Design and Operation Plan of a Pumped Molten Chloride Salt Loop for Testing Long-Term Durability and Stability

Seungjin Seo, YunDong Lee, Jong Woo Kim, Ji-whan Kim
Hyundai Engineering and Construction, 75, Yulgok-ro, Jongno-gu, Seoul, 03058, Republic of Korea,
**Corresponding author:*
**Corresponding author:ssj1124@hdec.co.kr*

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1. Introduction

A molten salt reactor (MSR) is an advanced reactor that operates based on the molten salt system as its fuel and coolant. Following the Molten Salt Reactor Experiment (MSRE) conducted in the 1960s, MSRs have been developed worldwide due to the advantages of molten salt. The implementation of a molten salt fuel system leads to high thermal efficiency, safety from meltdown accidents, and small reactor size due to the low pressure of the molten salt system based on its high boiling point (and low vapor pressure).

In the Republic of Korea, MARINA, a marine molten salt reactor concept, has been developed by Hyundai Engineering and Construction and the Korea Atomic Energy Research Institute. MARINA has been designed to be operated continuously for 20 years with chloride-type molten salt, including sodium, potassium, and magnesium chloride (in the case of the 2nd circuit). There have been several challenges in the development of MSR, including MARINA, to secure the operational safety of the chloride molten salt system under forced convection circulation during the long-term operation period, in terms of corrosion, leakage, and damage to the structure and components.

This study presents the construction and operation plan of a forced convection chloride molten-salt loop designed for long-term operation and corrosion testing, as well as instrumentation validation. The first stage of the experiment plan is evaluating the long-term stability of the forced convection of the chloride salt system above 1,000 hours. Although some studies conducted in the past (from the 1950s to the 1960s) already achieved similar objectives, it is necessary to reproduce the long-term stability of forced convection in the chloride salt system with relatively larger-scale loop devices. Also, through these loop experiments, the corrosion test of the candidate materials of the MARINA can be conducted under the flow-induced corrosion environment to evaluate the material durability under the MARINA operation. Lastly, the instrumentation for the molten salt system can be implemented and evaluated through this loop experiment before MARINA operation, which should be implemented under further extreme conditions compared to that of the pressurized water-cooled reactor.

2. Literature Review

Decades after the major ORNL molten-salt reactor programs, universities, national laboratories, and reactor developers have resumed molten-salt loop research. Publicly reported forced convection chloride-salt facilities remain much less numerous than nitrate- or fluoride-salt systems. Chloride salts are attractive for high-temperature heat transport because they can operate beyond the practical temperature range of commercial nitrate salts, are based on relatively inexpensive constituents, and do not provide the neutron-moderating behavior associated with light-element fluoride salts. These potential benefits are accompanied by demanding requirements in chemistry control of the molten salt system. The impurities in the system, especially moisture and oxygen, accelerate the corrosion of the structure and component, leading to the dramatic decrease in the durability and stability of the molten salt system. Especially, the chromium depletion occurs and reduce the advantage of the stainless steel which has been widely used in the Nuclear Power Plants.

Table 1 shows the list of forced convection chloride molten salt loops conducted from the 1960s [1-8]. These loops, constructed and operated in the 1960s, showed long operation periods, while these recent studies showed shorter operation periods, lower than 100 hr. Most of these recent studies underwent the operation issue in terms of leakage, damage, and pump failure.

Table 1. List of forced convection chloride molten salt loop studies.

Institute	Descriptions
Virginia Technology [1-2], 2023	Salt: NaCl-KCl-$MgCl_2$ (29.4-25.8-44.7 mol%) Salt amount: 40 kg (25 / 15, 2 batches) Operation temperature: 650 ºC Operation flow rate: 0.45 L/s Operation period: 50 / 80 / 100 hr
Oak Ridge National Laboratory [3], 2022	Salt: NaCl-KCl-$MgCl_2$ (16-39-45 wt%) Salt amount: 155 L (200 kg in batch, max 400 kg) Operation temperature: 550-725 ºC Operation flow rate: 3-7 kg/s Operation period: 6.3 hr (pumped), 558 hr (no-flow)
University of Wisconsin Madison [4-5], 2024	Salt: NaCl-KCl-$MgCl_2$ (16-39-45 wt%) Salt amount: max 170 kg (tank) Operation temperature: 550- ºC Operation flow rate: 4.72 L/s Operation period: 90 hr, 2 min (shaft seizure)
Massachusetts Institute of Technology [6], 2023	Salt: NaCl-KCl-$MgCl_2$ (11.7-42.38-47.8 wt%) Salt amount: about 10 kg (tank 8 L) Operation temperature: 750-950 ºC Operation flow rate: 0.033 L/s Operation period: 48 hr (pump unprimed)

