

Comparative Depletion Analysis of a Marine Molten Salt Fast Reactor Considering Explicit Primary Loop Geometry

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1. Introduction

A long-life maritime Molten Salt Reactor (MSR) capable of operating for over 22.5 years without refueling at a thermal power of 100 MWth is currently under development. Unlike conventional solid-fueled reactors, the inherent characteristic of liquid-fueled MSRs is the continuous circulation of the fuel salt through both the active core and the external primary loop components, including heat exchangers and pumps.

In preliminary core conceptual designs, a simplified approach (Core-only model) has been widely adopted for computational efficiency. This approach omits the complex 3D geometry of the external loop and instead numerically adds the out-of-core fuel volume to the material volume parameter. In this study, a detailed model (Full-loop model) that explicitly implements the entire primary loop geometry, including the heat exchanger and piping, was developed using the OpenMC code. By comparing the detailed model with the simplified model, this study aims to verify the impact of the spatial distribution of the fuel inventory on the macroscopic depletion characteristics and localized physical phenomena.

2. Methods and Results

The reference marine MSR core utilizes a fast-spectrum design with NaCl-KCl-UCl₃ fuel salt enriched to 19.75 w/o HALEU and an MgO reflector. All criticality and depletion calculations were performed using the OpenMC Monte Carlo code (version 0.14.0) with the ENDF/B-VII.1 cross-section library.

2.1 Geometric Modeling and Volume Approach

For a rigorous comparison, both models (Case A and Case B) were strictly controlled to have perfectly identical total fuel inventory and thermal power (100 MWth), ensuring a constant specific power per unit mass. The general specifications of the core are presented in Table I.

The molten salt's mol fraction is 43.3:21.7:35.0 (NaCl-KCl-UCl₃), Cl-37 are enriched with 99% a/o, Li7 enriched with 99.995 % a/o.

Parameter	Value	Material/ Note
Thermal Power	100MWth	
Cycle Length	22.5 EFPY	No refueling
Fuel Salt	6.5 m ³	NaCl-KCl-UCl ₃ (43.3:21.7:35.0)
Active Core Radius	95.0 cm	
Reflector Thickness	30.0 cm	MgO
Reactor Vessel	5.0 cm	SS316H
Secondary Coolant	-	LiCl-KCl Eutetic

- Case A (Simplified Model): The geometry is limited to the active core and the upper/lower plenums inside the reactor vessel. The physical volume of the out-of-core fuel is omitted geometrically but numerically compensated by adjusting the volume parameter during the OpenMC material definition.

- Case B (Full-loop Model): The actual geometry of the primary loop is explicitly modeled. Pipe elbows and reducers were precisely constructed using YTorus and ZCone surfaces, respectively. The heat exchanger region was modeled in detail using a HexLattice-based shell-and-tube structure, with LiCl-KCl eutectic applied as the shell-side secondary coolant.

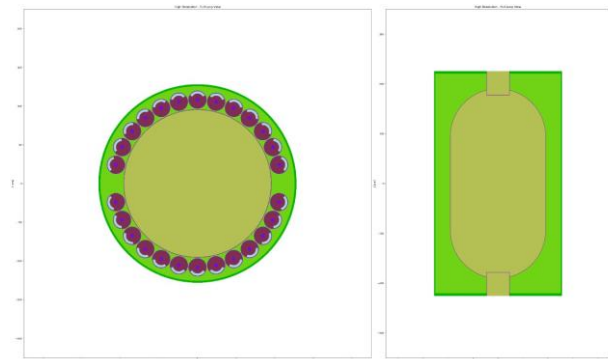


Fig. 1. Full primary loop geometry of the MSR Case A (X-Y and X-Z plane views).

Table I: Core Specification

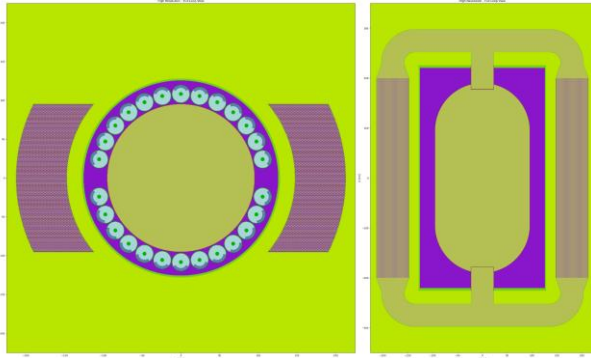


Fig. 2. Full primary loop geometry of the MSR Case B (X-Y and X-Z plane views).

