MICRO-SIZE MULTI-MODULE MOLTEN SALT AND METAL REACTOR (MSMR) FOR HIGH POWER AND LONG LIFETIME

JAEHYUN RYU
KAIST (Korea Advanced Institute of Science & Technology)
Daejeon, Korea
Email: ryujh@kaist.ac.kr

Corresponding author: YONGHEE KIM,
Email: yongheekim@kaist.ac.kr

INTRODUCTION: The Molten Salt Reactor (MSR) has gained attention for its safety characteristics. MSRs operate at low pressure and rely on passive heat removal, which significantly reduces the risk of severe accidents. They also offer limited release of toxic fission products such as cesium and iodine, which are chemically bound in the salt phase – these are often referred to as “salt seekers.” In addition, MSRs exhibit a strong negative fuel temperature coefficient, providing enhanced self-regulation.

However, thermal-spectrum MSRs face a major drawback: moderation in the active core worsens the neutron economy, lowering the conversion ratio and limiting fuel sustainability. To address this, the Molten Salt Fast Reactor (MSFR) adopts a fast neutron spectrum, eliminating moderation and enabling a higher conversion ratio. Still, when considered for long-life operations, even MSFRs require a large fuel inventory due to the inherently low uranium density in molten salt fuel, especially when using low-enriched uranium. To overcome this limitation, we present an improved design based on the Molten Salt and Metal Reactor (MSMR), which was previously proposed as a novel reactor concept in which the fuel and salt are physically separated but remain in the liquid state [1].

The liquid metal fuel, placed at the bottom, is overlaid by a lighter molten salt layer. This separation allows for a higher uranium fraction in the fuel, lowering the critical mass and enabling a more compact reactor design. Fission products migrate from the fuel into the salt layer: noble metals remain in the fuel due to their low solubility and high density, while salt seekers such as cesium, iodine, and strontium are captured in the salt with the aid of natural circulation. Fission gases migrate upward and accumulate in a gas plenum above the salt. The metallic fuel is composed of uranium and manganese, with a composition selected from the eutectic region of the U-Mn phase diagram. This ensures both a low melting point (~710°C) and high uranium density, allowing for compact core design and manageable thermal margins. Unlike prior designs that assumed 19.75 wt.% enrichment, the multi-module MSMR concept uses lower enrichment to achieve high power and long lifetime. The new design increases thermal output to 5 MW(th) while maintaining long operating life and a compact system footprint.

1. REACTOR DESIGN

The metallic fuel used in this design based on the uranium-manganese (U-Mn) binary alloy system. According to the U-Mn phase diagram, the eutectic composition with the lowest melting point 989 K – corresponds to a mixture containing 94 wt.% uranium [2]. This composition was selected to simultaneously satisfy two key requirements: a sufficiently low melting point to mitigate material compatibility and corrosion issues, and a high uranium density to support a compact core design with reduced critical mass. For the salt layer, a ternary salt mixture of NaCl-KCl-$MgCl_2$ was selected. This mixture exhibits a low melting point around 653 K [3]. The salt is mixed with SiC pebbles at a 65 vol% ratio to reduce neutron leakage with enhanced moderation. The salt and gas plenum heights are 10 cm and 5 cm, respectively.

The fuel and salt layers are enclosed within a 0.5 mm thick tantalum container, internally alloyed with 5 wt.% tungsten to improve corrosion resistance [4] and coated on the inner surface with a 10 µm TaC layer. Outside the container, tin thermal bonding material and potassium-filled heat pipes are arranged radially. The reflector material is MgO, with a thickness of 10 cm at the top, 20 cm at the bottom, and a minimum of 22 cm radially. The reactor core comprises 1 central module surrounded by 6 peripheral modules, forming a compact multi-module array. Each module has a fuel diameter of 32 cm and a height of 63.3 cm. The U-235 enrichment is 11 wt.% in the central module and 12 wt.% in the surrounding modules to compensate for the relatively higher power density in the core center. Figure 1 and 2 show the top and side views of the MSMR, respectively.

