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Neutronics feasibility of simple and dry recycling technologies for a self-sustainable breed-and-burn fast reactor

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ABSTRACT

This paper is concerned with the neutronics analysis of extremely simplified recycling technologies of spent fuels in a small breed-and-burn fast reactor (B&BR). The discharged fuels of the first generation B&BR, which achieved an average burnup of 160 GWd/MTHM, were used to construct a second generation B&BR core. Two types of high proliferation resistant recycling technologies, melt refining and the newly suggested super-simplified melt and treatment, were applied to process and treat the discharged fuels. Because the burnup profile of discharged fuels varies largely depending on its position in the core, the recycling of the discharged fuels was also carried out by grouping them into recycling regions including 1, 3, and 6 recycling regions. In this study, the core performance of the 2nd generation B&BR loaded with the recycled fuel, which was produced by different recycling technologies and recycling regions, was analyzed and compared. An optimum fuel loading scheme was also adopted to maximize the performance of the 2nd generation B&BR in terms of the burnup reactivity change, core lifetime, and power profiles.

1. Introduction

A breed-and-burn fast reactor (B&BR) is a special type of fast reactor which offers a very high fuel utilization by breeding fissile fuel and concurrently using the bred fissile fuel *in situ*. This attribute is reflected in the B&BR core configuration which always has 2 fuel regions: a sufficient starter/igniter region and a thick blanket region. The starter/igniter region acts as the initial core, provides early criticality, and also supplies neutrons to the blanket region. The center of the active core starts from the initial core region and gradually moves to the blanket region through the fissile breeding and burning process. Depending on the design objectives and considerations, the blanket region can be located above or below or even next to the initial core region. There are also many fuel options for the blanket region, for example natural uranium (∼99.3% U-238), depleted uranium (∼99.8% U-238), and used nuclear fuel (UNF) from existing nuclear fleets which still contain more than 90% of U-238. Meanwhile, the initial region can be loaded with low enriched uranium (LEU), and this type of core is defined as a 1st generation B&BR. The discharged fuel of a B&BR can also be used for the initial core region because it is still rich in plutonium fissile fuel. If the B&BR uses a discharged fuel from an *n*th generation of a B&BR, it is referred as the (n + 1)th generation B&BR. In the long term, this means that uranium enrichment facilities will be less important for B&BRs because they are only required for the 1st generation reactor. On the other hand, fuel recycling technologies become crucial. The availability of blanket fuels is not an issue because there is much unused depleted uranium and UNF.

In this study, the possibility of 2nd generation B&BR using simple dry fuel recycling technologies is explored in order to investigate self-sustainability of the B&BR. A 1st generation B&BR was designed and studied at KAIST specifically from a neutronics perspective (Hartanto, 2015). The reactor has a 400 MWth power and can achieve an average core discharge burnup of 160 GWd/MTHM or about 52.3 effective full power years (EFPYs). The blanket region uses metallized UNF from pressurized water reactors (PWR UNF-6Zr) (Hartanto, 2015), and it is located above the LEU-Zr initial core region. The details of the design core configuration are described subsequently. It should be mentioned that the 2nd generation core has the same structural dimension as the 1st generation core.

A proper fuel recycling technology for B&BRs is essential because they should have characteristic safeguards. A dry reprocessing technology such as melt refining is recommended because it has a non-proliferation attribute in which there is no separation

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of U, TRUs (transuranics), and some of the FPs (fission products). This technology is proven because it has been used in the Argonne National Laboratory to recycle the EBR-II fuel (Stevenson, 1987; Hesson et al., 1963). Melt refining has also been selected by other B&BR studies to perform fuel reconditioning when its cladding reaches the maximum radiation damage (Greenspan and Heidet, 2011; Sanzo et al., 2014; Karim et al., 2016). During the melt-refining process, gaseous and volatile fission products are completely disposed as well as about 95% of rare earth (RE) isotopes. Meanwhile, almost all of the uranium can be recovered; however, there are significant losses of the TRUs. It has also been observed that the associated processes of melt refining are not very simple. In this study, another fuel recycling method, namely super-simplified melt and treatment (SSMT), is proposed in order to enhance the proliferation-resistance and economy of the recycling. During SSMT, it is assumed that only the gaseous and volatile fission products are completely removed, while other nuclides such as RE nuclides, uranium, and transuranic are entirely recovered. In this paper, the impact of the two recycling technologies for 1st generation B&BR fuel on the 2nd generation B&BR core performance was compared. The impact of the different recycling scenario such as whole core or region-wise recycling was also studied. Neutronics calculations were done with the Monte Carlo code McCARD (Shim et al., 2011) in conjunction with the ENDF/B-VII.0 nuclear library.

The remainder of paper is organized as follows. A brief description of the B&BR core concept is given in Section 2. The two fuel recycling methods are explained in detail in Section 3. The results from the 2nd generation B&BR and its discussion are provided in Section 4. Finally, conclusions are drawn in Section 5.

