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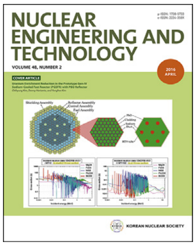

Original Article

Impacts of Burnup-Dependent Swelling of Metallic Fuel on the Performance of a Compact Breed-and-Burn Fast Reactor

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ABSTRACT

The U-Zr or U-TRU-Zr cylindrical metallic fuel slug used in fast reactors is known to swell significantly and to grow during irradiation. In neutronics simulations of metallic-fueled fast reactors, it is assumed that the slug has swollen and contacted cladding, and the bonding sodium has been removed from the fuel region. In this research, a realistic burnup-dependent fuel-swelling simulation was performed using Monte Carlo code McCARD for a single-batch compact sodium-cooled breed-and-burn reactor by considering the fuel-swelling behavior reported from the irradiation test results in EBR-II. The impacts of the realistic burnup-dependent fuel swelling are identified in terms of the reactor neutronics performance, such as core lifetime, conversion ratio, axial power distribution, and local burnup distributions. It was found that axial fuel growth significantly deteriorated the neutron economy of a breed-and-burn reactor and consequently impaired its neutronics performance. The bonding sodium also impaired neutron economy, because it stayed longer in the blanket region until the fuel slug reached 2% burnup.

1. Introduction

The breed-and-burn fast reactor (B&BR) has been gaining more interest recently because it can offer a very high fuel utilization [1–4]. This is achieved by its ability to breed its own fuel and to use that newly-bred fuel *in situ*, thus avoiding costly fuel reprocessing. This results in an extremely long life and a high fuel burnup. The fertile fuel (U-238) is placed in either axial and/or radial blanket regions, depending on design considerations. The initial core of the B&BR is usually fueled with low-enriched uranium (LEU) and the core gradually transforms into a Pu-dominant one.

At Korea Advanced Institute of Science and Technology (KAIST; Daejeon, Korea), a compact sodium-cooled B&BR is under investigation for the sustainable utilization of nuclear energy [5–7]. The small B&BR is a metallic-fueled and metallized pressurized water reactor (PWR) spent nuclear fuels (SNFs) are simply recycled as the blanket material. Innovative

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design solutions and ideas have been proposed to deal with the design challenges of the B&BR. In the B&BR designs, metallic fuel is usually preferred to ceramic fuel, because it provides a higher conversion ratio through its increased fuel inventory and lower fuel temperature due to its high thermal conductivity. In the KAIST B&BR, the driver fuels are metallic U-Zr for the initial LEU core and SNF-Zr for the blanket region.

In contrast to ceramic fuel, metallic fuel swells a lot more radially and axially due to neutron irradiation. Therefore, to accommodate the radial swelling, the metallic fuel slug is usually designed to occupy ~75–85% of the volume inside the fuel rod in sodium-cooled fast reactors (SFRs). Typically, a smear density of 75% is adopted in standard SFR design. The remaining ~15–25% is used to accommodate the fuel swelling due to irradiation and is initially filled with the bonding sodium for efficient heat transfer to the cladding and coolant. Some of the bonding sodium infiltrates into the pores of the swollen metallic fuel, and most of the bonding sodium is pushed to the gas plenum region of the fuel when the fuel slug has completely swollen and contacted the cladding. The axial swelling of the fuel slug is less of a concern, because the conventional fast reactor fuel rod has a long gas plenum for the fuel to swell.

The irradiation test results in EBR-II reported that the metallic fuel slug swelled significantly both radially and axially at initial ~1–2% burnup [8]. Fig. 1 illustrates the burnup-dependent axial growth of several cylindrical metallic fuels, showing that U-10Zr fuel swells substantially, ~8% at 2% burnup, while the irradiation fuel swelling becomes smaller with increasing Pu content in the fuel. Additionally, after the metallic fuel contacts the cladding at ~1–2% burnup, the axial swelling rate is much slower due to the frictional forces between the fuel and cladding [9].

As shown in Fig. 1, ~10% axial growth of the U-10Zr alloy fuel is expected, and its neutronic impact will be rather significant. However, it is not easy to model the accurate burnup-dependent fuel swelling in an actual 3-D core analysis. In fact, an approximate irradiation fuel growth is taken into account in standard SFR analysis with multi-batch fuel management by assuming that the fuel has fully grown from the beginning. Fortunately, the assumption turns out to be reasonably accurate, since most of the fuels are already > 2% burned and just a small fraction of the core is fresh.

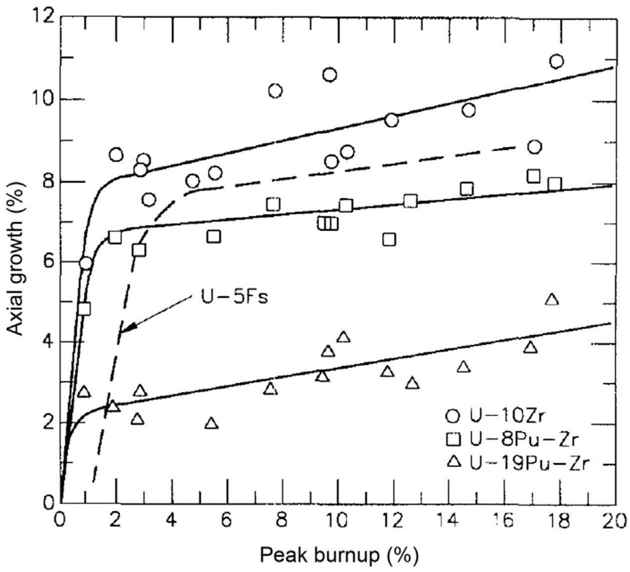

Fig. 1 – Axial growing rate for various metallic fuels. Reprinted from Progress of Nuclear Energy, Vol. 31, G.L. Hofman, L.C. Walters, and T.H. Bauer, Metallic Fast Reactor Fuels, Page. 91, 1997, with permission from Elsevier.

