ANL/CFCT-25/1

Preliminary Design of Engineering-Scale Salt Accident Analysis Facility to Support Molten Salt Reactor Licensing

Chemical and Fuel Cycle Technologies Division, Argonne National Laboratory

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Acronyms

ARE	Aircraft Reactor Experiment
CFD	Computational fluid dynamics
EDS	Energy dispersive X-ray spectroscopy
FLiNaK	LiF-NaF-KF eutectic (46.5-11.5-42 mol %)
ICP-MS	Inductively coupled plasma-mass spectrometry
LBE	Licensing basis event
LIBS	Laser induced breakdown spectroscopy
LWR	Light water reactor
MCA	Maximum credible accident
MSR	Molten salt reactor
MSRE	Molten Salt Reactor Experiment
NRC	Nuclear Regulatory Commission
SAAF	Salt Accident Analysis Facility
SEM	Scanning electron microscopy
TOF-MS	Time-of-flight mass spectrometry

Abstract

Systems-level nuclear accident analysis codes for reactor licensing must be validated using experimental data that represent behaviors expected during actual full-scale accidents. Some behaviors may arise from coupled processes and only manifest at large scales. This report presents the preliminary design of the Salt Accident Analysis Facility (SAAF, pronounced “safe”), which is an experimental test facility to be constructed at Argonne that can be used to conduct integrated salt accident tests at an engineering scale. The measurement capabilities of the SAAF are based on previously developed methods and will provide the representative datasets that are needed to support molten salt reactor (MSR) licensing. Details of the design, the processes to be quantified, the measurement techniques for quantifying the processes, the variables that can be adjusted to simulate different accident scenarios, and operational considerations are presented herein. This report provides stakeholders the opportunity to give feedback on the test facility capabilities and planned analyses before it is constructed.

1 Introduction and objective of report

Molten salt reactor (MSR) developers in the U.S. will likely navigate reactor licensing by following the modernized licensing framework for advanced reactors outlined in U.S. Nuclear Regulatory Commission (NRC) Regulatory Guide 1.233 (2020). This advanced reactor licensing approach involves identifying and evaluating the consequences of licensing basis events (LBEs). LBEs are sequences of events that encompass a wide range of postulated off-normal and accident scenarios and are classified according to their expected frequency of occurrence. Quantifying the consequences of LBEs involves using validated models to evaluate accident progression and to predict the mechanistic source term when radiological release is expected to occur. One challenge that MSR developers face in producing successful license applications is a lack of experimental data to support the development and validation of accident analysis models. In addition, existing nuclear accident analysis codes are tailored to the U.S. commercial fleet of light water reactors (LWRs). These codes will need to be significantly modified (or newly developed) to incorporate and address the features and chemistries of MSRs, which are fundamentally different from those of LWRs. The integrated safety analysis code MELCOR is one such accident consequence modeling tool that was originally developed for LWRs and is currently being modified to accommodate MSR-relevant systems (Christian et al., 2024; Gelbard et al., 2023; Haskin et al., 2023; Humphries et al., 2018; Smith et al., 2021).

The specific LBEs to be evaluated during the licensing process will depend on aspects of the reactor design and the potential consequences of each postulated event. All MSR developers will likely evaluate an accident scenario involving the unintended release of molten fuel salt from the primary loop into the next layer of containment (e.g., a salt spill accident). The consequences of a molten fuel salt release event will also likely provide an upper bound to the consequences of other LBEs due to the severity of the potential radiological impacts. For example, a partial spill of molten fuel salt was considered to be the maximum credible accident (MCA) for the Molten Salt Reactor Experiment (MSRE) (Beall et al., 1964). Experimental efforts should focus on generating data on the consequences of molten fuel salt release accidents to most effectively support MSR licensing.

Filling gaps in our ability to predict radionuclide dispersal and reactor performance for postulated fuel salt release accidents will require conducting accident simulation experiments that provide insights into coupled processes (i.e., integral effects tests) (Leute et al., 2021; Shahbazi and Grabaskas, 2021; Smith et al., 2021). Tests that address individual processes are necessary to provide the mechanistic detail required for model development, but integrated tests are needed to capture the complexities of inter-dependent processes. In addition, the data used to validate accident progression models for nuclear reactor licensing should originate from experiments conducted at relevant spatial and temporal scales. Realistically simulating some MSR accidents will require using large quantities of molten salt (i.e., on the order of tens of liters) because some behaviors may only manifest at larger scales. This necessitates the design and operation of an engineering-scale test system for experimentally simulating and quantifying the consequences of processes that occur during salt accidents.

This report presents the preliminary design of an engineering-scale test facility for MSR accident analyses that can handle up to 15 liters of molten salt and simultaneously monitor multiple processes that influence the outcome of an accident. In addition, the processes that can be evaluated in the facility, the measurement techniques for quantifying the effects of these processes, the test variables that can be changed to simulate different accidents, the operational and safety considerations of the design, and the remaining steps to take to achieve the engineering scale testing capability are identified. The design is modular and enables testing multiple accident scenarios and variables using the same facility. The data generated using this test system can also provide insights into the conditions under which safety features may fail and inform decisions during the reactor design phase.

The objective of this report is to present the preliminary design of the engineering-scale test facility for stakeholder review prior to system construction. The design may evolve based on stakeholder feedback to maximize the value of the test results.

2 Approach towards conducting engineering-scale tests

Figure 1 presents the phased and iterative approach being taken towards conducting salt accident simulation tests at an engineering scale to provide the necessary datasets for validating accident progression models for MSRs. The approach consists of three staggered phases that progress concurrently and culminate in the ability to conduct engineering-scale tests.

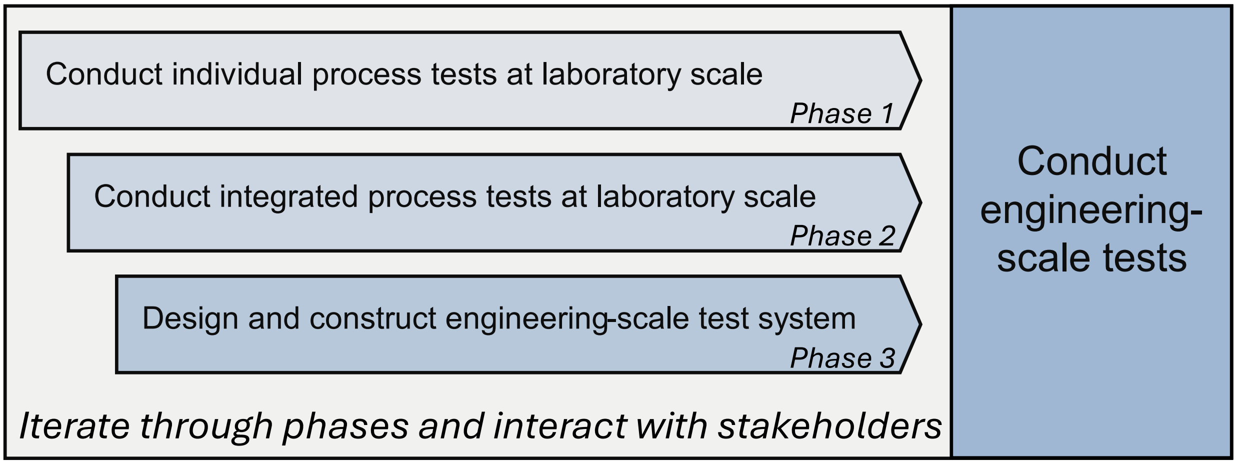

Figure 1: Phased and iterative approach towards conducting engineering-scale tests to generate datasets for MSR accident progression model validation.

The simulation, measurement, and data analysis techniques for quantifying the consequences of salt accidents must be developed and proven prior to being employed for engineering-scale tests. To date, few experimental studies have simulated salt accidents or investigated processes to provide insight into the consequences of postulated MSR accidents. This lack of experimental experience prompted the development of the approach towards conducting engineering-scale tests shown in Figure 1. Phase 1 began in FY21 by conducting individual process tests at a laboratory scale using a fluoride salt composition (FLiNaK; Thomas and Jackson (2021)) and continued in FY22 by conducting individual process tests using a chloride salt composition (eutectic NaCl-UCl_3; Thomas and Jackson (2022)). The main motivation for conducting individual process tests using small amounts of salt (i.e., tens to hundreds of grams) is to quickly and cost-effectively gain experience to support engineering-scale testing, including:

- Identifying the safety-affecting processes to measure,
- Developing methods to experimentally simulate the safety-affecting processes, and
- Developing techniques to quantify the safety-affecting processes.

The data generated from laboratory scale tests can also be used for process model development while progress is made towards conducting engineering scale tests. The experience gained during individual process testing was applied to study coupled processes at a laboratory scale in FY23 (Phase 2; Thomas and Jackson (2023)). Conducting integrated process tests at a laboratory scale provided experience in measuring processes simultaneously and informed design considerations for an integrated engineering-scale test system. A conceptual design of the engineering-scale test system was also developed during FY23 (Phase 3; Thomas (2023)). A technique to measure the size and concentration of salt aerosol particles in real time that will be employed in the engineering-scale test system was developed and demonstrated in FY24 (Thomas, 2024). This report on the preliminary design of the engineering-scale test system is a component of Phase 3 that incorporates the experience gained to date from the laboratory-scale tests conducted as part of Phase 1 and Phase 2.

3 Overview of Salt Accident Analysis Facility design

The Salt Accident Analysis Facility (SAAF, pronounced “safe”) is an engineering-scale experimental test system that will be used to simulate aspects of postulated MSR accidents to support safety assessments for reactor licensing. The SAAF will be installed at Argonne in an existing argon atmosphere glovebox and is comprised of two subsystems: the salt transfer vessel and the salt containment system. The accident simulation is initiated by releasing molten salt from the salt transfer vessel at a controlled flow rate into the salt containment system. Molten salt is transferred through tubing by pressurization of the salt transfer vessel with argon gas. The salt containment system receives the transferred molten salt and contains any generated products (e.g., salt aerosol particles, salt splash, evolved gas) to facilitate analysis and maintain safety. The configuration of the salt containment system is adaptable and determined by the simulated accident scenario and evaluated processes. Drawings of the SAAF with an open catch pan configuration of the salt containment system and with a closed vessel configuration of the salt containment system are provided in Figure 2A and Figure 2B, respectively. The salt transfer and containment system surfaces are shown without insulation in Figure 2 to showcase the design features.