2. B&BR core concept

The reference reactor in this study (Hartanto, 2015) has a power of 400 MWth and a power density of 90.149 W/cc. The core contains 78 fuel assemblies, 7 control assemblies, and 126 reflector assemblies shown in Fig. 1. Those assemblies are arranged into a configuration of 10 hexagonal rings. As seen in Fig. 1, the total core height is 180 cm, and there is about a 40 cm HT9 bottom reflector supporting the core region. The coolant inlet and outlet temperatures are 360 °C and 510 °C, respectively.

The fuel assembly contains 124 metallic fuel pins summarized in Table 1 and shown in Fig. 2. The fuel pin is relatively large with a diameter of 1.9 cm. The ratio of the fuel pin pitch to the diameter is about 1.064. As depicted in Fig. 2, the fuel pin is an annular configuration instead of the traditional solid cylindrical metallic fuel pin. This annular design was chosen to minimize the axial swelling rate. The traditional solid U-10Zr and U-19Pu-Zr metallic fuels have been reported to grow axially by about 10% and 5%, respectively, at a 20% burnup (Hofmann et al., 1997). Axial swelling of the fuel is not preferred when trying to achieve a high performance B&BR because the volume expansion of the core enhances the neutron leakage thereby reducing the core criticality. On the other hand, the axial swelling rate of the annular metallic fuels were confirmed to be relatively small at about 0.6% for the U-2Zr fuel (Horak et al., 1962), and it was even smaller as the plutonium content in the fuel was increased (Beck et al., 1968). Because the discharged fuel of the 1st generation B&BR contains a significant amount of Pu, it is expected that the axial swelling rate in the B&BR is very small at about just 1%–2%.

In addition, a thin gap of about 40 μm is also placed in between the fuel and the cladding. In fact, the B&BR fuel rods do not use any sodium bonding because sodium can significantly reduce the core conversion ratio by slightly softening the neutron spectrum (Hartanto et al., 2016). Despite the absence of sodium bonding, it should be noted that there is no concern for the thermal conductivity of the swelled metallic fuel because the thin gap is closed due to the thermal expansions of the fuel and cladding almost as soon as the fuel assemblies are dipped into the sodium pool. For this reason, it is assumed in the neutronics simulation that the gap between the fuel and cladding is closed from the beginning of the core lifetime.

To improve the performance of the metallic fuel, a diffusion barrier or liner coating can be adopted in the B&BR fuel design. The

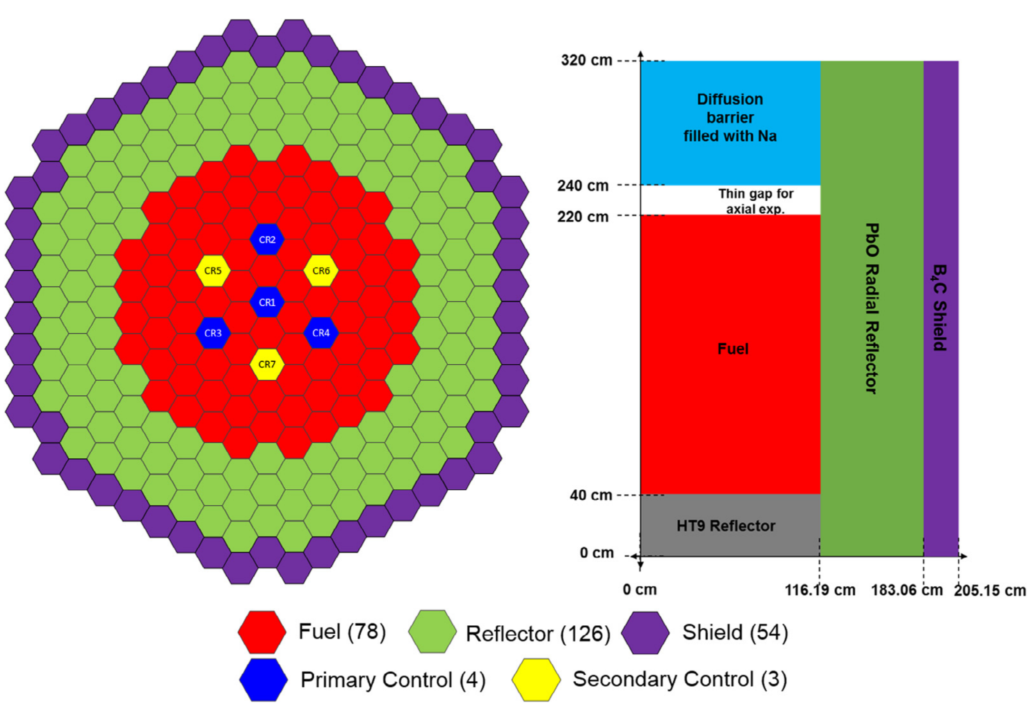

Fig. 1. Core radial and axial configurations.