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ARTICLE

Breed and burn reactor concept to maximize uranium utilization without fuel shuffling

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Breed and burn (B/B) reactor keeps criticality by generating fissile nuclides from natural or depleted Uranium (U) with minimum need of reprocessing. Some studies are considering B/B concepts that the burning wave is stabilized and fixed at the center of the core by frequent shuffling of fuel assemblies. In general, fuel shuffling is not performed in fast reactors because the fuel assembly ducts are deformed by fast neutron irradiation. Therefore, the concept of a B/B reactor that does not require shuffling of the fuel assemblies while maximizing the use of U resources was considered. A B/B reactor is proposed that consists of an active core divided into an upper and lower core by an internal blanket. The active cores and the blanket are made of a U-Pu-Zr ternary alloy and U-MA-Zr alloy, respectively. The burning wave gradually converges from the upper and lower active core zones to the internal blanket zone, then forms a single synthetic wave. The Minor Actinides (MAs) mixed in the internal blanket zone works to promote the production of fissile nuclides and accelerate the burning wave propagation. The core configuration was surveyed using a fuel pin-cell model to determine optimum design parameters such as core height of active cores, thickness of the internal blanket zone and Plutonium (Pu) enrichment. The core specification was determined to have a small reactivity swing over a 50-year burn period. Based on the specifications obtained, a full core calculation was performed to investigate the behavior of the burning wave and the core performances. The optimization of the core specifications resulted the reactivity swing to be 2.57%. During the beginning and middle operation phases, the burning wave moved axially from the upper and lower active cores to the internal blanket zone. In the latter phase, it spread radially to the outer core. As a result, almost all fuels including internal blanket zone are burnt rather uniformly and achieved about 30% of averaged burnup. It was found that the core achieves uniform averaged burnup and high U resource utilization because the burning wave travels throughout the whole core.

Keywords: Breed and Burn; burning wave; No need for shuffling; high burnup

1. Introduction

Global energy demand and nuclear installed capacity will increase due to the growing need to transition to clean energy. Annual uranium demand is predicted to increase from 59,200 tU to 100,224 tU between 2018 and 2040 [1].

Once-through fast breeder reactors can achieve 2~3 times higher burn-up than once-through light water reactors. Breed and Burn (B/B) fast reactor requires enriched U or Pu fuel at start-up but can maintain criticality by supplying natural or depleted U after start-up. Thereby, generating new fissile nuclides, the natural U resource is effectively utilized and the fissile nuclides are burned while minimizing reprocessing.

The first concept of the B/B reactor was first proposed by S.M. Feinberg in 1958. After that, the CANDLE burning method, a type of traveling wave reactor, was proposed by Hiroshi Sekimoto in 2001 [2]. In the CANDLE reactor, burning wave propagates autonomously in the axial direction with a constant shape. This makes it possible to minimize changes in reactor characteristics with time. However, in order to refuel the core, the fuel assemblies are needed to split axially into burnt and unburnt region. This is one of the key technical challenge of the original CANDLE concept.

Some studies have examined the B/B concept, in which the burn wave is stably localized at the core center by frequent shuffling of the fuel assemblies [3]. The power density of neighboring fuel assemblies may be different in the case of shuffling because of the different multiplication factors of the assemblies. This is a difficult problem that makes stable cooling of the core. In general, however, the fast neutron irradiation in fast reactors causes expansion of the fuel and structural materials, which leads to void swelling. The fuel assembly ducts are deformed by the effects of void swelling, and fuel shuffling is not performed. Therefore, the concept of a B/B reactor was considered to maximize the use of uranium resources without fuel shuffling.

2. Reactor concept

A B/B reactor has an active core which is axially divided into an upper and lower core by an internal blanket. The active core uses U-Pu-Zr ternary alloy fuel and the internal

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blanket uses U-MA-Zr alloy fuel. The burning wave propagates from the upper and lower active core to the internal blanket and becomes single wave. Then, the wave expands to the outer core periphery region. In general, minor actinides (MA) quickly build up to fissile material because they have a higher neutron absorption cross section about 2 to 10 times larger than U-238. Therefore, the addition of MA to the internal blanket promotes the formation of fissile material and accelerates the propagation of burning wave. In a fast reactor, the cladding material reaches its irradiation limit ($< 4 \times 10^{23}$n/cm^2) and must be replaced every several years [4]. After recladding, the fuel is reloaded maintaining its original composition and axial position at the time of discharging.