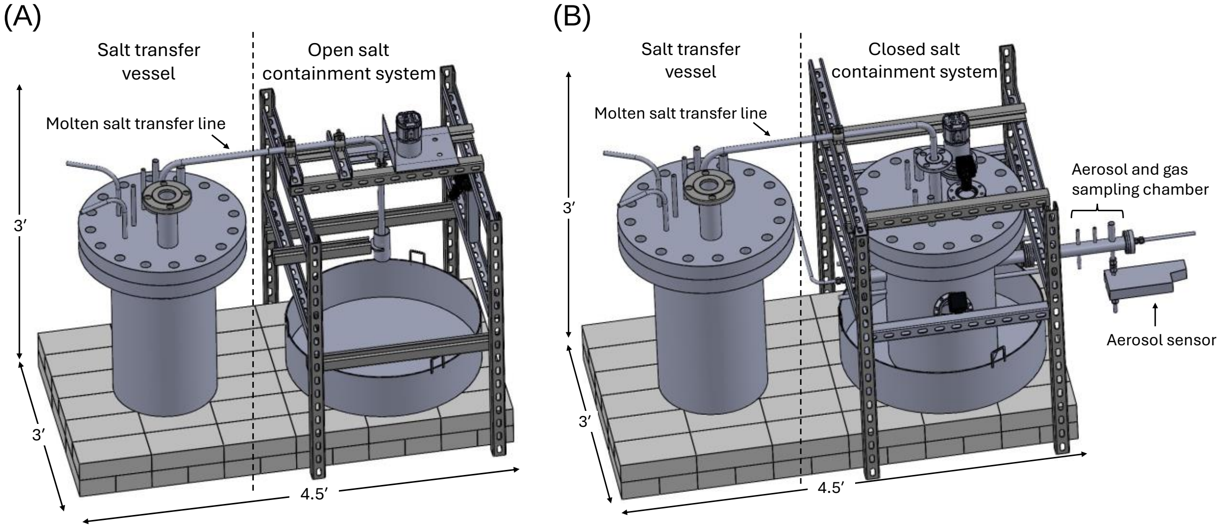

Figure 2: Proposed designs of the SAAF utilizing (A) open and (B) closed configurations for the salt containment system.

The SAAF has been designed to simulate accident scenarios involving the unintended release of molten salt from a containment structure, which may be classified as a spill, leak, spray, or other form of release. A molten salt accident scenario to be evaluated in the SAAF is defined by the combination of variables under investigation, including but not limited to:

- The initial salt release conditions (e.g., flow rate and velocity; initial salt temperature; total salt mass; and orifice size, shape, location, and orientation),
- The environmental conditions in which the salt release occurs (e.g., inert atmosphere, air atmosphere, and relative humidity), and
- The containment features (e.g., catch pan dimension, geometry, and material; containment vessel volume, dimension, and geometry; and insulation material, thickness, and location).

Multiple initial conditions and variables can be tested in the SAAF by changing system components (e.g., using salt transfer tubing with different diameters, nozzles with different orifices, and different containment system atmospheres). Possible test variables are described in Section 5. Accident scenarios to simulate may include:

- A large breach at the base of the reactor vessel and total release of the full fuel salt inventory (i.e., release of large salt volume at a high flow rate).
- A small and low-pressure breach of the primary containment that produces a gradual salt leak (i.e., release of small salt volume at a low flow rate).
- A salt leak through a small orifice (e.g., weld failure in piping) under elevated pressure driven by the pressure head of the salt that produces a molten salt spray.
- Salt interactions with insulation due to unintended molten salt release from insulated piping.

4 Detailed system designs and capabilities

4.1 Rationale for utilizing pressurized transfer of molten salt

Molten salt transfer by vessel pressurization was chosen as the mechanism to simulate salt releases in the SAAF rather than gravity driven mechanisms (e.g., tilt pour) for the following reasons:

- Ease of automation and controllability.
- Ability to achieve flow rates and velocities that are not limited by gravity.
- Flexibility to produce different flow behaviors at the transfer tube outlet and accommodate different containment geometries.
- Ability to replace salt contacting structures (liners and transfer line tubing) in a cost-effective way to minimize cross-contamination.
- Relatively compact design that does not require molten salt to be elevated prior to release, unlike a gravity-driven release.
- Demonstrated transfer of hundreds of kilograms of molten FLiNaK salt from a vessel pressurized by helium gas to a basin during a test for the Aircraft Reactor Experiment (ARE) (ORNL, 1955).

4.2 Design of salt transfer vessel

The salt transfer vessel consists of a pressure vessel within a furnace that heats the salt to the desired initial temperature for the accident scenario being simulated. An annotated drawing of the salt transfer vessel is shown in Figure 3. Molten salt is transferred from the heated pressure vessel to a separate salt containment system through the molten salt transfer line by pressurizing the vessel headspace with argon gas. The inlet of the transfer line will be centered and positioned approximately 0.5 in. above the base of the vessel. This gap between the vessel base and transfer tube inlet will allow molten salt to flow into the tube but will leave a small amount of residual salt in the vessel. The molten salt transfer line will be insulated, heated, and constructed from seamless stainless steel tubing. The transfer line is attached to the pressure vessel lid by flanged connections that are designed to facilitate removal and replacement of the transfer line tubing.

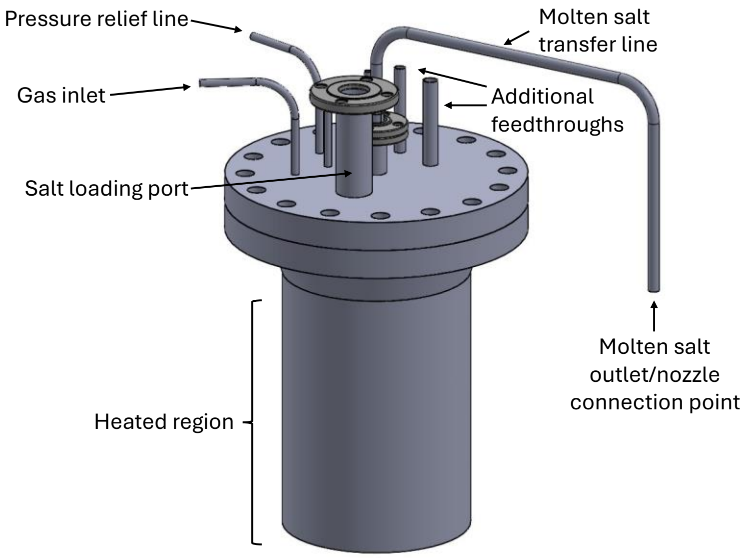

Figure 3: Annotated drawing of the salt transfer vessel.

The salt within the pressure vessel will be contained in a nickel crucible to prevent direct contact between the molten salt and vessel walls. Utilizing a nickel crucible as a liner for the pressure vessel will limit cross-contamination when testing different salt compositions and will minimize salt-induced corrosion of the interior walls. The interior base of the nickel crucible will be tapered towards the center to encourage molten salt pooling near the salt transfer line inlet and to maximize the transferred volume. The pressure vessel is designed with a removable bolt-sealed lid that will enable inspections of the interior and the removal of the nickel crucible. The vessel lid contains a two-inch inner diameter port for loading crushed salt under ambient conditions after the vessel lid and salt transfer line have been secured. A cap is bolted to the salt loading port using flanged connections during heating and pressure-induced molten salt transfer. The key dimensions and operating ranges of the salt transfer vessel are:

- Interior dimensions: 12.25 in. diameter and 22 in. height
- Maximum molten salt volume: 15 L (limited by interior vessel dimensions)
- Minimum molten salt volume: Approximately 0.5 L (limited by volume of residual salt).
- Maximum molten salt temperature: 800 °C (limited by ASME Boiler and Pressure Vessel Code).

- Maximum operating pressure: 10 psig

Figure 4 presents a simplified schematic of the cross-section of the salt transfer vessel that can be used to visualize the pressurization and salt transfer mechanism. To initiate molten salt transfer upon reaching the desired salt temperature within the vessel, the controlled pressurization of the vessel headspace with argon gas is achieved by opening the supply gas valve. The supply gas line incorporates a ballast as an engineering control that will first be pressurized to a desired pressure with the supply gas valve closed and isolation valve open. The isolation valve will then be closed when the desired pressure in the ballast is reached. Only the gas contained in the ballast will be used to pressurize the salt transfer vessel to ensure that over pressurization of the vessel cannot occur. The supply gas valve will be shut off immediately after the target pressure is reached within the vessel. The duration of vessel pressurization should be significantly shorter than the salt transfer duration to ensure that the supply gas line is closed before all the salt is transferred. Salt exiting the vessel while the supply gas valve is closed will cause the pressure within the vessel to decrease over time because the headspace volume will increase as the salt volume decreases. This pressurization protocol ensures safety and will produce representative flow rates and velocities at the transfer line outlet that decrease over time due to the time-dependent loss in pressure head. The gas used to pressurize the vessel may need to be heated to minimize temperature changes to the salt. Supply gas line heating will be investigated during shakedown testing.

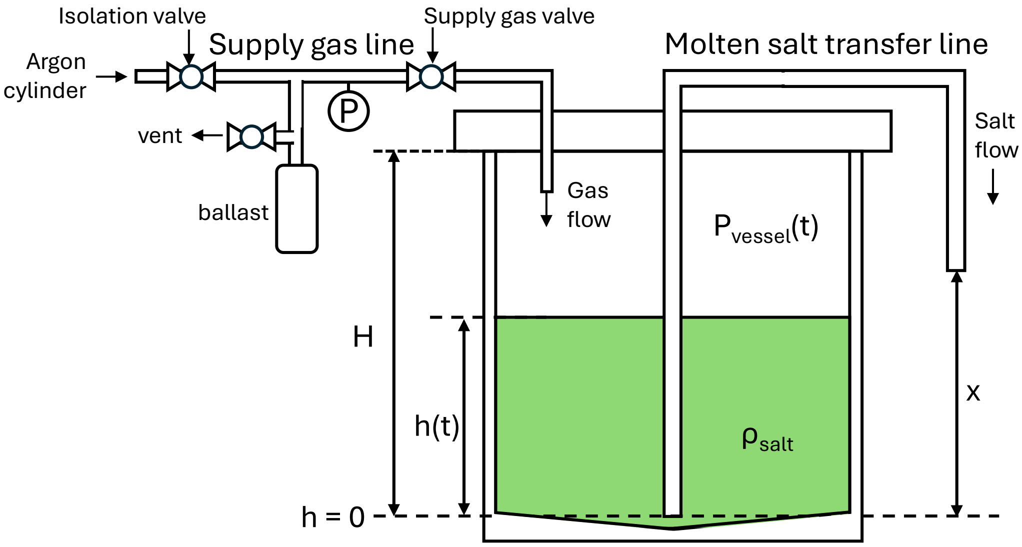

Figure 4: Simplified schematic of salt transfer vessel cross-section used for fluid mechanics equation derivations.

