

Preliminary Evaluation for the Design of a Critical Experiment Facility for Validation of a Chloride-Based HALEU Molten Salt Reactor

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1. Introduction

Chloride-based molten salt reactors (MSRs) have emerged as promising advanced reactor concepts due to their ability to operate for long periods without refueling and their operational flexibility. In particular, the sodium-potassium-uranium chloride system (NaCl-KCl-UCl₃) employing high-assay low-enriched uranium (HALEU) is being developed in Korea under the MARINA marine reactor program.

As part of the reactor development process, verification and validation of core physics codes are essential. A dedicated critical experiment facility is required to support neutronic model validation, uncertainty reduction, and future licensing preparation. However, the design of such a facility must consider constraints beyond neutronic performance alone.

The primary considerations for the design of the critical experiment facility include:

- Neutronic similarity to the MARINA reference reactor (Ck)
- Total fissile inventory limitations imposed by HALEU availability
- Constraints associated with reflector material usage

In this study, the total fuel loading of the critical experiment facility is limited to 6 metric tons due to HALEU supply constraints. This paper presents a preliminary neutronic evaluation to define the design direction of a critical experiment facility intended to validate the MARINA chloride-based HALEU MSR

2. Methods and Results

To assess the feasibility of the proposed critical experiment configuration under the imposed fuel inventory constraint, comparative neutronic analyses were performed.

In consideration of the anticipated HALEU pricing and supply timeline, the total fuel salt mass for the critical experiment facility is planned to be limited to 4.71 metric tons. Accordingly, the configuration of the critical experiment must be optimized under this predefined fissile mass constraint.

Under this limitation, the ability to achieve criticality and maintain neutronic similarity to MARINA was evaluated for various design options. All neutronic calculations were performed using the SCALE code system.

Two major design parameters were investigated:

- Core geometry (cylindrical vs spherical)
- Reflector material (MgO vs BeO)

2.1 Criticality comparison according to reflector material and core geometry

(1) Geometry Comparison

Spherical core configurations reduce neutron leakage due to their minimized surface-to-volume ratio. Under the same fuel loading, spherical cores are therefore expected to exhibit improved neutron economy compared to cylindrical cores.

The spherical configuration was defined with a radius of 70 cm. The cylindrical configuration was defined with a radius of 62 cm and a height of 119 cm. The reflector is composed of MgO, while SS316H with Ni-coating is utilized for the structural material. For consistency in the analysis, the ENDF/B-VIII.0 library was applied across all calculations. These dimensions were selected to maintain consistent total fuel volume under the imposed fuel salt mass (4.71 ton) limitation while allowing a direct comparison of neutron leakage characteristics.

All configurations were evaluated using identical fuel composition and total loading conditions. The effective multiplication factor (k_{eff}) was calculated for each geometry to assess the relative neutron economy under the 6-ton fuel constraint.

- Cylindrical core: $k_{eff} = 0.99503$ ($\sigma = 16.8$ pcm)
- Spherical core: $k_{eff} = 0.99810$ ($\sigma = 19.3$ pcm)

The preliminary results indicate that the spherical configuration provides improved criticality margins (307 pcm or 0.31%).

(2) Reflector Material Comparison

The reflector material significantly affects neutron leakage and spectrum characteristics.

BeO reflector configurations demonstrated superior neutron reflection capability, resulting in increased keff under the same fuel loading condition. This improvement is primarily attributed to the lower neutron absorption cross section and favorable scattering properties of beryllium oxide, which enhance neutron return to the core region and improve neutron economy. Under the fixed fuel inventory constraint, this effect becomes particularly important, as the available fissile mass is limited.

The reflector comparison was conducted while maintaining the cylindrical core configuration consistent with the MARINA reference design, with a core radius of 62 cm and a height of 119 cm.

However, the MARINA reference reactor adopts an MgO reflector in its conceptual design. Therefore, consistency with the reference system must be considered when selecting the reflector material for the critical experiment facility.