3. Calculation methods

Neutronic analyses were performed using the neutron transport Monte Carlo code MVP/MVP-BURN [5] and the nuclear data library JENDL-4.0. Pin-cell and full core calculations were performed with 10,000 histories, 200 batches, and 50 discard batches. Expected statistics error is <0.05%. In the burnup calculations, the number of burnup steps was set to 5 years and the number of sub-burnup steps to 20. The core used as a reference is the 2,000 MWth CANDLE core investigated at Tokai University [4]. The core specifications were determined by conducting parameter surveys with regard to core height, internal blanket height, and Pu enrichment to ensure that the reactivity swing was less than 3.3%. The final core specifications were examined by parameter survey regarding the core height, internal blanket height, and Pu enrichment to ensure that the reactivity swing below 3.3% [6]. The initial core height, internal blanket height, and Pu enrichment were set to 50 cm, 50 cm, and 13%, respectively as reference core.The core specifications and layout are shown in the **Table 1**, **Figure 1** and **Figure 2**. A full core analysis was performed with the optimized core configuration resulting from the pin-cell model analysis. In the thermal hydraulics analysis, the temperature distribution was obtained by solving the steady-state heat transfer equation using the power density obtained from the neutronic calculations. The equations used in the calculations are shown below. $\vartheta_{coolant}(z)$, $\vartheta_{cladding}(z)$ and $\vartheta_{fuel}(z)$ are the temperatures of the coolant, cladding and fuel at axial position z, respectively. w is the coolant flow rate, C_p is the specific heat, w is the heat transfer coefficient, λ is the thermal conductivity and $r_{cladding}$ is the cladding outer diameter.

Table 1. Design parameter for B/B core.

Design parameters of core	
Thermal output	2,000 [MW$_{th}$]
Fuel type	U-Pu-Zr
Cladding materials	HT-9
Coolant	Sodium
Reflector	SUS304
No. of assembly	217
Equivalent core radius	194
Active core height (upper/lower)	50/50 [cm]
Blanket height	50 [cm]
Primary coolant temperature (inlet/outlet)	668/823 [K]
Design parameters of fuels	
Active core fuel	$^{Nat.}$U-13%Pu-6%Zr
Blanket fuel	$^{Nat.}$U-10%MA-6%Zr
Pu composition (^{238}Pu/^{239}Pu/^{240}Pu/^{241}Pu/^{242}Pu)	2/52/26/12/7 [%]
MA composition (^{237}Np/^{241}Am/^{243}Am/^{244}Cm)	54/30/13/4 [%]
Pin pitch	14.4 [mm]
Cladding outer diameter	13.2 [mm]
Cladding thickness	0.5 [mm]
Smear density	75 [%]
Pin/assembly	271

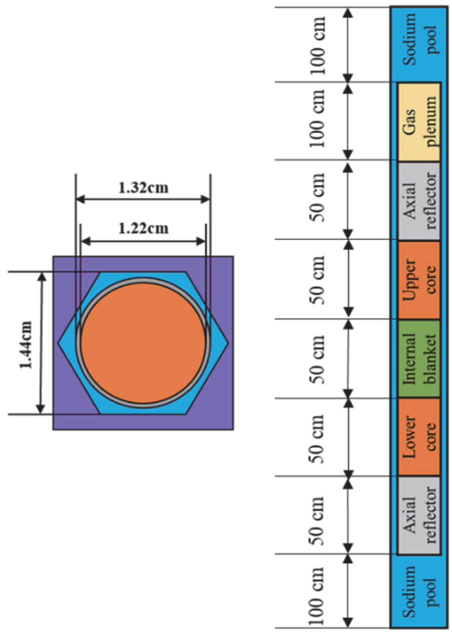


Figure 1. Pin-cell model for parametric survey.

