MSR Salt Spill Accident Testing Using Eutectic NaCl-UCl$_3$

Chemical and Fuel Cycle Technologies Division, Argonne National Laboratory
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After initial publication of this report the authors were made aware of some minor errors. These errors have been corrected in the present version.

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MSR Salt Spill Accident Testing Using Eutectic NaCl-UCl₃

Prepared by
Sara Thomas and Josh Jackson
Chemical and Fuel Cycle Technologies Division, Argonne National Laboratory

September 23, 2022
Acknowledgements

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### Acronyms

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<tr>
<td>FLiNaK</td>
<td>LiF-NaF-KF eutectic (46.5-11.5-42 mol %)</td>
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<tr>
<td>ICP-MS</td>
<td>Inductively coupled plasma-mass spectrometry</td>
</tr>
<tr>
<td>ICP-OES</td>
<td>Inductively coupled plasma-optical emission spectroscopy</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>LWR</td>
<td>Light water reactor</td>
</tr>
<tr>
<td>MSR</td>
<td>Molten salt reactor</td>
</tr>
<tr>
<td>MSRE</td>
<td>Molten Salt Reactor Experiment</td>
</tr>
<tr>
<td>MSTDB-TC</td>
<td>Molten Salt Thermal Properties Database–Thermochemical</td>
</tr>
<tr>
<td>MSTDB-TP</td>
<td>Molten Salt Thermal Properties Database–Thermophysical</td>
</tr>
<tr>
<td>NRC</td>
<td>Nuclear Regulatory Commission</td>
</tr>
<tr>
<td>PTFE</td>
<td>Poly(tetrafluoroethylene)</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning electron microscopy</td>
</tr>
<tr>
<td>SOFT</td>
<td>Salt reactor Onsite reprocessing Fast converter Task</td>
</tr>
<tr>
<td>SSCs</td>
<td>Structures, systems, and components</td>
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Abstract

Assessing the potential consequences of identified accident scenarios is an essential part of the licensing process for a new nuclear reactor and is achieved by using accident progression models. A likely accident scenario that will be evaluated by developers of molten salt reactors (MSRs) is a spill of radionuclide-bearing fuel salt onto the reactor containment floor (i.e., a salt spill accident). Models to determine the consequences of a molten salt spill accident need to be parameterized and validated using experimental data, but little experimental effort has been dedicated to fill these data gaps to date. Specifically, data is needed to enable model development for individual processes (e.g., spreading, heat transfer, corrosion, radionuclide vaporization, and aerosol generation) that quantifies the sensitivities towards the initial conditions of the spill, the ambient environment, and the features of the containment. In addition, integrated experiments that simulate salt spill accidents will need to be conducted to provide insight into coupled processes and data for model validation, but these experiments will require the use of proven methods to quantify the processes under evaluation.

The overarching objectives of this work are to develop universal methods to simulate processes that are important to the consequences of a salt spill accident for a variety of salt compositions, to determine the effectiveness of the methods and measurement techniques in producing the data required for model development, to generate data that can be used to parameterize individual process models, and to provide key insights into the behavior of spilled molten salt that should be considered in models and future integrated salt spill tests. The tests described herein were conducted using a chloride salt composition representative of fast spectrum MSRs (eutectic NaCl-UCl$_3$) to highlight individual processes expected to affect the fate of spilled molten fuel salt and the radionuclides within during a salt spill accident. The processes addressed in this report include 1) molten salt spreading on stainless steel, 2) molten salt heat transfer (as a static pool and during spreading), and 3) molten salt splashing and aerosol generation. The test methods to assess molten salt spreading and molten salt splashing and aerosol generation were developed previously and successfully applied to eutectic NaCl-UCl$_3$ as part of this work. New methods to assess molten salt heat transfer from a static pool were developed as part of this work and applied to both FLiNaK and NaCl-UCl$_3$. The primary variables that were evaluated include initial salt temperature, the initial amount of salt being spilled, and the presence of volatile surrogate fission products (e.g., cesium and iodine) in the salt.

