power distributions explain the trend of the sodium trends given in Table III. For example, the large negative sodium void worth at BOC of the first cycle is due to the large radial neutron leakage through the outer region where the power densities are high while the small positive sodium void reactivity worth is resulted from the reduced radial neutron leakage. However, it should be noted that the power densities at EOC of the first cycle is still higher than those of the fifth cycle, which explains the fact that the sodium void worth at EOC of the first cycle is smaller than those of the fifth cycle.

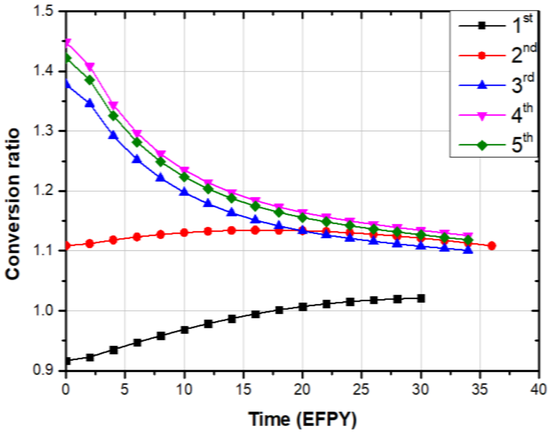


Fig. 4. Comparison of the conversion ratios

Table III. Comparison of the reactivity coefficients

Parameters	1st cycle	2nd cycle	5th cycle
Fuel axial expansion (pcm/K)	[a]-0.3892/ [b]-0.2076	-0.2806/-0.1976	-0.2799/-0.2071
Radial expansion (pcm/K)	-0.7062/-0.6312	-0.6152/-0.6363	-0.6613/-0.6380
Sodium coolant density (pcm/K)	-0.2898/0.2221	-0.0109/0.4179	0.2233/0.4115
Fuel doppler coefficient (pcm/K, 900K)	-0.4259/-0.4532	-0.4254/-0.3641	-0.4719/-0.3536
Sodium void reactivity worth (pcm)	-1318.9/257.4	-545.8/801	201.5/760.2

[a]Values at BOEC.
[b]Values at EOEC.

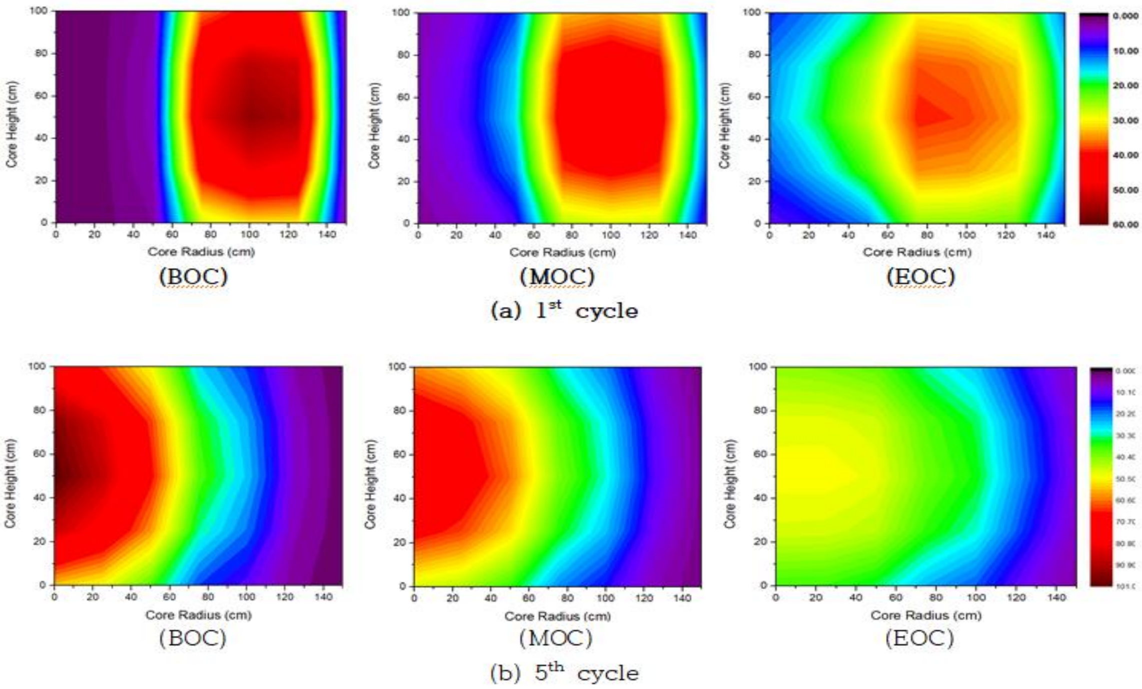


Fig. 5. Comparison of the R-Z power distributions for the 1th and 5th cycle.

IV. Summary and Conclusions

In this preliminary work, a new small sodium cooled ultra-long-cycle core with multi-cycle analysis is neutronically designed and analyzed to show the feasibility. The results showed that it is possible to neutronically design the ultra-long-cycle core even with small core size with shuffling and partial reprocessing only for specific batch fuel. Every fuel cycle has longer cycle lengths than 30 EFPYs but the subsequent cycles after the first cycle have large burnup reactivity swings ranging from 5800 to 6192 pcm, which would require a large control rod reactivity worth. This optimization for reducing the burnup reactivity swings will be performed as a future work by the partial reprocessing and shuffling strategies. On the other hand, the core has very good reactivity coefficients including negative or small positive sodium void reactivity worth, which improves inherent safety of the core. In particular, it was shown that it is possible to obtain quite high discharge burnup with the shuffling and partial reprocessing strategies, which significantly enhances the utilization of the uranium resources.

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REFERENCES

[1] H. Hyun and S. G. Hong, "A Sodium-Cooled Ultra-Long-Life Reactor Core having Improved Inherent Safety with New Driver-Blanket Burnup Strategy," Vol.41, p.7082 (2016).

[2] H. Hyun, S. G. Hong and W. You, "Physics Study of Sodium-Cooled Ultra-Long-Life Core using New Driver-Blanket Burnup Strategy," Transactions of the American Nuclear Society, Vol.113, p. 1099, 2015.

[3] E. Greenspan, "A Phase Development of Breed-and-Burn Reactors for Enhanced Nuclear Energy Sustainability, Sustainability," Vol.4, p.2745, 2012.

[4] B. J. Toppel, "A User's Guide for the REBUS-3 Fuel Cycle Analysis Capability," ANL-83-2, ANL, IL, USA (1983).

[5] Derstine KL. "DIF3D10.0: Code System Using Variational Nodal Methods and Finite Difference Methods to Solve Neutron Diffusion and Transport Theory Problems," CCC-783, IL, USA, ANL, 2011.

[6] R. E. MacFavlane, "TRANSX 2: A Code for Interfacing MATXS Cross-Section Libraries to Nuclear Transport codes," LA-12312-MS,LANL,NM,USA. (1992).