

A Systematic Framework for Molten Salt Selection in Fusion Reactor Breeding Blanket Applications

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1. Introduction

As the national fusion roadmap advances toward the realization of a fusion demonstration reactor, the imperative for a rigorously optimized blanket system has become increasingly pronounced. While ceramic materials, liquid metals, and molten salts have been identified as primary candidates for blanket media, recent developments—particularly the adoption of a FLiBe-based molten-salt breeding blanket by Commonwealth Fusion Systems (CFS) for the ARC reactor—have highlighted molten salt systems as a compelling solution for managing the substantially elevated thermal loads anticipated in high power density demonstration reactors. In Korea, conceptual studies for the fusion demonstration reactor have thus far centered predominantly on solid ceramic blanket configurations. Nevertheless, molten salt breeding blankets constitute a technically viable alternative that warrants systematic investigation, particularly in light of their potential advantages in thermal management, tritium breeding, and operational flexibility. Consequently, this study seeks to establish an assessment of molten-salt feasibility as blanket media by conducting a comprehensive evaluation of candidate salt compositions with respect to economic viability, engineering feasibility, and tritium breeding capability. Through this structured analysis, the study aims to identify and propose optimized salt composition options suitable for application in future fusion blanket systems.

2. Methods and Results

2.1. MCDM and Criteria

A fundamental requirement for stable blanket operation is maintaining the molten-salt medium in a fully liquid state. Because pure salts generally possess high melting points, they are not suitable for direct use under blanket operating conditions. By mixing pure salts to form eutectic compositions, the melting point can be significantly reduced; thus, multicomponent (two or more constituents) salt mixtures are more appropriate as blanket materials. Numerous binaries and higher-order eutectic combinations exist, and their thermo-physical behavior, tritium-breeding characteristics, and handling costs vary widely depending on composition. Owing to this diversity, it is not straightforward to determine the preferred salt composition for blanket application through simple comparative evaluation.

When multiple criteria must be considered simultaneously, Multi-Criteria Decision Making (MCDM) provides a systematic methodology for establishing priority among alternatives. Because research on molten-salt media for fusion blankets is still in an early stage, subjective expert-driven weighting may introduce bias. Therefore, an objective, data-based MCDM framework is adopted to determine the priority ranking of candidate salt compositions. Although their underlying logic is generally consistent, variations in algorithmic structure can lead to differences or distortions in ranking outcomes. Because the choice of algorithm itself can influence the priority assessment, ensemble methods have been introduced to mitigate such dependence. An ensemble-based MCDM approach is applied to the selection of molten-salt compositions. When p weighting methods and q ranking algorithms are employed, a total of $(p \times q)$ ranking matrices are generated. Statistical aggregation, voting schemes, or optimization-based aggregation methods are then applied to these matrices to derive an ensemble ranking, which is subsequently analyzed to determine the final recommended priority order.

To derive these rankings, the evaluation criteria for comparing candidate salt compositions are organized into three groups: economic factors, engineering feasibility, and neutron-interaction characteristics. The detailed criteria are economic factors (procurement cost, purification cost, and safety cost), engineering feasibility (liquid-phase temperature range, redox potential, hydrogen solubility, compatibility with structural materials, flow Figure of Merit (FOM), and heat-transfer FOM), and neutron-interaction characteristics (tritium breeding ratio and activation product generation).

2.2. Alternatives and Performance

As an initial step toward selecting pure salts based on procurement cost, the molten-salt compositions were restricted to binary systems, and candidate salts capable of forming stable eutectic mixtures with LiCl or LiF were examined. A survey of commercially available salts revealed that several chlorides do not form eutectic equilibria with LiCl or LiF. Some exhibit instability in binary mixtures due to intrinsic nature, resulting in unstable binary salt compositions.

By excluding salts with unfavorable characteristics and selecting only those chlorides and fluorides that both form eutectic compositions with LiCl or LiF and are available on the commercial market, 40 chlorides and 24

fluorides were identified as viable candidates. Assuming that binary eutectic compositions can be formulated from these salts and applying a procurement cost threshold of 3 million KRW per kilogram without imposing temperature-related constraints, a total of 29 binary salt combinations can be selected. Figure 1 illustrates the unit purchase cost of binary salt mixtures as a function of composition. As shown, the cost of the mixture is strongly influenced by the unit price of the counterpart chloride or fluoride that forms a eutectic with LiCl or LiF. This behavior arises because certain salts are priced highly in the commercial market due to their scarcity; consequently, even when such salts occupy only a small molar fraction in the mixture, the overall cost of the mixture becomes significantly elevated.

