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[Thesis outline]

Small rotational fuel shuffling breed-and-burn fast reactor with nitride fuel and sodium coolant

Tsendsuren AMARJARGAL

This thesis aims to assess the feasibility and performance of designing a small Rotational Fuel-shuffling Breed-and-Burn (RFBB) fast reactor using nitride fuel and sodium coolant (RFBB-NS). To achieve this purpose, the thesis focused on the three key stages. First, analysis of the simplified core design of RFBB-NS: In this stage, we assessed the basic core design parameters of the RFBB-NS reactor to understand its feasibility and preliminary performance characteristics. The second stage focused on examining the sodium void worth in the simplified core. Lastly, we proceeded to design the detailed core configuration of the RFBB-NS reactor, considering factors such as fuel arrangement and control rods. The neutron transport and fuel burnup were performed using Serpent 2.1.0, a continuous-energy Monte Carlo code with the ENDF/B-VII.0 cross-section library. Fuel cell geometry with a porous vent plug was modeled in two-dimensional axisymmetric with R-Z coordinates. For simplicity, the software modeled a cylindrical fuel cell equivalent to a hexagonal cell for neutronic calculation. Heat removal analyses were carried out using COMSOL 5.4 Multiphysics Software. The heat source is defined by a fitting equation for axial power distribution in the hottest channel, which is obtained from the neutronic analysis. The results revealed that the simplified core with rotational fuel shuffling at an 860-day cycle length could achieve an equilibrium state at criticality close to unity. In this equilibrium state, the power density profile during BOEC and EOEC is unchanged. The average discharge burnup was 187 MWd/kg-HM. With this amount of burnup, the plutonium vector was acceptable in the mid-zones of fuel. However, in the top and bottom zones, it was higher than the accepted value. A steady-state heat removal analysis was performed for the hottest channel, revealing that the maximum fuel temperature was lower than the operational temperature limit and that the ODS cladding material temperature was lower than the melting temperature of nitride fuel. However, the maximum cladding temperature was slightly higher (656 DPA) than the suggested temperature for nitride fuel integrity.

The sodium void reactivity coefficient was investigated in small RFBB-NSs and five different voiding scenarios were investigated at BOEC and EOEC. When a small portion of the core center was voided, the reactivity coefficient was around 1$ at both BOEC and

EOEC, while when the middle portion of the core center was voided, it was around 2$. Finally, when the whole core was voided, the estimated reactivity was around 4$ at both BOEC and EOEC. It was thus confirmed that the sodium coolant void coefficient in RFBBs with nitride fuel and sodium coolant was the comparable as that in conventional SFR designs in the equilibrium condition. This suggests that the sodium void coefficient cannot be a serious issue from the point of view of safety in small RFBBs with sodium coolant and nitride fuel.

The detailed 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 (~299 MWd/kgHM) compared to the previous study, with higher burnup values achieved in the top and bottom zones. This higher burnup resulted in a lower Pu vector in the discharged fuel, thus solving one of the issues that arose in the simplified core analysis.

The improved design demonstrated superior burnup performance compared to the simplified core study, with higher burnup values achieved in the top and bottom zones of the core. However, it's worth noting that the peak radiation damage (743 DPA) to the cladding material slightly exceeded the constraint set in this particular study. Therefore, the further development of cladding material to withstand such high irradiation is necessary.

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. When six control rods were inserted, the core was subcritical at 0.98. When an active core region is fully voided, sodium void worth was around 4$ at BOEC and EOEC. In terms of heat removal, nitride fuel has a higher melting temperature than metallic fuel. So, it is capable of providing a sufficient safety margin for the operation than metallic fuel.

In conclusion, these results demonstrate the burnup performance of the RFBB-NS core design, addressing criticality in the equilibrium state, average discharge burnup, peak damage on cladding material, plutonium composition in discharged fuel, average power density profile, sodium void reactivity in different voiding scenarios, the temperature profile and pressure drop in the hottest channel.