Argonne National Laboratory [7], 1966	Salt: NaCl-KCl-$MgCl_2$ (about 30-40-30 mol%) Salt amount: - Operation temperature: 510-550 ºC Operation flow rate: 0.221 L/s Operation period: 160 hr + 850 hr
Brookhaven National Laboratory [8], 1960	Salt: NaCl-KCl-$MgCl_2$ (30-20-50 mol%) Salt amount: 2.55 kg Operation temperature: 520 / 515 / 500 ºC Operation flow rate: 0.202- 0.693 L/s Operation period: 1034 / 656 / 1000 hr

2.1. Corrosion, Leakage, and Failure During Loop Operation

The corrosion mechanism of the chloride salt environment is strongly affected by the level of impurities, especially moisture. $MgCl_2$ can undergo hydrolysis when there are bonded H_2O molecules in its structure, forming MgOHCl, MgO, and HCl [10]. These reactions are distributed in several temperature regions, and the products lead to the corrosion of structural materials and damage of the components. The impurities should be removed through the pre-treatment process of the salts before loop operation, by avoiding these hydrolysis reactions. These loop studies which have issues in the pre-treatment of salt reported the structure corrosion and damage during loop operation [1, 9].

Virginia Tech reported leakage from flange and valve connections during operation of its forced convection chloride loop [1]. Leaked salt contacted insulation and electrical heating equipment, and the researchers reported strong, irritating odors, heater and controller failures, discoloration or corrosion of nearby equipment, and a completely failed welded joint. The published account associated these events with salt leakage, electrical shorting, and possible electrolysis of chloride salt. This experience demonstrates that leakage, electrical isolation, off-gas monitoring, ventilation, and emergency drainage must be treated as integrated design issues rather than independent component checks.

2.2. Uncertainty of long-term operation stability of chloride salt in forced convection system

In the 1960s, ANL and BNL each operated forced-circulation chloride-salt loops for more than 1,000 h, demonstrating the feasibility of long-duration operation [7-8]. In contrast, some recent forced-circulation chloride-salt loop studies have encountered leakage, corrosion damage, and other operational problems within the first 100 h, indicating a gap between historical and contemporary operating experience [1-6]. Therefore, before conducting flow-assisted corrosion and instrumentation tests, it is necessary to re-establish the long-duration operability and safety of the forced-circulation chloride-salt system and thereby reduce the associated uncertainties.

3. Loop Description

3.1. Experimental Objectives

The objective of this study is to establish the safety and operability of a forced convection chloride-salt loop through progressively extended operation up to 1,000 h. The present experiment focuses on demonstrating stable, long-duration operation of the integrated system, including salt heating and circulation, inert-gas control, salt transfer and drainage, leakage management, and reliable measurement. The qualified loop will subsequently provide an experimental environment for follow-on flow-assisted corrosion and instrumentation experiments, including material exposure, corrosion monitoring, pump vibration monitoring, flow measurement, salt-chemistry control, and off-gas diagnostics in further research.

During the experiment, the loop is intended to operate without observable salt leakage or serious structural or component damage. The circulation path will be maintained at a sufficiently uniform temperature to prevent local salt freezing, flow-path restriction, and blockage, while the pump, heaters, valves, gas system, and drainage system remain functional. Instrument signals should remain stable and explainable throughout the experiment, and any deviation in flow, temperature, pressure, gas composition, or equipment condition should be traceable from the operating records.

3.2. Experimental Procedure

The experimental sequence consists of equipment inspection, salt preparation, salt pretreatment inside a glovebox using a dedicated pretreatment tank, a salt-injection experiment using a dedicated salt-injection apparatus, salt transfer to the auxiliary tank, salt transfer from the auxiliary tank to the main tank, forced-circulation loop operation for up to 1,000 h, and final salt drainage and analysis. Before salt handling, the mechanical components, piping, welds, flanges, valves, heaters, electrical systems, instrumentation, and argon gas system will be inspected to confirm their readiness for operation. The vacuum procedure needs to control and remove impurities such as oxygen and moisture within the loop and injection devices before the experiment. Before salt loading and injection, these devices should be brought to the operating temperature to prevent the salt from freezing.

The molten salt will first be transferred through the dedicated salt-injection apparatus to confirm that pressure-driven salt transfer can be performed reliably. The salt will then be transferred into the auxiliary tank and subsequently transferred to the main tank under argon pressure. The pump will operate by circulating the molten salt through the circulation line continuously at the same rotation speed. At the end of the experiment, the drain valve will be opened and heated to drain the molten salt after loop operation. The drained salt and

collected deposits will then be analyzed, and the loop condition and operating records will be evaluated.