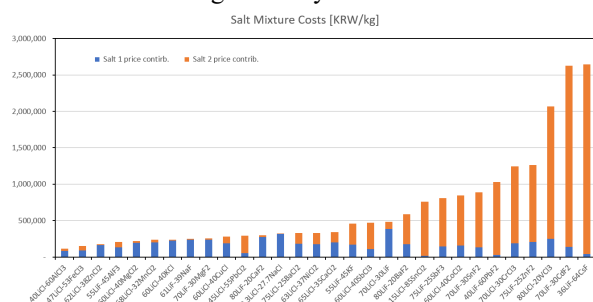


Fig. 1. Purchase cost assigned according to the molten-salt composition. (Salt 1 refers to LiCl or LiF)

The removal of moisture is more complex when water is present in the form of water molecules bound to chlorides or oxides, as this requires additional purification steps. The purification cost is therefore evaluated using a hygroscopicity scale. Fig. 2 provides a comparative assessment of purification costs for each salt. For molten-salt mixtures expected to serve as blanket materials, whether binary or ternary, the purification cost is determined by the salt with the highest hygroscopicity among the constituent salts.

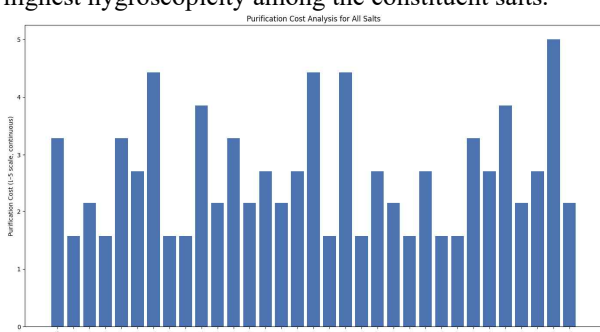


Fig. 2. Relative comparison of salt purification costs.

When salt is used as blanket materials, they undergo four stages: preparation, storage, purification, and operation. The relative risks associated with each stage differ. Based on qualitative assessments of the criteria defined for each stage, the contribution of each stage to the overall safety cost for each salt was evaluated, and the results are visualized in Fig. 3. The salts expected to incur the highest shielding costs are AlCl_3 and BeCl_2 ,

followed by SbCl_3 , SbF_3 , SnF_2 , and VCl_3 . LiCl ranks near the middle among the candidates.

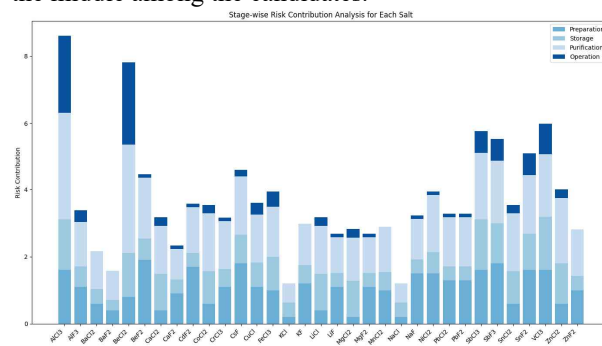


Fig. 3. Contribution analysis of the estimated costs to the total safety cost according to the risk at each stage of salt handling

The thermo-fluid performance of molten-salt mixtures considered as blanket materials is evaluated using the Figures of Merit (FOM) proposed by Bonilla and Sanders. Bonilla's FOM represents the minimum pumping power required to sustain flow in the molten-salt mixture, whereas Sanders' FOM indicates the minimum heat-transfer surface area required in a heat exchanger. Although the density, viscosity, specific heat, and thermal conductivity data used for these calculations inevitably contain uncertainties. The available data were compiled into a reference table. Using these property values, the temperature-dependent variations of the FOM indicators were calculated, and the results are presented in Fig. 4 and 5.

