On receiving the 19th Reactor Physics Division Award

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It is a great honor for me to receive the 19th Reactor Physics Division Award from the Atomic Energy Society of Japan. I would like to express my sincere gratitude to the Reactor Physics Division and to all the members of the selection committee for this generous recognition. I am deeply humbled and grateful.

This award is by no means the result of my individual effort alone. The research recognized here has been made possible through the continuous support and guidance of my supervisors, and colleagues. I would especially like to acknowledge my professor Toru Obara at Institute of Science Tokyo who provided me with both academic freedom and rigorous training in reactor physics. His encouragement allowed me to explore challenging topics and to develop my own research direction in molten salt reactor physics.

Research Motivation and Background

My research journey in reactor physics began with a fundamental question: how can we better understand and design advanced reactor systems that possess not only favorable neutronic performance but also realistic operational feasibility?

Among various Generation IV reactor concepts, Lead-cooled fast reactors (LFRs) have attracted significant attention due to their inherent safety characteristics, flexibility, and potential for efficient resource utilization. Efficient utilization of uranium resources has long been a central objective in fast reactor development. The breed-and-burn (B&B) concept presents a theoretically attractive approach, in which fertile isotopes are gradually converted into fissile material in situ, allowing sustained operation with extended fuel residence time and minimal reprocessing.

However, traditional B&B implementations are facing significant structural and operational challenges. The requirement for a self-propagating wave imposes strict constraints on core geometry, fuel arrangement, and material endurance. These limitations complicate practical deployment.

Recognizing these challenges, the Rotational Fuel-Shuffling Breed-and-Burn (RFBB) strategy was proposed as an alternative realization of the B&B principle. Instead of axial wave propagation, RFBB employs radial fuel shuffling. Fresh fuel assemblies are loaded at the periphery of the core, gradually moved toward regions of higher neutron importance, and discharged after achieving high burnup. Through this controlled radial movement, the system achieves progressive breeding without relying on a physical burning wave.

When I began my research at Tokyo Institute of Technology, I was particularly interested in understanding the equilibrium characteristics of an LFR-based RFBB system. In solid-fueled fast reactors, the equilibrium state is determined by the interplay between neutron economy, fuel management strategy, and material constraints. Unlike idealized B&B wave concepts, RFBB relies on periodic shuffling and spatial reactivity redistribution, making equilibrium analysis closely tied to fuel assembly movement patterns.

This motivated me to focus on the equilibrium analysis of an LFR-based RFBB core employing metallic fuel and lead-bismuth eutectic coolant. My goal was not only to evaluate equilibrium compositions, but also to clarify the physical mechanisms governing breeding performance, neutron balance, isotopic evolution, and power distribution stability. By systematically analyzing these coupled behaviors, I sought to determine whether RFBB could achieve a self-sustaining condition within realistic engineering constraints.

Equilibrium Analysis of the LFR-Based RFBB Core

Building upon the initial motivation, the first stage of my research focused on the equilibrium behavior of the LFR-based RFBB system. The equilibrium state in this context does not simply represent a high-burnup behavior, but rather a dynamically sustained configuration in which fissile production and consumption reach long-term balance under periodic fuel shuffling.

In the RFBB framework, the spatial redistribution of fuel assemblies plays a central role in determining neutron economy. As assemblies move radially from peripheral regions toward the core center, their reactivity contribution and isotopic composition evolve simultaneously. Therefore, equilibrium analysis required coupling burnup calculations with predefined shuffling sequences to capture the cyclic nature of core operation.

Through systematic simulations, I evaluated key performance indicators including effective multiplication factor stability, discharge burnup, and radial power distribution. The results demonstrated that, under optimized shuffling intervals and shuffling pattern, the LFR-based RFBB core can sustain criticality without continuous external fissile input once equilibrium is reached. The isotopic composition gradually converges toward a stable distribution, indicating that in-situ breeding compensates for fissile depletion over successive cycles.

This equilibrium feasibility study established a necessary foundation. However, it also revealed a critical limitation: equilibrium configurations assume that the reactor has already accumulated sufficient fissile inventory. In practice, any reactor must begin from an initial startup configuration.