The calculated keff values under the loading condition are:

- MgO reflector: keff = 0.99503 ($\sigma = 16.8$ pcm)
- BeO reflector: keff = 1.17772 ($\sigma = 25.5$ pcm)

Table I presents the main design parameters and neutronic results of the modeled configurations.

Table I: Summary of Design Parameters and Results

Parameter	Reference	Critical Experiment		
	MARINA	Sphere	Cylinder	Cylinder (BeO)
Fuel Salt Composition	NaCl-KCl-UCl ₃			
Fuel Enrichment	HALEU (~19.75 wt% U-235)			
Core Geometry	Cylindrical	Spherical	Cylindrical	Cylindrical
Core Radius(cm)	90	70	62	62
Core Height(cm)	~250	N/A	119	119
Reflector Material	MgO	MgO	MgO	BeO
Reflector Thickness(cm)	~45	50	50	50
Structural Material	SS316H (Ni-coated)			
Total Fuel Salt Mass	~11 tons	4.71 tons		
Keff (σ , pcm)	Reference system	0.99810 (19.3)	0.995032 (16.8)	1.17772 (25.5)

While BeO improves neutron economy and provides a larger criticality margin(18,269 pcm, 18.4%) under

limited fuel salt mass, it may alter the neutron energy spectrum and reaction rate distribution relative to the MARINA design. Differences in moderator-to-absorber ratios and scattering behavior can influence spectral hardness and sensitivity profiles, which in turn affect the similarity index (CK).

Consequently, the reflector selection introduces a trade-off between maximizing criticality under fuel constraints and maintaining neutronic representativeness with respect to the MARINA reactor.

In addition, BeO is a toxic material requiring strict handling procedures, and its fabrication complexity and high cost must also be carefully considered in reflector selection.

2.2 Neutronic Similarity Analysis

The index is a vital correlation coefficient used in nuclear criticality safety to objectively quantify the similarity between an application system and a benchmark experiment based on shared nuclear data-induced uncertainties. A high value mathematically justifies benchmark selection by indicating that two systems will likely manifest the same computational bias.

To calculate this index, the SCALE system first generates sensitivity vectors(S), which measure the relative change in the effective multiplication factor (k_{eff}) due to a relative change in nuclear data (Σ). This is defined as $S = \frac{\Delta k/k}{\Delta \Sigma/\Sigma}$. This generation is accomplished using either TSUNAMI-1D for simple geometries or TSUNAMI-3D for complex geometries.

Once established, the TSUNAMI-IP module mathematically propagates these system-specific sensitivities alongside nuclear covariance matrices (C_{aa}) to calculate the data-induced variance (σ_k^2) using the sandwich equation: $\sigma_k^2 = S \cdot C_{aa} \cdot S^T$.

Finally, the index is computed as the Pearson correlation coefficient. It is calculated by dividing the shared variance, or covariance (σ_{12}^2), between the application (System 1) and the benchmark (System 2) by the product of their individual standard deviations, expressed simply as: $C_k = \frac{\sigma_{12}^2}{\sqrt{\sigma_{11}^2} \sqrt{\sigma_{22}^2}}$. [1,2,3]

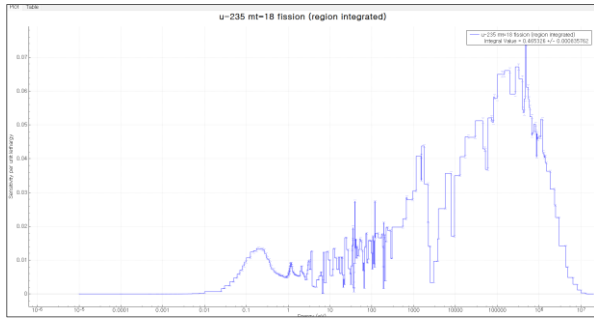


Figure 1. Energy-dependent sensitivity profile of the ^{235}U fission cross-section.

