

Previous Studies of Molten Salt Natural Circulation Loop Experiment: Design Considerations & Operational Incidents

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1. Introduction

The Molten Salt Reactor (MSR) is one of the most promising Gen-IV nuclear systems in which fissile material is dissolved in high-temperature molten salt, allowing the salt to function simultaneously as both a fuel carrier and a primary coolant [1]. Unlike conventional light water reactors (LWRs) that rely on solid fuel and high-pressure operation, MSRs inherently eliminate the risk of core meltdown accidents, as the liquid fuel can be drained and passively solidified in a designated tank [2]. Furthermore, MSRs offer distinctive advantages such as high thermal efficiency enabled by elevated operating temperatures, online refueling and fuel reprocessing, and reduced proliferation risks due to the continuous fuel cycle. These features underscore MSRs as leading candidates among Gen-IV nuclear power systems.

To ensure the safe and efficient operation of MSRs, a comprehensive understanding of heat transfer and fluid dynamics in molten salts is essential. In particular, natural circulation plays a crucial role in passive safety systems, as it allows heat removal from the reactor core without reliance on mechanical pumps [3]. The molten salt natural circulation loop experiment provides an effective platform for investigating key thermal-hydraulic phenomena under realistic operating conditions. Unlike water-based systems, molten salts exhibit higher boiling points, low vapor pressure, and distinctive thermophysical properties such as high thermal stability, low thermal conductivity, high specific heat capacity, and a wide temperature range of liquid state, which necessitate dedicated experimental validation.

The significance of molten salt natural circulation loop experiment studies can be attributed to their capacity to provide reliable benchmark data for validating computational models, which are indispensable for reactor design and safety assessment. Moreover, such experiments contribute to identifying critical issues such as salt solidification, flow instabilities, and heat transfer enhancement strategies. Consequently, research on molten salt natural circulation loops is not only vital for advancing the fundamental understanding of MSR thermal hydraulics

but also for establishing robust safety basis for future deployment of molten salt reactors.

Beyond these contributions, operational experience from molten salt natural circulation loop experiment facilities has revealed a series of practical challenges and unanticipated events that accompany the use of real molten salts under natural circulation conditions. Difficulties include sustaining chemical purity of the salt, unplanned solidification within loop segments, heater malfunctions that trigger localized freezing, and instability in flow or temperature fields. While often regarded as experimental setbacks, such events provide essential insights into the intrinsic vulnerabilities of molten salt systems.

Accordingly, the present review not only consolidates the outcomes of previous molten salt natural circulation loop experiments but also critically examines the reported operational incidents and the remedial measures adopted. By systematically identifying these challenges and documenting the corresponding mitigation strategies, this study seeks to establish a body of knowledge that extends beyond steady-state performance data. In doing so, the review aims to furnish practical guidance for the development of operational protocols, emergency procedures, and safety scenarios that will be directly applicable to the future deployment of MSRs. The operational findings from these experiments offer a useful basis for enhancing safety margins and supporting the reliable design of molten salt reactors.

2. Experimental Studies on Molten Salt Natural Circulation Loops

2.1 Molten Salt Convection Loop in the Oak Ridge research Reactor (ORR)-ORNL

The molten salt convection loop experiment conducted at Oak Ridge National Laboratory (ORNL) in the 1960s was one of the pioneering efforts in developing MSR technology. This experiment used FLiNaK (LiF-NaF-KF) as the molten salt, chosen for its high thermal stability and low vapor pressure. The loop, approximately 2 meters in height, was designed with nickel and stainless-steel piping and incorporated a heater and air cooler for temperature control. The

objective was to explore natural circulation behavior, where heat is transferred from the reactor core through natural fluid movement, without the need for mechanical pumps. This early experiment provided critical data on the thermal-hydraulic characteristics, such as flow dynamics and heat transfer efficiency, which are essential for MSR operation. Fig. 1 shows a schematic representation of the in-pile molten salt convection loop that was operated at Oak Ridge National Laboratory (ORNL) [4].

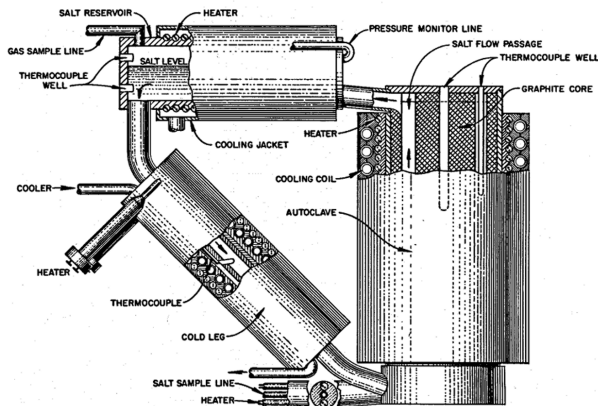


Fig. 1. Layout of In-pile molten salt convection loop No.1 of ORNL [4]

While the experiment demonstrated successful operation of the molten salt in natural circulation, it also highlighted several challenges. One key concern was the compatibility of materials with molten salts at high temperatures. During the 1960s, the material technology to withstand the corrosive nature of fluoride salts at high temperatures was still underdeveloped. As a result, the experiment focused on investigating the corrosion behavior of metal alloys in high-temperature fluoride salts. The need for more robust materials capable of enduring the aggressive chemical environment of molten salts became apparent.