The major accomplishments of this study include demonstrating the effectiveness of the developed methods and measurement techniques in quantifying desired processes for a range of salt compositions and applying the methods to a uranium-bearing salt. These methods can be applied to study the complex salt compositions of interest to MSR developers, the wide range of environmental conditions of interest to modelers, and the effects of variables relevant to salt spill accident scenarios. The developed methods and insights gained from these laboratory tests that are focused on individual processes will be incorporated into scaled-up, integrated process tests that simulate molten salt spill accidents.
1 Introduction

Demonstrating reactor safety is an essential part of the U.S. Nuclear Regulatory Commission (NRC) licensing process for a new nuclear reactor. Safety demonstration for advanced, non-LWR reactors like molten salt reactors (MSRs) are expected to involve multiple approaches. These include identifying hazards; assessing initiating events and potential accident scenarios that challenge the fundamental safety functions (i.e., reactivity control, decay heat removal, and radionuclide retention); analyzing the safety of structures, systems, and components (SSCs); evaluating defense-in-depth; and calculating the source term for licensing basis events (Holcomb et al., 2021; NRC, 2016, 2020; Nuclear Energy Institute 2018). The primary challenge to addressing these licensing topics for MSRs is that a significant experimental program is required to supplement the sparse amount of existing data relevant to MSR operation, most of which was generated over 50 years ago and pertained to a single reactor concept during the Molten Salt Reactor Experiment (MSRE). Very few experimental data are available to address the consequences of potential MSR accidents. These data are needed not only to develop and validate new (or significantly modified) modeling tools for MSR mechanistic source term and accident analysis, but also to inform the design and decision-making processes to ensure the safe and successful operation of an MSR.

A postulated accident scenario that will likely be evaluated by an MSR developer during the licensing process involves a rupture within the primary loop that leads to molten fuel salt spilling onto the reactor containment floor. Figure 1 identifies processes that will likely determine the fate of the spilled salt and the radionuclides within it during such an accident, including flowing and spreading, heat transfer, corrosion and warping, vaporization, splashing, aerosol generation, condensation and deposition, and evaporation and resuspension. A recent report identified the experimental data that needs to be generated to support source term models that will satisfy NRC requirements for reactor licensing (Shahbazi and Grabaskas, 2021). Experiments that provide insight into the behavior of spilled molten salt and the radionuclides within the salt were listed as a high priority.

This report summarizes the results from a suite of laboratory experiments that were conducted to provide technical bases for accident progression and mechanistic source term models for molten salt reactors (MSRs). A data package containing complete datasets for some of the tests that is intended to support model development is available from the authors. The datasets available for specific results are indicated in the following sections.

1.1 Objectives and experimental approach

The objective of this project is to provide the experimental data that are needed to close identified gaps in mechanistic source term and accident progression models for molten salt spill accidents. During FY22, tests were conducted using a representative chloride salt composition (eutectic NaCl-UCl₃) to complement the data collected during FY21 using a representative fluoride salt composition (eutectic FLiNaK). The objective was addressed by designing and conducting modular laboratory-scale experiments that focused on specific high-priority processes likely to occur during or after a molten salt spill accident.

The goals of the work described herein include:

- Develop universal methods to generate data for a variety of salt compositions that quantify aspects of individual processes and can be incorporated into integrated process tests,
• Generate data needed to develop and validate individual process models that are applicable to specific salt compositions, and

• Identify key factors and priorities that should be included in models and considered when developing integrated process and engineering-scale salt spill tests.

Figure 1: Schematic that depicts molten salt spilling from a leak in the primary loop of a generic MSR onto a catch pan lining the primary containment floor (from Thomas and Jackson, 2021).