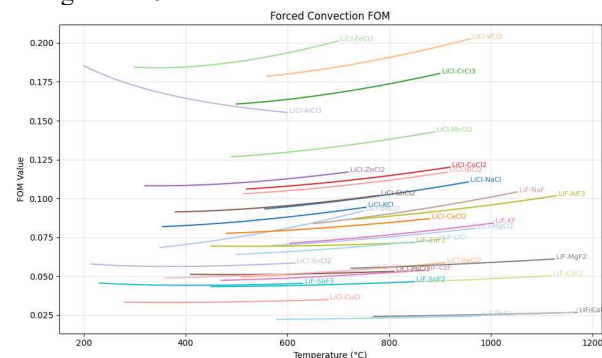


Fig. 4. FOM value representing the pumping power required for forced circulation of the salt mixture

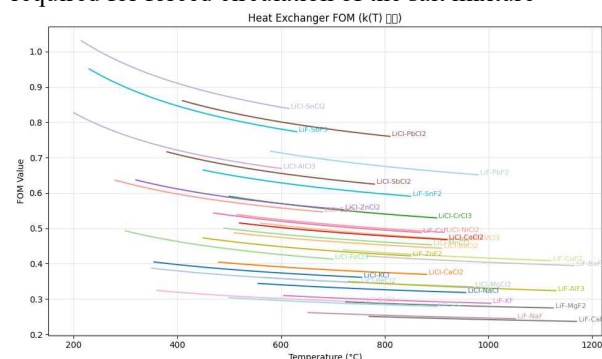


Fig. 5. FOM value representing the heat-transfer area required for the salt mixture in the heat exchanger

The neutron-reaction characteristics related to tritium breeding proceed in two stages. In the first stage, the priority of salt compositions is identified by calculating a Figure of Merit (FOM) using the neutron reaction cross sections of the constituent elements in the salt. In the second stage, based on the results of the first-stage evaluation, a detailed assessment is performed for selected salt compositions using multi-physics computational codes within a three-dimensional geometric model. Goth et al. proposed the following FOM as a methodology for selecting chloride salts, and this FOM is adopted here. Using FENDL3.2, FOM of salt mixtures are evaluated and presented as Fig. 6.

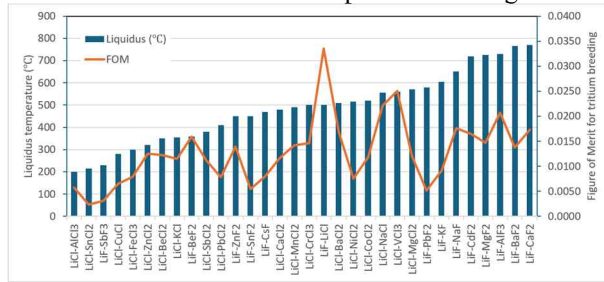


Fig. 6. FOM value of tritium breeding ratio of salt mixtures

Among the criteria, the performance evaluation for the criterion based on thermochemical data is currently in progress, and once this evaluation is completed, the MCDM method will be applied to derive the ranking of the salt compositions.

3. Conclusions

Molten-salt breeding blankets in fusion reactors are emerging as a promising alternative for tritium production. Selecting salt compositions that satisfy the operating conditions of fusion reactor blankets while exhibiting excellent tritium-breeding characteristics is the starting point of this study. To determine suitable salt compositions, pure salts are first prioritized based on purchase cost, and a preliminary evaluation is underway for two-component combinations according to the criteria established for ensemble MCDM analysis. Although the evaluation for all criteria is still in progress due to delays in obtaining thermochemical data, assessments related to economic factors and FOM-based flow, heat transfer, and tritium breeding performance have been completed. In the future, criteria based on thermochemical data and neutron characteristics in three-dimensional geometry will be evaluated. Using the collected performance data, the ensemble MCDM method will then be applied to finalize the priority ranking of salt combinations.

REFERENCES

- [1] B.N. Sorben, et al., ARC: A compact, high-field, fusion nuclear science facility and demonstration power plant with demountable magnets, *Fus. Eng. Des.* 100 (2015) 378-405.
- [2] C. F. Bonilla, "Comparison of Coolants," in *Nuclear Engineering Handbook*, H. Etherington editor, Sect. 9-3, Chap. 6.5, pp. 9-90, 1958.

- [3] J. P. Sanders, A Review of Possible Choices for Secondary Coolants for Molten Salt Reactors, ORNL CF-71-8-10, 1971.
- [4] N.E. Goth, J.M. Brown, T. Ghaddar, L. Scott, J.W. Bae, P. Britt, Optimal chloride salt mixture for a fusion blanket, ORNL/TM-2023/3052, 2023

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