Another significant issue was the potential leakage of molten salt from the system. The high temperatures and pressure gradients within the loop posed a risk of salt leakage, which could compromise the integrity of the system. Ensuring the loop was sealed and maintaining temperature control to prevent leakage was critical. However, despite these challenges, there were no major accidents during the experiment, and the study contributed valuable insights into the feasibility of molten salt circulation in MSRs.

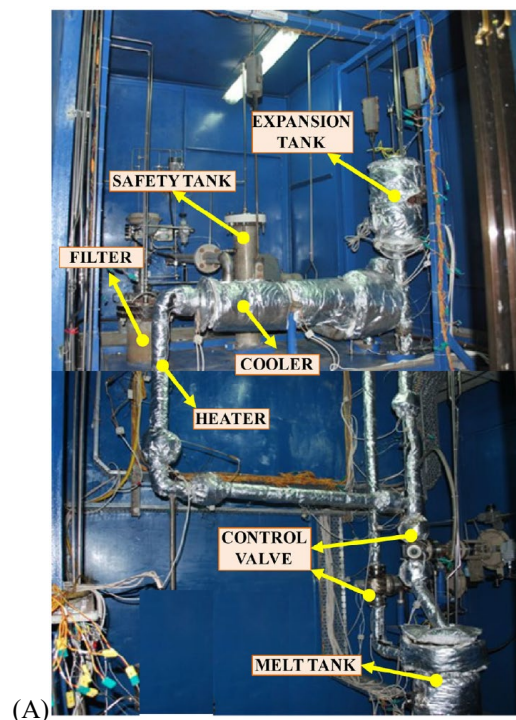
2.2 Molten Salt Natural Circulation Loop (MSNCL)-Bhabha Atomic Research Centre (BARC)

The Molten Salt Natural Circulation Loop (MSNCL) experiment, conducted at the Bhabha Atomic Research Centre (BARC) in India, represented a significant advancement in the study of molten salt natural circulation and its application in MSRs. The experiment utilized Solar Salt ($\text{NaNO}_3\text{-KNO}_3$, 60:40.wt%),

selected for its favorable thermal-hydraulic properties at high temperatures. The loop was designed with a rectangular geometry, incorporating both horizontal and vertical heater-cooler orientations to replicate real-world MSR conditions. A key feature of the MSNCL setup was the use of Inconel 625 piping, chosen for its excellent resistance to high-temperature corrosion, which is essential for long-term operation in molten salt systems. The primary objective of the experiment was to investigate steady-state natural circulation behavior, validate theoretical models, and better understand how loop geometry influences stability and flow distribution [5, 6].

In addition to the experimental setup, the research team at BARC developed and employed LeBENC, an in-house one-dimensional computational code, to simulate and validate the experimental results. LeBENC was specifically designed to model natural circulation loops, and it played a crucial role in comparing theoretical predictions with actual experimental data [5].

The theoretical models, validated through the MSNCL experiments, provided valuable insights into the thermal-hydraulic behavior of molten salts under natural circulation conditions. This included flow patterns, temperature gradients, and heat transfer efficiency within the loop. The combination of experimental data and theoretical simulations allowed the team to refine their understanding of molten salt behavior, thereby contributing to the development of more accurate MSR designs. Fig. 2 illustrates both the experimental facility and the nodalization of the loop as simulated by the LeBENC code.



(A)

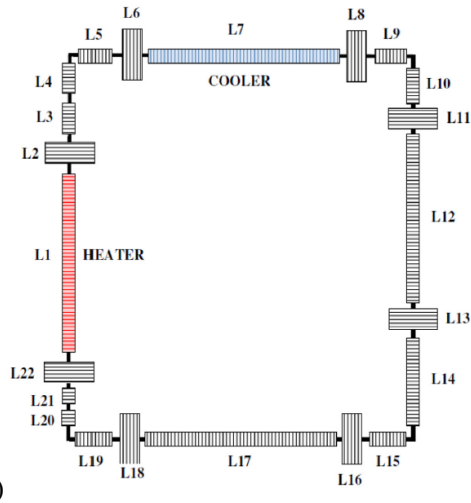


Fig. 2. (A) MSNCL Facility and (B) Nodalization of MSNCL modeled in LeBENC [5].