3.3.Salt preparation

The experiment will use eutectic NaCl–KCl–$MgCl_2$ salt (15.11-38.91-45.98 wt%), and each of the salt products should be commercial ultra-dry-grade salts to minimize the initial moisture introduced with the raw materials. However, the pretreatment of the salts is still necessary to minimize the initial moisture level before salt melting, to prevent the generation of HCl during heating. A pretreatment tank, which is mountable on the furnace of the glovebox and salt injection devices, is used to prevent the injection of impurities during salt transfer and pretreatment.

3.4. Salt-Injection Experiment

A dedicated salt-injection apparatus has been designed and fabricated to evaluate whether molten salt can be transferred reliably between tanks using argon pressurization. The apparatus is separated from the main loop so that potential problems during initial melting and injection, such as incomplete transfer, local freezing, blockage, leakage, pressure instability, or residual salt accumulation, can be identified without exposing the loop pump and other major components to unnecessary risk. The experiment will examine pressure response, transfer time or rate, temperature distribution, residual salt, and evidence of freezing or blockage during transfer. Pretreating and transferring the salt through this dedicated apparatus is also expected to minimize the introduction of impurities during salt injection into the main loop.

3.5. Forced convection Loop Operation Experiment

The pretreated salt will be transferred into the auxiliary tank and then transferred to the main tank using argon pressurization. After the circulation piping, valves, pump region, and drainage path have been preheated and confirmed to be above the required temperature, the pump will be started to circulate the molten salt. Loop operation will be progressively extended toward 1,000 h while monitoring flow rate, temperature, pressure, and impurities level of cover-gas. At the end of operation, the drain valve will be opened, and the drainage path will be heated as necessary to prevent local freezing and promote controlled salt discharge into the drain tank. The drained salt will subsequently be analyzed for composition and impurities, and the loop will be cooled and inspected to evaluate deposits, corrosion, leakage paths, welds, flanges, valves, pump condition, instrument interfaces, and the overall structural integrity of the system. The operating and instrumentation records will also be reviewed to evaluate circulation stability, thermal behavior, abnormal events, and the suitability of the loop for subsequent flow-assisted corrosion and instrumentation experiments.

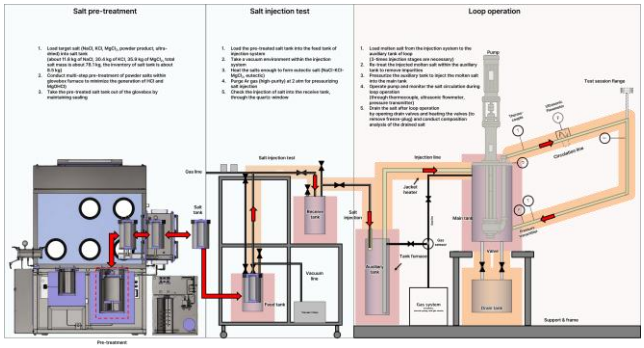


Figure 1. Experimental procedure of forced convection molten salt loop including salt pretreatment and injection test.

3.6. System Configuration

The forced convection loop consists of three tanks, namely an auxiliary tank, a main tank, and a drain tank, together with salt-injection, transfer/circulation, and drain lines and a vertical molten-salt pump. An argon system provides purging, cover gas, and pressure-driven salt transfer. Off-gas from pretreatment and operation will be routed through a scrubbing stage before discharge.

The loop is designed for NaCl-KCl-MgCl2 with a total salt inventory of approximately 35 L. Approximately 1.5 L of this inventory is expected to occupy the circulation piping. The tanks and primary piping are constructed from SS316L. The intended operating temperature is above 500 °C, with operation near 600 °C under consideration. The final temperature set point and margin will be established during detailed design and commissioning, accounting for salt freezing behavior, local temperature gradients, heat loss, and instrument limits (630 °C).

The pump is a commercial Nagle unit selected to reduce uncertainty associated with using an unproven pump concept. However, pump rotational speed must not be treated as a direct measurement of flow. The actual operating point is determined by the intersection of the pump curve and the system-resistance curve. Flow will therefore be measured directly during commissioning. The basis and meaning of the vendor's 2,500 h entry also require confirmation and should not be interpreted as demonstrated molten-salt service life.

The current design information lists a loop pressure of 1 bar and an initial salt-transfer pressure of 2 bar. Whether these values are gauge or absolute pressures must be defined before commissioning. The valve arrangement includes a high-temperature needle-valve concept and a freeze-plug or freeze-valve concept; the final configuration, drainage function, and fail-safe behavior remain to be confirmed.

