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Molten Salt Loop Operational Experience and Test Campaigns in FY24

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Nuclear Energy and Fuel Cycle Division

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ABBREVIATIONS

ANL	Argonne National Laboratory
DOE	US Department of Energy
DOE-NE	DOE Office of Nuclear Energy
FASTR	Facility to Alleviate Salt Technology Risks
ICP-OES	inductively coupled plasma optical emission spectroscopy
LSTL	Liquid Salt Test Loop
MSRE	Molten Salt Reactor Experiment
NEAMS	Nuclear Energy Advanced Modeling and Simulation
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
SAM	System Analysis Module
SBIR	Small Business Innovation Research
SNL	Sandia National Laboratories

1. BACKGROUND

The Facility to Alleviate Salt Technology Risks (FASTR) at the US Department of Energy (DOE) Oak Ridge National Laboratory (ORNL) was developed to demonstrate technology for high-temperature chloride salt systems (Figure 1).[1, 2] FASTR is primarily constructed using alloy C-276 and is designed to operate at temperatures of up to 725°C. The facility is loaded with 250 kg of NaCl-KCl-$MgCl_2$ salt. This salt provides a relevant test environment for de-risking technology while avoiding the costs and hazards associated with beryllium-based or uranium-bearing salts. The facility's major components include a centrifugal pump for salt circulation, an air-based heat exchanger to reject heat, a suite of instrumentation, and trace heating to prevent salt freezing. The salt was purified in 2020 and 2022, and the pumped loop first operated in December 2022.[3,4]

FASTR is a unique US capability for high-temperature molten halide salt testing. FASTR's scale, co-located purification system, and relatively large power (465 kW) differentiates it from other testing systems. Furthermore, access to the DOE-supported facility and efficient communication of results—which are generally disseminated publicly—distinguish FASTR as being broadly significant throughout the molten salt reactor community.

FASTR is similar to ORNL's Liquid Salt Test Loop (LSTL),[5] although FASTR contains chloride-based salt instead of the fluoride-based salt (LiF-NaF-KF) found in LSTL. Furthermore, FASTR is approximately 2× larger than LSTL in terms of pipe size and length, power, salt volume, flow rate, and number of thermocouples. The LSTL first operated in 2016. At the end of FY23, there was a suspected gas leak in the LSTL that halted operation[6]. At the start of FY24, a leak in the LSTL pump's tank gas space was confirmed. Because the gas-space leak prevented operation of LSTL, FY24 efforts were focused on operation of FASTR. This report summarizes the progress made during FY24 in support of the DOE Office of Nuclear Energy (DOE-NE) work package, AT-24OR070202 Salt Loop and Capability for Testing Sensors and Off Gas Components.

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[1] K. R. Robb, P. Mulligan, G. Yoder Jr., K. Smith, J. Massengale, *Facility to Alleviate Salt Technology Risks (FASTR): Preliminary Design Report with Failure Modes and Effects Analysis*, ORNL/TM-2019/1370, December 2019.
[2] K. R. Robb, E. Kappes, P. Mulligan, *Facility to Alleviate Salt Technology Risks (FASTR): Design Report*, ORNL/TM-2022/2803, December 2022.
[3] K. R. Robb, S. Baird, J. Massengale, N. Hoyt, J. Guo, C. Moore, *Engineering-Scale Batch Purification of Ternary $MgCl_2$-KCl-NaCl Salt Using Thermal and Magnesium Contact Treatment*, ORNL/TM-2022/2554, August 2022.
[4] K. R. Robb, E. Kappes, *Facility to Alleviate Salt Technology Risks (FASTR): Commissioning Update*, ORNL/TM-2023/2846, March 2023.
[5] G. Yoder Jr., K. R. Rob, E. Dominguez-Ontiveros, D. K. Felde, D. L. Fugate, D. E. Holcomb, *Start-up Operation Experience with a Liquid Fluoride Salt Forced Convection Loop*, ORNL/TM-2023/2978, August 2023.
[6] K. R. Robb, E. Kappes, D. Orea, *Molten Salt Loop Testing of Sensors and Off-Gas Components - FY23 progress,* ORNL/LTR-2023/3087, September 2023.

Figure 1. The FASTR at ORNL.