The schematic in Figure 4 was used to derive equations to predict molten salt flow behavior using fundamental fluid mechanics principles. Key system parameters shown in Figure 4 were used in the derivations, including the total interior height of the vessel (H), the salt level (h), the vessel headspace pressure (P_{vessel}), the density of the molten salt (ρ_{salt}), the vertical position of the transfer line outlet relative to the vessel base (x), and time (t). Time-dependent equations for h, P_{vessel}, flow rate at the transfer line outlet, and flow velocity at the transfer line outlet were obtained. The derived equations were used to perform scoping calculations to show the range of flow rates and velocities that the as-designed salt transfer vessel can produce at the transfer line outlet. In addition, the scoping calculations show how flow behavior changes over time as a function of different combinations of initial conditions and system properties, including the initial vessel headspace pressure (P_0), the transfer line inner diameter (d), the initial salt level in the vessel (h_0), and x. The results of the scoping calculations are presented in Figure 5, and descriptions of the scenarios that were evaluated are provided in Table 1.

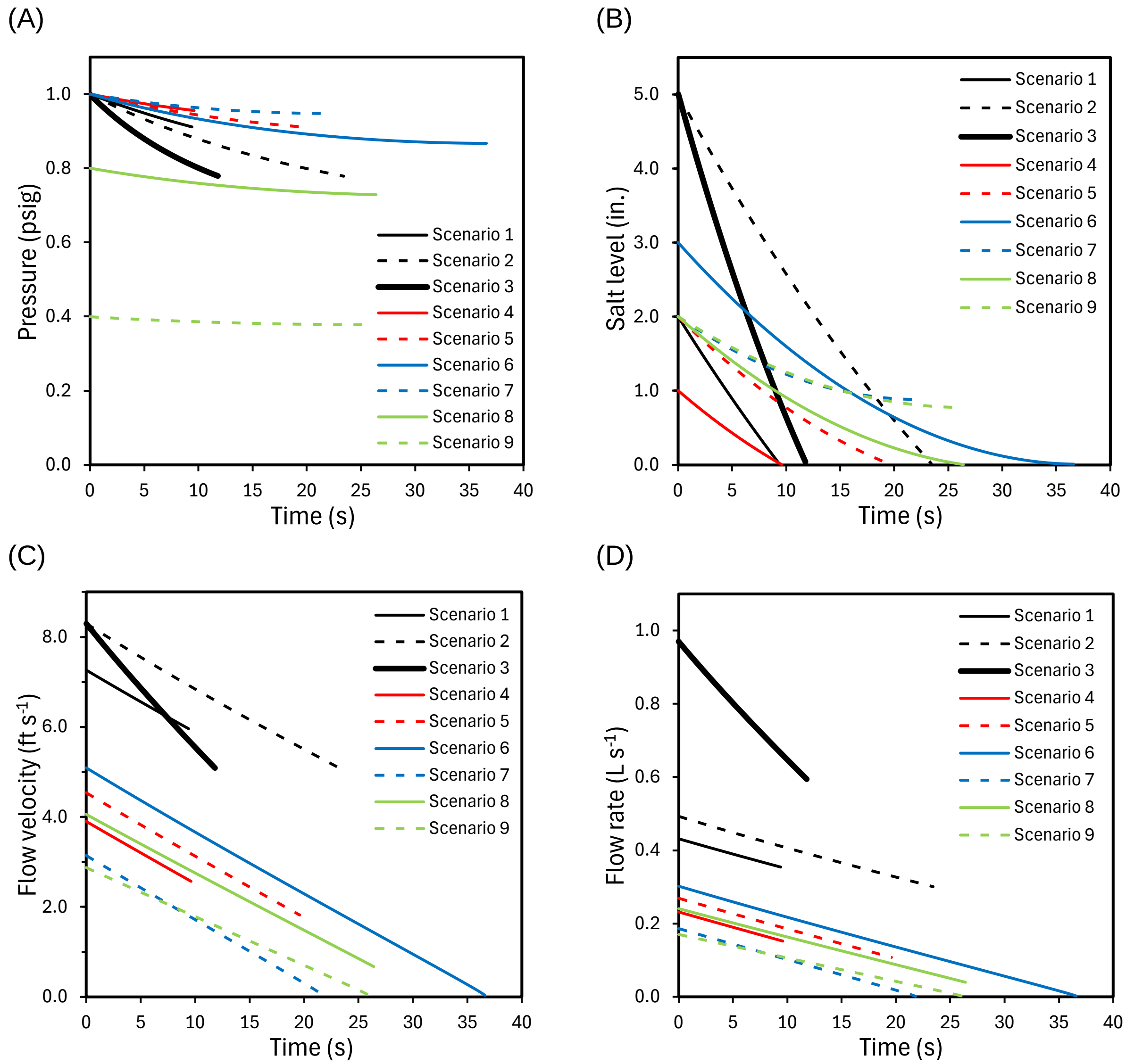

Figure 5: The (A) vessel headspace pressure, (B) salt level in vessel, (C) flow rate at transfer line outlet, and (D) flow velocity at transfer line outlet during the salt transfer process for different modeled scenarios of molten salt transfer.

The curves plotted in Figure 5 correspond to the period of active molten salt transfer, which ceases when either the salt level reaches zero (i.e., drops below the transfer line inlet) or when the salt velocity and flow rate at the transfer line outlet reaches zero. The combinations of initial conditions and system properties for Scenarios 6, 7, and 9 do not provide enough driving force to transfer all the available molten salt out of the vessel (excluding the small amount of residual salt remaining in the tapered bottom). For these scenarios, the salt velocity and flow rate at the transfer line outlet reach zero with available molten salt remaining in the vessel. Other combinations of initial conditions and system properties in Table 1 lead to all of the molten salt being transferred out of the vessel (salt level reaching zero) before the salt flow rate and velocity reach zero.

Table 1: Summary of initial conditions and system properties for modeled scenarios [a]

Scenario	d (in.)	P_0 (psig)	h_0 (in.)	x (in.)	Total salt volume released (L)
1	0.31	1	2	6	3.7
2	0.31	1	5	6	9.3
3	0.435	1	5	6	9.3
4	0.31	1	1	12	1.9
5	0.31	1	2	12	3.7
6	0.31	1	3	12	5.6
7	0.31	1	2	14	2.1
8	0.31	0.8	2	10	3.7
9	0.31	0.4	2	6	2.3

[a] The salt density (ρ_{salt}) was assumed to be 2 g cm^{-3} for all scenarios.

Results from scenarios that differ by the value of one variable in Table 1 (e.g., Scenarios 1 and 2) were compared to show how molten salt flow behaviors are affected by the initial vessel pressure, initial salt level, transfer line inner diameter, and vertical position of the transfer line outlet. A higher initial salt level (h_0) will produce higher flow rates and flow velocities at the transfer line outlet due to the greater pressure head (compare results from Scenarios 1 and 2). Likewise, placing the transfer line outlet at greater heights above the initial salt level (i.e., greater values of x minus h_0) will decrease the molten salt flow rate and velocity at the outlet (compare Scenarios 1, 5, and 7). Utilizing larger diameter salt transfer line tubing will produce the same initial flow velocity at the outlet but yield a higher salt flow rate (compare Scenarios 2 and 3). The flow velocity over time will decrease at a higher rate when the transfer line tubing diameter is larger because larger diameter tubing results in salt being removed from the vessel at a higher flow rate, which leads to a higher rate of pressure head loss.

The scoping calculations were performed assuming no pressure head loss due to friction and a constant molten salt density of 2 g cm^{-3} for simplicity. The actual flow rates and velocities of molten salt at the transfer line outlet will differ slightly from what has been presented in this section. However, the results of the calculations provide insights into trends and the sensitivities of the flow behaviors to system parameters. The calculated flow rate and flow velocity through the transfer line outlet will decrease with increasing salt density. In addition, nozzles can be attached to the transfer line outlet to significantly affect the flow velocity and behavior of the molten salt at the outlet (i.e., to induce sprays). The scoping calculations did not assess the effect of adding nozzles. Very low flow rates (i.e., drips of molten salt) can be achieved by incorporating a funnel with a small orifice at the outlet of the molten salt transfer line to produce gravity-driven flows.

4.3 Design of salt containment system

Molten salt will be released from the salt transfer vessel at a controllable flow rate into a modifiable containment system that is configured to measure the target processes. The salt containment system will have two primary configurations: a catch pan that is open to the glovebox atmosphere and a closed vessel that is isolated from the glovebox atmosphere. The designs of these two configurations are described in this section. Section 6 provides details on the processes to be quantified within the salt containment system and techniques and guidelines for measurement.

The open catch pan design will be employed in tests with lower velocity salt releases (e.g., to assess molten salt spreading). An annotated drawing of this salt containment system is provided in Figure 6A. A profile view and top section view of the same system are provided in Figure 6B and Figure 6C, respectively. Tests to study lateral spreading on a flat surface require a larger footprint. An open-atmosphere design was selected to minimize the size of the containment structure. Insulation will be placed at the underside of the catch pan and potentially around the outer walls. A metal frame will support the molten salt transfer line and measurement equipment such as infrared and visible light cameras and thermocouples. A stainless steel tube that encapsulates the transfer line outlet (i.e., spray guard) will contain any outward lateral spray to prevent molten salt deposition on sensitive areas. Salt sprays can be intentionally generated and assessed in the closed vessel configuration of the salt containment system.