All the fuel pins undergo similar irradiation behavior in the long-life B&BR core design, which utilizes single-batch fuel management. Therefore, it is likely that the conventional approximation of the fuel growth may be quite unrealistic. In this work, burnup-dependent fuel growth of the U-Zr metallic fuels is practically modelled and compared with conventional approximate models [10] to identify its impacts on the B&BR core design and analysis. The neutronics simulation has been performed using the Monte Carlo code McCARD [11] in conjunction with the ENDF/B-VII.0 neutron library.

2. Materials and methods

2.1. *B&BR concepts*

Fig. 2 shows the schematic configurations of the sodium-cooled KAIST B&BR. It is a linear B&BR design, because the breed-and-burn wave is traveling only in one direction, which is from bottom to top. The reactor power is 250 MWth (~100 MWe). The fuel assemblies and the reflector assemblies are arranged in an 8-ring hexagonal core. The core consists of 78 fuel assemblies, 78 reflector assemblies, and seven control rod assemblies, and its equivalent radius is 111.3 cm. Although no shielding assemblies are modelled in Fig. 2, the reflector assemblies should be surrounded by shielding materials in the actual design. In the axial direction, total core height is 230 cm with a 40-cm bottom HT-9 reflector, 150-cm core region, and 40-cm upper gas plenum. In the core region, initial LEU driver fuel occupies the space up to 70 cm from the bottom. The seven control rod assemblies can be grouped into primary and secondary control rods, as shown in Fig. 2. A relatively small number of control rods are required in the B&BR, since the burnup reactivity swing can be very small.

Fig. 3 depicts the concepts of fuel assembly (FA) and fuel-pin designs in the KAIST B&BR. The fuel assembly consists of 127 fuel pins, as shown in Fig. 3. The fuel-rod diameter and P/D ratio are 1.9 cm and 1.064, respectively. The HT-9 cladding thickness is 0.06 cm. The fuel-slug radius for the initial core fuel is 0.74463 cm and 0.77076 cm for the blanket region fuel. Note that a relatively large fuel slug is adopted to maximize the fuel-volume fraction for an improved conversion ratio in the B&BR. It is also worthwhile to note that a different fuel-slug size is used to accommodate a large fuel swelling in the B&BR [6]. A relatively low smear density of 70% is used in the LEU driver fuels due to a high fuel burnup, and the standard smear density of 75% is adopted in the blanket region. The fuel in the initial core and in the blanket region is LEU-Zr and SNF-Zr, respectively. The thickness of the assembly duct is 3 mm and the flat-to-flat distance of the fuel assembly is 23.72 cm. The resulting volume fraction of fuel, coolant, and structure is 63.34%, 22.65%, and 14.01%, respectively.

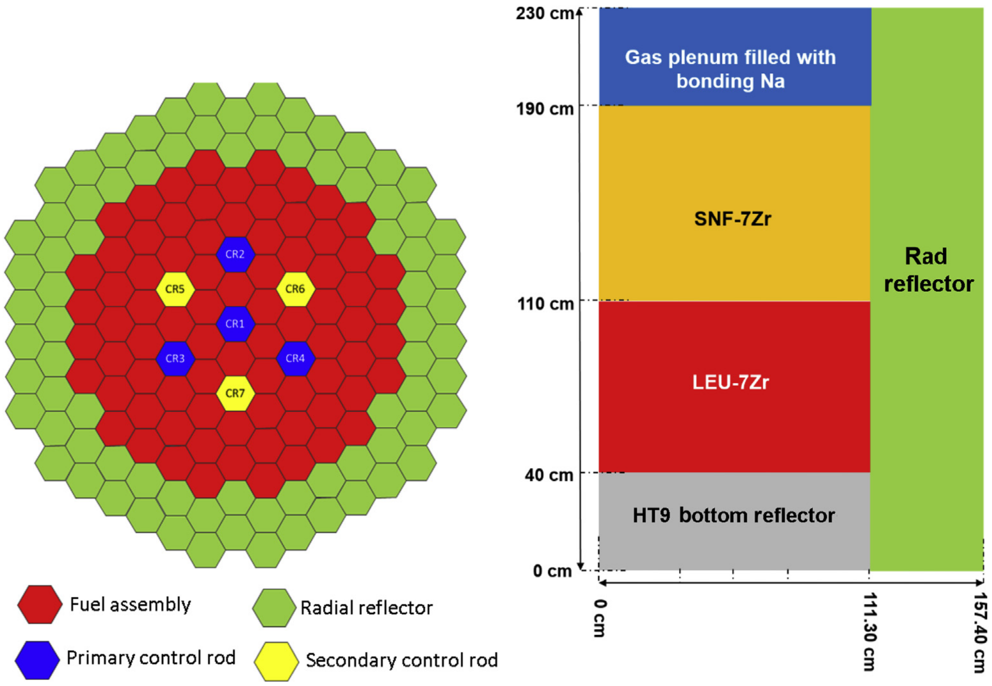

Fig. 2 – Radial and axial B&BR core configurations. B&BR, breed-and-burn reactor.