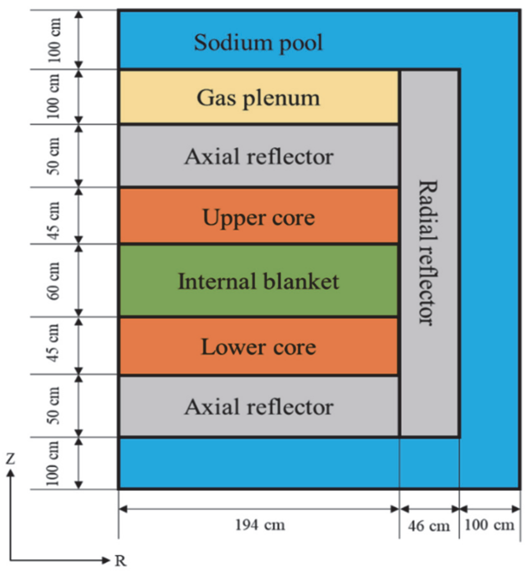


Figure 2. Layout of B/B core.

$$\vartheta_{coolant}(z) = \vartheta_{coolant}(0) + \frac{1}{wC_p}\int_0^z q'(z)dz \quad (1)$$

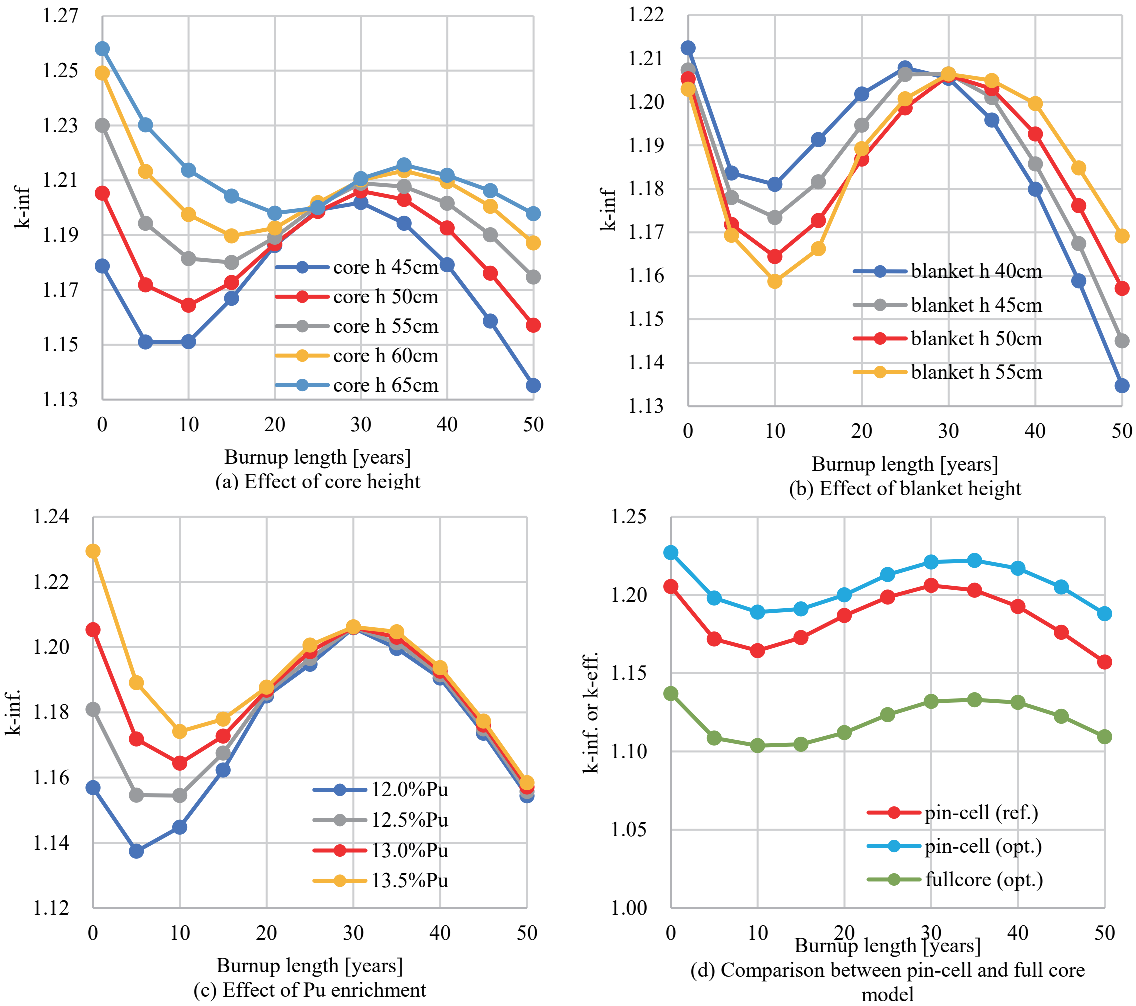
$$\vartheta_{cladding}(z) = \vartheta_{coolant}(z) + \frac{q'(z)}{2hr_{cladding}} \quad (2)$$

$$\vartheta_{fuel}(z) = \vartheta_{cladding}(z) + \frac{q'''(z)r_f^2}{4\lambda_{fuel}} \quad (3)$$