2. FY24 SYSTEM OPERATION AND TEST CAMPAIGNS

2.1 SUMMARY OF HIGHLIGHTED PROGRESS

During FY24, the FASTR salt loop was operated once, and a variety of testing was completed. Highlighted progress includes the following:

- Maintained the system in an operational state.
- Ran 7 pump speeds over the course of 6.3 h to gather the system's hydraulic data and to continue facility shake-down.
- Added accelerometers to the pump and captured the first vibration data set.
- Completed 11 tests analyzing salt particulate (i.e., droplets, mist, vapors) in the gas space.
- Exposed a Raman probe for Pacific Northwest National Laboratory (PNNL) and returned the probe to PNNL for analysis.
- Operated the Argonne National Laboratory (ANL) electrochemical probe and returned the resulting dataset.
- Facilitated test of novel flow and pressure sensors for Sporian Microsystems through the Small Business Innovation Research (SBIR) program.
- Collaborated with Sandia National Laboratories (SNL) and ORNL colleagues to develop computational models of the LSTL and FASTR systems.

2.2 MAINTENANCE ACTIVITIES

Several maintenance activities were completed to ensure that FASTR remains operational. This included replacing bottles of argon, which is used as a cover gas to keep the system inert. A failed gas mass flow controller was replaced. Several additional activities were completed to maintain compliance with DOE requirements for pressure systems and electrical requirements.

After the first FASTR loop operation at the end of 2022, there was a suspected small leak in the transfer line. A failed fitting was identified and confirmed during FY24 and was replaced with a custom fabricated adapter. A stainless-steel compression fitting had been used to connect two high-nickel alloy tubes. The differential thermal expansion between the alloys resulted in a small leak and failure of the trace heating. This failure is very similar to an instance that occurred previously with LSTL. In the case of FASTR, the stainless-steel fitting was used to connect two different sized tubes. A custom adapter made of the tube alloy was cost prohibitive at the time of construction and necessitated the use of a stainless-steel fitting. To resolve the issue in FY24, the failed stainless-steel fitting was removed and replaced with a custom adapter made of C276. The trace heating along the tubes was also replaced because the leak from the failed fitting caused the heater to become unreliable.

2.3 AEROSOL CHARACTERIZATION

The amount and size distribution of particulates (condensed vapors, droplets, mists, etc.) are known to have impacted the operation of the Molten Salt Reactor Experiment (MSRE).[7] Accordingly, data for the gas space particulate characteristics are of interest to sensor developers, code developers, and reactor designers.

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[7] Engel, J. R., P. N. Haubenreich, and A. Houtzeel. *Spray, Mist, Bubbles, and Foam in the Molten Salt Reactor Experiment*. ORNL-TM-3027. Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States), 1970.

During FY23, a series of tests was conducted to characterize the aerosols within the LSTL (LiF-NaF-KF) storage tank. These tests used a particle impactor which contains 10 plates (i.e., stages) with orifices designed to cause specific ranges of particulate to collect (i.e., impact) on the series of stages. The collected particulates could then be analyzed to determine their mass, size distribution, and composition.

In FY24, a similar series of aerosol characterization tests was conducted using the particle impactor attached to FASTR's ($NaCl$-KCl-$MgCl_2$) storage tank. The arrangement is illustrated in Figure 2. A total of 11 tests were completed, including stagnant/quiescent salt testing, as well as tests in which the salt was sparged by a flow of gas (0–3.2 lpm in the salt). After the tests were completed, the collected aerosols (Figure 3) were removed and analyzed via inductively coupled plasma optical emission spectroscopy (ICP-OES). These test results summarized in Table 1 are currently being analyzed, and a draft paper addressing the LSTL and FASTR tests is under development.

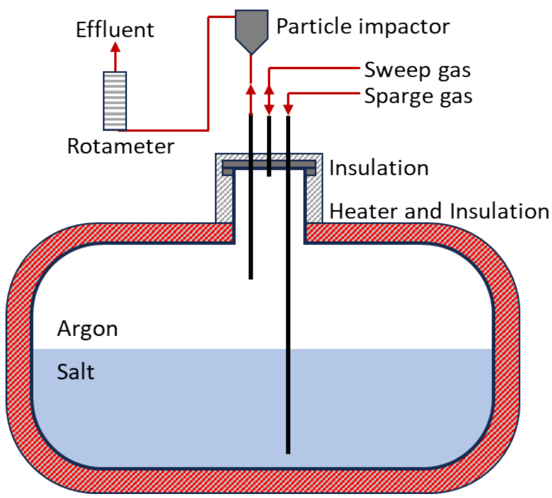

Figure 2. Illustration of aerosol characterization test setup.

