Neutronic Self-sustainability of a Breed-and-Burn Fast Reactor Using Super-Simple Fuel Recycling

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Abstract. This is a preliminary study to investigate the feasibility of self-sustainable sodium-cooled breed-and-burn fast reactor (B&BR) based on newly suggested fuel recycling technology, which is very simple and highly proliferation resistant. First 400 MWth B&BR core concept is derived in the previous researches and following spent nuclear fuel (SNF) is used to the start the second B&BR, which has same geometry as first B&BR. In this study, recycling of B&BR SNF in 3 scenarios are simulated: single zone, 3-zone and 6-zone recycling, and the performance of second B&BR with each strategy is analyzed. It should be noted that the fuel loading pattern is optimized to maximize the performance of second B&BR in terms of burnup reactivity change, core lifetime and power profiles. Finally, the impact of different recycling scenarios and different recycled fuel loading on the next generation B&BR was investigated.

Key Words: Sustainability; B&BR; FAST; Fuel Reprocessing

1. Introduction

Fast reactor, which utilizes fast neutrons, can achieve high neutron economy and resulting fuel utilization can be very effective. Breed-and-burn fast reactor (B&BR) is a unique concept of fast reactor, which can achieve an extremely long lifetime by breeding the fissile fuels and using the bred fuels in situ. Nevertheless, there are still fissile contents in the discharged fuel, such as uranium isotopes which are not burnt in the driver fuel and plutonium isotopes which are converted from fertile nuclides in the blanket. In addition to the fissile materials however, there are also noticeable amount of rare earth nuclides which absorb the neutrons and volatile or gaseous fission products like xenon, krypton or iodine in the SNF. These materials reduce the reactivity of the core by absorbing the neutrons or reducing the core density, which make the SNF difficult to be used as fuel anymore. In this regard, there was a previous research to start the new B&BR using the reprocessed B&BR SNF. A fuel reprocessing technology named melt refining was tested in EBR-II from 1964 to 1969 [1] and it was also applied in our previous study which showed that 2nd B&BR can be started using the recycled SNF of 1st B&BR [2]. However, about 95% of rare earths are removed during the melt refining and the associated processes are not very simple. Moreover, the actinide loss can also be significant. To enhance the proliferation-resistance and economy of the reprocessing, a super-simplified melt and treatment (SSMT) process without removing rare earth nuclides is suggested and the feasibility study to start the 2nd B&BR using SSMT is carried out in this paper.

The neutronic feasibility of B&BR self-sustainability based on SSMT is studied in terms of the burnup reactivity change, core lifetime and power profiles. Neutronics calculations are carried out using the Monte Carlo code McCARD [3] in conjunction with ENDF\B-VII cross-section library.

2. First B&BR Core

A 400MWth B&BR core developed by KAIST is used as a reference core in this study [4]. The radial and axial layout of the core is shown in Fig. 1 and core parameters and fuel assembly design parameters are tabulated in Table I and II, respectively. The height of the fuel region is 180 cm and the LEU-Zr fuel region is arranged in a pan-shape to reduce the core excess reactivity below 1.0$ during operation. And the SNF from PWR with an irradiation history of 50 GWd/MTHM and after 10 years of cooling is considered as a blanket fuel in the form of SNF-6Zr or SNF-8Zr. The driver fuel region (U-Zr) has a smeared density of 70% and it is 75% for the blanket fuel region (SNF-Zr). The core contains 78 fuel assemblies, 4 primary control assemblies and 3 secondary control assemblies. There is 40 cm axial HT-9 reflector at the bottom of the core.