Experimental methods were applied to study three processes important to the consequences of a salt spill accident, including:

• Molten salt heat transfer (as a static pool and during spreading)
• Molten salt spreading on sloped stainless steel sheets
• Molten salt splashing and aerosol generation

A method to quantify the heat transfer behavior of a static pool of molten salt was developed as part of this work and measurements were made using eutectic FLiNaK and eutectic NaCl-UCl₃. The results of measurements made with both salt compositions are included in this report. One goal during this work was to assess the universality of the methods by applying them to a representative chloride salt having thermophysical and thermochemical properties different than those of eutectic FLiNaK. Specifically, the intention was to confirm that the methods developed using eutectic FLiNaK also simulate the targeted processes and quantify the response
characteristics required for model development for a fundamentally different salt composition. To investigate this, tests were conducted using different volumes of salt heated to different temperatures. Tests that quantified molten salt splashing and aerosol generation were conducted with eutectic NaCl-UCl₃ salt doped with surrogate fission products to provide data on radionuclide distribution within a containment geometry after a salt spill accident.

1.2 Motivation for individual test methods

The motivation for conducting laboratory tests on molten salt spreading and on molten salt splashing and aerosol generation is described in detail in a previous report (Thomas and Jackson, 2021). The methods to assess molten salt heat transfer from a static pool were developed as part of this work to provide data that supports heat transfer model development for static pools of molten salt. Some MSR developers may consider an accident scenario in which molten salt spills onto a catch pan on the containment floor and forms a static pool. The ability to accurately model the heat transfer from the static pool of molten salt to its surroundings is essential to consequence analysis for this scenario. Specifically, the heat transfer behavior is significant to the consequences of a molten salt spill accident for the following reasons:

- It determines the duration that the molten salt surface stays molten, which has implications for radionuclide vaporization and possible escape to the next containment layer.
- It determines the temperature of the catch pan and the potential of the catch pan to lose its integrity due to warping or ablation. A loss of substrate integrity may expose concrete or other sensitive materials to molten salt and produce hazardous gases and cause pressurization of the containment.
- It determines the duration that the molten salt stays in contact with the catch pan, which may lead to increased corrosion and loss of integrity.
- It enables the identification of requirements for decay heat removal systems that may need to be installed underneath the catch pan to ensure reactor safety.

2 Salt composition, preparation, analysis, and thermophysical properties

2.1 Composition and rationale

Eutectic NaCl-UCl₃ (66-34 mol %) was used as a representative chloride salt to generate the data needed for process modeling and to compare with the results of tests completed during FY21 with FLiNaK. The eutectic composition of the NaCl-UCl₃ system was determined from an earlier analysis of liquidus and solidus temperature measurements (Rose and Thomas, 2021). The optimized phase diagram is shown in Figure 2.
Eutectic NaCl-UCl₃ was chosen as the representative chloride salt because it is of interest to developers of fast spectrum MSRs and provided an opportunity to demonstrate application of the test methods to a uranium-bearing salt. Some tests were performed with NaCl-UCl₃ that was doped with surrogate fission products cesium and iodine to understand the fate of semi-volatile radionuclides that may represent a significant fraction of the source term after a spill. Radioisotopes of cesium and iodine will accumulate in the fuel salt as products of fission, decay, or neutron absorption (Compere et al., 1975). Radiotoxicities of ¹³⁷Cs and ¹³¹I are particularly high (Eckerman et al., 1988) and both have long-lived half-lives. In addition, the cesium and iodine-bearing species that form in chloride salts (e.g., CsI, I₂, HI, ICl) are relatively volatile (McFarlane et al., 2019). The abundance of cesium and iodine in the fuel salt will depend on many factors including the reactor design, the choice of fuel, the operation schedule, and burnup. The fission product concentration in the fuel salt as a function of reactor lifetime was recently estimated using depletion calculations for the SOFT (Salt reactor Onsite reprocessing Fast converter Task) reactor design, which employs UCl₃ and PuCl₃ fuel in NaCl carrier salt (McMurray et al., 2021). The depletion calculations predicted a total cesium concentration of 0.5 mol % in the fuel salt after 30 years of operation, whereas the total iodine content was below 0.05 mol% and not reported. To produce surrogate fuel salts for testing, surrogate fission products are usually added to base salts at compositions at or above those expected after 30 years of operation so that the measured processes or properties will represent upper bounds to the effects (McMurray et al., 2021).