The SNF in the blanket region is assumed to be derived from metallization of the PWR SNF through a simple reduction process. The resulting metallic SNF material is melted to fabricate an SNF-7Zr metallic fuel. In the SNF treatment process, no fission products are intentionally removed from the original SNF, and the resulting metallic SNF should contain many kinds of fission products. To determine the metallic SNF composition, it is assumed that the fission gases and volatile fission products with a low boiling temperature (< 1,000°C) can be removed from the original SNF. Table 1 shows the composition of the metallized SNF fuel. From Table 1, the fraction of the remaining fission products is still significant,

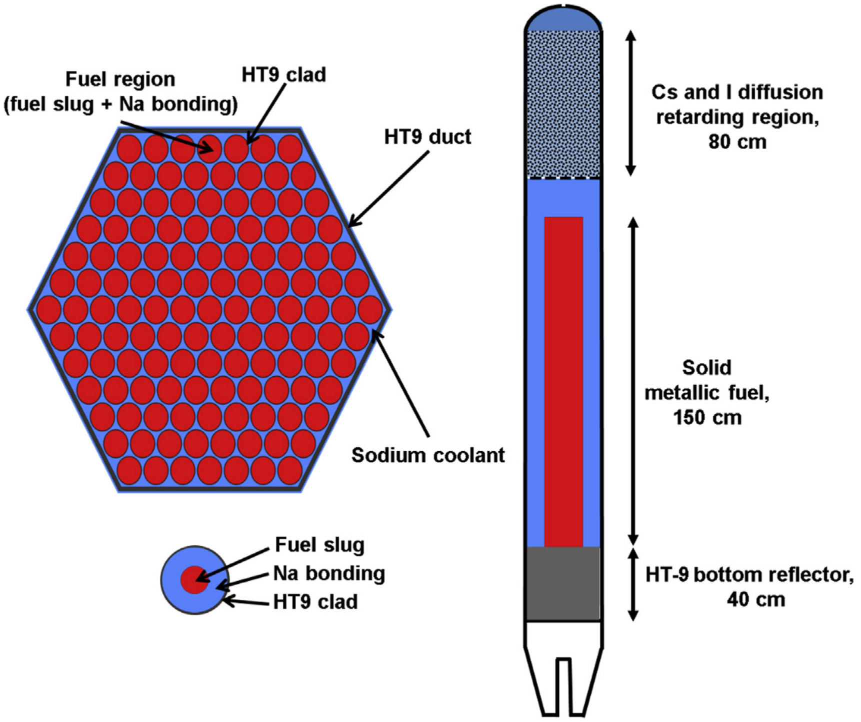

Fig. 3 – Fuel rod and fuel assembly configurations.

Table 1 – Blanket fuel composition from PWR spent fuel.

Isotope	wt.%	Isotope	wt.%
Ge	8.938E-05	Ce	3.221E-01
Sr	1.075E-01	Pr	1.528E-01
Y	6.358E-02	Nd	5.550E-01
Zr	5.102E-01	Pm	1.536E-03
Nb	5.461E-07	Sm	1.111E-01
Mo	4.587E-01	Eu	1.713E-02
Tc	1.051E-01	Gd	1.678E-02
Ru	2.963E-01	Tb	3.176E-04
Rh	6.012E-02	Dy	1.561E-04
Pd	1.755E-01	Ho	1.378E-05
Ag	9.360E-03	Er	3.097E-06
In	3.836E-04	U	9.554E+01
Sn	1.095E-02	Np	5.758E-02
Sb	2.351E-03	Pu	9.348E-01
Ba	2.471E-01	Am	7.176E-02
La	1.676E-01	Cm	3.157E-03

PWR, pressurized water reactor.

about 3.39 wt%. In the metallic SNF, the U content is about 95.54% and the transuranic fraction is about 1.07%, including 0.94% Pu.

In the radial reflector assembly, a tighter lattice is adopted and 91 reflector pins are placed in each reflector assembly to enhance reflector performance. Unlike conventional fast reactors, the reflector material is lead magnesium eutectic (LME) in the current B&BR core [7]. In this work, LME was chosen as the reflector material, since its melting temperature is rather low and its neutron performances are better than the conventional HT-9 reflector and are similar to that of pure lead. The LME-containing reflector pin diameter is 2.32 cm and the thickness of the HT-9 cladding is 0.10 cm. The cladding of the reflector pin is thicker than that of the fuel pin in order to accommodate the possible corrosive behavior of the lead-based material. In the reflector assembly, the volume fraction of LME, coolant, and structure is 65.13%, 17.78%, and 17.09%, respectively. The configuration of the reflector assembly is shown in Fig. 4. It should be mentioned that the special reflector design does not affect the burnup-dependent swelling of the metallic fuel.