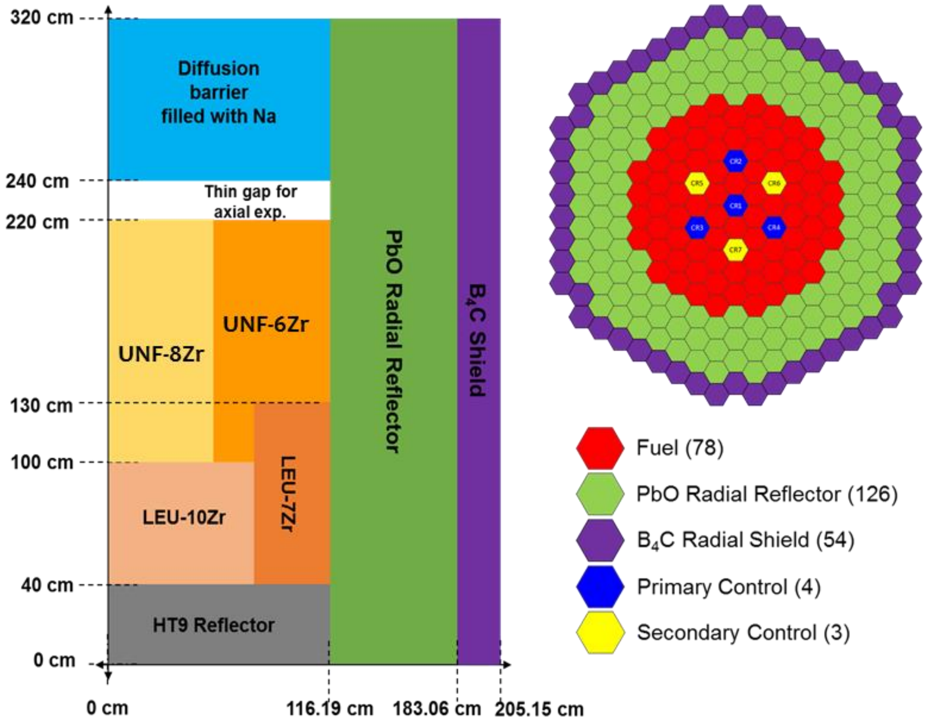

FIG. 1. B&BR core configuration

Above the active core region, there are 20 cm gap for the fuel expansion and 80 cm diffusion retarding area. One notes that the diffusion retarding region is designed to slow the diffusion of volatile and long-lived isotopes such as Cs-137 and I-131; in fact, by I-131 may probably have decayed even before it is vented out [5]. Gaseous fission products such as Kr and Xe can diffuse upward through the micro-hole membranes from the active fuel region, pass through the diffusion retarding region, and finally be released out of the rod to relieve its internal gas pressure. This venting of fission gaseous is advantageous for a long-life nuclear reactor since the fuel cladding has now one fewer variable that can significantly compromise its integrity. This is because as the pressure or hoop stress on the cladding is reduced, its corresponding strain is greatly decreased as well [6].

To improve the neutron economy, annular fuel pin concept without bonding sodium is adopted [6]. Inner radii of the annular fuel are 0.48013 cm for the driver and 0.43695 cm for the blanket. This annular design was chosen to minimize the axial swelling rate. Traditional solid U-10Zr and U-19Pu-Zr metallic fuels were reported to grow axially about 10% and 5% respectively at 20% fuel burnup [7]. In spite of the absence of sodium bonding, it should be noted that there is no concern about the thermal conductivity of swelled metallic fuel since the thin gap is closed due to fuel and cladding thermal expansions almost as soon as the fuel assemblies are dipped into the sodium pool. For this reason, it is assumed in the neutronics simulations that the gap between fuel and cladding is closed from the beginning of the core lifetime.

TABLE I: Core major design parameters

Design Parameters	Value
Power, MWth	400
Core height, cm	180
Initial core height (IC/OC), cm	60 / 90
Active core equivalent radius, cm	116.19
Whole core equivalent radius, cm	205.15
Coolant inlet temperature, ^{o}C	360
Coolant outlet temperature, ^{o}C	510
Power density, W/cc	90.149
Discharge burnup, GWd/MTHM	160
Core lifetime, EFPYs	52
Peak Cladding DPA	700

TABLE II: Fuel assembly design parameter.

Parameter	**Fuel Assembly**
No. of fuel pins	124
Fuel pin diameter, cm	1.90
Fuel inner radius, cm (driver / blanket)	0.48013 / 0.43695
Fuel outer radius, cm	0.88600
Gap thickness, cm	0.04
Cladding thickness, cm	0.055
Diffusion barrier thickness, cm	0.005
Fuel (driver / blanket)	U-Zr / SNF-Zr
Cladding	HT-9
P/D ratio	1.064
Wire wrap diameter, cm	0.1216
Assembly pitch, cm	24.00
Assembly duct thickness, cm	0.30
Assembly gap, cm	0.25
Fuel/Structure/Coolant vol. frac., %	63.34/14.01/22.65

In the fuel assembly, the fuel, structure, coolant volume fractions are about 63.34%, 14.01%, and 22.65%, respectively. A PbO reflector is used in order to improve the neutron economy of a compact B&BR core [4, 8]. In the reflector, the PbO reflector, structure, and coolant volume fractions are 64.39%, 16.9%, and 18.71%, respectively.