The doped NaCl-UCl₃ used in the experiments contained 0.9 mol % CsCl and 0.099 mol % CsI so that the total cesium concentration was approximately 1 mol % and the cesium-to-iodine molar ratio was approximately 10. The cesium and iodine concentrations and molar ratio reflect the upper bounds of what is expected in the fuel salt after extended operation of a chloride fast reactor. The same mole fractions of cesium and iodine were added to FLiNaK for tests conducted in FY21.
2.2 Salt preparation

The NaCl-UCI₃ salt mixture was synthesized previously by reacting a mixture of NaCl-ZnCl₂ salt with uranium metal to form zinc metal and UCI₃ (Lichtenstein, 2021). This reaction is shown in Equation 1:

\[ 3\text{ZnCl}_2 + 2\text{U} \rightarrow 2\text{UCI}_3 + 3\text{Zn} \]  

Equation 1

The starting NaCl-ZnCl₂ mixture was prepared by adding reagent salts to graphite crucibles that had been cleaned using methanol and dried at 300 °C for eight hours. The reagents were mechanically mixed and then heated in a furnace at 600 °C for eight hours. A uranium ingot was polished, cleaned with methanol, and dried under inert atmosphere prior to use. The cleaned uranium metal was suspended in the molten NaCl-ZnCl₂ mixture and this combination was heated at 700 °C for 60 hours to react all the ZnCl₂ with uranium to form UCl₃ and zinc metal. Metallic zinc was removed by evaporation.

The starting NaCl-ZnCl₂ mixture was intentionally prepared to be UCl₃-rich relative to the desired composition, and small amounts of dried NaCl were added as trim to adjust the composition to the eutectic composition of 66 mol% NaCl and 34 mol% UCl₃. The salt composition was confirmed by testing aliquots of the prepared salt to determine total uranium and sodium content by using ICP-OES. The zinc content as well as the trace metal impurities in the salt were measured by using ICP-MS. The composition results that were averaged from three replicate samples are provided in Table 1.

### Table 1: Concentrations of NaCl, UCl₃, and trace metals in the synthesized NaCl-UCI₃ salt

<table>
<thead>
<tr>
<th></th>
<th>NaCl</th>
<th>UCl₃</th>
<th>Cr</th>
<th>Ni</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>(mol %)</td>
<td>65.9 ± 0.8</td>
<td>34.1 ± 0.8</td>
<td>8 ± 1</td>
<td>30 ± 5</td>
<td>110 ± 8</td>
</tr>
</tbody>
</table>

*a The values are the mean ± one standard deviation.  
*b Fe was below the detection limit in all samples

The eutectic NaCl-UCI₃ salt containing surrogate fission products was made by mixing the pre-made NaCl-UCI₃ with prescribed amounts of dried CsCl and CsI. Prior to mixing, the CsCl and CsI powders were baked to dryness separately in nickel crucibles at 300 °C for 12 hours, and the eutectic NaCl-UCI₃ salt was ground into a fine powder using an agate mortar and pestle. Before each test, the desired amounts of eutectic NaCl-UCI₃, CsCl, and CsI were weighed out directly into a nickel crucible and then mixed. The mixture in the nickel crucible was heated to and fused at the desired temperature in a furnace and allowed to equilibrate for approximately two hours to homogenize the mixture. Heating the spiked salts for longer than two hours after reaching the desired temperature was avoided to minimize the loss of cesium and iodine due to vaporization while still in the furnace.

All reagents used had a purity of > 99% except for the ZnCl₂ used in salt synthesis, which had a purity of > 98%. Preparation of the FLiNaK used in the heat transfer tests of static molten salt pools (Section 3.2) is described in Thomas and Jackson (2021).

