Feasibility of Rotational Fuel-shuffling Breed-and-Burn Fast Reactor with Nitride Fuel and Sodium Coolant

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Introduction

In recent years, renewable energies like solar and wind have gained attention as a way to reduce greenhouse gas emissions. However, the intermittent nature of renewable energies makes it challenging to meet the base load demand. Nuclear power is a potential solution(1), as it produces large amounts of electrical energy per unit mass of fuel and emits no greenhouse gases. Despite these advantages, concerns about nuclear waste disposal, safety, proliferation, and the short-term availability of uranium reserves have led to scrutiny from governments and environmentalists.

To address these concerns, in 2001 scientists established the Generation IV International Forum (GIF) to develop advanced nuclear reactor designs, culminating the following year in the selection of six designs based on sustainability, economics, safety and security, and proliferation resistance criteria. Fast breeder reactors, such as the sodium-cooled fast reactor(2), are a promising option for sustainable energy production because they can use nearly 100% of natural uranium's energy value. To achieve this high fuel utilization, it must reprocess the fuel when the peak radiation damage reaches a certain threshold. However, due to the separation of plutonium or trans-uranium elements from used or spent fuel, reprocessing poses a significant proliferation risk. To avoid this issue, breed-and-burn (B&B) reactors(3) have been proposed that can sustain a fission reaction when fueled directly with natural uranium without the need for reprocessing. To initiate the chain reaction, the B&B core must first be fed an adequate amount of fissile fuel such as enriched uranium. Thereafter, the B&B core is capable of continued operation while being fed solely with natural or depleted uranium. However, B&B reactors require improved neutron economy(4,5) to establish and maintain criticality in normal operating conditions. One proposed solution is rotational fuel shuffling(6), which involves loading fresh fuel from the edge of the core and moving it stepwise towards the center while discharging spent fuel. This helps to maintain a high neutron economy by ensuring that high burnup fuel is always in close proximity to the central region of the reactor core. Detailed analyses of small rotational fuel-shuffling breed-and-burn fast reactors (RFBBs) have been performed(7,8).

A small RFBB reactor with nitride fuel and sodium coolant was analyzed, and the results confirmed the feasibility of the concept with a simplified core design(9). Moreover, the sodium void reactivity coefficient in RFBB-NS was investigated, revealing that it was the same as that in conventional SFR designs in the equilibrium condition. However, it is important to note that the core design was a simplified one, lacking both a fuel assembly duct and control rod assemblies, which are necessary to realize the reactor concept. Still, the presence of such devices may diminish the neutron economy, which could make the reactor concept unfeasible. The purpose of this study is to design the RFBB-NS, including assembly duct and control rod assemblies, and to show its feasibility.

Brief results of the study

Neutron transport and fuel burnup analyses were performed for the improved RFBB-NS design. The reactor reaches a critical state and k-eff converges at the equilibrium state by the use of lead–bismuth reflectors. The equilibrium state was obtained after 35 shuffling steps with an 1120-day shuffling interval (cycle). Also, it can be seen that the reactivity swing between shuffling steps was small due to burnup performance.

The burnup characteristics of the equilibrium cycle were analyzed in detail. Burnup is expressed in megawatt-days per kilogram of initial heavy metal, and the results indicate that the burnup at the top and bottom of the zones was ~166 MWd/kgHM, which is significantly higher than in the feasibility study(9). This higher burnup resulted in a lower Pu vector in the discharged fuel, thus solving one of the issues that arose in the previous study.

Moreover, the burnup at middle zone was ~395 MWd/kg/HM, resulting in an average discharge burnup of ~299 MWd/kgHM or 31% FIMA. However, the high burnup values achieved in the improved RFBB-NS design require a fuel cladding material that can withstand high radiation damage. The estimated DPA of the cladding was about 743, while the maximum allowable constraint for radiation damage in cladding material is around 650 DPA for this study. Therefore, a key challenge in the design of an RFBB will be the development of a fuel cladding material capable of withstanding such high irradiation.

In rotational fuel shuffling, fresh fuel assemblies were loaded at the core periphery and discharged at locations far from the core center. The power distribution peaked at the core center and gradually decreased in the radial direction. Changes of power distribution at the BOEC and EOEC were small. This implies the safe operation of RFBB-NS. While the uncertainties associated with the power distribution have been assessed, it is found that they exert minimal impact on the heat removal calculation. The uncertainty from Monte Carlo calculation were around 0.00162% for Beginning of Equilibrium Cycle (BOEC), suggests that the variations in power distribution have negligible consequences for the heat removal assessment. Despite the small magnitude of these uncertainties, rigorous evaluations continue to be essential to guarantee that the obtained results align with acceptable limits for temperatures of fuel, cladding, and coolant in the system.

The temperatures of the fuel, cladding, and coolant were all found to be within acceptable limits. This indicates that the design was successful in controlling the heat produced by the reactor and averting any potential harm to the coolant, cladding, or fuel. The pressure drops in the hot channel remained within acceptable limits. This suggests that the coolant was able to flow through the reactor without encountering significant resistance or blockages, and that the pump was not a limiting factor.

Brief conclusion

The practical design of an RFBB-NS was studied. Burnup analysis revealed that the reference design of the RFBB cannot reach criticality due to the presence of duct material and control rod channels. To address this, the core was modified by applying lead–bismuth reflectors. The thus-modified design of RFBB-NS showed promising results in neutron transport, burnup, and heat removal analyses. By decreasing the active height of the core and placing axial reflectors at its top and bottom, the pressure drop in the long coolant channel was reduced to acceptable levels. The use of lead–bismuth reflectors improved the neutron economy, allowing the reactor to reach criticality and the k-eff to converge at equilibrium. The improved design showed superior burnup performance compared to the previous study, with higher burnup values achieved in the top and bottom zones. However, the peak radiation damage to the cladding material slightly exceeded the constraint set used in this study. During BOEC and EOEC, the power distribution in the radial direction remained constant, and the maximum fuel centerline temperature, cladding outer temperature, coolant outlet temperature, and pressure drop in the coolant channel were all within acceptable limits.

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