The passive safety device, FAST module, is presented in this study. It is a cylindrical neutron absorber rod loaded into an empty pin in the fuel assembly [9]. During normal operating condition, the FAST module floats above the active core region. When there is a huge coolant temperature increment e.g. 100 K, the absorber rod losses its buoyancy and invariably dips down into the active core, thereby inserting additional negative reactivity into the care. In case of loss of coolant accidents, the absorber drops further due to gravity. Position of the FAST module during these scenarios are depicted in Fig. 2.

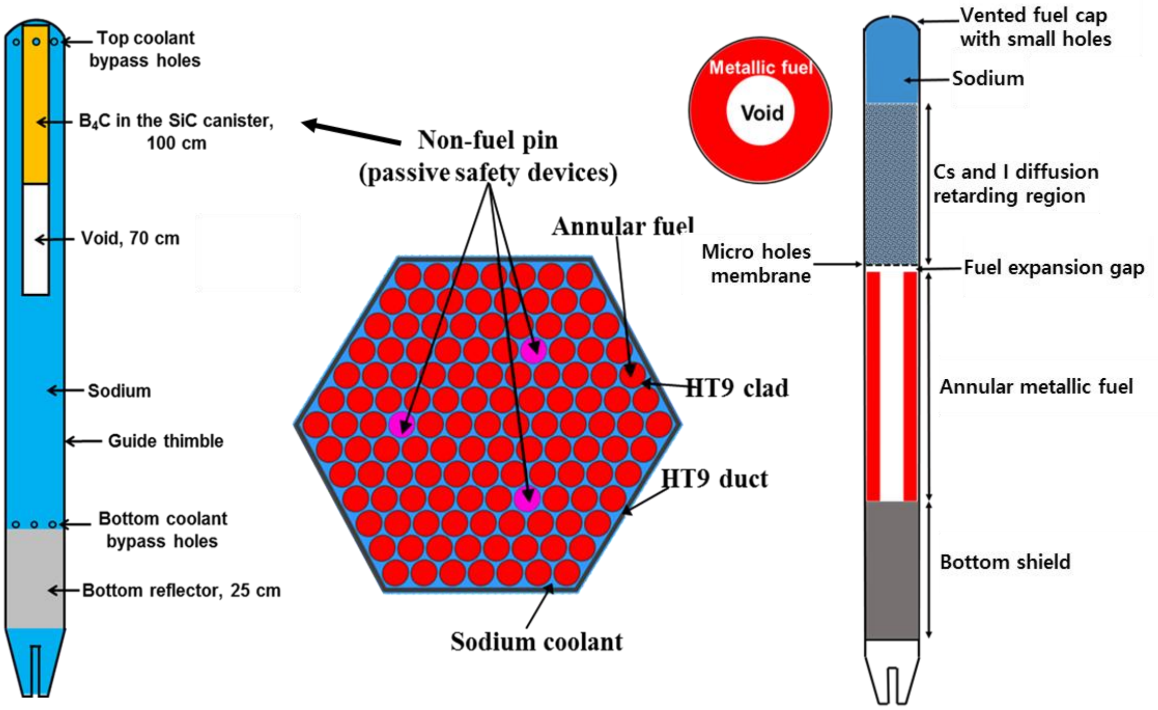

FIG. 2. Fuel pin, passive safety device and assembly configurations.

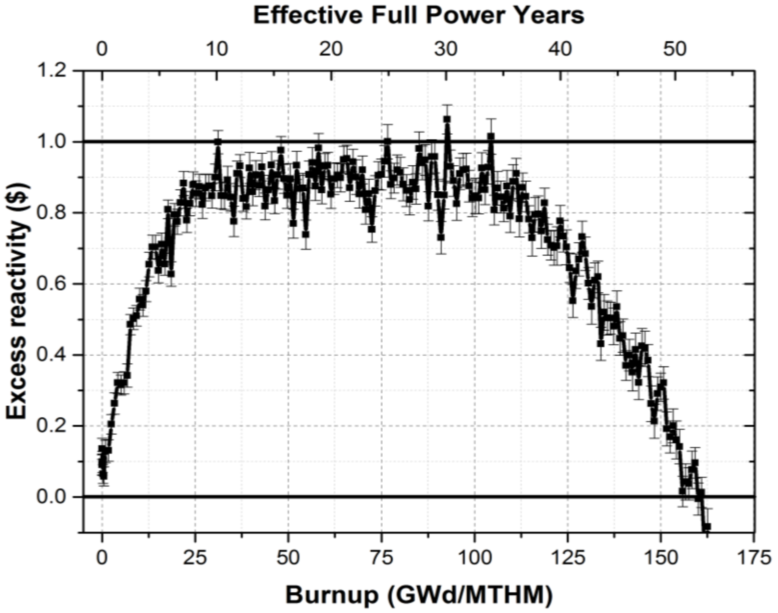

FIG. 3. Excess reactivity evolution

The neutronics burnup calculation using McCARD was completed with explicit modeling of the assemblies. It is shown in Fig. 3 that the achievable core average discharge burnup is about 160 GWd/MTHM, equal to 52.3 years of operation without fuel refueling. The maximum excess reactivity is well managed below 1$ during reactor operation as expected by using a concave initial core configuration. In terms of pcm, the maximum excess reactivity is about 550 pcm.