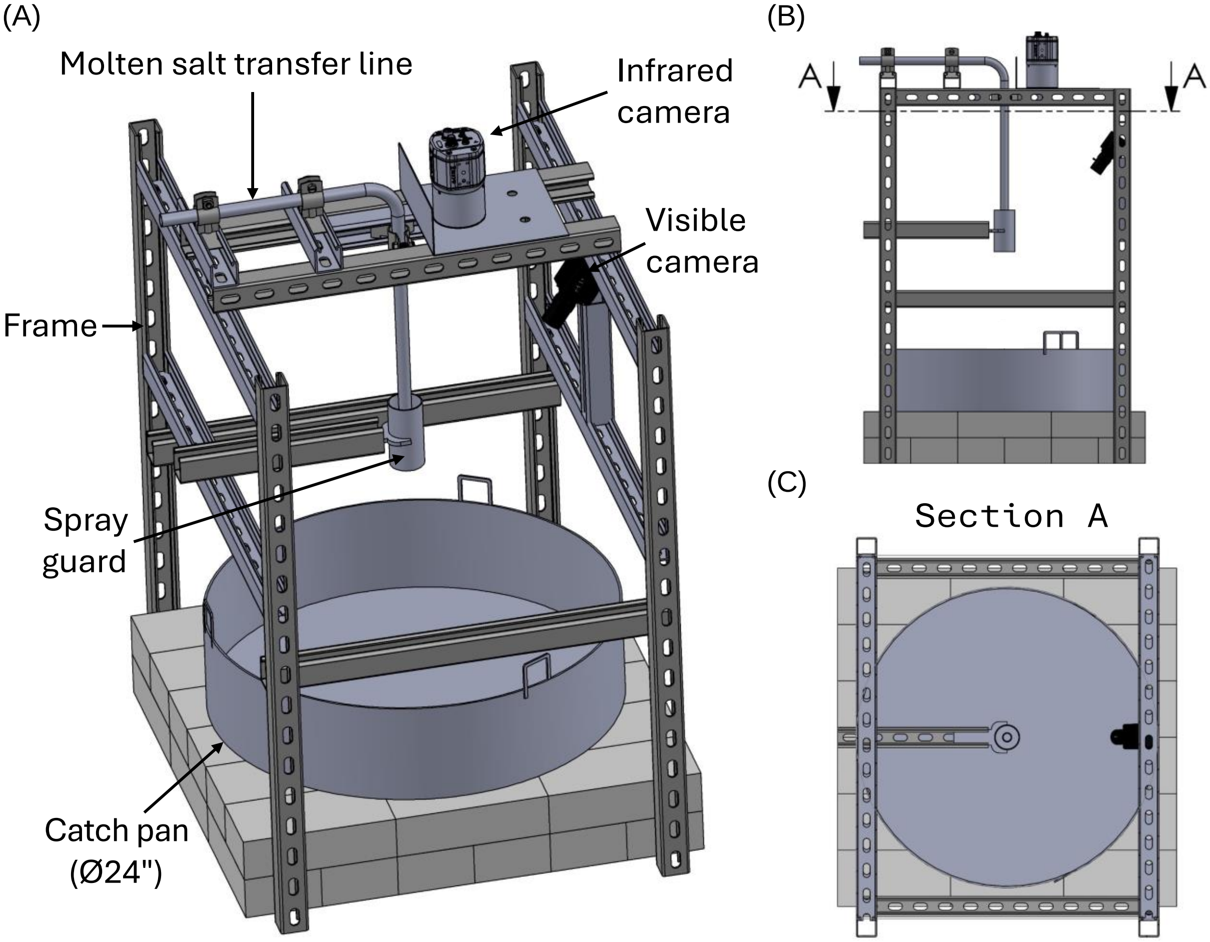

Figure 6: (A) Annotated drawing, (B) profile view, and (C) top view from Section A of the open-atmosphere catch pan configuration of the salt containment system.

The closed vessel configuration of the salt containment system is isolated from the glovebox atmosphere to contain high velocity salt releases (i.e., those producing salt sprays or jets that impact surfaces with significant force) and any gaseous or particulate products that are produced. An annotated drawing of the closed vessel configuration of the salt containment system is provided in Figure 7. Like the salt transfer vessel, the salt containment vessel is designed with a removable bolt-sealed lid to enable interior access. Tests in the closed vessel will be able to be conducted in different atmospheres (e.g., in air) and will be designed to contain generated gases and aerosol particles to facilitate sampling the gas space. The vessel walls and lid contain multiple feedthroughs that can be used to flow gas into the vessel, sample gas from the vessel, install thermocouples, and connect sensors for real-time monitoring of aerosol particle properties and gas composition. For tests conducted in an air atmosphere, air from a compressed air cylinder will flow into and out of the salt containment vessel through tubing vented to the glovebox exhaust to prevent air release into the argon atmosphere glovebox that houses the SAAF. Viewports with wavelength-selective windows protrude diagonally from the vessel walls and vertically from the vessel lid to enable infrared and visible light cameras to view the vessel interior. The salt containment vessel can be conveniently placed on the catch pan used in the open-atmosphere configuration to optimize space usage when alternating between containment systems. The drawing in Figure 7 shows the downward-facing cameras without their supports and the vessel without insulation to provide a clearer view of the system components and their relative positions. Figure 8 presents additional views of the closed vessel configuration of the salt containment system.

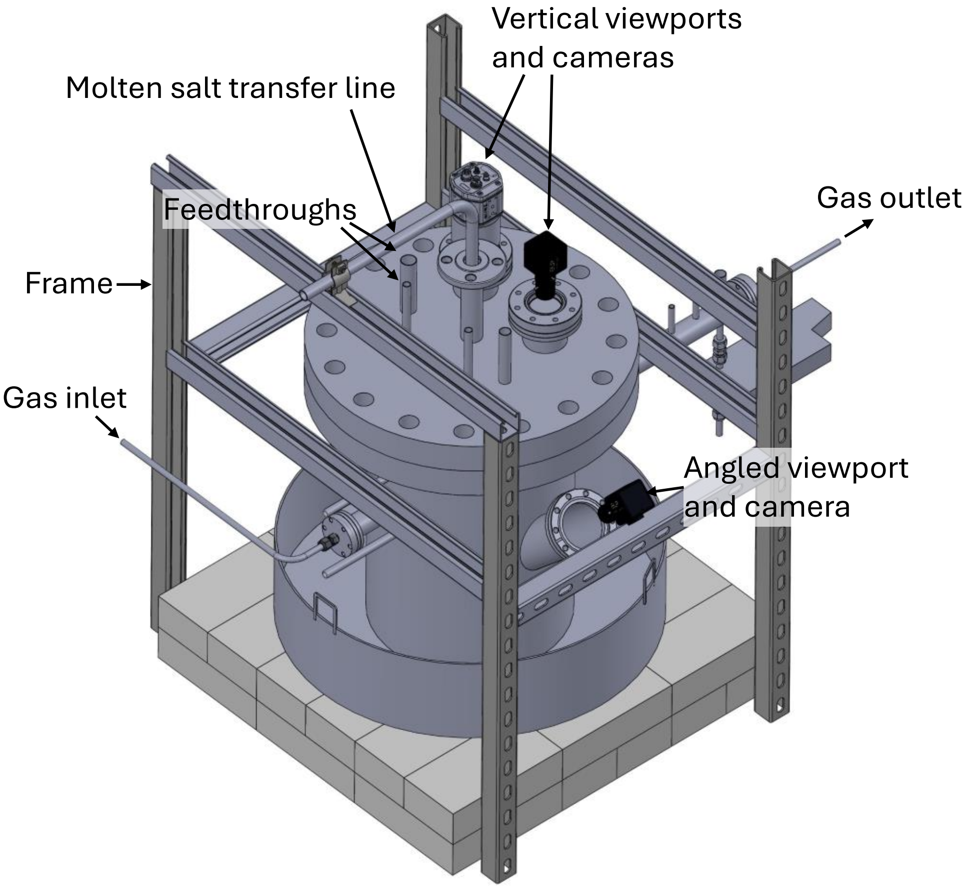

Figure 7: Annotated drawing of the closed vessel configuration of the salt containment system.

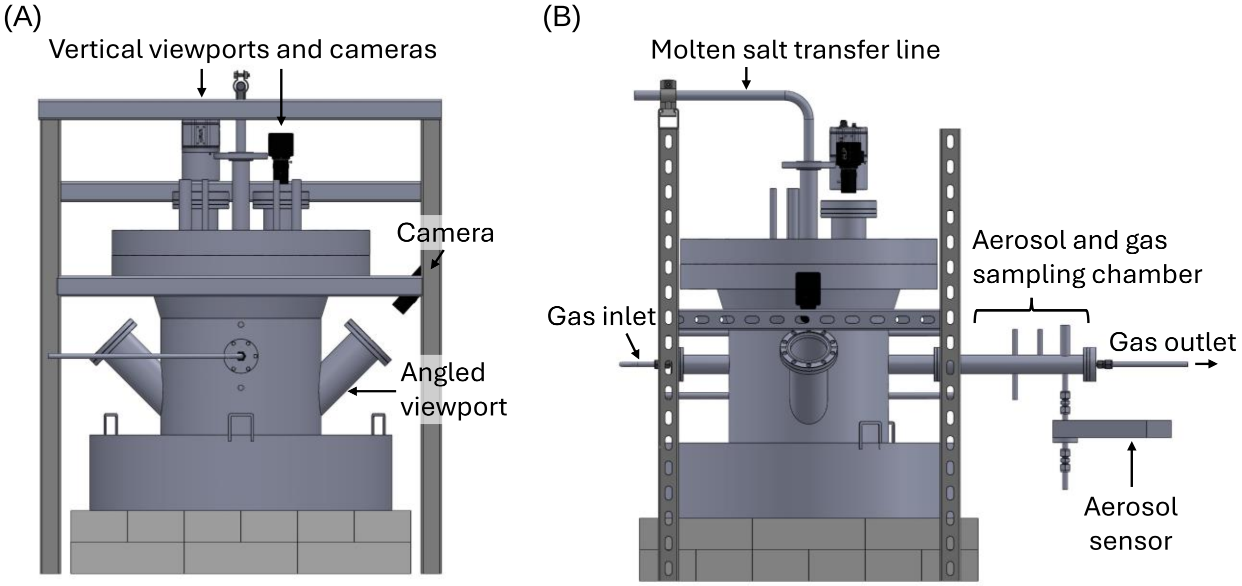

Figure 8: Profile of the closed vessel configuration of the salt containment system viewed from the (A) front and (B) side.