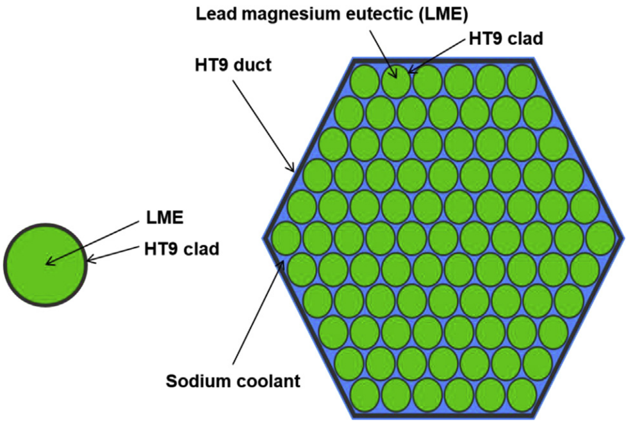

Fig. 4 – Reflector assembly configuration.

2.2. *Burnup-dependent swelling simulation strategy*

In the current Monte Carlo analysis with the continuous-energy Monte Carlo code McCARD, the heterogeneous core is explicitly modelled in detail. The Monte Carlo assembly-wise depletion calculations are done with 50,000 histories per cycle and the total number of Monte Carlo cycles is 250 (50 inactive cycles). The resulting standard deviation of k-eff is ~20 pcm.

To simulate the realistic burnup-dependent swelling of the metallic fuel, as shown in Fig. 1, the local burnup of each fuel region should be calculated. The local fuel burnups in this study are grouped into 30 zones, i.e., three radial zones and 10 axial regions, in order to simplify the calculation. The radial grouping consists of: (1) fuel assemblies in the second, third, and fourth rings (1st radial zone); (2) fifth ring fuel assemblies (2nd radial zone); and (3) sixth ring fuel assemblies (3rd radial zone). In the axial grouping, the first zone is from the bottom of the active core up to 60 cm, and then the next axial zone is every 10 cm until the top of the active core. The first radial zone consists of many fuel assemblies from several fuel rings, because the burnup in that region is similar. The fuel burnup in the first axial zone is also similar. These group zones are shown in Fig. 5. Another assumption used in this simulation is that there is no bonding sodium filling the pores of the swollen metallic fuel.

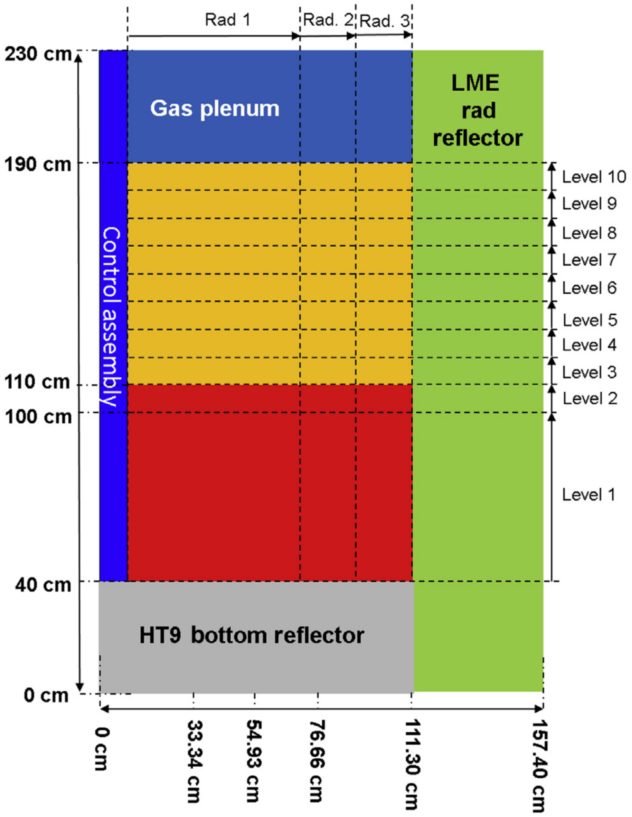

Fig. 5 – Burnup grouping in B&BR depletion. B&BR, breed-and-burn reactor; LME, lead magnesium eutectic; Rad, radial.

Table 2 – Fuel-slug radius and height change as a function of burnup.

Burnup (a/o)	LEU-7Zr fuel-slug radius (cm)	SNF-7Zr fuel-slug radius (cm)	Fuel-slug height (cm)
0	0.74463	0.77076	10.0
1	0.82054	0.83252	10.4
2	0.89000	0.89000	10.8
10	0.89000	0.89000	10.9
20	0.89000	0.89000	11.0
30	0.89000	0.89000	11.2

Several burnup points were chosen as the condition where the fuel slug will swell, as shown in Table 2. The axial and radial swelling rates considered was based on the irradiation test results in EBR-II (Fig. 1). The fuel will swell radially and was assumed to touch the cladding at 2% burnup. The fuel slugs in B&BR are U-7Zr and SNF-7Zr and the content of plutonium in these fuels is quite small. Therefore, it was assumed that the axial swelling of the metallic fuel follows the axial swelling behavior of U-10Zr, as shown in Fig. 1. It is recalled that the content of Pu in the SNF-Zr was ~1%. As shown in Table 2, the fuel grew rather quickly and linearly up to 2 a/o burnup and continued to grow gradually beyond 2 a/o burnup.