The conversion ratio of the core is shown in Fig. 4. It was calculated for the inner core region, outer core region, and whole core. The inner core region includes second to fourth ring fuel assemblies, while the remaining fuel assemblies are grouped into the outer core region. As expected, the inner core region has a much higher conversion ratio than the outer core due to more blanket fuels in the inner core region.

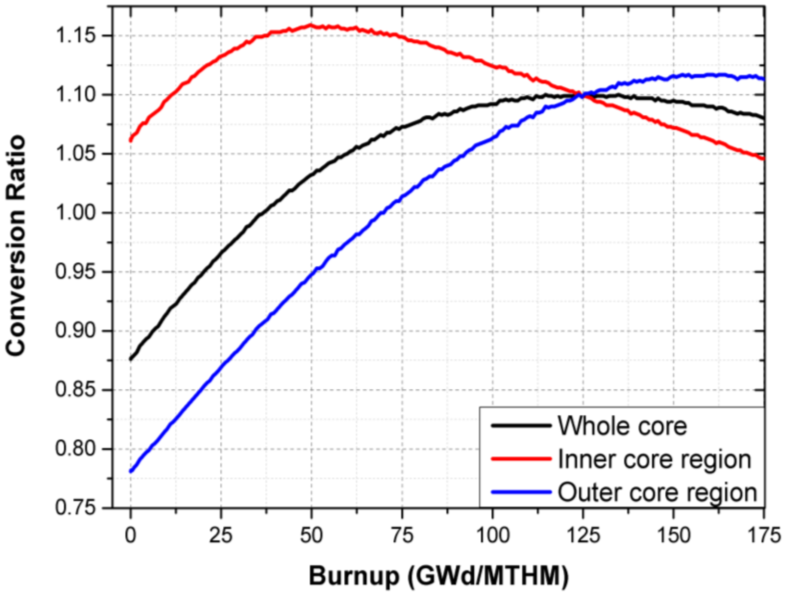

FIG. 4. Conversion ratio

3. Sustainability with Super Simplified Melt and Treatment (SSMT)

The SNF from the first B&BR should be reprocessed or reconditioned so that it can be re-used in the second B&BR. A fuel reprocessing technology named melt refining was used in EBR-II from 1964 to 1969 [1]. Melt refining technology has been successfully proven to recycle the EBR-II spent fuel from 1964 through 1969. The processing procedure starts from the disassembling and chopping of the spent fuels. Then the products are mixed into a ZrO_2 crucible. The mixing is heated up to 1400°C. The gaseous fission products such as Xe and Kr, and the highly volatile elements at 1400°C such as I and Cs, will be completely removed both during preoperational work and during melting process. The elements that react chemically with ZrO_2 at 1400°C such as rare earth and yttrium will be removed by more than 95%. The reaction will form a hard slag in the crucible. The remaining elements after the process are U, TRU, and noble metals. Then, the molten metallic fuel is injected to the casting to fabricate the new metallic fuel. Although the reactor performance can be favorable with the old melt refining due to removal of neutron-absorbing rare earth nuclides, it is reported that significant amount of TRUs is also removed during the refining process and a proliferation issue is also raised. Actually, the crucible material for the melt-refining should be carefully treated after the refining process and it cannot be reused.

To enhance the proliferation-resistance and economy of the reprocessing, a super-simplified melt and treatment (SSMT) process without removing rare earth nuclides is suggested. In the newly suggested SSMT, the gaseous fission products are only removed, while the rare earth nuclides are assumed to be fully recovered together with the other fuel materials so that there is no nuclear proliferation concern and the whole process can be a lot more simplified. As a consequence, it is clearly expected that the neutron economy with the SSMT process becomes worse. It should be noted that U, TRU, and noble metals are also assumed to be 100%

recovered in the SSMT process. The procedures of melt refining and SSMT are compared in Fig. 5.

For the neutronics analysis, composition of the SNF from the 1st B&BR is reprocessed and fuel density after SSMT is calculated by conserving the mass and considering 0.1% axial swelling of the fuel.