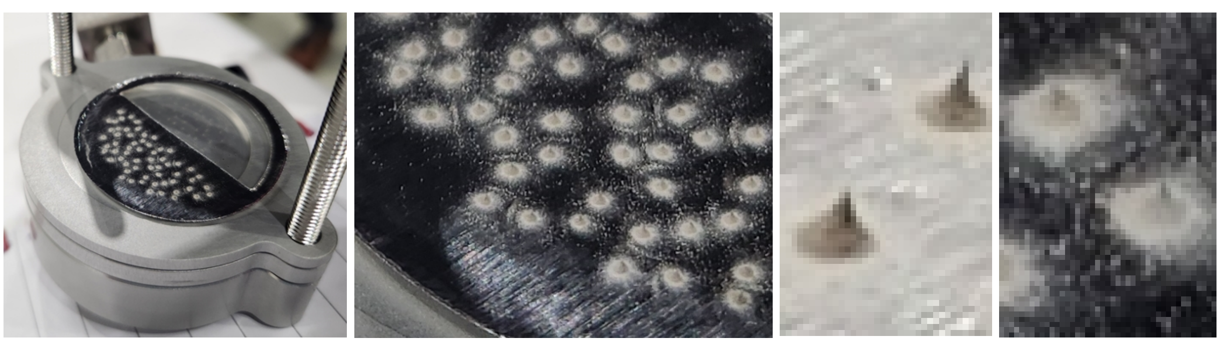

Figure 3. Salt aerosols deposited in particle impactor.

Table 1. Summary of aerosol test conditions

Test	Salt temperature (°C)	Sparging rate (slpm)	Sparging rate adjusted for temp and pressure (lpm)
1	499	0.00	0.00
2	531	0.00	0.00
3	546	0.00	0.00
4	559	0.00	0.00
5	560	0.00	0.00
6	560	0.00	0.00
7	561	0.00	0.00
8	564	0.77	1.62
9	562	1.02	2.14
10	563	1.52	3.19
11	502	1.17	2.28

2.4 SENSOR TESTING

2.4.1 Raman Probe Exposure (PNNL)

Raman spectroscopy is a promising technique for in-situ analysis of the chemical structures of species in salt systems. However, the technique requires optical access. During FY23, two Raman probes were exposed to the gas space in LSTL to discern the impact of the gas space on the optical characteristics of the probes. The study was continued in FY24 by exposing a Raman probe to the FASTR storage tank gas space. The probe was inserted through the top flange of the storage tank and protruded approximately 1 in. below the flange. The probe was exposed to the gas space while the salt was at ≥500°C for 558 h and for approximately 355 h while the salt was held at 560°C. The probe was then removed and shipped to PNNL for analysis.

2.4.2 Electrochemical Sensor (ANL)

Electrochemical techniques provide unique in-situ information regarding the impurity concentration and redox of the salt. FASTR contains four sensors that were developed at ANL. During FY24, the sensor in the pump tank was operated. Analysis of the results by colleagues at ANL indicated low impurity levels (i.e., <1 ppm Cr^{2+}, Fe^{2+}, and OH^{-}), and they also showed that the salt has maintained an acceptable redox potential. Several historical and more recent demonstrations of maintaining corrosion control within fluoride salt systems are documented in the literature. The most recent results from this work are significant and serve as an important demonstration of a similar ability to control the salt chemistry and corrosion rates in pumped flow chloride salt systems of significant scale.

2.4.3 Industry Pressure and Flow Sensor

Flow and pressure sensors provided by Sporian Microsystems were installed and tested on FASTR. This work was supported separately through the SBIR program.

2.5 PUMP OPERATION

2.5.1 Hydraulics

The pump was operated at 7 different speeds during 3 different intervals for a total of 6.3 h of run time. The pump speed vs. time, as well as the flow loss pressure drop on the return side of the loop (from the top of the loop back to the pump tank), are plotted in Figure 4. These data were compared against the predicted flow loss for the return side of the loop shown in Figure 5. This new data align with previous measurements from 2022 and reinforce confidence in the hydraulic model for predictions. Using the predicted system performance as presented in Figure 6, the current testing spanned 31.5–45.1 gpm. After the two pump operations shown in Figure 4 were completed, the pump was restarted again and operated continuously for approximately 3.8 h. The resulting data are being used for code prediction and sensor testing of blind comparisons and will be published at a later date.

