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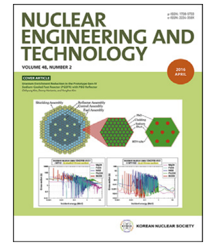

Original Article

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-

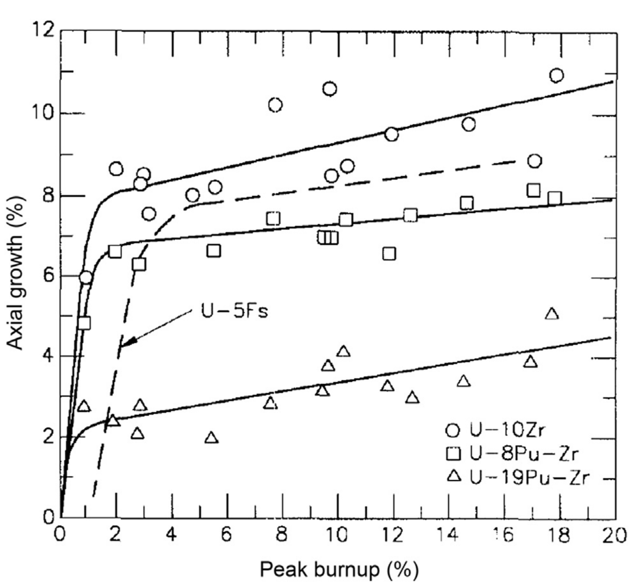

Fig. 1 – Axial growing rate for various metallic fuels. Reprinted from Progress of Nuclear Energy, Vol. 31, G.L. Hofman, L.C. Walters, and T.H. Bauer, Metallic Fast Reactor Fuels, Page. 91, 1997, with permission from Elsevier.

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.

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.