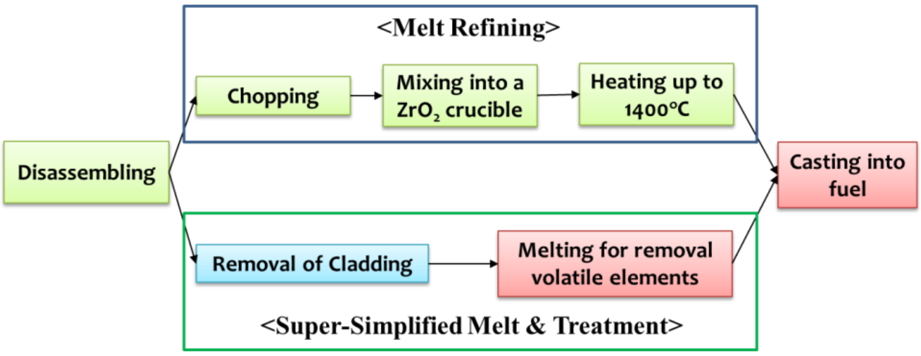

FIG.5. Procedures of melt refining and SSMT.

First, it should be noted that the geometry of the 2nd B&BR is exactly the same as in the 1st B&BR. In this study, SSMT is used to recycle the B&BR fuel. There are many ways to recycle the SNF from the 1st B&BR by SSMT (1st SNF). In this study, 3 possible recycling scenarios are considered as shown in Fig. 6 since the composition of the fuel after SSMT for the 2nd B&BR is strongly dependent on the zone-wise SSMT of the 1st SNF. The resulting fuel compositions after each SSMT scenarios are shown in table III, IV, and V.

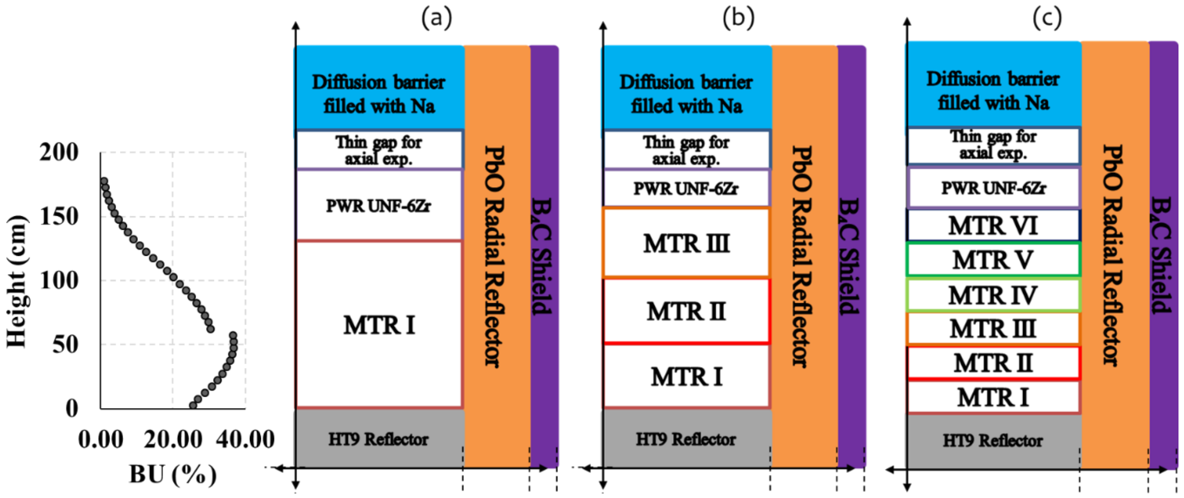

FIG. 6. Schematic of 3 recycling scenarios

(a: SSMT with 1 MTR, b: SSMT with 3 MTRs, c: SSMT with 6 MTRs)

The first scenario is that all the fuel assemblies from the 1st B&BR are reprocessed together by SSMT without any zone separation. In the second scenario, 1st SNF is divided into 3 zones, i.e. highly burned (bottom), medium-burned (middle), and low- burned (top) zones. Similarly, in the third scenario, 6 zones are considered. It should be mentioned that loading patterns of fuels after SSMT are optimized to maximize the cycle length of the 2nd B&BR.

TABLE III: Fuel composition after 1-region SSMT.

Composition	(weight %)					
FP (RE)	Zr	U	Np	Pu	Am	Cm

11.39 (6.03)	9	72.2	0.21	7.1	0.09	0.005
Pu vector						
Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	Pu-243	Pu-244
1.56%	81.19%	15.54%	1.09%	0.62%	0.00%	0.00%

TABLE IV: Fuel composition after 3-region SSMT.