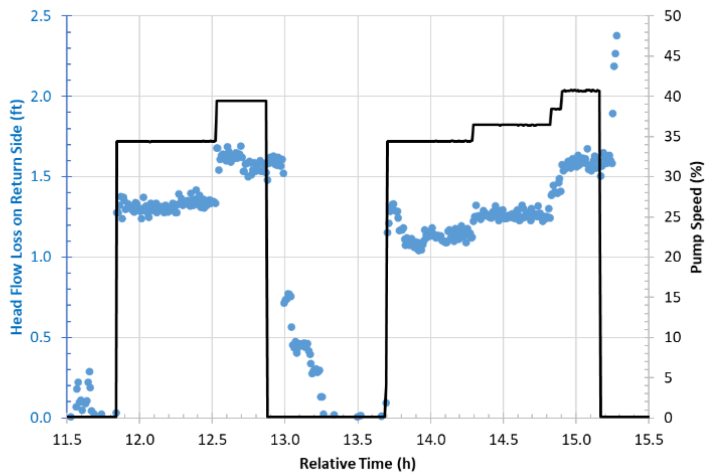

Figure 4. Flow loss data during pump operation.

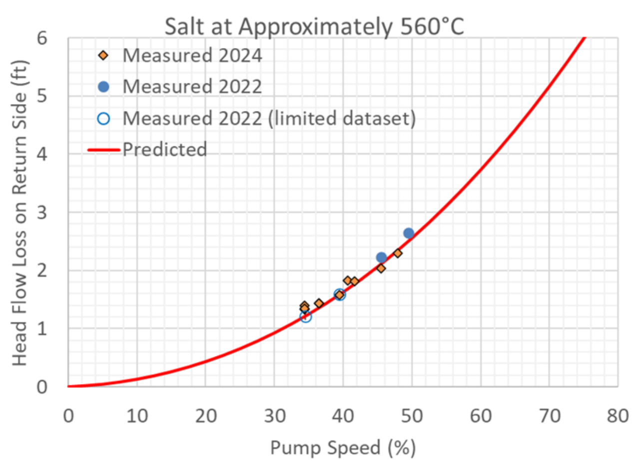

Figure 5. Comparison of the predicted and measured head flow loss in the return side of the loop for the salt test data.

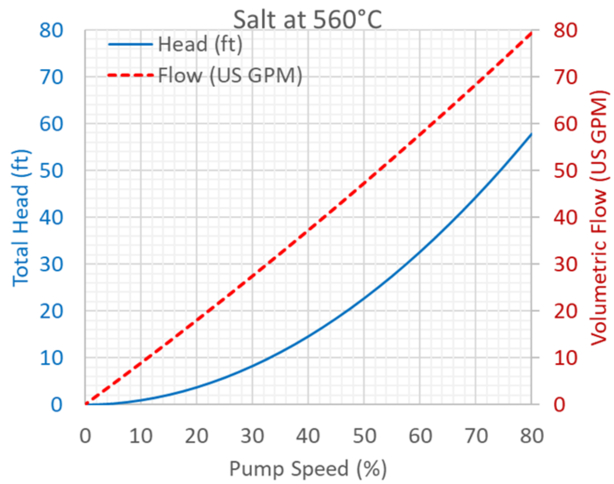

Figure 6. Predicted total head and flow rate as functions of pump speed for salt at 560°C. [8]

2.5.2 Vibration

Two accelerometers were attached to the pump pedestal 90° apart, as shown in Figure 7. They are located above the shaft seal and below the lower set of shaft bearings. These accelerometers were used to measure a preliminary set of vibration data for the pump; examples are shown in Figure 8. The information obtained from these tests will be used to identify which resonances should be avoided during operation, and it will also be used to identify changes to pump vibration and potential degradation over time.

Figure 7. Locations of accelerometers on pump.

[8] K. R. Robb, E. Kappes, *Facility to Alleviate Salt Technology Risks (FASTR): Commissioning Update*, ORNL/TM-2023/2846, March 2023.