The fission power of each zone was tallied at every burnup step and then used to calculate the local burnup of each zone. The simulation model was changed when the local burnup exceeded the burnup point, as listed in Table 2. After the fuel-slug radius (r) and height (h) were modified accordingly, the Monte Carlo simulation was restarted from that burnup point in order to account for the impact of the burnup-dependent fuel swelling. To ensure that the fuel mass of the swollen fuel is the same when the volume has changed, the fuel density of that region is multiplied by a volume swelling factor (F_V). The volume swelling factor is a function of radial (F_R) and axial (F_A) swelling factors, as defined in Eqs. (1–3). Fig. 6 illustrates the calculation flowchart.

$$F_R = \left(\frac{r_{after}}{r_{before}}\right)^2 \tag{1}$$

$$F_A = \frac{h_{after}}{h_{before}} \tag{2}$$

$$F_V = F_R \times F_A \tag{3}$$

3. Results and Discussion

3.1. *Impacts of burnup-dependent swelling on B&BR performance*

Fig. 7 shows how the core lifetime depends upon the swelling models and Zr-content of the metallic fuel. The black and red lines indicate the cores fueled with U-7Zr and SNF-7Zr fuels. In the case of the black line, conventional pre-swollen metallic fuel was considered, and the lifetime was ~133 GWd/MTHM. Meanwhile, when the burnup-dependent fuel swelling was considered (red line), the core lifetime became much shorter, only ~50 GWd/MTHM. The much smaller core lifetime is ascribed to the higher neutron leakage and smaller conversion ratio. To achieve a lifetime of 133 GWd/MTHM with

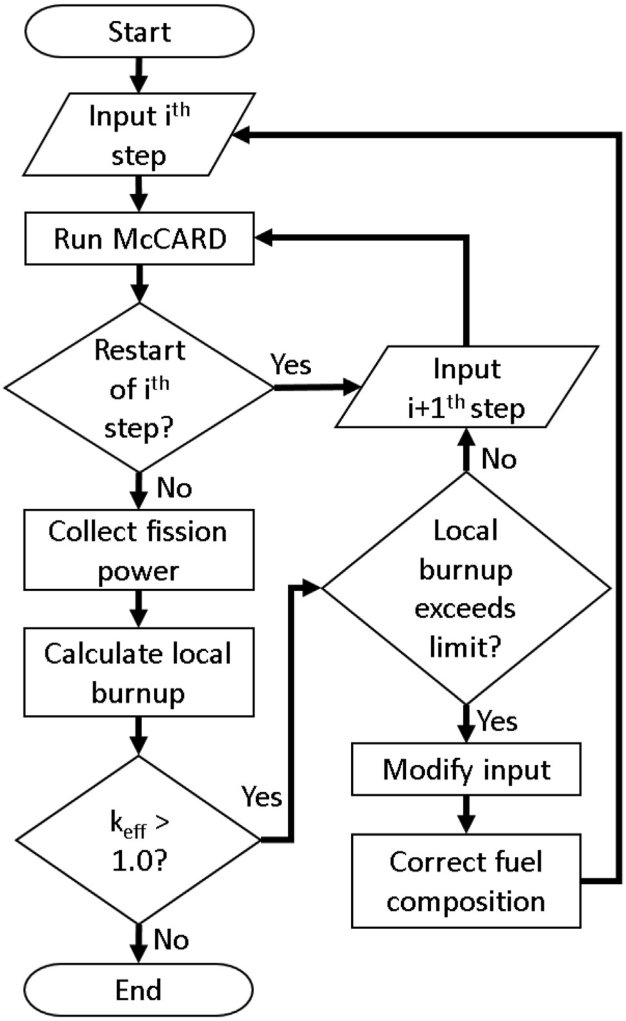

Fig. 6 – Flowchart of the burnup-dependent swelling simulation.

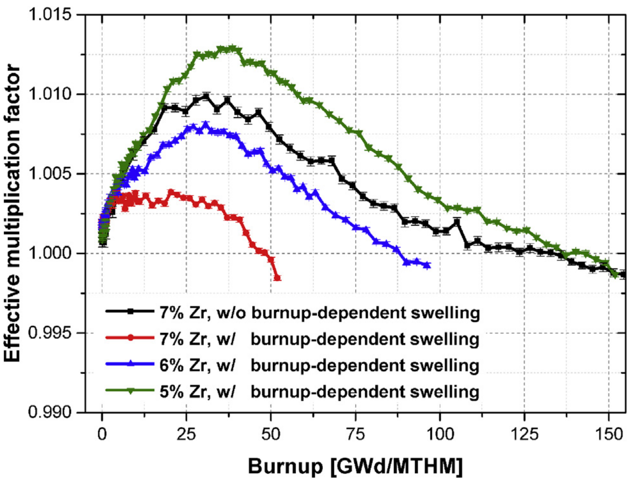

Fig. 7 – Impact of fuel-swelling models on the core lifetime.

consideration of the burnup-dependent fuel swelling, the fuel volume fraction in the core can be increased by reducing the Zr fraction in the alloy fuel down to ~5–6%. Thus, it is clear that the core lifetime of a B&BR strongly depends upon the fuel-swelling model, and the practical swelling behavior should be adopted for reliable estimation of core performance. As discussed previously [5–7], the core height of a B&BR should be enough, i.e., >~160–170 cm, to reach a quasi-equilibrium breed-and-burn stationary state. As shown in Fig. 7, the 5% Zr core doesn't reach the equilibrium state at the end-of-life (EOL) condition, but it is rather close to a quasi-equilibrium state.

The conversion ratios of the four cores are provided as a function of burnup in Fig. 8. The conversion ratio is defined as the ratio of the fissile nuclides produced to fissile nuclides destroyed. As sown in Fig. 8, for the cores using U-7Zr and SNF-7Zr, the conversion ratio was clearly lower when the burnup-dependent fuel swelling was taken into account, as compared to the conventional approach. It is clear that lowering the Zr content of the fuel leads to higher conversion ratios. The axial power profiles at beginning of life (BOL) and EOL are shown in Fig. 9. The BOL power distributions are very similar for the cores, but quite different in the EOL conditions, as expected.