Composition (weight %)							
Region	FP (RE)	Zr	U	Np	Pu	Am	Cm
MTR1	17.07 (9.10)	11.320	62.870	0.330	8.330	0.080	0.002
MTR2	13.81 (7.19)	8.950	68.370	0.220	8.560	0.090	0.008
MTR3	4.3 (2.32)	7.080	83.695	0.110	4.700	0.110	0.005
Pu vector							
Region	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	Pu-243	Pu-244
MTR1	1.09%	86.82%	10.30%	0.57%	1.21%	0.00%	0.00%
MTR2	1.46%	80.06%	16.65%	1.25%	0.58%	0.00%	0.00%
MTR3	2.00%	78.73%	17.77%	1.24%	0.27%	0.00%	0.00%

Table V: Fuel composition after 6-region SSMT.

Composition							
Region	FP (RE)	Zr	U	Np	Pu	Am	Cm
MTR1	25.84 (7.98)	10.970	65.560	0.320	8.200	0.078	0.001
MTR2	30.98 (10.03)	11.680	60.130	0.340	8.450	0.090	0.002
MTR3	27.38 (9.13)	9.940	63.570	0.270	8.690	0.086	0.006
MTR4	18.52 (5.42)	8.030	72.770	0.170	8.430	0.095	0.010
MTR5	12.62 (2.85)	7.250	81.010	0.130	6.140	0.098	0.006
MTR6	10.17 (1.79)	6.920	86.350	0.090	3.270	0.116	0.003
Pu vector							
Region	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	Pu-243	Pu-244
MTR1	1.80%	80.30%	16.63%	1.07%	0.21%	0.00%	0.00%
MTR2	2.19%	77.18%	18.89%	1.41%	0.32%	0.00%	0.00%
MTR3	1.70%	77.98%	18.42%	1.45%	0.46%	0.00%	0.00%
MTR4	1.23%	82.03%	14.99%	1.07%	0.68%	0.00%	0.00%
MTR5	1.08%	86.86%	10.53%	0.61%	0.92%	0.00%	0.00%
MTR6	1.12%	86.74%	9.88%	0.50%	1.76%	0.00%	0.00%

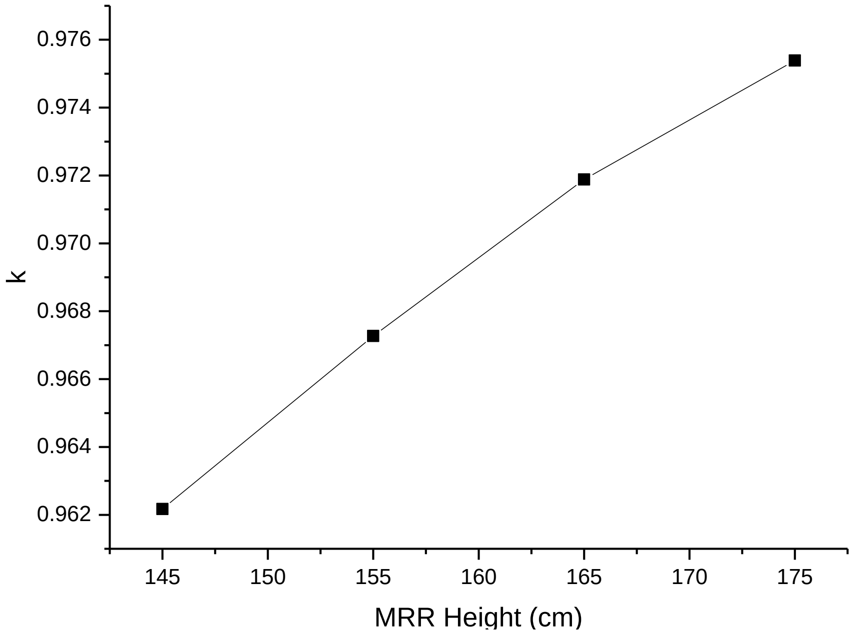

FIG. 7. Initial k-eff of 2nd *B&BR vs. the height of the driver fuel in case of 1-MTR strategy*

If all fuel assemblies from the 1st B&BR are recycled together through the SSMT (case (a)), 2 tons of gaseous fission products are removed and the resulting maximum core height is 174.5 cm and remaining 4.5 cm is filled with PWR SNF-6Zr. Figure 7 shows the relationship between the height of driver fuel and initial k-eff. It is shown that even though all fuels from the 1st B&BR is used as driver fuel for the 2nd B&BR, the second core cannot be critical, which is largely ascribed to the 100% recovered rare earth materials.