Despite the success of the MSNCL experiment, several challenges emerged during the research. One of the primary concerns was loop geometry, as the orientation of the heater and cooler significantly impacted the stability and efficiency of circulation. Tests showed that variations in horizontal and vertical orientations led to differences in temperature distribution and flow stability, highlighting the sensitivity of natural circulation to system configuration. Additionally, similar to the challenges faced in the ORNL molten salt convection loop experiment, the MSNCL study also encountered issues related to salt contamination and material performance at high temperatures. While the loop was designed to withstand the corrosive nature of molten salts, there were signs of wear and degradation in the materials used over time. These findings highlighted the need for more durable materials capable of withstanding the aggressive chemical environment of molten salts, as well as more refined operational protocols to prevent contamination and ensure the long-term viability of MSR systems.

2.3 Molten salt visualization loop – Texas A&M

More recently, Texas A&M University advanced molten salt research by constructing a transparent, vertically oriented FLiNaK loop equipped with high-resolution Particle Image Velocimetry (PIV) and a water-cooled section. Reis et al. investigated the thermal-hydraulic behavior of fluoride-based molten salts under accidental heater shutdown conditions in a natural circulation flow visualization loop. The experiments were conducted using a transparent, vertically oriented loop equipped with a heater section and a water-cooled heat exchanger. FLiNaK was employed as the working fluid due to its high thermal stability, low vapor pressure, and suitability for high-temperature natural circulation studies. The transparent design allowed direct visualization of flow patterns and temperature fields using high-resolution Particle Image Velocimetry (PIV), enabling a detailed assessment of

the dynamic response of molten salts during non-nominal operation [8, 9].

During the experiments, the research team deliberately turned off the heater to simulate failure scenarios, leading to localized cooling and subsequent partial solidification of the molten salt. They observed the onset of solid formation near the heater section, the evolution of the solidified front, and its interaction with the surrounding liquid flow. Solidified salt presented a significant impedance to natural circulation, causing flow reversal and localized thermal stratification. These observations highlighted the challenges of resuming normal circulation after heater failure, emphasizing the importance of maintaining adequate temperature margins to prevent operational interruptions and potential safety hazards.

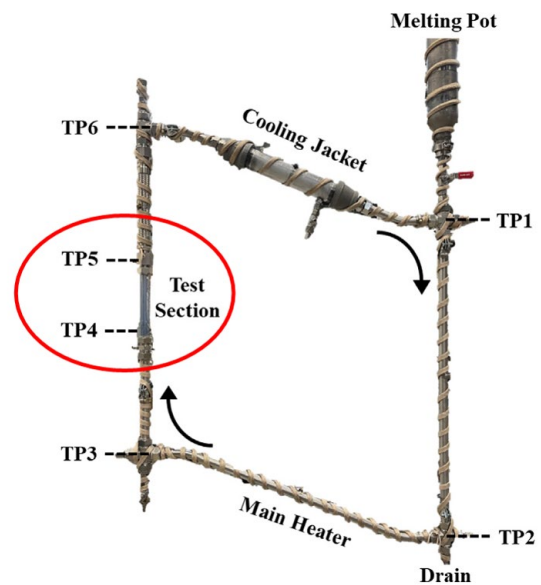


Fig. 3. Diagram of molten salt visualization loop with PIV test section [8]

In addition to visualizing the fluid dynamic response, the team provided critical insights into operational risk management for molten salt systems. This experiment identified potential mitigation strategies, including controlled reheating procedures, bypass flow designs, and monitoring of temperature gradients to prevent extensive solidification. These findings extend previous natural circulation research by demonstrating the coupled effects of heater failure, flow stagnation, and salt solidification on system behavior. The study underscores the need for robust thermal management and system design considerations to ensure safe and reliable operation of molten salt reactors, particularly in scenarios involving sudden loss of heat input.

Table I: Experimental studies on molten salt natural circulation loops

Authors (Year)	Salt Composition	Loop Description	Key Findings
ORNL, U.S. (1960s) [4]	FLiNaK (LiF-NaF-KF)	Small-scale NCL with electric heater and air cooler, stainless steel loop	First molten-salt NCL data; benchmark thermal-hydraulics of molten salt
BARC, India (2016) [5, 6]	Solar Salt ($\text{NaNO}_3\text{-KNO}_3$ (60:40 wt%))	Square loop with heater, air heat exchanger, expansion tank; operated at $\sim 300\text{-}400^\circ\text{C}$	Experimental & theoretical comparison; derived flow/temperature correlations.
Texas A&M, U.S. (2024) [7, 8]	FLiNaK + Ar	Flow visualization NCL with transparent test section, PIV diagnostics	Observed salt solidification & restart challenges; emphasized operational safety margins.

