

An Update on the State of Knowledge (SoK) for the Maritime Molten Salt Reactor (MSR) Phenomena Identification and Ranking Table (PIRT)

Young Jin Go, Kyung Rae Yook, Moon Hyeok Kang, Jeong Ik Lee*

Dept. Nuclear & Quantum Eng., KAIST, 373-1, Guseong-dong, Yuseong-gu, Daejeon, 305-701, Republic of Korea

* Corresponding author: jeongiklee@kaist.ac.kr

***Keywords :** MSR(Molten Salt Reactor), PIRT(Phenomena Identification and Ranking Table), SoK(State of Knowledge)

1. Introduction

Molten Salt Reactors (MSRs) are increasingly recognized as a promising option for future nuclear energy systems due to their inherent safety features, high operating outlet temperature, and flexibility in fuel-cycle utilization. Despite these advantages, MSRs are still at the conceptual stage, with no demonstration reactor currently in operation. Their diverse design options and limited experimental database pose significant challenges for developing reliable safety analysis codes to evaluate the designed safety system.

To address these challenges, the Phenomena Identification and Ranking Table (PIRT) methodology has been widely applied as a systematic framework. PIRT identifies and prioritizes key thermal-hydraulic and neutronic phenomena under defined scenarios, evaluates their current state of knowledge, and thereby supports model development and code validation strategies. In the broader context of advanced reactor licensing, as discussed in TICAP (2021) [1], PIRT also provides a technical basis for identifying important safety phenomena and linking them with regulatory requirements.

The general workflow of the PIRT process is illustrated in Figure 1, beginning with problem definition and proceeding through phenomena identification, importance ranking, and state-of-knowledge evaluation.

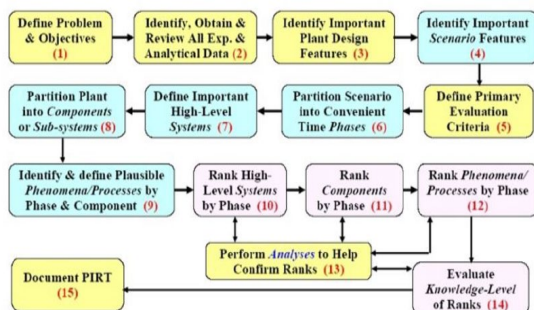


Figure 1. Typical Application of the PIRT Process [2]

At the initial stage, the scope and boundary conditions of the assessment are defined to ensure consistency with reactor design and safety objectives. The process then advances to identifying thermal–

hydraulic and neutronic phenomena of interest, which are systematically ranked according to their safety significance under postulated scenarios. Finally, each phenomenon is paired with a state-of-knowledge assessment, allowing gaps and uncertainties to be explicitly captured.

In 2024, a preliminary PIRT was established for the Korean maritime MSR (KMSR). Building on this foundation, this study focuses not on re-establishing the entire PIRT process but on updating the state of knowledge (SoK) for maritime MSR. By integrating recent experimental findings and simulation results, the updated SoK aims to refine the assessment of critical phenomena and highlight areas requiring further research. This ensures that the PIRT remains a living document, continuously aligned with the evolving knowledge base and providing a structured foundation for future safety evaluations and research on MSR development.

2. SoK Update for Korean MSR

2.1. Background and Need for Update

The initial PIRT development for the Korean maritime MSR (KMSR) was grounded on internationally recognized reference documents, including BNL-114869 (2018) [3], TICAP (2021), and ORNL’s Fundamental Safety Function PIRT (2021) [4]. These reports provided the methodological basis for systematically identifying relevant thermal-hydraulic and neutronic phenomena for evaluating their relative importance under postulated scenarios.

Building upon these references, a preliminary PIRT (Pre-PIRT) was developed in the previous study to adapt the general framework of MSR safety to the specific context of maritime applications. This preliminary step was aimed at supporting the development and validation of safety analysis codes, identifying key phenomena in representative accident scenarios, deriving the requirements for thermal-hydraulic experiments, and developing criteria for selecting design-basis accidents.

The effectiveness of a PIRT exercise depends not only on the identification and ranking of phenomena but also on the continuous assessment of the associated

state of knowledge (SoK). As emphasized in the ORNL Fundamental Safety Function PIRT (2021), SoK evaluation is not a one-time effort but requires periodic updates to reflect new experimental findings, numerical results, and operational insights. Without such updates, the practical value of PIRT in guiding code development, safety assessment, and design validation becomes limited.

The KMSR Pre-PIRT was grounded on the internationally established pool of phenomena, particularly those catalogued in BNL (2018). While these lists were primarily defined for the fuel-salt system, the KMSR Pre-PIRT extended the same framework to include the coolant-salt system, the pump system, and the drain tank, thereby enabling a more comprehensive evaluation of thermal-hydraulic behavior across multiple subsystems.

2.2. Methodology of SoK Update

The SoK update was performed by incorporating the most recent experimental and computational findings while maintaining consistency with authoritative references such as ORNL, NRC, BNL, and DOE reports. In particular, recent studies (2023–2025) provided improved data on fuel-salt thermophysical properties, including heat capacity and viscosity, which reduced uncertainties in the original PIRT assumptions. Additional progress was made in understanding salt fouling and plate-out behavior, as well as heat exchanger performance and drain tank cooling characteristics.

2.3. Representative Phenomena and Improvements

In total, 41 thermal–hydraulic and material interaction phenomena were reassessed through the SoK update. The evaluation showed that while the majority of the phenomena remained at the same knowledge level, several categories demonstrated meaningful improvement, and a few areas still require focused research. Representative examples of phenomena with notable updates are as follows.