Table 3 compares the local burnup distributions of the core models using the burnup-dependent fuel swelling. It is clear that the fuel burnup was higher at the initial LEU core region and became progressively lower with the core height, as the active core was moving upward with burnup. One notes that the peak local burnup can be ~30% at the initial LEU core for the core fueled with U-5Zr and SNF-5Zr, which provided the longest lifetime. Based on the core performance, it is expected that, for the core model, without considering the burnup-dependent swelling, the local burnup distribution is similar to that of the core with 5% Zr fraction. It should be mentioned that the fuel axial growth is all different depending on the local burnup, and that the fuel height in each burnup zone is slightly different from other groups in the Monte Carlo depletion analyses of the cores (Fig. 10). Additionally, the actual local peak burnup can be higher than those listed in Table 3, since some of the burnup zones are rather big.

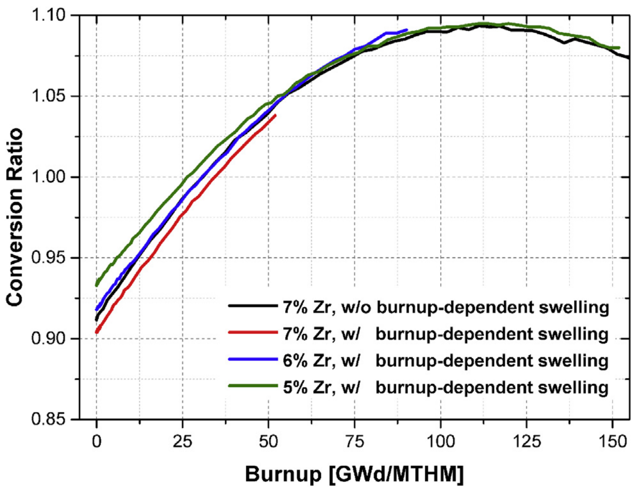

Fig. 8 – Conversion ratio as a function of the core-average burnup.

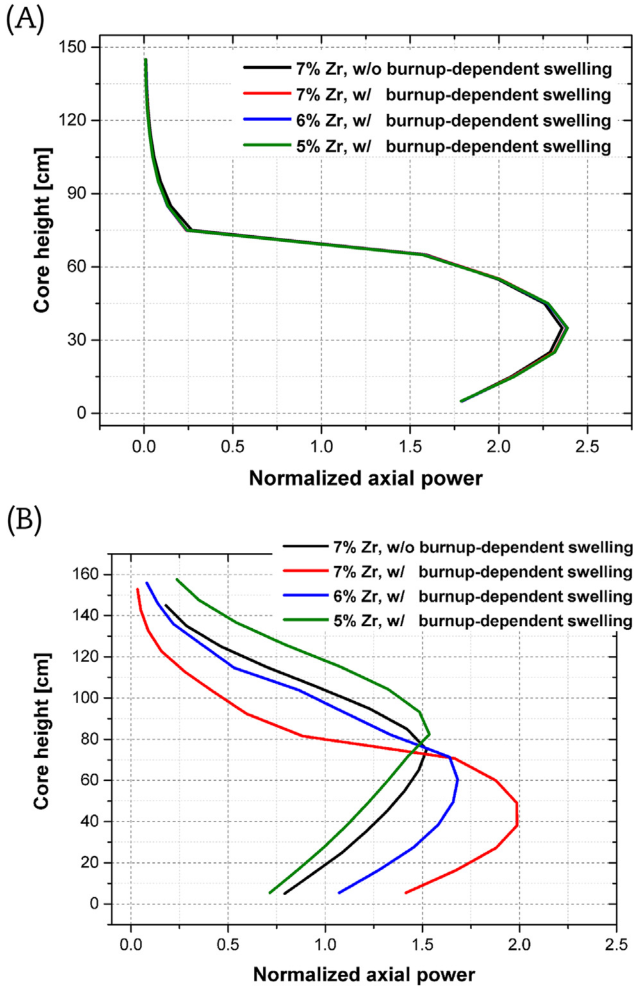

Fig. 9 – Axial power distributions in the B&BR cores. (A) Beginning of life. (B) End of life. B&BR, breed-and-burn reactor

The core lifetime of a B&BR is strongly affected by the modeling of realistic burnup-dependent fuel swelling. The deteriorated neutronic performance in the case of a realistic

Table 3 – Local burnup distribution at EOL (7% Zr/6% Zr/5% Zr) in GWd/MTHM.

Axial	Radial 1	Radial 2	Radial 3
10	1.3/5.0/18.4	0.6/2.3/9.0	0.6/1.9/6.6
9	1.9/8.1/29.0	0.9/3.6/14.4	0.8/2.8/10.2
8	3.2/13.7/45.9	1.6/6.4/24.1	1.3/4.7/16.1
7	5.6/24.3/70.6	2.8/11.7/37.7	2.2/8.1/24.9
6	9.6/34.4/102.7	50.5/19.5/57.9	3.8/13.3/37.2
5	15.2/58.7/139.3	9.2/30.8/85.33	6.5/21.0/53.97
4	23.9/77.2/178.5	15.5/47.7/117.3	11.0/35.7/99.64
3	35.9/106.7/215.6	25.1/71.4/152.0	17.61/46.76/99.6
2	85.48/188.6/293.9	67.0/148.0/235.0	50.5/110.2/175.8
1	100.5/200.2/283.2	81.5/162.8/232.8	61.7/122.2/174.7

EOL, end of life.