4. Calculation results

4.1. Parametric survey for optimization of core configuration

It is a problem that when the burning wave changes with time, the critical swing changes drastically. **Figure 3** illustrates the effect of each parameter on the criticality of the optimized core. Criticality swing are characterised differently in beginning/middle/end of calculation (BOC/MOC/EOC). In the BOC, the criticality decreases with the fissile mass decrease in the active core. In the MOC, the reactivity turns to increase because fissile material is produced in internal blanket. In the EOC, the reactivity decreased again due to reduced fissile mass in the internal blanket and also due to increased neutron leakage to the radial direction.



(a) Effect of core height

(b) Effect of blanket height

(c) Effect of Pu enrichment

(d) Comparison between pin-cell and full core model

Core height [cm] — Δk/kk'

Blanket height [cm]	35	40	45	50	55	60	65
35	7.69%	5.40%	3.94%	3.27%	3.11%	2.75%	2.71%
40	8.67%	6.33%	4.69%	3.56%	3.29%	2.65%	2.67%
45	9.42%	6.96%	5.25%	4.01%	3.36%	2.57%	2.64%
50	10.21%	7.61%	5.84%	4.47%	3.45%	2.95%	3.38%
55	10.66%	8.10%	6.37%	4.96%	3.92%	3.43%	3.61%
60	11.18%	8.63%	6.70%	5.41%	4.23%	3.58%	3.75%

(e) Minimum reactivity swing with changing core height and blanket height

Figure 3. Effect of design parameters and calculation models on criticality and reactivity swing.

Figure 3 (a) shows the effect of active core height on criticality for a fixed blanket height of 50 cm and Pu enrichment of 13%. The active core heights of upper and lower region are main parameter to determine the criticality and the core life. Increasing the core height tends to make the criticality larger during the burning cycle. It also delays the time to reach the local minimum and local maximum of criticality. It was found that increasing the core height works to reduce the reactivity swing, namely, the difference between local minimum criticality and local maximum criticality. The effect of internal blanket height on criticality for a fixed core height of 50 cm and Pu enrichment of 13% is shown in Figure 3 (b). The internal blanket height also affects the criticality in the early and late burning phases. Increasing the internal blanket height results in a large initial reactivity and a small late reactivity. Therefore, increasing the internal blanket height also contributes to reduce the difference between local minimum and maximum criticality. In Figure 3 (c), the effect of Pu enrichment on criticality for a fixed core height of 50 cm and blanket height of 50 cm is shown. By increasing the Pu enrichment, only the initial criticality is enhanced. Initially loaded Pu is burnt out in the decade of the early burning phase and rarely work in the latter phase. After that, the criticality is maintained by the newly produced Pu in the internal blanket.

Figure 3 (e) shows the additional parametric survey for minimizing reactivity swings, it is resulted that the reactivity swing can be minimized down to 2.57% with the active core height of 60 cm, the internal blanket height of 45 cm, and the Pu enrichment of 12.5%, which satisfies the targeted criteria of reactivity swing less than 3.3%.

Figure 3 (d) compares the criticalities calculated by the pin-cell model and full core model using core configration with minimized reactivity swing. The full core calculation considers the leakage and reduces the criticality.

The initial loaded HM weights for the optimized core are shown in **Table 2**. The initially loaded HM weights are 120.5 tons of U, 12 tons of Pu, and 3.7 tons of MA in total. Namely, in our breed and burn reactor concept requires 1.5 time larger Pu produced from Rokkasho reprocessing plant annually, to start up the 2000MWth rating reactor and operate it for 50 years. Also, this core can consume 5 times as much MA as produced from Rokkasho reprocessing