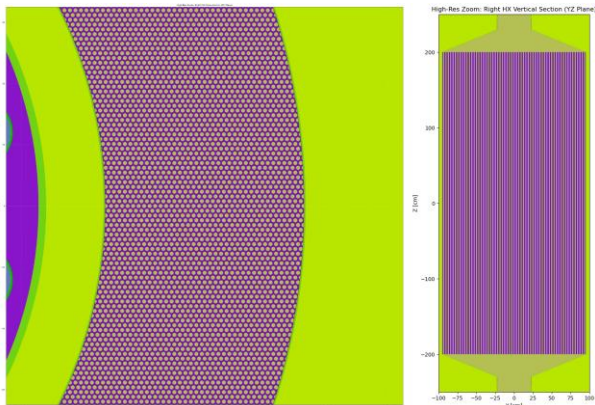


Fig. 3. Zoom-in view of the top-right elbow connection and high-resolution cross-section of the heat exchanger (HexLattice).

2.2 Depletion Calculation Results and Core Physics

The depletion calculations over the extended operational cycle revealed that the decline curves of the effective multiplication factor k_{eff} between Case A and Case B exhibited excellent macroscopic agreement. As illustrated in Fig. 4, a precise evaluation indicates that Case B incurs a minor reactivity penalty of approximately -50 to -120 pcm across the cycle compared to Case A. This slight discrepancy is physically attributed to the "geometric fast neutron leakage" through the physically opened upper and lower primary pipe connections in Case B, which are modeled as closed boundaries (vacuum boundary used in upper & lower pipe connection) in Case A. Nevertheless, a maximum difference of ~100 pcm over a 20-year period is practically negligible and can be easily compensated by minor control drum adjustments. This validates that the volume-homogenized simplified model (Case A) retains sufficient engineering validity and conservative margins for long-term reactivity control evaluations with significantly lower computational cost.

To physically support this macroscopic agreement, the 47-group neutron energy spectrum (Fig. 5) and the normalized axial power distribution (Fig. 6) at Beginning of Life (BOL) were compared. The power distribution

are looks same because, the both models are has same geometry in active core. Despite the new geometric leakage boundaries in Case B, both the hardened fast neutron spectrum and the cosine-shaped spatial power distribution perfectly coincided. This physically demonstrates that the total mass exposed to the neutron flux—which dictates the specific power—is the governing factor determining the core physics, rather than the spatial dispersion of the out-of-core fuel geometry.

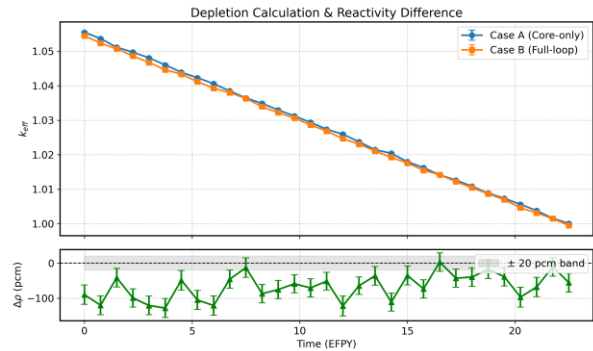


Fig. 4. Comparison of the effective multiplication factor k_{eff} decline curve and the reactivity difference ($\Delta\rho$) over the 22.5 EFY operational cycle between the simplified core-only model (Case A) and the explicit full-loop model (Case B).

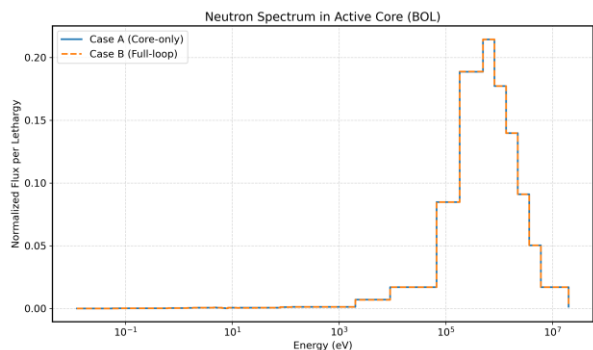


Fig. 5. Comparison of the normalized 47-group fast neutron energy spectrum within the active core at the Beginning of Life (BOL), demonstrating identical spectral hardening for both models.