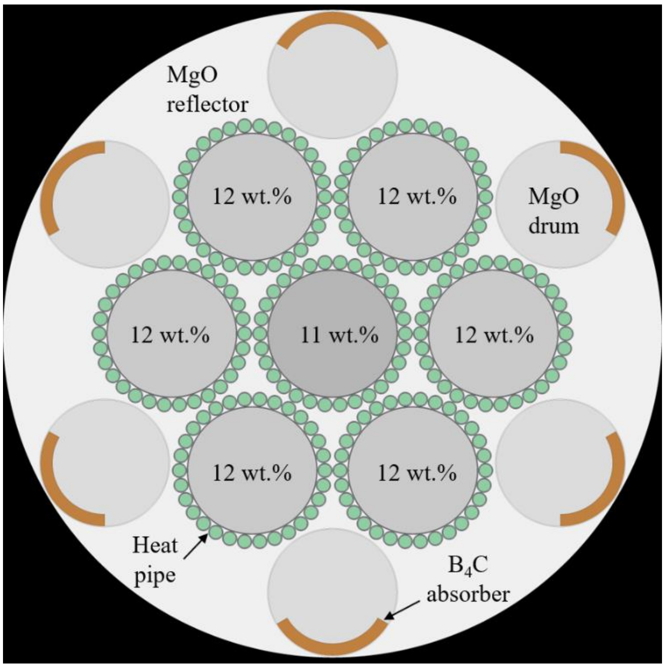

*FIG. **1**. Top view of MSMR*

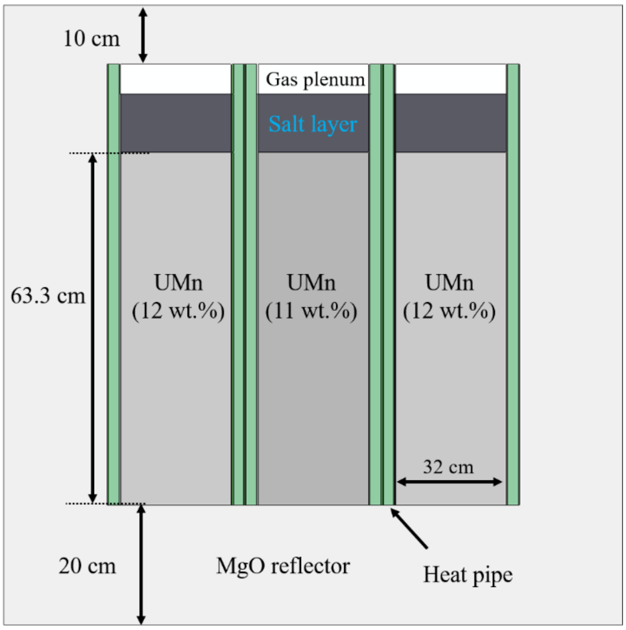

*FIG. **2**. Side view of MSMR*

Reactivity control is achieved via 6 rotating MgO-based control drums embedded in the radial reflector. These drums regulate core reactivity through mechanical rotation. The reactor is designed for once-through operation without refueling, excess reactivity is limited to within 1 $ for safety. A total number of 210 potassium-filled heat pipes, each with an inner diameter of 3.12 cm, are used for heat removal.

2. NUMERICAL RESULTS

Neutronic analysis was performed using Serpent 2.2 and the ENDF/B-VIII.0 library, with 250,000 histories per cycle, 100 inactive cycles, and 300 active cycles. The burnup calculation shows a total reactivity decrease of 700 pcm over 120 years, indicating an expected operational lifetime of approximately 120 years from a fuel utilization perspective. At the end of this period, the fuel reaches a burnup of approximately 40 MWd/kgU, with a corresponding conversion ratio of approximately 0.762. Figure 3 shows the reactivity decrease and corresponding fuel burnup obtained from the burnup calculation. Figure 4 shows the neutron spectra in both the fuel region and the whole core. Although some degree of moderation occurs due to the presence of MgO reflectors, the majority of neutrons remain in the fast energy region,

