Long-term Control of Excess Reactivity in Molten Salt Fast Reactors Using Pebble-type Burnable Poisons

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1. Introduction

This study aims to design a power source for ships based on Molten Salt Reactors (MSRs), which offer high energy efficiency with high operation temperatures, compact size, and modular design. With zero carbon emissions and minimal environmental impact, MSRs are regarded as a sustainable energy solution, making them particularly well-suited for long-term ship operations as a safe and efficient nuclear technology for maritime use.

However, in order to operate for several decades with a power output of several hundred megawatts, particularly without refueling for economic efficiency, the excess reactivity at the beginning of the cycle is significantly high. This raises significant challenges in designing control systems capable of effectively regulating the reactor and ensuring its safe shutdown.

As a potential solution to this issue, a concept was developed wherein pebbles composed of gadolinium (Gd) and graphite circulate through the primary loop, acting as a Burnable Poison (BP). This concept specifically focuses on its application to fast reactor systems, where the use of thick reflectors is inevitable, aiming to reduce the contribution of fission from thermal neutrons near the reflector region and to design a burnable poison that can gradually deplete. Based on the results, this paper presents an analysis of the BP performance and core characteristics with the Gd pebble, evaluating whether reactivity can be effectively controlled over an extended period with only the initial loading.

2. Concept and calculaton methods

2.1 Reference core design

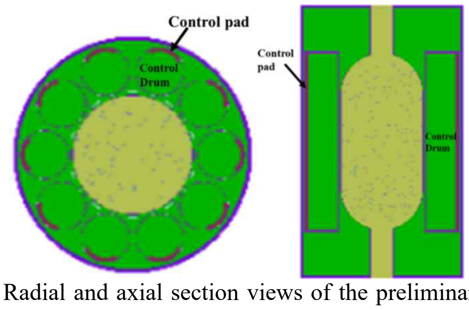

Fig. 1. Radial and axial section views of the preliminary core design.

The core selected for the evaluation was designed to achieve power output of 100 MWth, with 28 years of long-term operation as a power source for a ship. The active core is a cylinder with a radius of 80 cm and a height of 188 cm, with hemispherical caps (radius 80 cm) affixed to both the top and bottom. BeO is applied to the exterior surface at a thickness of 75 cm. To reduce the core size when employing KCl-NaCl-UCl_3 fuel salt, the use of BeO reflectors was required. As part of the preliminary burnup evaluation conducted to estimate the required control reactivity, it was determined that, with a total fuel inventory volume of 12m³, including both the internal and external core, the K-eff at the beginning of the cycle should exceed 1.14. As the primary control mechanism, 10 control drums were placed in the reflector region, as shown in the Figure 1 above. In order to accommodate the height of the control drums, the axial length of the effective core was designed to be longer than the radial dimension, thus maximizing the height of the control drums. Furthermore, neutron absorbers in the form of plates were added to the surface of the active core, serving as a secondary shutdown system.

2.2 Concept of Gd pebble

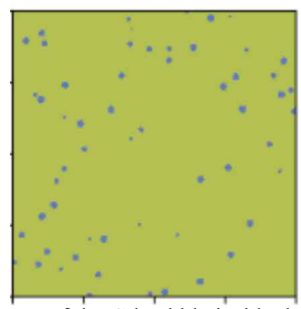

Fig. 2. The diagram of the Gd pebble inside the core region.

The current core design imposes a significant burden on the control performance of the control systems. To meet the required control performance, an excessively large number of control drums and control plates are needed. Therefore, a concept using pebble-shaped burnable poisons was devised. Despite the core being designed for a fast-spectrum, the BeO reflector allows some thermal neutrons to enter the active core surface, resulting in thermal fission. In this context, a pebble BP with neutron posion material, such as Gd was examined to lower the excess reactivity at the beginning of cycle.

This pebble is made up of spherical Gd particles encased in a double layer of graphite, which is chemically stable, has a high melting point, and is compatible with the fuel salt. This design enables the concept of solid-state flow within the fuel salt. Drawing on prior experience in the fabrication of complex fuels such as TRISO fuel, it is anticipated that producing pebbles with a radius of 1cm can be achieved with little difficulty.

OpenMC provides several convenient functions via its Python API, allowing for the generation of particle locations and their placement within a lattice. This feature generates an explicit model of pebble particles. *The explicit modeling of pebbles allows to generate random, non-overlapping configurations of particle spheres constrained by the user-specified container. In OpenMC, the random configuration is generated using a combination of random sequential packing (RSP) and close random packing (CRP).* For all calculations, OpenMC, a program developed at the Massachusetts Institute of Technology, was used. The ENDF/B-VII.1 cross-section library was employed for iterative K-eigenvalue and depletion calculations. The analysis considered $NaCl\text{-}KCl\text{-}UCl_3$ with HALEU (High-Assay Low-Enriched Uranium) as the fuel salt, which contains approximately 19.75% enriched U-235.

3. Feasibility evaluation of Gd pebble

3.1 Gd pebble performance Evaluation with depletion calculation

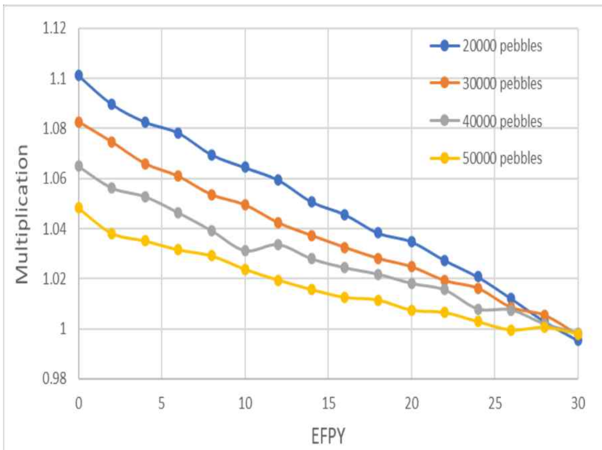

Fig. 3. Multiplication letdown curve with Gd pebbles.