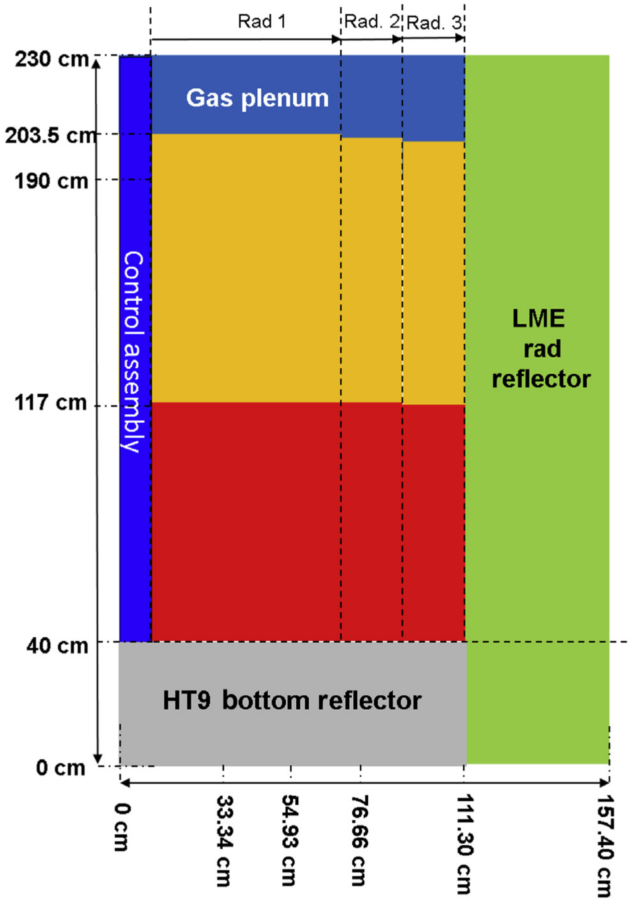

Fig. 10 – Axial configuration at EOL of core with 5% Zr metallic fuels. EOL, end of life; LME, lead magnesium eutectic; Rad., radial.

fuel-swelling model is largely ascribed to two main reasons. The first is the reduced fuel density due to the axial fuel growth with burnup and enhanced neutron leakage, leading to lower neutron economy and lower conversion ratio. Fig. 11 shows that the radial neutron leakage is noticeably enhanced with the realistic swelling of the metallic fuels. The bonding sodium in the metallic fuel is also closely related to fuel irradiation swelling. As was discussed in the previous section, the fuel smear density, typically 75%, is relatively low in the metallic fuel, and the large gap between fuel slug and cladding is filled with the bonding sodium for an effective heat transfer. In the current B&BR, an even lower smear density is considered due to the much higher peak fuel burnup as compared to standard fast reactors. Due to its noticeable volume fraction in the B&BR core, the bonding sodium contributes to neutron moderation, and the neutron economy is deteriorated.

3.2. *Consideration of bonding sodium in metallic fuels*

In the conventional simulation of SFRs and B&BRs without burnup-dependent fuel swelling, the bonding sodium is assumed to be removed completely from the fuel region to the upper gas plenum from the BOL condition. Therefore, it cannot account for the softened neutron spectrum due to the bonding sodium. However, in this burnup-dependent swelling simulation of a B&BR, the bonding sodium stayed in the fuel region until the local burnup of the fuel slug reached 2% burnup. Since this is a breed-and-burn core where the active core will slowly travel upward from the initial core to the blanket without any refueling, the bonding sodium in the upper core, particularly in the blanket region, will stay much longer than that in the lower LEU region. In a fast reactor such as B&BR, which requires a hard neutron spectrum for a good neutron economy, the core performance strongly depends on the neutron spectrum changes.

In order to see the impact of the bonding sodium on the neutronics performance of the B&BR, a core loaded with 7% Zr fuel was reanalyzed in view of the bonding sodium. The fuel slug was modeled with and without bonding sodium during the entire depletion period. The simulation was performed without any burnup-dependent swelling, and the results are shown in Fig. 12. The corresponding neutron spectra are plotted in Fig. 13, and it is shown that the neutron spectrum was slightly softened by the bonding sodium. It should be

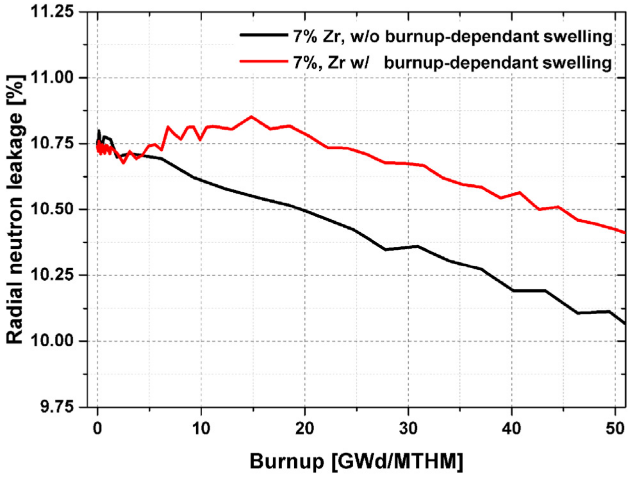

Fig. 11 – Radial neutron leakage in a B&BR core loaded with 7% Zr metallic fuels. B&BR, breed-and-burn reactor.