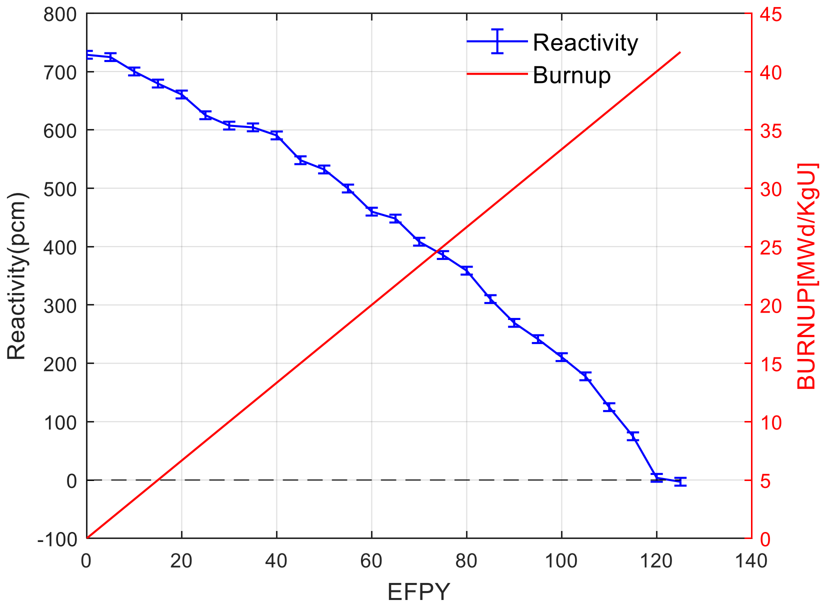

Fig. 3. Reactivity and burnup variation with EFPY

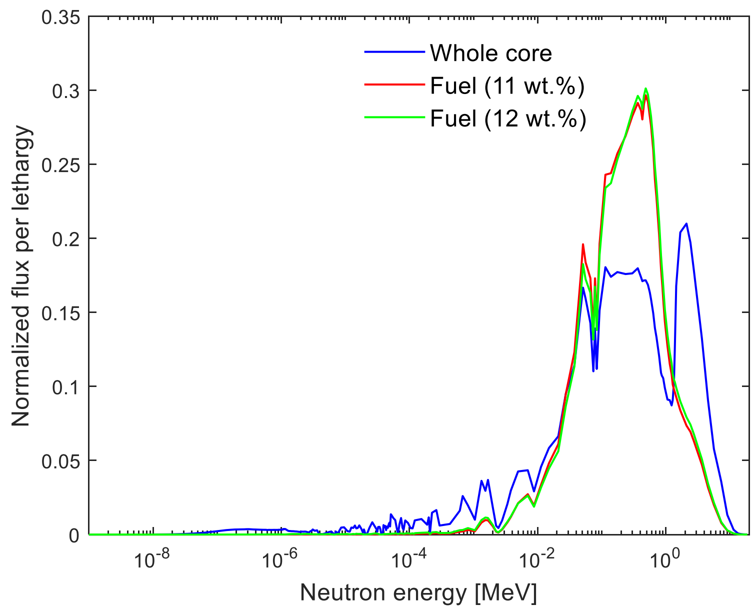

FIG. 4. Neutron spectra in the fuel region and for the whole core

In the MSMR, reactivity is controlled via the rotation of control drums positioned in the reflector region. Each drum is equipped with 120-degree absorber pads containing 3 cm thick B_4C, enriched to 90 wt.% in B-10. Since the liquid metal fuel contracts and increases in density upon solidification, it can introduce a significant positive reactivity insertion. To address this, the control drum worth was evaluated at both the nominal operating temperature of 1033 K and a room-temperature condition of 298 K, well below the solidification point. As summarized in Table 1, the results confirm a substantial shutdown margin, ensuring safe reactor operation under a wide range of thermal conditions.

TABLE 1. CONTROL DRUM WORTH & SHUTDOWN MARGIN

Temperature	298 K	1033 K
N-1 drums worth [pcm]	2966.9 ± 9.9	3137.2 ± 9.4
N drums worth [pcm]	3682.7 ± 9.7	3908.7 ± 9.4
Shutdown margin (N-1) [pcm]	994.6 ± 7.1	2408.5 ± 7.3

A negative temperature coefficient is a key feature for ensuring passive safety. To evaluate this, the fuel temperature coefficient was calculated at 100 K intervals from 989 K to 1233 K under both BOL and EOL conditions. The results show a consistently strong negative coefficient of approximately -2 pcm/K across the entire range, primarily attributed to the density variation of the liquid metal fuel. The calculation was performed using 2.5 million neutron histories per cycle, 100 inactive cycles, and 300 active cycles. The salt temperature coefficient was found to be negligible.

TABLE 2. FUEL TEMPERATURE COEFFICIENT

Temperature	BOL	EOL
989 K – 1033 K	-2.13 ± 0.07	-2.30 ± 0.07
1033 K – 1133 K	-2.13 ± 0.03	-2.32 ± 0.07
1133 K – 1233 K	-2.17 ± 0.03	-2.31 ± 0.07

REFERENCES

[1] Ryu, Jaehyun, Eunhyug Lee, and Yonghee Kim. "Neutronic Feasibility of Ultra-compact, Long-life Molten Salt Metal Reactor (MSMR)." 2023 Nuclear and Emerging Technologies for Space, NETS 2023. American Nuclear Society, 2023.

[2] H. OKAMOTO, “Mn-U (Manganese-Uranium),” Journal of Phase Equilibria and Diffusion, vol. 30, no. 3. p. 300, Jun. 2009. doi: 10.1007/s11669-009-9511-4.

[3] C. VILLADA, W. DING, A. BONK, and T. BAUER, “Engineering molten MgCl2–KCl–NaCl salt for high temperature thermal energy storage: Review on salt properties and corrosion control strategies,” Sol. Energy Mater. Sol. Cells, vol. 232, Oct. 2021, doi: 10.1016/j.solmat.2021.111344.

[4] R. J. CASH, R. M. FISHER, and M. R. CORE, “Compatibility studies of several molten uranium and thorium alloys in niobium, tantalum, and yttrium,” 1964.