5 Test variables

The accident scenarios that will be simulated in the SAAF will be defined by the combination of different variables that are tested. The variables that can be tested in the SAAF are discussed in this section.

5.1 Conditions of the salt release

The conditions of the salt release include the total mass of salt used, the flow rate and velocity of molten salt as it is released, the dimensions and location of the outlet orifice, the initial salt temperature, and the distance between the transfer line outlet and catch pan (i.e., the drop height). Scoping assessments performed using the MELTSPREAD code for different ex-vessel molten salt spreading scenarios indicated that the flow rate of salt as it impinges on the catch pan has the greatest effect on molten salt spreading, surpassing the effects of salt thermophysical properties and initial salt temperature (Thomas et al., 2021, 2022). The velocity and flow rate of the released salt will decrease over the duration of the simulated accident due to the method that will be used to pressurize the salt transfer vessel (see Section 4.2). The velocity of the salt as it impinges on the catch pan surface will affect splatter and aerosol formation and can be varied by changing the orifice size of the transfer line outlet, the drop height, and the initial pressure of the salt transfer vessel headspace (as demonstrated in Section 4.2). A smaller orifice, a taller drop height, and a higher initial vessel pressure will produce higher velocity impacts. The temperature of the salt that is released will have a significant effect on the vaporization rate of volatile surrogate fission products during tests.

The wide range of salt release conditions that can be represented with the SAAF enables the simulation of diverse accident scenarios. Transferring a large mass of salt at a high flow rate into a catch pan in the salt containment system would simulate a large breach of the reactor vessel that rapidly releases a large amount of the fuel salt. Another accident scenario to simulate could be a small breach in the piping of the primary loop that leads to a small amount of the fuel salt slowly leaking onto a catch pan. A funnel could be placed at the outlet of the salt transfer line to produce a low flow rate of salt onto the catch pan (i.e., drips). A low salt leak rate was chosen for the “maximum credible accident” scenario for the MSRE (Beall and Guymon, 1965; Beall et al., 1964). Testing high velocity leaks through a small orifice at the transfer line outlet would simulate a leak through a pinhole that could produce sprays that generate significant quantities of radionuclide-bearing aerosols due to jet breakup or mechanical breakup upon surface impact.

5.2 Environmental conditions

Postulated MSR salt release accidents could occur under an inert atmosphere (e.g., Ar or N_2 gas with low O_2 and H_2O content) that is maintained within a primary containment layer, an atmosphere that is a mixture of inert gas and air produced by air ingression into the primary containment, or under an air atmosphere. Tests in the SAAF can be conducted under an inert argon atmosphere that will be provided by the argon atmosphere glovebox that houses the facility. In addition, tests can be conducted under mixed argon-air and air atmospheres that can be maintained within the sealed vessel configuration of the salt containment system. The relative humidity of air atmospheres is also of interest due to the known and anticipated effects that O_2 and H_2O absorption by salt have on salt chemistry, salt redox potential, salt thermophysical and thermochemical properties, and salt wetting behavior. Relative humidity in the containment vessel atmosphere can also be investigated. Running tests under inert gas, dry air, and humid air (e.g., 80% relative humidity) atmospheres should bound the possible atmosphere compositions for salt accident scenarios. Stringent engineering controls to contain and mitigate the effects of corrosive gas generation will be required when tests are run in humid air atmospheres (see Section 7.5).

The temperature of the salt containment vessel atmosphere can also be elevated from ambient temperature using heaters to create conditions that are realistic to containment atmospheres of MSRs. For example, a MELCOR simulation of a molten salt spill accident showed that the temperature of the reactor cell atmosphere reached nearly 500 °C (Luxat and Wieselquist, 2022).

5.3 Containment configuration, materials, and insulation

Features of the catch pan in both configurations of the salt containment system can be changed to test different accident scenarios including catch pan dimensions, geometry, wall thickness, and material. A large-diameter cylindrical catch pan would be ideal for tests that investigate molten salt spreading without obstruction. In this scenario, spreading could be modeled in one dimension (radially) and heat transfer could be modeled in two dimensions (radially and as a function of depth). A smaller-diameter cylindrical catch pan can be used to investigate the cooling and radionuclide release behavior from accumulated molten salt pools. The catch pan will absorb heat from the salt, and the amount of heat absorbed will increase with increasing wall thickness. Catch pans made of different materials (e.g., stainless steel and carbon steel) and surface roughness can also be tested. Surface roughness is known to affect the wetting behavior of molten salts (Grosu et al., 2019) and will likely influence the spreading behavior. All tests will be conducted using insulation at the underside of the catch pan or salt containment vessel to prevent significant heating of the glovebox floor and to simplify the heat transfer model that applies to the system by minimizing heat transfer pathways. The use of insulation on the outer catch pan walls can be treated as a test variable. Finally, the salt containment subsystem of the SAAF can be adapted from what is presented in Section 4.3 to accommodate testing molten salt spreading on a sloped catch pan that drains though tubing into a storage tank. This salt containment configuration can be employed to investigate the function of a drain tank safety feature for containing fuel salt spills that is being considered for some MSR designs.

5.4 Salt composition

Surrogate fuel salt compositions that represent either thermal spectrum (i.e., fluoride-based) or fast spectrum (i.e., chloride-based) MSRs can be tested in the SAAF. These compositions will consist of the base salt with added depleted uranium and surrogates to represent transuranic elements and fission, corrosion, and activation products. The use of surrogates for radioactive salt constituents to simulate accidents using kilograms of molten salt is a cost-effective strategy that will provide the physical and chemical insights needed for model development.

Salt compositions can simulate a variety of burnups that are inspired from the results of depletion calculations for MSRs (Fei et al., 2022; Lo et al., 2022; McMurray et al., 2021; Taube, 1978), experimental analyses of fuel salt inventories (i.e., from the MSRE; Compere et al. (1975)), knowledge of decay chains, radiotoxicity, the anticipated influence on the source term and other safety factors, and uncertainties in transport and retention behavior. Salt compositions can be simplified by grouping elements with similar expected chemical behavior as was done for a demonstration of the application of MELCOR for MSRs (Luxat and Wieselquist, 2022). A FLiNaK-based surrogate fuel salt composition was determined and tested in laboratory scale simulation of a salt spill accident (Thomas and Jackson, 2023). This FLiNaK-based surrogate fuel salt composition can serve as a basis for selecting fluoride-based compositions to test in the SAAF. The thermophysical and thermochemical properties of the surrogate fuel salt compositions as a function of temperature will need to be known (or reasonably estimated) for the results from tests conducted in the SAAF to be useful for model development. The effects of impurities (e.g., surrogate fission products) on the thermophysical properties of molten salts are being evaluated under the MSR Campaign (Rose et al., 2023).

5.5 Simulation of decay heat

The heat released due to radioactive decay (i.e., decay heat) during an accident can have undesired radiological and structural consequences including enhanced release of volatile radionuclides and corrosive gases and the uncontrolled heating of the catch pan and underlying materials (e.g., concrete). Decay heat in a pool of accumulated molten salt in the salt containment system can be simulated in the SAAF by using a heating element. Artificially simulating decay heat by immersing a heating element into the molten salt pool may create artifacts that affect some measurements. For example, vapor condensation and aerosol deposition could occur on the exposed region of the heating element and affect aerosol measurements.

5.6 Simulation of fission and sparge gas presence in salt

Prior to salt transfer for accident simulation in the SAAF, the molten salt can be sparged with inert gas to introduce bubbles that simulate those expected to be present in the fuel salt of an MSR due to the in-situ production of gases (i.e., noble gas fission products, tritium, radiolysis products, and highly volatile halides) and use of sparge gases (Shahbazi et al., 2022). The initial presence of bubbles is expected to influence radionuclide dispersal during a salt release accident due to those bubbles bursting and releasing radionuclide-bearing droplets upon impact with a surface. The type of gas used and the duration of sparging can be test variables to assess the impact of entrained gas on accident consequence.

5.7 Simulation of salt leaking through insulation at transfer line outlet

A rupture in insulated piping could lead to molten salt leaking through the insulation, which may obstruct the flow and lead to chemical reactions between the salt and insulation. The SAAF can be used to assess molten salt flowing through insulation at the transfer line outlet. The presence of insulation and the type and thickness of insulation would be test variables.

6 Processes to quantify and associated measurement techniques

6.1 Flow characteristics of the molten salt during release

The flow behavior of molten salt from the transfer line outlet should be characterized and measured, if possible, during the accident simulation because it defines, in part, the accident and determines the accident progression pathway. The spray pattern and the flow velocity of a jet of molten salt at the outlet of the transfer line can be measured by using a high-speed camera. The flow behavior of molten salt through insulation can also be quantified using footage from a high-speed camera. The mass flow rate of molten salt spilling into a catch pan can be measured in real time by using a data logging scale. This measurement would require placing the balance underneath an insulated catch pan, confirming that the combined mass of the catch pan and the released salt is less than the balance weight capacity, and ensuring that the flow rate of the salt is slow enough to be reliably recorded. The accuracy of using a data-logging balance (Mettler Toledo MS32001L/03) to measure mass flow rate was demonstrated by measuring the mass of water accumulating in a catch pan at a known flow rate over time and is described in Thomas and Jackson (2023). The tested balance recorded mass at 0.083 second intervals and has a two second settling time. This resulted in some oscillation in the measured mass when compared to the known spilled mass. A data logging balance such as the one tested with water would be appropriate for estimating the mass flow rate of relatively long duration releases of molten salt that occur for at least ten seconds. When measurements are challenging, models of the flow of molten salt from the salt transfer vessel and into the salt containment system could be developed using computational fluid dynamics (CFD) to understand how different initial conditions produce different flow behaviors at the transfer line outlet.