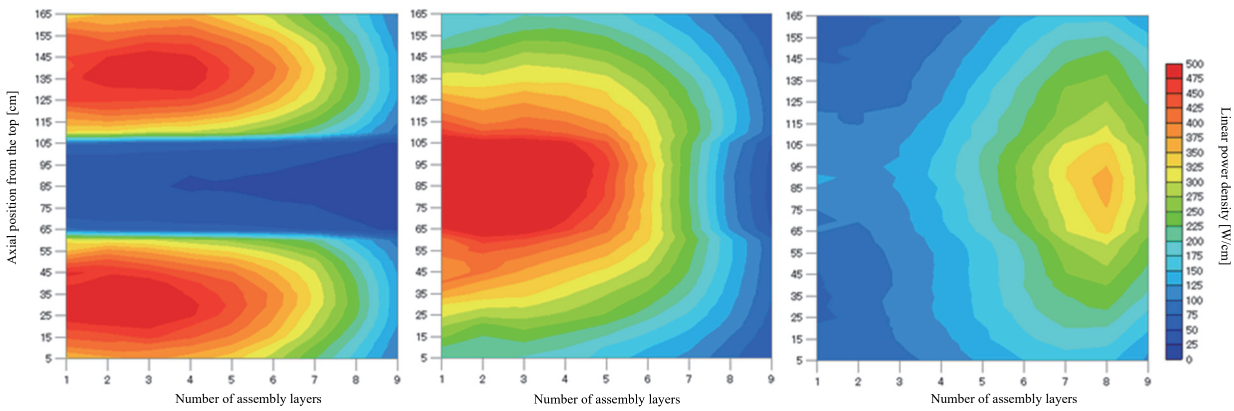
4.2. Propagation characteristics of burning wave

Figure 4 shows the linear power density distribution each of the BOC, MOC, and EOC. The burning wave has two peaks at the upper and lower active core in the BOC, and neutrons leak into the internal blanket, where fissile is newly produced. In the EOC, the fissile generated in the internal blanket starts to work as major fuel for criticality, so the burning wave propagates to the internal blanket region and becomes a single wave. In the end of the burning phase, the burning wave moves to the periphery region of the core, which is the unburnt area, and the whole core is uniformly burnt. As the wave moves to the periphery of the core, the power density per assembly becomes small, because number of fuel assemblies on the circumference of a circle proportionally increases with the radius.

Table 2. Initial fuel composition of core and blanket.

[ton]

	^{235}U	^{238}U	U Total	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu	Pu Total	^{237}Np	^{241}Am	^{243}Am	^{244}Cm	MA Total	Total
Active core	0.6	86.3	86.9	0.3	6.5	3.2	1.5	0.9	12.4	0.0	0.0	0.0	0.0	0.0	99.3
Internal blanket	0.2	33.3	33.5	0.0	0.0	0.0	0.0	0.0	0.0	2.0	1.1	0.5	0.1	3.7	37.3
Total (core+blanket)	0.8	119.6	120.4	0.3	6.5	3.2	1.5	0.9	12.4	7.5	1.1	0.5	0.1	3.7	136.6



(a) BOC (b) MOC (c) EOC

Figure 4. Time change of burning wave.

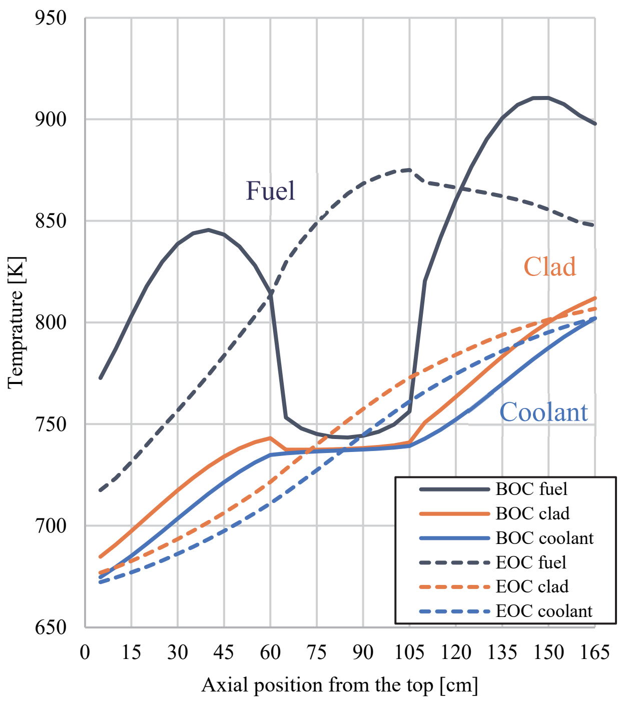


Figure 5. Axial temperature distribution.