The Figure 3 displays the results of burnup calculations done at two-year intervals under effective full power with all drum-out conditions. The amount of total loaded fuel is fixed in each calculation. For the reference core, which does not use Gd pebbles, the initial cycle reactivity is 1.14285(12), and after 28 years of operation, the reactivity at the end of the cycle is evaluated to be 1.00285(15). Burnup calculations were performed by gradually increasing the number of natural Gd-containing pebbles in spherical form, with a radius of 0.9 cm, inside a graphite core with a radius of 1.0 cm, from 20,000 to 50,000 pebbles. The results showed that as the cycle neared its end, the case with Gd pebbles converged to the reference case without pebbles, indicating that the Gd pebbles, which acted as burnable poisons, were completely depleted and no longer had any effect. Unlike conventional burnable poisons, which are typically burned early in the cycle, Gd pebbles primarily absorb neutrons as they pass near the reflector and are gradually depleted over an extended period. The burnup process continues for approximately 15 years as the pebbles circulate within the primary system.

3.2 Power distribution and Peaking factor

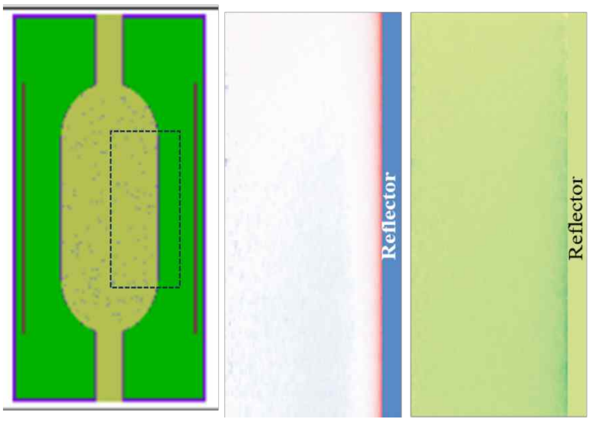

Fig. 4. Power distribution with Gd pebble and power variation due to the use of pebbles.

The power distribution of the active core was evaluated by constructing a mesh with a radius of 1 cm and a height of 1 cm. In the radial direction, a reflector with a thickness of 10 cm was considered, while in the axial direction, the region extending to the inlet and outlet pipes was included. The output distribution per unit volume was assessed for these regions. The Figure above depicts the cylindrical region of the effective core, excluding the upper and lower hemispheres, extracted from this analysis.

The maximum power was evaluated to be 69.74 Watts at the mesh of the boundary surface, highlighted in red, between the active core and the reflector, while the average output across the entire mesh was 14.77 Watts. This indicates that a significant portion of the power is concentrated near the reflector. The Figure 4 illustrates the output differences before and after the application of the pebble burnable poison, with darker green shades representing larger differences. When Gd pebbles were applied to the same core, the power slightly decreased towards the boundary surface, with areas marked in dark green, and the three-dimensional peak output coefficient reduced from 4.86 to 4.72.

3.3 Evaluation of Temperature Coefficient

Table I: Evaluation of the temperature coefficient based on the use of pebbles.

Note	Reference	with Gd pebble
K_{eff} at BOC	1.14285 (12)	1.06403 (11)
Fuel Temperature Coefficient [pcm/K]	-0.67	-0.15
Fuel Density Coefficient [pcm/K]	-4.73	-6.34
Reflector Temperature Coefficient [pcm/K]	+3.93	+4.35
Isothermal Temperature Coefficient [pcm/K]	-1.51	-2.15

The evaluation results indicate that an increase in reflector temperature in the current core design leads to positive reactivity insertion. To ensure inherent safety, the fuel salt temperature and density coefficients must remain sufficiently small. Additionally, it is necessary to verify whether the conditions for a sufficiently negative temperature coefficient are met when Gd pebbles are applied. As shown in the Table I above, the isothermal temperature coefficient was evaluated by separating the fuel salt temperature coefficient, density coefficient, and reflector temperature coefficient. The evaluation was carried out at conditions that corresponded to a 100°C increase over the normal operating temperature of 625°C. When Gd pebbles are used, the neutron importance near the reflector increases, leading to a tendency for the reflector temperature coefficient to increase. However, since the density change of the solid-phase pebbles is less than that of the fuel salt, the number of pebbles per unit volume increases as the fuel salt temperature rises, resulting in a more negative density coefficient. As a result, using Gd pebbles reduces the isothermal temperature coefficient.

4. Conclusions

This study proposes the concept of Gd pebbles as a method to reduce initial excess reactivity in long-cycle cores utilizing fast spectrum system. The Gd pebbles function as a burnable poison, and the effectiveness of their application was evaluated by examining the reduction of peaking factor near the reflector and assessing design feasibility through temperature coefficient analysis.

Using 40,000 pebbles, each with a radius of 1 cm, composed of Gd and Graphite, it was found that the prompt critical excess reactivity could be reduced by approximately 8000 pcm. Over a 15-year operational period, a stable criticality was maintained, and then the effect of the Gd pebbles diminished, resulting in a gradual decrease in criticality. The peak power near the reflector decreased from 4.86 to 4.72, and while the use of Gd pebbles increased the reflector temperature coefficient and decreased the fuel salt density coefficient, the greater decrease in the density coefficient led to a more negative isothermal temperature coefficient.

Future research will involve a detailed evaluation that takes into account uncertainties related to actual production and application of the pebbles, with the aim of optimizing pebble design and control drum configuration to explore the most compact core design.

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