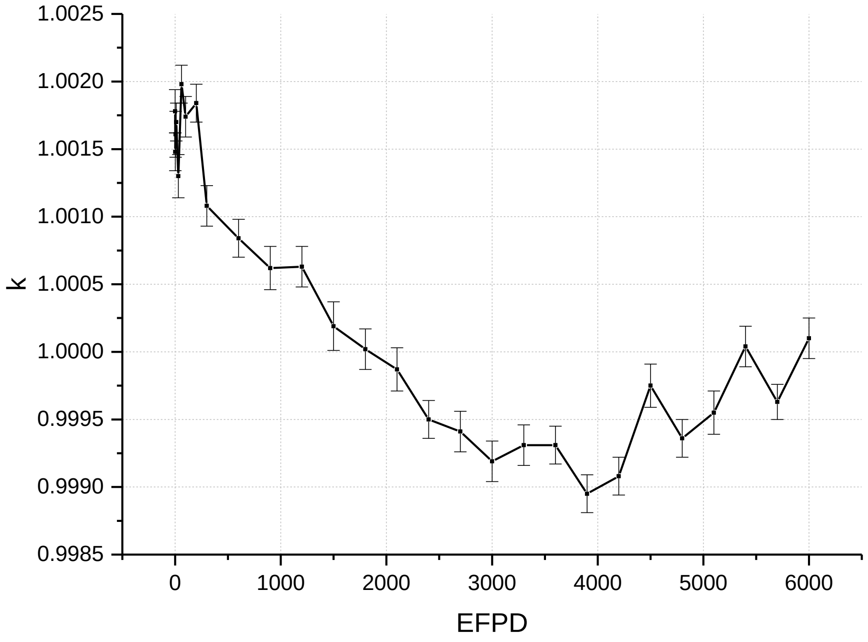

FIG. 8. Core lifetime using 3-MTR fuel recycling strategy

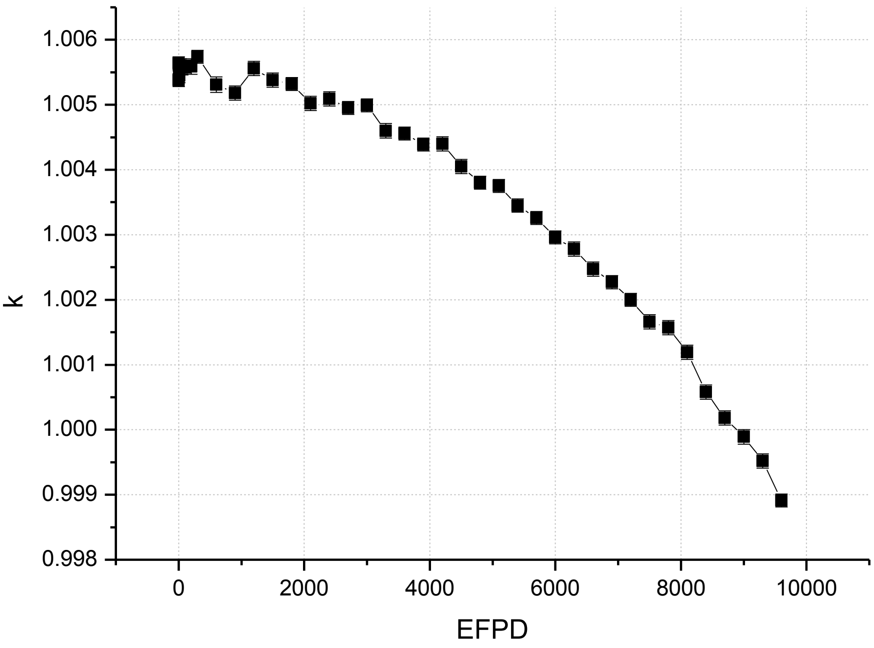

FIG. 9. Core lifetime using 6-MTR fuel recycling strategy

For the improvement of SNF utilization efficiency, 1st B&BR core is divided into 3 melt-treatment regions (MTR) with an equal height of 60 cm (case (b)). The amount of fuel after SSMT is 15.26 tons (MTR I), 16.75 tons (MTR II), and 17.95 tons (MTR III). The fuel composition after SSMT is tabulated in table 5. The arrangement of each zone and PWR SNR-6Zr blanket fuel is properly chosen to achieve the criticality of the 2nd core. There are 2 possible variations of the 2nd B&BR core arrangement since MTR III is loaded at the top to maximize the neutron economy. It is found that the optimum axial core configuration for the 3-MTR strategy is 50 cm MTR II, 45cm MTR I, 55cm MTR III, and 30 cm PWR SNF-6Zr (loading from bottom to top). Figure 8 shows the depletion calculation result of optimum core configuration with the 3-MTR strategy. It is observed that the lifetime of the core is only around 1800 EFPD and achievable fuel burnup is around 16.85 GWd/MTHM. One can easily conclude from the Fig. 8 that the 2nd B&BR is not in a breed-and-burn condition.