6.2 Molten salt spreading on catch pan and draining through tubing

Molten salt that is unintentionally released during an accident will spread until movement is halted due to salt freezing, salt surface tension force, or physical obstruction. The spreading behavior of molten salt must be understood when modeling accident progression because the extent of spreading can affect the vaporization rates of radionuclides (surface area exposed to atmosphere), the time for the salt surface to freeze and halt radionuclide vaporization, and the duration that molten salt contacts structures and threatens their integrity. The spreading behavior of the molten salt will depend on the conditions of the release (e.g., flow rate and velocity), the thermophysical properties and wetting behavior of the salt, and the conditions of the ambient environment.

Molten salt spreading can be assessed in either configuration of the salt containment system discussed in Section 4.3. The open-atmosphere configuration shown in Figure 6 is specifically intended for spreading tests. The released molten salt will spread laterally on the catch pan until it comes to rest as a static pool with a final geometry that depends on the postulated accident scenario being tested. A camera that records in the infrared region of the electromagnetic spectrum rather than the visible light region is the recommended tool to quantify the spreading behavior of molten salt on a metal substrate (i.e., catch pan). This is because optically transparent salts will be difficult to distinguish from the catch pan in images collected with a visible-spectrum camera due to insufficient color contrast between the materials. Color contrast between two materials in an image captured by an infrared camera is provided both by differences in the emissivities and temperatures of the materials. Quantifying the spreading behavior of FLiNaK and eutectic NaCl-UCl_3 on a sloped stainless steel catch pan using an infrared camera was demonstrated in laboratory scale tests conducted at Argonne (Thomas and Jackson, 2021, 2022). Both tested salts have emissivities that are greater than 0.9 (estimated from cooling curve using known melting temperature) and were easily distinguished from the polished stainless steel substrate (approximate emissivity of 0.3). Measurable parameters of spreading behavior such as the leading edge position and the total covered area of salt on the substrate over time since first impact can be determined by analyzing frames of an infrared video. Image analysis typically involves converting each frame of the video into a binary image using image processing software, where the pixels of the salt are assigned a "1" and the pixels of the substrate are assigned a "0". Objects of known dimension in the field of view of the camera enable the calibration of pixel size so that distances and areas can be quantified. Time-dependent temperature measurements made by the infrared camera can provide cooling curves for the salt at each pixel to indicate the time at which the salt surface solidifies (i.e., to show when latent heat phase occurs). There are limitations for using an infrared camera to measure temperature (see Section 6.3).

The camera will have to be placed at a sufficient height above the substrate used for spreading measurements to ensure that the area of interest is in the field of view. Past laboratory scale molten salt spreading tests employed an infrared camera with a wide 42° lens (FLIR T540) to measure a larger area without having to place the camera at an impractical height. The lens of the infrared camera as drawn in Figure 6 is 3.5 inches from the center of the catch pan and would need to be at least 40 inches above the catch pan base to include the entire catch pan in the field of view. The infrared camera as drawn in Figure 7 views through a 1.9-inch diameter window of a viewport with an inner diameter of 2.6 inches, and the camera lens is 4.5 inches from the center of the containment vessel. For a camera with a 42° lens, the viewport length would have to be less than 3.4 inches, and the camera would have to be at least 27 inches above the containment vessel base to ensure an unimpeded view of the vessel interior.

A catch pan with drain could be added to the design shown in Figure 6 to study molten salt flowing and freezing behavior during gravity driven flow by simulating spilled salt draining into a passively cooled drain tank. Tests on this subject could reveal the conditions that lead to freezing and fully blocking the tubing or could test the efficacy of freeze plugs.

6.3 Heat transfer from salt to surroundings and effect of decay heat

The heat transfer behavior of salt to its surroundings affects the safety outcome of an accident by determining the duration that molten salt is in direct contact with containment structures (structural integrity) and by determining the salt surface temperature and time of freezing (radionuclide vaporization rate). Decay heat should be simulated in some tests to accurately represent the heat generated due to the radioactive decay of fission products present in ex-vessel fuel salt. The residual power density in the fuel salt immediately after shutdown is expected to be approximately 5% of the nominal power (Allibert et al., 2016; Thomas and Jerden, 2020). A rise in salt temperature caused by decay heat could significantly increase the rate of radionuclide vaporization or lead to degassing of the concrete beneath the catch pan.

Quantifying heat transfer and the effect of decay heat in tests run at the SAAF will provide the data needed to validate the heat transfer models that will be incorporated into accident progression codes for MSRs. This can be done by measuring the temperature of the salt, the surfaces of containment structures, and the atmosphere of the salt containment system over time as the salt from the simulated accident cools. Decay heat can be simulated using a heating element for accident scenarios that involve the accumulation of a pool of molten salt in a catch pan. The formation of a solid crust layer at both the salt-catch pan and salt-atmosphere interfaces will affect heat transfer because the solid layer may possess different thermal properties than the molten salt (i.e., act as an insulator). Crust formation will need to be included in models but direct measurements to quantify crust formation will be challenging and would require temperature measurements with fine spatial resolution along the depth of the salt.

Insights gained from using infrared cameras and thermocouples to measure the temperature of molten salts and metal surfaces during laboratory scale testing (Thomas and Jackson, 2021, 2022, 2023) are briefly discussed in the remainder of this section. The primary advantage of using an infrared camera to measure the surface temperature of materials is that it is a contactless measurement. The limitations and considerations for using infrared cameras to measure surface temperature during testing in the SAAF include:

- The emissivity of the material as a function of temperature must be known to correct measurements made by an infrared camera and obtain actual temperature. The emissivities of most molten salt compositions are unknown. The emissivity of FLiNaK and eutectic NaCl-UCl_3 have been estimated from salt cooling curves measured using an infrared camera and are above 0.9 (Thomas and Jackson, 2022). Temperature measurements made using an infrared camera will be more accurate for high emissivity materials (emissivity near 1) because the required emissivity correction is minor. Metal surfaces tend to be highly reflective of infrared radiation and have low emissivities. Low emissivity materials are typically coated with a high emissivity material (i.e., temperature compatible matte-finish paint) to avoid having to make large corrections to infrared camera-measured temperatures.
- Thin layers of molten salts can be transparent to infrared radiation, as has been observed for eutectic NaCl-UCl_3 spreading on a stainless steel sheet (Thomas and Jackson, 2022). For salts that transmit infrared radiation, the temperature measured by the infrared camera does not solely represent the salt surface temperature but is also affected by the internal salt temperature and possibly the temperature of the material below. An infrared camera will not be used to measure the surface temperature of thin salt layers because the measured apparent temperature would need to be corrected using both the transmissivity and the emissivity of the salt. Whether the salt layer is thick enough for reliable temperature measurements made by using an infrared camera can be assessed from the cooling curve that is measured at each salt pixel (by comparing known and measured salt freezing temperature).

- The camera must be placed at a sufficient height to ensure that the entire material is visible in the field of view, as described in Section 6.2. Objects of known dimension should be placed within the field of view to calibrate the spatial scale.

Single- or multi-junction thermocouples can be employed to measure vertical and lateral temperature gradients in sufficiently deep pools of salt that have accumulated in the salt containment system. The considerations and limitations for using immersed thermocouples to measure salt temperature include:

- The thermocouple sheath should be composed of a material that sufficiently resists corrosion when contacted by molten salt to prevent corrosion products from contaminating the salt.
- Grounded junction and thinner diameter thermocouples provide a faster temperature response when compared to ungrounded and wider diameter thermocouples. Thinner

diameter thermocouples will have shorter lifespans when used to directly measure molten salt temperature and grounded junction thermocouples are subject to electrical interference.

- Thermocouples immersed in molten salt can provide a local heat sink due to the high thermal conductivity of the metal sheath relative to the salt (Thomas and Jackson, 2022). This heat-sink effect can be minimized by using thinner thermocouples (lower thermal mass) and by insulating the part of the thermocouple sheath that is exposed to the atmosphere. The number of immersed thermocouples used should be limited to avoid affecting the heat transfer behavior of the salt.

The temperature of metal surfaces (e.g., underside and walls of catch pan) can be measured by using thermocouples with beaded or bare wire junctions suitable for surface attachment. Considerations for surface temperature measurements made by using thermocouples include:

- Obtaining accurate temperature measurements requires that the thermocouple junction have good thermal contact with the surface and be fully encapsulated with a thermally-conductive material.
- Thermocouple junctions for surface temperature measurements can be attached to the surface using thermally conductive but electrically insulating cement. The cement bond should be reinforced by using a high-temperature epoxy to prevent fractures of the cement due to physical contact or when placed under vacuum for transfer into the SAAF glovebox.
- The thermocouple junction could be attached to the metal surface directly by spot welding, but the metal-on-metal contact may introduce electrical noise in the measured signal.

6.4 Salt aerosol concentration, size distribution, and composition

Aerosols are liquids or solids that are suspended in a gas and are capable of remaining suspended for prolonged periods. For this reason, the formation of radionuclide-bearing aerosols due to an accident in a nuclear facility is a potential pathway for the release of radioactive material to the environment and has significant implications for the accident source term. Radionuclide-bearing aerosols in the respirable size range are particularly hazardous because they can deposit in the respiratory tract when inhaled and expose internal organs to radiation. The formation mechanisms and properties of radionuclide-bearing aerosols generated under different accident scenarios involving molten fuel salt were recently identified as significant knowledge gaps that must be filled to meet the requirements of MSR licensing (Holcomb et al., 2021; Shahbazi et al., 2022). The mechanisms of radionuclide-bearing aerosol formation that are possible during a molten fuel salt accident include vapor condensation, mechanical breakup of salt from impact on surfaces, jet breakup from pressurized sprays, bubbles bursting at the molten salt surface, and radioactivity (e.g., beta recoil) (Shahbazi et al., 2022).