4.3. Temperature distribution evaluation

Temperatures of fuel, cladding, and coolant were evaluated in the hottest subchannel throughout the burnup period which is an assembly located in the center (0^{th} layer) of the core. **Figure 5** shows the temperature distribution calculated from the power density obtained by neutronic analysis. The temperature distribution for the MOC in this figure is omitted for avoiding the schematic complexity. Similar to the burning wave, the fuel temperature distribution has a peak in each active core in the BOC. The cladding and coolant temperature show a step-like increase in the BOC. The two peaks of fuel temperature are united and become a single peak in the MOC, resulting in a moderate temperature gradient in the active core region. The cladding and coolant temperatures are changed from a step-like to sloped distribution in the EOC. Through the burnup period, the fuel and cladding temperature were kept below their limits of 1373 K and 923 K, respectively [7].

4.4. Cladding damage by fast neutrons

In B/B reactors, cladding material is damaged by fast neutron irradiation during long-term operation. The peak of the neutron flux shifts with time as well as the burning wave. Therefore, the time to reach the irradiation limit of the cladding material can be prolonged to some extent. **Figure 6** shows the time dependence of cumulative fast neutron irradiation. The fast neutron fluence of the cladding material located at the core center reaches its limit in 7 years, 14 years 20 years, 30 years, and 49 years of operation. In BOC, the fast neutron fluence increases mainly in the upper and lower active cores. From the MOC to the EOC, the time interval of cumulative fast neutron irradiation increases from 7 to 20 years because the neutron flux moves from the internal blanket region to the periphery of the core. In addition, during such time interval, recladding process by simplified reprocessing is necessary.

4.5. Effective use of natural uranium resources

Figure 7 illustrates the axial fuel composition distribution after 50 years of burnup. The fission products (FPs) content ratio is equal to fissioned fraction of the heavy metals, namely the fuel burnup. The burning wave propagated to the whole core therefore it burnt not only the active core, but also the internal blanket and the periphery of the core. As a result, a high burnup of about 30% on average was achieved in the entire core. The radial fuel composition distribution after 50 years of burnup is shown in **Figure 8**. It was shown that the burnup decreases with radial positions, but the burnup even at the periphery edge of the core achieved about 12%. It can be said that the overall fuel loaded in the core was burnt rather uniformly because of sweeping propagation of burning wave.

5. Conclusions

The core configuration and burnup characteristics of the B/B reactor were investigated. In a B/B reactor with an active core divided into upper and lower regions by an internal

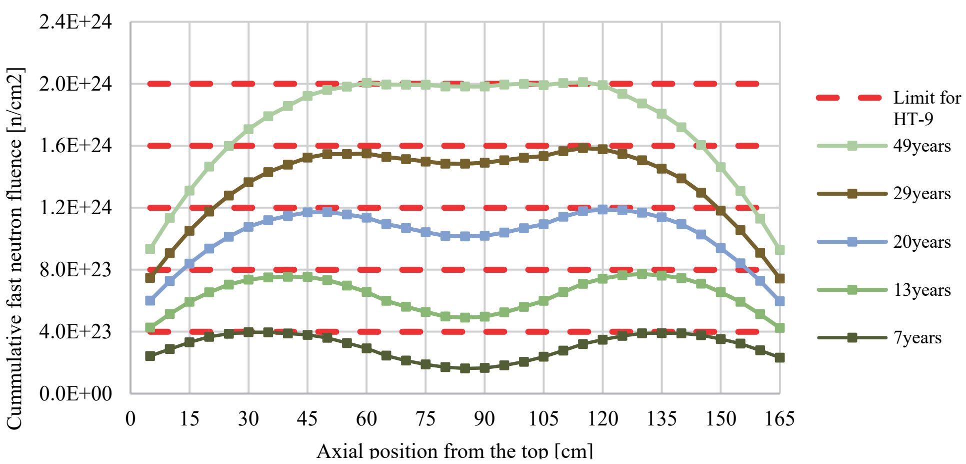


Figure 6. Cumulative fast neutron fluence with operation time.