Startup Core Design and Transition Strategy

The transition from startup to equilibrium represents one of the most technically demanding aspects of B&B systems. At startup, the core begins with fresh fertile material and a limited fissile inventory. The system must gradually build sufficient plutonium while maintaining criticality and avoiding excessive reactivity fluctuation.

To address this challenge, I developed a structured methodology for startup core design. First, reference infinite multiplication factors were derived from equilibrium compositions of individual fuel assemblies. Based on these reference values, appropriate initial enrichment levels were estimated for each radial position. This provided a baseline enrichment distribution that approximates the reactivity characteristics of the equilibrium core.

However, enrichment adjustment alone proved insufficient to guarantee smooth reactivity evolution during early cycles. Due to the shuffling pattern, highly enriched assemblies could be discharged immediately, resulting in reactivity drops and instability.

To mitigate this issue, a modified fuel management approach referred to as the Push-Back strategy was introduced. Instead of physically reversing the shuffling direction, this strategy selectively extends the residence time of specific high-enrichment assemblies in regions of higher neutron importance during early cycles. By doing so, neutron economy is improved.

Through iterative optimization of enrichment distribution, shuffling intervals, and residence time adjustment, the startup configuration achieved controlled reactivity variation and gradual convergence toward the equilibrium state. This demonstrated that the RFBB concept can transition from an initial condition to sustained breed-and-burn operation without relying on large external fissile support.

Reactivity Control and Safety Considerations

Beyond achieving criticality, practical reactor design requires satisfying safety-related constraints. Therefore, the startup and equilibrium configurations were further evaluated relating to the shutdown margin, power distribution behavior, and material irradiation limits.

Control rod worth was assessed under peak reactivity conditions to confirm that sufficient negative reactivity is available to bring the reactor into a subcritical state. The results indicated that the control system provides adequate shutdown margin even under conservative assumptions.

Material irradiation performance was examined through displacement per atom (DPA) estimation for cladding regions. Because extended fuel residence time is a central feature of RFBB, irradiation damage becomes a critical design parameter. The analysis showed that, while peak DPA approaches design limits in high-flux regions, values remain within acceptable ranges under optimized operating conditions.

Power distribution behavior was also evaluated throughout startup and equilibrium cycles. Although early cycles exhibit localized peaks due to enrichment heterogeneity, radial power profiles gradually flatten as isotopic composition stabilizes. This trend contributes to improved thermal-hydraulic feasibility during long-term operation.

These analyses highlight that RFBB design must integrate neutronic performance with safety and material constraints from the outset.

Balancing Neutronic Optimization and Engineering Realism

An important insight gained from this research is that maximizing breeding performance alone is insufficient. Reactor physics optimization must be balanced against engineering feasibility.

For example, increasing operating power enhances neutron flux and accelerates breeding. However, higher power density imposes stricter thermal-hydraulic requirements and increases structural stress. Similarly, extending fuel residence time improves fuel utilization but intensifies material irradiation concerns.

To explore these trade-offs, alternative operating scenarios were evaluated, including adjustments to coolant velocity and reductions in thermal power. These studies demonstrated that multiple design pathways can achieve acceptable neutronic performance while preserving safety margins.

Such comparative analysis underscores the importance of integrated design philosophy. Reactor physics, thermal-hydraulics, and material performance cannot be treated as isolated domains; they must evolve together in a coherent framework.

Future Research Direction

Although the present work demonstrates the feasibility of equilibrium operation and startup transition in an LFR-based RFBB system, several aspects require further investigation.

Future efforts will focus on refining axial enrichment distribution, optimizing shuffling patterns to further flatten power profiles, and conducting detailed transient safety analyses. Long-term structural material validation under high DPA conditions remains essential for confirming extended fuel residence capability. Additionally, system-level assessments incorporating economic considerations and fuel cycle integration will be necessary to evaluate practical deployment potential.

My long-term objective is to bridge the gap between conceptual breed-and-burn strategies and deployable fast reactor systems. By integrating neutronic design with engineering realism and sustainability considerations, I believe that the RFBB strategy offers a promising direction for enhancing fuel utilization in fast reactors.

Again, receiving this award from the Atomic Energy Society of Japan is both an encouragement and a responsibility. I sincerely thank my supervisor, and colleagues for their invaluable support.