Fuel-salt properties.

For fuel salts, recent studies have reported progress in both thermophysical measurements and atomistic simulations. Liquidus and solidus temperatures of surrogate salts have been experimentally determined, providing improved phase boundary data [5]. Ab initio molecular dynamics (AIMD) simulations have been applied to predict the heat capacity, offering consistency with experimental observations [6]. In addition, viscosity has been investigated using both molecular dynamics simulations and rolling-ball viscometers, leading to a more reliable characterization

of flow properties across relevant operating conditions [7] [8]. These updates provide a stronger basis for thermal-hydraulic modeling and reduce reliance on extrapolated property data. Table 1 summarizes the updated SoK for fuel-salt thermophysical properties

Table 1. Knowledge level of Fuel-salt Heat Capacity

BNL /NRC	ORNL	KMSR	SoK in 2024 Pre-PIRT	Updated Sok (2025)
L	M(↑)	M	L	M(↑)

Plate-out and Fouling

Recent experimental progress has been made in both detection and deposition studies on the behavior of fission products and corrosion products. ORNL has developed a laser-induced breakdown spectroscopy (LIBS) technique capable of millisecond-scale detection of elements and isotopes within molten salts, enabling real-time tracking of fission product behavior [9]. Complementarily, KAERI has performed natural circulation loop experiments with SS304, SS316L, and high-nickel alloys over 500 hours, observing mass gain/loss and the formation of deposits on structural materials [10]. These recent experimental findings and detection techniques can provide a more reliable basis for predicting deposition behavior in both fuel and coolant salt systems. Table 2, 3 present the updated SoK for plate-out and fouling phenomena.

Table 2. Knowledge level of Fuel-salt Plate-out and Fouling

BNL /NRC	ORNL	KMSR	SoK in 2024 Pre-PIRT	Updated Sok (2025)
L	L	M	L	M(↑)

Table 3. Knowledge level of Coolant-salt Plate-out and Fouling

BNL /NRC	ORNL	KMSR	SoK in 2024 Pre-PIRT	Updated Sok (2025)
L	L	M(↑)	L	M(↑)

3. Conclusions and Future Works

This study presented an updated State of Knowledge assessment for molten salt reactor (MSR) thermal–hydraulic phenomena within the systematic PIRT framework. Building on internationally recognized references (BNL, NRC, ORNL, DOE) and the domestic Pre-PIRT effort, a total of 41 phenomena were

reassessed. Meaningful updates were achieved in areas such as fuel-salt thermophysical properties, salt fouling, and fission product plate-out, thereby reinforcing the iterative nature of the PIRT process illustrated in Figure 1.

The results confirm that PIRT must be treated as a living framework: by continuously integrating new experimental data, numerical analyses, and operational insights, it evolves from a static list of phenomena into a tool that actively directs research priorities and supports regulatory readiness.

Looking forward, the outcomes of this update will serve as the basis for extending the current three core accident scenarios into newly developed ones tailored to KMSR conditions. In particular, new scenarios associated with off-gas system behavior and maritime-specific operational challenges will be introduced, thereby expanding the coverage of representative events. In parallel, additional figures of merit (FOMs) will be applied to phenomena and scenarios with strong relevance to these conditions.

Ultimately, these efforts will lead to an updated ranking table that integrates newly developed scenarios, expanded FOMs, and reassessed knowledge levels. This progression will not only strengthen the credibility of domestic PIRT activities but also provide a clearer research pathway to reduce knowledge gaps, enhance code validation, and support the safe deployment of maritime MSRs.

REFERENCES

- [1] Southern Company, "Technology Inclusive Content of Application Project For Non-light Water Reactors", SC-16166-202, 2021
- [2] Gary E. Wilson and Brent E. Boyack, "The role of the PIRT process in experiments, code development and code applications associated with reactor safety analysis", *Nuclear Engineering and Design* 186, pp. 23-37, 1998.
- [3] David J. Diamond et al, "Phenomena Important in Modeling and Simulation of Molten Salt Reactors", BNL-1146869, 2018
- [4] David E. Holcomb et al, "Molten Salt Reactor Fundamental Safety Function PIRT", Oak Ridge National Laboratory, ORNL/TM-2021/2176
- [5] Soumya Sridar et al, "Thermodynamic modeling of the KCL-LiCl-NaCl-UC13 system for molten salt electrolysis and reprocessing of spent nuclear fuel", *Calphad*, Volume 88, 2025
- [6] M.A. Rose, "Property Measurements of NaCl-UC13 and NaCl-KCl-UC13 Molten Salts", Argonne National Laboratory, ANL/CFCT-22/45, 2023
- [7] Hyeonwoo Kim et al, "Physical properties of KCl-UC13 molten salts as potential fuels for molten salt reactors", *Journal of Nuclear Materials*, Volume 577, 2023
- [8] Nicholas Termini et al, "FY24 Progress Report on Viscosity and Thermal Conductivity Measurements of Nuclear Industry-Relevant Chloride Salt: An Experimental

and Computational Study", Oak Ridge National Laboratory, ORNL/TM-2024/3650, 2024

[9] Hunter B. Andrews et al, "Real-Time Elemental and Isotopic Measurements of Molten Salt Systems Through Laser-Induced Breakdown Spectroscopy", Oak Ridge National Laboratory, TN37830, 2024

[10] Taeho Kim et al, "Corrosion Behavior of Candidate Structural Materials for Molten Salt Reactors in Flowing NaCl-MgCl₂", *Hindawi, International Journal of Energy Research*, Volume 2024