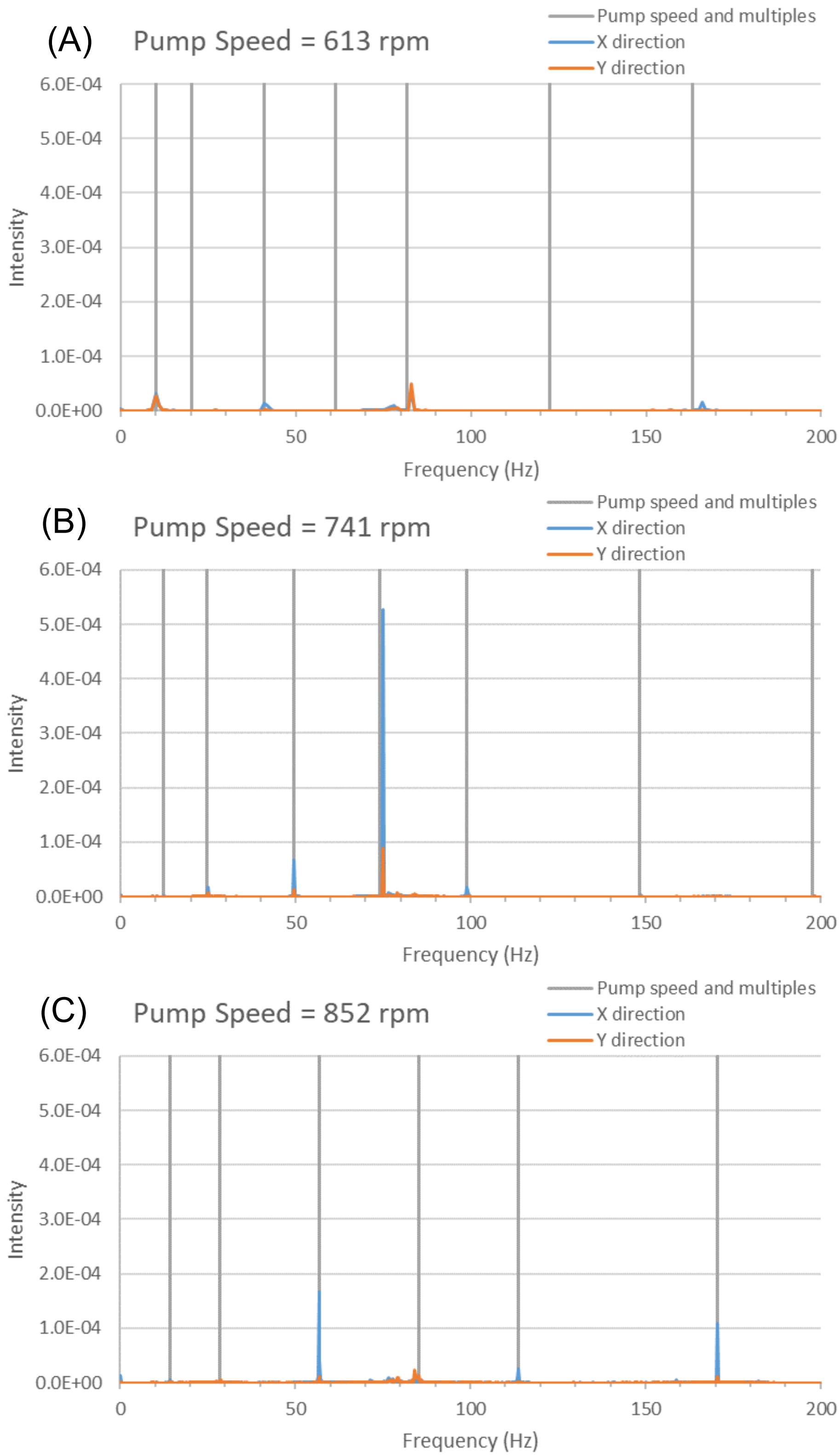

Figure 8. Example pump vibration intensity measured at different pump speeds: (A) 613 rpm, (B) 741 rpm, and (C) 852 rpm.

2.6 MELCOR AND SAM SYSTEM-LEVEL MODEL DEVELOPMENT COLLABORATIVE SUPPORT

The MELCOR code is sponsored by the US Nuclear Regulatory Commission and is developed and maintained by SNL. It is a system-level code primarily used to assess radionuclide transport during off-nominal events. The System Analysis Module (SAM) is a system-level DOE-NE Nuclear Energy Advanced Modeling and Simulation (NEAMS) code under development for fast-turnaround design and analysis. The capabilities of both codes are being developed for application to molten salt reactor systems. Models of LSTL were developed during FY22 and FY23, and initial discussions were held in FY24 with both modeling teams to determine the information required to model FASTR. In future years, it would be desirable to create MELCOR and SAM models of FASTR for use in code validation and data interpretation.