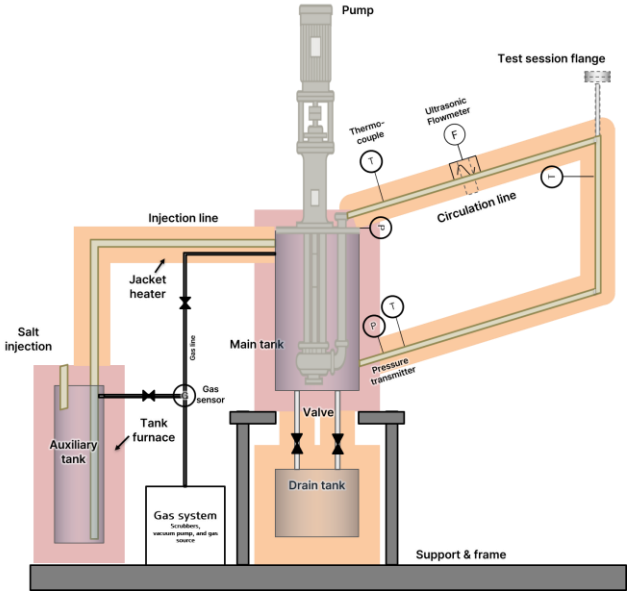


Figure 2. Structural diagram of forced convection molten salt loop.

3.7. Instrumentation and Heating

The initial instrumentation consists of K-type surface thermocouples, pressure transmitters, moisture and oxygen sensors for the cover-gas system, and a FLEXIM clamp-on ultrasonic flowmeter. Thermocouples and pressure transmitters will be installed at selected tank ports and circulation-line locations. The gas sensor will be installed in the gas-outlet line to monitor moisture and oxygen as indicators of ingress and pretreatment performance.

The ultrasonic flowmeter will provide a direct indication of flow during initial commissioning. Its calibration, acoustic coupling, installation geometry, temperature capability, and local bare-pipe requirements must be verified before operation. The approximately 50 to 60 cm installation region may require a locally uninsulated or partially insulated configuration. This region must be assessed for heat loss, circumferential temperature nonuniformity, and freezing risk during normal circulation, minimum-flow operation, heat-up, standby, and drainage.

Vertically spaced thermocouples may be used as an interim qualitative indication of the liquid level, but this arrangement requires validation and should not be represented as a calibrated continuous level measurement. Direct vibration measurement is deferred unless an accelerometer or equivalent condition-monitoring instrument is installed. Electrochemical corrosion and redox monitoring are also deferred to later campaigns.

Measurement uncertainty and acceptance limits must be quantified before scientific campaigns begin. In particular, pressure range and reference, flow uncertainty, thermocouple installation error, gas-sensor response, and the interpretation of temperature-based level indication must be documented. Scientific interpretation of corrosion or mass-transfer data will not be credible unless these measurement limitations are controlled.

The tanks will be heated in furnaces, while the piping and drain path will use jacket or clamp-type heaters. Heating will be divided into independently controlled zones to reduce cold spots and support staged melting, transfer, circulation, and drainage. Particular attention is required at valves, flanges, weld transitions, instrument interfaces, and the ultrasonic-flowmeter installation region.

The ultrasonic-flowmeter assembly may create an approximately 60 cm region that cannot be insulated in the same manner as the adjacent heated piping. The parts of the pipe circumference not occupied by the flowmeter may be heated or partially insulated, subject to confirmation that the arrangement does not impair acoustic coupling or exceed the temperature limits of the mounting fixture, transducers, cables, or connectors. A removable ventilated thermal shield may be evaluated, but the flowmeter assembly should not be enclosed in a manner that prevents the intended thermal separation of the transducers from the hot pipe.

A preliminary heat-loss evaluation estimated approximately 3 kW of heat loss from the circulation line under an assumed 650 °C condition without crediting line heating. This value remains a design estimate and must be confirmed against the final geometry, insulation details, ambient conditions, flowmeter installation, and heater arrangement. The combined furnace and jacket-heater capacity is expected to offset the calculated heat loss, but adequacy must be demonstrated through temperature mapping during commissioning. The governing acceptance criterion is not heater capacity alone; all salt-containing regions must remain above the approved freezing-management limit with sufficient margin during the relevant operating and transient conditions.

4. Conclusion

A forced convection molten chloride salt loop has been constructed to test the long-term operation stability and further corrosion and instrumentation tests. The construction will be finished before November 2027, and 1,000 hr operation test will be conducted after device inspection and water test, along with discussion. Following qualification of the base platform, modular side-stream purification, corrosion specimens, electrochemical monitoring, vibration measurement, improved level sensing, and off-gas diagnostics may be introduced in later campaigns.

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