Aerosol formation from surrogate fuel salt will be investigated in the SAAF using the closed vessel configuration of the salt containment system shown in Figure 7 and Figure 8. Real-time measurements of aerosol concentration, size distribution, and composition will be required to produce data at the necessary temporal resolution to support accident progression model development. This is because aerosol properties will change over time as formation mechanisms change and as generated aerosol particles aggregate, experience thermophoresis-induced transport and deposition, and react with the environment. For example, mechanical processes such as splashing and bubble bursting may be the dominant aerosol formation mechanisms during an active molten salt spill event. However, aerosols may still form from the static pool of accumulated molten salt after the active spill has stopped due the vapor condensation mechanism. These aerosols may have significantly different characteristics than those formed due to mechanical processes during the active spill. An accurate accident progression model would need to predict changes in aerosol properties and formation rates over time.

Aerosol measurement technology and the relevance to aerosol modeling for molten salt systems has been thoroughly summarized in Shahbazi et al. (2022). Real-time characterization of salt aerosol particles was recently developed and demonstrated using cesium iodide salt particles that were generated by condensing salt vapor (Thomas, 2024). This method uses optical light scattering to measure particle size distribution and concentration in real time and will be employed in the SAAF. An optical light scattering technique was selected over other techniques (e.g., time of flight-mass spectrometry; TOF-MS) due to the capabilities and features of a commercially available spectrometer system that are compatible with the SAAF test system:

- The sensor (welas®) is compact and separate from the controller (Promo®). The controller will be located outside of the SAAF glovebox and connected to the sensor with fiber optic cables. This will conserve space and expose only the sensor to the conditions in the SAAF.
- Only the interior of the sensor cuvette contacts the gas stream being sampled. The cuvette can be constructed from corrosion-resistant materials (e.g., Hastelloy), can withstand gas temperatures up to 450 °C (material-dependent), and is easily replaceable. This sensor design will withstand the corrosive and high temperature gas streams expected to be generated in the SAAF.
- The aerosol measurement is non-destructive, which will enable the integration of other in-line measurement equipment or the collection of aerosol particles on compatible filters for future analysis. Post-test filter analyses could include gravimetric concentration determination and elemental composition determination by using inductively coupled plasma-mass spectrometry (ICP-MS).
- The particle concentration measurement can be calibrated to work for any gas composition and at any gas temperature within sensor cuvette operational limits. This is a requirement for the real time aerosol measurement technique because accidents will be simulated under different atmospheres in the SAAF.
- Sensor cleaning and calibration are performed by the user. Other technologies required that the sensor be shipped to the manufacturer for calibration and cleaning, which is not practical for a sensor that will be contaminated with radiological material during testing.
- The sensor is capable of a wide range of size and concentration measurements. The welas® 2070 HP sensor model can measure particles with diameters between 0.2 µm and 40 µm and concentrations between 1 and 10^6 particles per cm^3.

Aerosol characterization and gas composition measurements will be performed in the aerosol and gas sampling chamber (1.5″ OD 316 stainless steel tube) that extends laterally from the body of the salt containment vessel (see Figure 8B). The aerosol sensor line extends vertically below from the main outlet tubing and does not incorporate any bends to mitigate particle deposition on tubing walls. A mass flow controller and vacuum pump draw particle-bearing gas from the head space of the containment vessel and through the aerosol sensor cuvette at a constant flow rate. The aerosol sampling configuration to be used in the SAAF is the same as what has been previously developed for laboratory scale tests so experience gained at a laboratory scale can translate to the engineering scale (Thomas, 2024). It is possible to collect aerosol particles within the aerosol and gas sampling chamber using adhesive coupons for size and composition determination of single particles by using scanning electron microscopy with associated energy-dispersive X-ray spectroscopy (SEM-EDS), as demonstrated previously (Thomas, 2024).

One drawback of the optical light scattering technique is that it measures the actual physical size of the particles and not the aerodynamic diameter, which is a measure of the true airborne behavior of the particle and a better property for parameterizing aerosol transport models. TOF-MS measures aerosol aerodynamic diameter but TOF-MS instrumentation that is compatible with high temperature, corrosive, and non-air gas streams are not commercially available. The optical light scattering spectrometer obtains particle size from the measured scattered signal using a calibration curve generated from standard spherical particles of known size and refractive index. The measurement can be corrected for refractive index, if known, but particle shape is assumed to be spherical like the calibrant material. Aerosol transport models will have to take into account the discrepancy and associated uncertainties between the measured physical aerosol size and true airborne aerosol behavior.

Another area that requires development is integrating a method for real-time measurements of aerosol composition with the optical light scattering sensor that measures aerosol size and composition in real time. A technique such as laser-induced breakdown spectroscopy (LIBS) can provide real-time elemental compositions of aerosol particles in a gas stream and has recently been demonstrated for analyzing salt aerosols (Andrews et al., 2025). A LIBS analysis cell could be incorporated into the aerosol sampling line immediately downstream of the optical light scattering sensor. LIBS measures any element within the plasma plume and does not differentiate aerosols from gases; however, aerosol particles have a significantly higher elemental density than gases and the aerosol composition should dominate the measured signals. Filters could be used to collect samples of the global aerosol population for elemental composition analysis by ICP-MS until a real-time aerosol composition method can be integrated, as done in laboratory-scale salt accident experiments (Thomas and Jackson, 2021, 2022, 2023).

Bubble formation in molten salts is linked to salt aerosol formation because bubble rupture at the molten salt surface is thought to produce salt aerosol particles in the respirable size range. Bubble formation affects radionuclide distributions in molten salt systems because radionuclides can become entrained in bubbles or concentrate at the liquid-gas interface (Shahbazi et al., 2022; Thomas and Jerden, 2020). Bubbles will rise to the salt surface and rupture, releasing the radionuclides they transported. For example, high noble metal radioisotope concentrations measured on filters that sampled the headspace of the MSRE pump bowl led to the hypothesis that noble metals concentrate on bubble surfaces and are released to the atmosphere as small particles when the bubble film ruptures (ORNL, 1968, 1969). A high-speed camera with the lens directed at the base of the salt containment vessel (see Figure 8) will film the surface of accumulating salt to characterize the bubbles of entrained gas that rupture at the salt surface to enable correlations with aerosol measurements. Single bubble bursting at water surfaces has been evaluated previously using a high-speed camera (Ke et al., 2017).

6.5 Gas composition and vapor condensation on structures

Volatile radionuclide species may be released to the atmosphere during accidents involving molten fuel salt. The oxidizing conditions that may develop for certain accident scenarios (i.e., air ingression) can produce highly volatile radionuclide species (e.g., cesium iodide, oxyfluorides, UF_6). Vaporization is one pathway that may lead to radionuclides escaping containment during an accident and is included in mechanistic source term models. Depending on vapor species concentrations and the detection limits of the analysis technique, it may be possible to monitor the gas composition in the headspace of the closed vessel configuration of the salt containment system shown in Figure 7 and Figure 8 to provide validation datasets on vapor species generation. Filtered gas samples with aerosol particles removed could be analyzed in real-time using mass spectrometry to measure individual species concentrations or using LIBS to measure elemental composition. Grab samples could also be taken and analyzed by using mass spectrometry if the concentrations of vapor species are too low to be detected in real time.

Radionuclide-containing vapors released during an accident involving fuel salt will also condense on structures. Quantifying the condensation of vapor species under different accident conditions will provide insight into the potential for condensation to act as a barrier to escape through failed containment layers. Also, the condensation of radionuclide-containing vapors can potentially cause issues due to undesired heating from radioactive decay. Vapor species condensation will be assessed in the salt containment vessel and aerosol and gas sampling chamber of the SAAF. Metal coupons will be placed in relevant locations and will act as removable surfaces on which vapor condensation can occur. The condensed material can be washed off and analyzed by using ICP-MS to provide elemental surface concentrations.

6.6 Abundance, size distribution, composition, and dispersal behavior of splatter

Salt splatter formation in this context occurs when molten salt has mechanically broken into fine particles that are too large to become suspended in the atmosphere and thus deposit on structures in their trajectory path. The dispersal of radionuclide-bearing splatter during an accident can expand the area impacted by radiation fields and can cause structural damage from heating due to radioactive decay. Methods to collect and quantify splattered salt have been developed previously in laboratory scale tests at Argonne (Thomas and Jackson, 2021, 2022, 2023)).

Samples of salt splatter can be collected on coupons during accident simulations in any configuration of the salt containment system. Previous testing with molten salt splatter showed that the splatter particles do not adhere to smooth metal surfaces but do adhere sufficiently when the coupons are coated in carbon tape adhesive. Different adhesives would be needed to collect splatter in high temperature atmospheres that exceed the temperature tolerance of carbon tape. All previously tested scenarios involving spilling molten salt into a catch pan to generate salt splatter indicated that the molten salt splatter freezes upon contact with a structure and not while traveling in the atmosphere (Thomas and Jackson, 2021, 2022).

After collecting splatter in relevant locations in the salt containment system, the adhesive-coated coupons can be collected for analysis. The concentrations and size distributions of splatter particles on the coupons can be determined by performing image analysis on photographs of the coupons taken with a visible light camera. This requires that the splatter particles have good visible contrast with the adhesive material background. Image processing software such as the Image Processing Toolbox^{TM} in MATLAB® can be used to identify and count the splatter particles. The known dimensions of the coupons can be used to calibrate pixel size and provide sizes (as projected particle area) of identified particles. The particle size detection limit will depend on the camera resolution; previous salt splatter analyses had a detection limit of approximately 50 µm. The same coupon can be analyzed by using SEM-EDS to obtain qualitative information on individual particle composition. All coupons should be stored and analyzed under an inert atmosphere to prevent changes to particle size and composition due to interactions with humidity.

6.7 Elemental composition and distribution in pooled salt after freezing

A mass balance performed at the conclusion of accident simulation tests conducted in the SAAF will provide information on the distribution of surrogate fission products and base salt constituents throughout the test system. Performing a mass balance analysis after simulated salt spill accidents was demonstrated at a laboratory scale using a surrogate fuel salt consisting of a FLiNaK base salt and fission product simulants (Thomas and Jackson, 2023). Specifically, the distribution of elements between the pool of accumulated salt in the containment system, the salt that remains in the salt transfer vessel, the salt splatter particles, and the aerosols and vapors will be quantified. This will require the measurement or estimation of the total mass of salt in each of these forms throughout the test system. This can be done by weighing recovered salt or making estimates from splatter particle, aerosol particle, and gas analyses. Samples will be taken from the residual salt in the salt transfer vessel, the accumulated salt in the salt containment vessel, residual salt in the salt transfer line, and the salt splatter and analyzed for elemental concentration by using ICP-MS. Multiple replicates of samples collected from multiple regions will need to be analyzed to obtain representative compositions of the bulk salt in each location. The total oxygen concentration in salt samples can also be determined using a LECO element analyzer to quantify the absorption of oxygen for tests conducted in an air or mixed argon-air atmosphere.