The TSUNAMI module within the SCALE code system provides a C_k to evaluate the degree of similarity between a critical experiment and an application by weighting nuclear data sensitivities to k_{eff} . According to NRC guidance, C_k values greater than approximately 0.95 indicate a very high degree of similarity, values between 0.90 and 0.95 indicate high similarity (requiring supplemental evaluation), and values below 0.90 are not considered sufficient to demonstrate high similarity.[3]

Because the purpose of the critical experiment is validation of the MARINA reactor, neutronic similarity is quantified using the similarity C_k index.

Two major design variables were investigated:

- Reflector material (BeO vs MgO)
- Core geometry (spherical vs cylindrical)

Reflector comparison

BeO reflector configurations demonstrated superior neutron reflection performance, reducing neutron leakage and therefore reducing the fissile loading required to reach criticality. This reduction in fuel mass improves compliance with the fuel cost gate.

However, MARINA employs MgO reflector material in its conceptual design. As a result, BeO-reflected configurations may exhibit deviations in neutron spectrum and leakage behavior compared to MARINA, potentially reducing C_k .

MgO reflector configurations, while requiring higher fissile loading, are expected to better reproduce the reference reactor's spectral characteristics and therefore achieve improved similarity indices. Through the application of TSUNAMI-3D and TSUNAMI-IP sequences, a C_k result of 0.971 was obtained.

MARINA Comparison

The MARINA reactor concept employs an MgO reflector and adopts a cylindrical core configuration. Although the reference design includes surrounding

control drums, these were excluded from the present analysis to enable a simplified and consistent comparison.

For the target critical experiment configuration, a cylindrical core geometry with an MgO reflector was applied to maintain structural and material consistency with the MARINA reference design. The calculated C_k index between this configuration and the MARINA reactor was 0.9902, as obtained from the TSUNAMI-based sensitivity analysis.

This result quantifies the neutronic representativeness of the proposed critical experiment relative to the reference reactor under simplified modeling assumptions.

3. Conclusions

This study presented a preliminary neutronic evaluation for the design of a critical experiment facility intended to validate the MARINA chloride-based HALEU molten salt reactor under a limited total fuel inventory.

Under the imposed HALEU availability constraint, both core geometry and reflector material were evaluated in terms of criticality and neutronic similarity. The spherical configuration demonstrated improved neutron economy compared to the cylindrical configuration due to reduced neutron leakage. However, for direct representativeness of the MARINA design, the cylindrical configuration was retained as the reference geometry for similarity evaluation.

With respect to reflector material, BeO exhibited superior neutron reflection capability and provided enhanced criticality margins under the limited fuel loading condition. This advantage becomes particularly significant when the total fissile inventory is constrained. Furthermore, the BeO configuration showed favorable characteristics in terms of neutron economy and, in some cases, improved similarity behavior.

However, several practical considerations must be addressed. BeO is a toxic material requiring strict handling and safety controls [5]. In addition, domestic production capability for high-purity BeO is limited, and procurement may involve supply chain challenges and high material costs [6]. These factors introduce technical, regulatory, and economic uncertainties that must be carefully considered.

In contrast, MgO, while slightly less favorable in terms of neutron economy, provides improved consistency with the MARINA reference design and does not present the same level of toxicity or supply difficulty.

In addition, the analysis indicates that a critical experiment employing fuel salt with the same U-235

enrichment as the MARINA reference reactor can maintain a high degree of neutronic similarity, even when minor spectral variations arise due to differences in reflector material or geometry. This finding suggests that preserving enrichment consistency plays a dominant role in achieving similarity and provides flexibility in selecting reflector and geometric configurations.

Therefore, reflector selection and geometric configuration should not be determined solely on the basis of criticality performance. A comprehensive assessment incorporating neutron economy, similarity to the reference reactor, enrichment consistency, material availability, toxicity, fabrication feasibility, and cost considerations is required.

This preliminary study establishes a technical basis for further detailed analyses and supports future decision-making for the development of a domestic chloride-based MSR critical experiment facility.

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