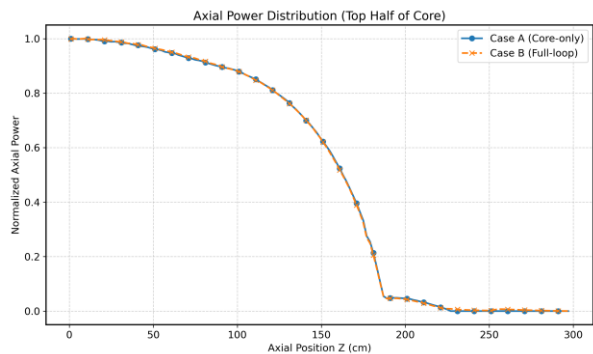


Fig. 6. Normalized axial power distribution along the core midplane (Z-axis) at BOL, verifying that the out-of-core pipe connections in Case B do not distort the spatial cosine power shape.

2.3 Tritium Production in Coolant Salt

While Case A proved its efficiency for macroscopic core depletion, the explicit full-loop model (Case B) provides exclusive and crucial advantages for localized radiological evaluations. Fig. 7 presents the tritium production rates via (n,t) reactions with Li-6, Li-7, and Cl-35 in the secondary coolant (LiCl-KCl Eutectic) at the shell-side of the heat exchanger.

The evaluation precisely captured that tritium generation is overwhelmingly dominated by Li-6 impurities (1.24×10^{-6} reactions per source neutrons). Conversely, the production from Li-7 was evaluated to be virtually zero. This is a highly physically valid result, as the (n,n't) reaction of Li-7 is a threshold reaction requiring a minimum neutron energy of ~ 2.5 MeV. Fast neutrons originating from the active core undergo significant scattering and energy degradation while streaming through the primary loop, resulting in a negligible population of >2.5 MeV neutrons reaching the heat exchanger region. These insights decisively demonstrate that strictly controlling Li-6 impurity levels is a more critical design parameter than bulk shielding for secondary coolant safety, proving the indispensable value of the detailed Case B model.

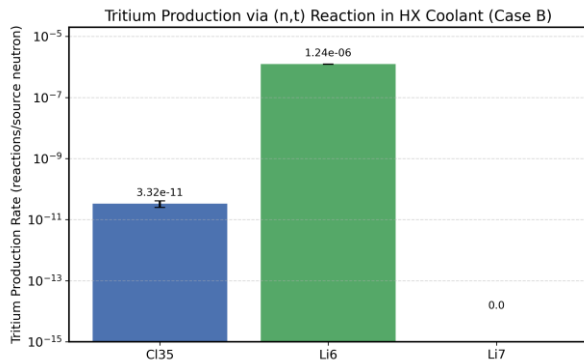


Fig. 7. Tritium production rates (reactions per source neutron) via (n,t) reactions with key isotopes (Li-6, Li-7, and Cl-35) in the secondary coolant at the shell-side of the heat exchanger, obtained exclusively from the full-loop model.

3. Conclusions

In this study, a comparative analysis of a marine MSR core was conducted between a volume-homogenized simplified model (Case A) and an explicit full-loop detailed model (Case B). The evaluation confirmed that explicitly modeling the external loop induces a minor

geometric neutron leakage penalty of ~ 100 pcm. However, this difference is practically negligible, validating the simplified methodology's high accuracy and computational efficiency for preliminary long-term depletion analysis over the 22.5-year cycle.

Furthermore, the explicit full-loop model developed in this study successfully quantified localized secondary radiological phenomena. It explicitly identified the absolute dominance of Li-6 over Li-7 in tritium production due to the degradation of fast neutron threshold energy during loop streaming. Consequently, the detailed primary loop model will serve as an essential foundation for comprehensive 3D radiation transport, shielding, and safety evaluations in future long-life MSR designs.

ACKNOWLEDGMENTS

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REFERENCES

- [1] OpenMC Documentation, <https://openmc.org/>.
- [2] Y. B. Go, S. J. Yoon, S. K. Zee, T. K. Park, "Effective Reactivity Control system on long-term cycle NaCl-KCl- UCl_3 fueled MSR core," Trans. of KNS Autumn Meeting, KNS, Changwon, Korea (2024).
- [3] Y. B. Go, S. J. Yoon, J. U. Seo, S. K. Zee, T. K. Park, "Core Design of Molten Salt Fast Reactor using PbO Reflector and Cycle Study," Trans. of KNS Spring Meeting, KNS, Jeju, Korea (2025).