Surrogate fission products may not be uniformly distributed in frozen salt. Cross sections and edge samples of the frozen salt pool that has accumulated in the salt containment system may be collected to determine elemental distributions using SEM-EDS. Breaking off samples of frozen salt with force becomes increasingly difficult with increasing thickness, which may limit specimen collection to test scenarios that yield thin layers of accumulated salt. Obtaining quantitative information on relative elemental distributions would require that sections be fixed in epoxy and have their surfaces smoothed and flattened either by using a microtome or by polishing. SEM analyses of cross sections could also provide information on the characteristics of bubbles that were present within the salt when it froze.

6.8 Corrosion of containment structures

The corrosion of stainless steel and other relevant structural materials that may be contacted by molten salt during an accident may cause severe damage to the reactor and lead to a loss in the ability to contain radionuclides. The production of highly corrosive gases due to reactions between molten salt and humidity during accidents involving air ingression can cause significant corrosion over short time scales. Samples of structures that experience notable corrosion during accident simulations conducted in the SAAF can be analyzed to determine the extent and mechanism of corrosion. Corrosion analysis will be primarily conducted for tests involving exposure to O_2 and humidity.

7 Considerations for safe, practical, and effective system operation

7.1 Testing at relevant scales

A relevant scale for experimental nuclear accident simulations can be defined as using quantities of salt and dimensions of containment structures that ensure the important physical and chemical processes are accurately represented and that results are applicable to reactor-scale accidents. For example, maintaining a containment surface area-to-salt volume ratio that is similar to what is expected at a reactor scale will ensure that the atmosphere of the containment structures in the test system reach realistic temperatures and result in realistic cooling behaviors of the salt and system components. The quantity of molten salt to use in the SAAF design described in this report that is suitable for representing MSR designs will likely be between one and fifteen liters; the exact amount to use in a test would depend on the accident scenario being investigated.

7.2 Automation and remote operation of salt release and measurements

Performing MSR accident simulations at the scale proposed in this report will require that the salt release into the containment system and the simultaneous measurements of processes of interest be automated and remotely operated. This protects workers, ensures reproducibility and control of test conditions (i.e., flow rate and flow direction), and enables accurate data collection of multiple processes. An industrial controller will be employed to initiate salt transfer to the containment system (by operating valves, mass flow controllers, and monitoring pressures of the salt transfer vessel). The industrial controller will also be programmed to simultaneously record measured data from thermocouples and the data-logging scale. The cameras and additional measurement equipment will be operated using the industrial controller, if possible, or will be operated remotely using manufacturer provided software. The simultaneous and remote operation of cameras and data loggers for temperature and mass flow rate measurements have been demonstrated at a laboratory scale (Thomas and Jackson, 2021, 2022, 2023).

7.3 Design modularity and redundancy of measurement equipment

The components of the SAAF are designed to facilitate replacing system components (e.g., changing the transfer line tubing due to corrosion or salt composition changes) and to enable testing multiple accident scenarios using the same facility. Testing different accident scenarios is accomplished by modifying the salt containment system (e.g., changing the catch pan geometry, dimension, and material) and the salt transfer line (e.g., changing the tubing diameter or attaching different nozzles at the outlet). Liners that prevent the permanent system components (i.e., the vessels) from being directly contacted by molten salt will be employed to prolong permanent component lifespan. The flanged connections that attach the transfer line tubing to the salt transfer and salt containment vessels are designed to facilitate frequent replacement of the salt transfer line. Redundant measurement equipment will be employed as much as possible (e.g., duplicate thermocouples in the same location) to ensure that measurements will continue to be made if one piece of equipment fails.

7.4 Anticipated operational challenges

The anticipated challenges of operating the SAAF include:

- **Salt freezing:** Salt freezing (whether intentional or not) can affect the integrity of structural components and the ability to remove thermocouples and tubing that has been in direct contact with molten salt. The salt transfer line tubing is attached to the salt transfer vessel lid using a flanged connection with a bore diameter that should be sufficiently large to enable removal of the transfer line with frozen salt on the exterior. Thermocouples that are immersed in molten salt in the containment system will become embedded in the salt when it freezes and a strategy for removing (or sacrificing) them will need to be considered.
- **Accessing components in glovebox:** The SAAF is located within a glovebox so that the salt used in testing can be heated in an inert atmosphere and to provide an engineering control to protect the operators. The components of the SAAF will need to be configured so that they are accessible for setup, sample collection, and maintenance.
- **Preserving samples:** Salt samples taken for future analysis will need to be collected and preserved in an inert and dry atmosphere to prevent changes caused by air exposure.

- **Cleanup:** The interior of the automated salt transfer vessel and salt containment vessel will need to be cleaned of solidified salt and purged of O_2 and H_2O-containing atmospheres to an acceptable state between tests. The test system will employ liners in both the salt transfer vessel and salt containment system, which can be replaced frequently or removed from the vessels for easier cleaning. Salt will be reused to minimize waste and will need to be removed from the salt containment system after each test. For some configurations (i.e., closed vessel), the liner containing frozen salt from the previous test can be removed from the salt containment system and placed directly into the automated salt transfer vessel to be reheated and tested. Other configurations (i.e., the open catch pan) would permit mechanically breaking up the solidified salt on the catch pan and manually removing it for reuse.

- **Disposal and reuse of salts:** The tested chloride and fluoride salt compositions will require special disposal considerations due to the possibility of reacting with water and humidity in air and generating hazardous gases (e.g., HF and HCl). Salts should be reused as much as possible to minimize the amount needing disposal. Some testing may involve intentionally contaminating salts with oxygen and water to simulate accidents involving air ingression. These tests should be designed to use the smallest amount of salt possible because the contaminated salt will require purification for reuse.

- **Disposal and reuse of materials:** The materials that come into direct contact with molten salt should also be replaceable or cleanable so that multiple salt compositions can be tested without cross-contamination.

- **Synthesizing surrogate fuel salt compositions that are representative of actual fuel salt:** One difficulty to achieving representative surrogate fuel salt compositions is selecting simplified compositions that provide relevant insights. Comprehensive chemical comparisons of the surrogate fuel salt compositions to be tested in the SAAF to actual fuel salt will be performed. In addition, emulating realistic fission product distributions in synthesized surrogate fuel salt will be difficult. This is because distributions of elements in a salt mixture that has been synthesized by mechanical mixing and fusing may differ from distributions created naturally due to fission. For example, immiscible fission product species may be more uniformly dispersed in actual fuel salt than in synthesized surrogate fuel salt. One benefit to batching salt components to synthesize kilogram-scale amounts of surrogate fuel salt for tests conducted in the SAAF is improved composition control when compared to batching gram-scale amounts for laboratory-scale tests. Some fission products with high pure species vapor pressures may be lost from the salt due to vaporization while the salt is heating in the salt transfer vessel. This challenge can be mitigated by adding surrogate fission products to the crucible in the salt transfer vessel between layers of the base salt to minimize mass loss due to vaporization during heating (Thomas and Jackson, 2023). Some loss due to vaporization during heating is inevitable and will be taken into account during synthesis.

7.5 Safety considerations and limitations

The safety considerations and possible limitations of the SAAF include:

- **Hazardous gas formation:** The reaction of salt components with oxidants in the environment and in materials such as insulation and concrete during accident simulations in the SAAF could produce hazardous gases. These include highly corrosive acids (HF and HCl) due to reactions between salt and H_2O (humidity) and highly volatile actinides (e.g.,

UF_6) that can form in the salt under oxidizing conditions. The gases generated due to salt interactions with the environment during tests conducted in air or due to accidental exposure to air will need to be managed with stringent engineering controls. These include utilizing scrubbers to remove gases from exhaust, employing sensors to detect releases, and managing rapid increases in pressure due to expected or unexpected gas production.

- **Use of beryllium-containing salts:** The fuel salt compositions of many MSR concepts contain beryllium. Beryllium is highly toxic if inhaled and requires stringent protective measures and monitoring during handling. The extra safety controls that will need to be implemented to work with beryllium in tests that intentionally disperse beryllium-bearing salt will be costly. In addition, running tests in the SAAF using beryllium-bearing salts will likely permanently contaminate the SAAF equipment with beryllium due to the low concentration threshold for beryllium contamination. Using a surrogate salt composition that can provide relevant insights may be preferred (at least initially) to avoid the challenges and costs of working with beryllium in engineering-scale tests.

8 Summary and next steps

This report presents the preliminary design of the Salt Accident Analysis Facility (SAAF) that will be constructed at Argonne and used to simulate and quantify the consequence of different postulated MSR accident scenarios to support MSR licensing. The next steps to take to support the successful utilization of this engineering-scale testing capability can be divided into different categories. The steps relating to system construction include:

- Manufacture the salt transfer vessel. The performance of the molten salt transfer mechanism may be demonstrated first using a prototype system at a laboratory scale.

- Manufacture the components of the open and closed salt containment systems.

- Prepare the argon atmosphere glovebox that will host the SAAF (e.g., perform electrical upgrades and install glovebox feedthroughs) and assemble components of test facility.

Some measurement techniques and data analysis methods will be investigated to enhance the capabilities of the SAAF, which include:

- Develop a CFD model of the salt transfer vessel (beyond the simple model introduced in Section 4.2) to more accurately predict how different initial conditions affect the molten salt flow behavior at the salt transfer line outlet.

- Develop technique to measure real-time aerosol composition in conjunction with the real-time size and concentration measurements. This could be achieved by in-line coupling of the non-destructive optical light scattering technique that provides size and concentration with a downstream LIBS sensor.

- Determine feasibility of measuring gas composition in real time at the gas concentrations expected in the aerosol and gas sampling line and develop method to employ in the SAAF.

Finally, the specific accident scenarios to be represented using the SAAF will be documented and prioritized, considering input from stakeholders, to ensure that the datasets generated using the facility meet the needs of modelers and MSR developers.

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