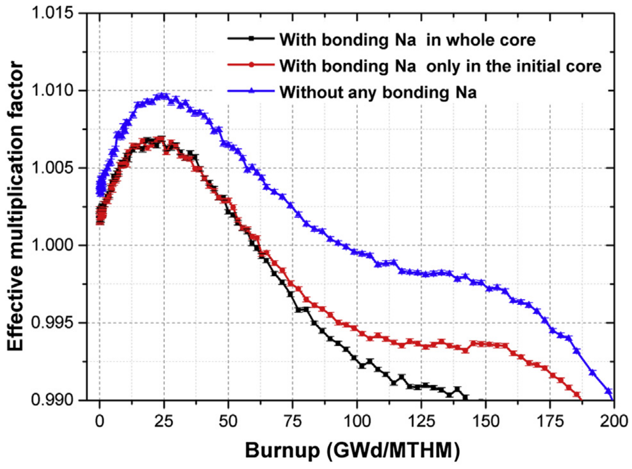

Fig. 12 – Impact of bonding sodium on the core lifetime.

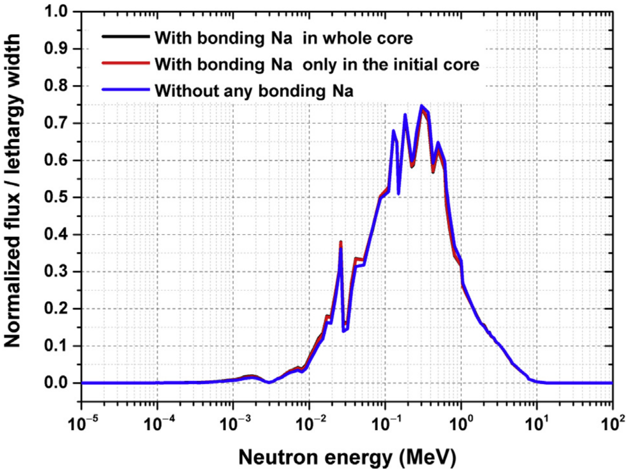

Fig. 13 – Impact of bonding sodium on the neutron spectrum.

noted that the bonding sodium in the initial LEU core strongly affected the core lifetime, and removal of bonding sodium in the blanket region can also noticeably improve the core reactivity.

From the above analyses, it is clear that the conventional bonding sodium in the metallic fuel needs to be removed to improve the neutronic performance of the B&BR. In this regard, a new metallic fuel based on particulate metallic fuel [12, 13] was proposed for an advanced SFR design. In the particulate metallic fuel, helium gas is used to fill the gap inside the fuel rod to improve heat transfer to the cladding. Another approach to remove the bonding sodium is the helium-filled mechanically-bonded metallic fuel pin design, suggested by researchers in India [14]. It will also be possible to remove the bonding sodium from a metallic fuel by adopting an annular metallic fuel concept [15]. In this annular metallic fuel, the He gas may not be necessary, since the initial gap between the fuel pin and cladding can be small and will quickly close due to the thermal expansion and irradiation growth of the annular fuel.

The second approach to improving the neutronic performance of the B&BR is to reduce the axial fuel swelling with burnup. The axial growth of metallic fuel can be effectively minimized by using annular metallic fuel. Based on the irradiation result of metallic U-20Pu-10Fs annular fuel with bonding sodium in the 1960s, the annular metallic fuel was observed to shrink in length by ~6% when the burnup was ~4% [15]. The initial annular hole slowly disappeared, closing initially at the center of the fuel and eventually continuing to both ends until the hole was no longer visible. There was another irradiation test using U-2Zr annular fuel with bonding sodium and vented fuel rod design up to 9.8% burnup that reported annular fuel-length growth of only 0.6% [16]. These experimental results also confirmed that increasing uranium content in the metallic fuel would lead to a larger axial growth. Recently, U-10Zr annular fuel without bonding sodium was simulated, and the axial swelling rate of the annular fuel was confirmed to be smaller than that of the traditional solid metallic fuel [17].

4. Conclusions

The burnup-dependent swelling of the cylindrical metallic fuel slug has been investigated in view of the neutronic performance for a small sodium-cooled U-Zr-fueled B&BR core adopting single-batch fuel management. The radial and axial swelling behaviors of the U-Zr metallic fuel are taken from the irradiation test results in EBR-II. This study confirmed that the neutronic lifetime of the B&BR core can be substantially decreased when the realistic burnup-dependent fuel swelling is considered due to impaired neutron economy. The deteriorated neutronic performance was largely ascribed to enhanced neutron leakage resulting from the axial fuel growth and the slightly softened neutron spectrum due to the longer residence time of the bonding sodium. It was concluded that the actual burnup-dependent fuel swelling should be considered for reliable analysis of the long-life B&BR loaded with U-Zr metallic fuel.

As an alternative to the conventional rod-type metallic fuel, a new annular metallic fuel without bonding sodium can be considered for a high-performance B&BR design, since the axial irradiation growth can be minimized with annular geometry and the neutron spectrum cannot be softened by the bonding sodium.

Conflicts of interest

The authors have no conflicts of interest to declare.

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