3. Reported operational incidents in experiments

Operational incidents observed in previous molten salt natural circulation loop experiments provide not only accounts of experimental difficulties but also design-relevant lessons for future MSR development.

At ORNL, failures such as ruptured sampling lines, water ingress through damaged jackets, and cracking near welded joints highlighted the vulnerability of metallic components exposed to high-temperature fluoride salts. Reported cases included a rupture of the sampling line that caused salt leakage, damage to coolant jackets that allowed water ingress, and cracking near welded joints of outlet piping. Failures of cooling coils and evidence of internal corrosion were also observed, as shown in Fig.4. These experiences emphasized the necessity of (i) stringent alloy qualification, (ii) welding integrity assurance, and (iii) continuous leak detection systems. Such requirements are directly applicable to reactor-scale loop design where long-term corrosion resistance and structural robustness are critical [4].

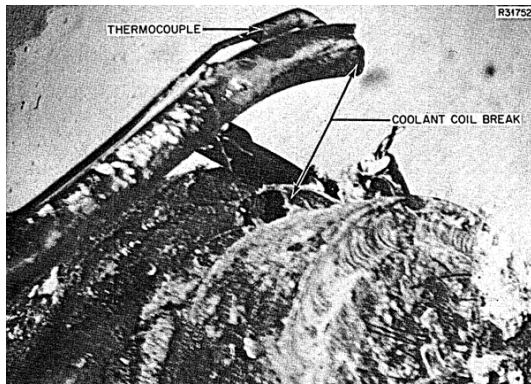


Fig. 4. Photograph of broken coolant salt coil of In-pile molten salt convection loop No. 1 of ORNL [4]

In the BARC MSNCL, while explicit records of leakage or rupture have not been disclosed, the studies revealed the sensitivity of natural circulation stability to

heater-cooler orientation and loop geometry. This suggests that geometry optimization is not merely an experimental detail but a fundamental design parameter for MSR primary circuits [7].

At Texas A&M, deliberate heater-trip scenarios resulted in localized cooling and partial salt solidification, as shown in Fig. 5. This led to flow blockage, reversal, and thermal stratification, and once solidification had initiated, recovery to stable circulation proved difficult. These findings underscored the necessity of maintaining adequate temperature margins, establishing controlled reheating procedures, and implementing real-time monitoring systems to ensure safe operation [8].

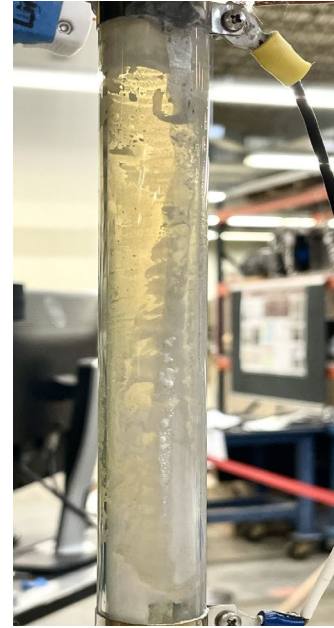


Fig. 5. PIV test section after salt solidification [8].

In summary, the incidents across ORNL, BARC, and Texas A&M experiments converge on three critical design aspects: material compatibility, geometry-driven flow stability, and operational resilience against freezing events. These findings are not only of retrospective value but also provide concrete design insights for MSR development, informing choices in material standards, loop layout, and emergency operating procedures.

4. Conclusions and further works

This paper summarizes the design, operation, and key findings from molten salt natural circulation loop experiments. Foundational studies at ORNL provided benchmark thermal-hydraulic data, while subsequent experiments at BARC and Texas A&M advanced understanding of loop geometry, material performance, and flow behavior under both steady-state and transient conditions. Reported operational incidents, including corrosion, leakage, and salt solidification, highlight the critical importance of robust materials, loop design, and

safety protocols. These experimental insights establish a practical knowledge base for molten salt reactor development, informing reliable reactor design, operational procedures, and emergency response strategies. Overall, the accumulated data and lessons learned provide essential guidance for the safe and effective deployment of future molten salt reactors. Future work will proceed as follows: (i) design of a chloride-salt natural-circulation loop, (ii) verification using a one-dimensional design/analysis code and steady/transient simulation codes, and (iii) operation and instrumentation of the experimental apparatus, including temperature / differential pressure measurements, heating control and freeze monitoring. The short-term objective is the loop design and the verification of the one-dimensional design code.

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