In case (c), the number of MTR zones is increased to 6 for more flexible and efficient use of the SNF from the 1st B&BR. The arrangement of each zone and PWR SNR-6Zr is carefully determined to improve the neutron economy. There are many variants of the 2nd B&BR core arrangement depending on height and location of each MTR and the fuel composition of each MTR after SSMT is tabulated in table 6. It is found that the optimum axial core configuration for the 6-MTR strategy is as follows: 25 cm MTR II, 20 cm MTR I, 20 cm MTR III, 25 cm MTR IV, 25 cm MTR V, 25 cm MTR VI and 40 cm PWR SNF-6Zr from the bottom. Figure 9 shows the depletion result of the optimum core configuration with the 6-MTR strategy. It is shown that the lifetime of the 2nd core is now around 24 EFPYs and achievable fuel burnup is around 89.16 GWd/MTHM. One can note that depletion curve is not linear and the neutron multiplication factor is gradually decreasing. Figure 10 shows the axial power distribution of the 2nd B&BR at BOC and EOC and it is clearly indicated that the active core slowly moved from bottom to top with depletion, which reflects that the core is near a breed-and-burn condition.

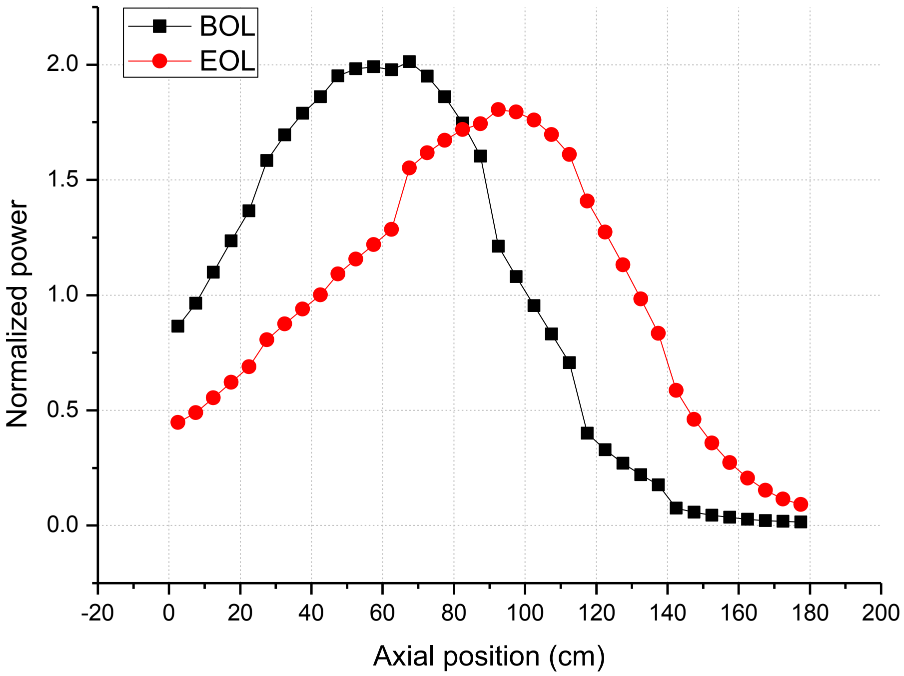

FIG. 10. Power distribution at BOL and EOL of the 2^{nd} core with 6-MTR fuel recycling strategy

4. Conclusions

Self-sustainability of a B&BR fuel cycle has been investigated by recycling the B&BR SNF after a highly proliferation-resistant processing which removes only gaseous fission products. Three types of recycling strategies were considered and it was confirmed that recycled B&BR fuel can be re-used to start a new B&BR core even without removing the rare earth fission products. A zone-wise fuel recycling turns out to be necessary since it provides a more efficient utilization of the recycled fissile material in the 2nd B&BR core. Similar study for the 3rd B&BR core is also worthwhile to find the equilibrium B&BR which is really self-sustainable.

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6. Acknowledgment

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (NRF-2016R1A5A1013919).