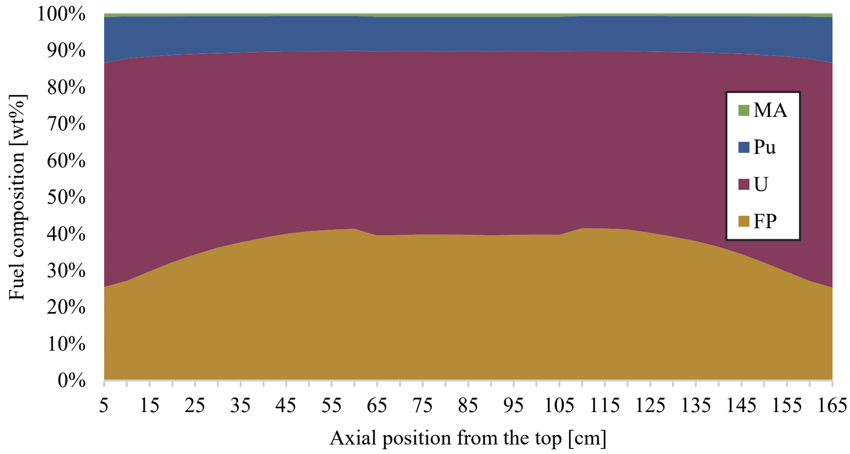


Figure 7. Axial distribution of radially averaged fuel composition after 50 years burning.

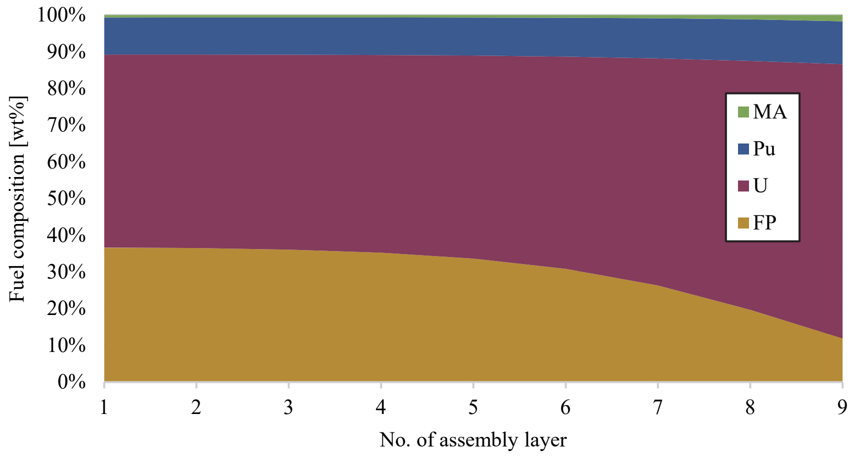


Figure 8. Radial distribution of axially averaged fuel composition after 50 years burning.

blanket. During the 50 years core life, the burning wave initially converges axially from the upper and lower active cores to the internal blanket region to form a single wave. After that, it spreads radially to the periphery region of the core. The optimum core specifications were core height, blanket height, and Pu enrichment of 60 cm, 45 cm, and 12.5%, respectively. The reactivity swing was minimized to 2.57% which is comparable value with that of a standard fast reactor. After 50 years of burnup, the whole core averaged burnup reached to about 30%. The cladding materials are damaged by long term irradiation by fast neutrons and must be recladded at intervals of 7 to 20 years. Consequently, it was found that the proposed B/B reactor can reduce the reprocessing burden and maximize the utilization of uranium resources without fuel shuffling and refueling. It is necessary to study the feasibility of metal fuel containing minor actinides without mixing plutonium assumed to be used in the internal blanket zone in this B/B reactor concept as a future challenge.

References

[1] L. Grancea, et al., Uranium Resources, Production and Demand 2020. No. NEA--7551. *Organisation for Economic Co-Operation and Development*, (2020).
[2] H. Sekimoto, K. Ryu and Y. Yoshimura, CANDLE: The new burnup strategy, *Nuclear Science and Engineering* 139 (2001).
[3] T. Obara, K. Kuwagaki and J. Nishiyama, Feasibility of burning wave fast reactor concept with rotational fuel shuffling, (2017).
[4] N. Takaki, et al., Preliminary engineering design of sodium-cooled CANDLE core, *AIP Conference Proceedings* 1448 (2012), American Institute of Physics.
[5] Y. Nagaya, K. Okumura, T. Sakurai and T. Mori, MVP/GMVP Version 3: General Purpose Monte Carlo Codes for Neutron and Photon Transport Calculations Based on Continuous Energy and Multigroup Methods, *JAEA-Data/Code 2016-018* (2017).
[6] H. Kinjo and H. Yokobori, Conceptual Design Study on Upgraded Monju Cores, *Cycle Organization Technical Journal* 7 (2000), pp. 47-57.
[7] S. Ohki, et al., Study on reactor core and fuel design of sodium-cooled fast reactor (metal fuel core), *Results in JFY 2005* (2006).