2.3 Analysis of salt composition by ICP-OES and ICP-MS

The concentrations of major cations (sodium and uranium) and trace elements (lithium, magnesium, potassium, calcium, chromium, iron, nickel, copper, zinc, cesium, and iodine) were analyzed by using inductively coupled plasma-optical emission spectrometry (ICP-OES) and
inductively coupled plasma-mass spectrometry (ICP-MS), respectively. The ICP-OES measurements were made with a PerkinElmer Optima 8300DV ICP Optical Emission Spectrometer, and the ICP-MS measurements were made with a PerkinElmer NexION 2000 ICP Mass Spectrometer. Both instruments were calibrated using standards prepared from NIST-traceable solutions. The salt samples were dissolved in water prior to analysis and were split into two aliquots: one for metals analysis and one for iodine analysis. For metals analysis, individual salt samples were weighed, transferred to a PYREX® beaker, and mixed with approximately 2 mL of deionized water and 2 mL of nitric acid (Optima Grade). The solutions were heated on a hot plate for approximately 30 minutes until the solids visibly dissolved. The solutions were then transferred to polypropylene centrifuge tubes and diluted to 25 mL with deionized water for analysis by ICP-MS. For iodine analysis, individual salt samples were weighed and transferred to a polypropylene centrifuge tube. The salt sample in the centrifuge tube was covered with water and swirled to dissolve the solids, after which the sample was further diluted to a total volume of 25 mL with deionized water.

The ICP-OES technique is typically accurate to within 5% of the measured value, and the ICP-MS technique is typically accurate to within 10% of the measured value. To verify the effectiveness of the method for trace iodine analysis in a NaCl-UCI₃ salt sample, NaCl-UCI₃ powder and CsI powder were dissolved in water separately and then mixed together at similar ratios of CsI to NaCl-UCI₃ salt as those used in this study. Approximately 115% of the added iodine was recovered by using ICP-MS (accounting for the trace iodine impurities present in the salt). A recovery of 115% indicates that small amounts of iodine can be measured relatively accurately in a solution containing significantly more NaCl-UCI₃. This over target recovery is likely attributed to propagated experimental error due to the small amounts of CsI required for this assessment.

The abundance of iodine, cesium, sodium, and uranium in particulates collected on PTFE filters for the molten salt splashing tests reported in Section 5 were analyzed by using ICP-MS. Specifically, each filter was transferred to a PYREX® beaker and then rinsed with methanol to reduce the hydrophobicity. The methanol was then fully evaporated, and the filter was rinsed and covered with deionized water. The immersed filter was agitation and allowed to leach for 1 hour. The filters were then removed from the solution, rinsed with deionized water, and set aside for future acid leaching, if desired. The rinse solutions were transferred to 50 mL centrifuge tubes, diluted to 25 mL with deionized water, and then analyzed for total elemental compositions by using ICP-MS.

The efficiency of iodine recovery using the reported methods with and without treatment with methanol was tested by using pure CsI powder and the results are shown in Table 2. The recovery of iodine was 95% regardless of whether the CsI powder was treated with methanol.

Table 2: Iodine recovery results

<table>
<thead>
<tr>
<th>Sample</th>
<th>Expected I (mg)</th>
<th>Measured I (mg)</th>
<th>Recovery (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CsI powder</td>
<td>21.6</td>
<td>20.6</td>
<td>95.0</td>
</tr>
<tr>
<td>CsI powder treated with methanol</td>
<td>34.7</td>
<td>33.0</td>
<td>95.0</td>
</tr>
</tbody>
</table>
2.4 Thermophysical properties of eutectic FLiNaK and eutectic NaCl-UCI₃

The thermophysical properties of eutectic FLiNaK and eutectic NaCl-UCI₃ are presented in this section for convenience and to facilitate a comparison of the heat transfer, spreading, and splatter formation behavior of these two salt compositions. Many of the FLiNaK thermophysical properties were obtained from the Molten Salt Thermal Properties Database–Thermophysical (MSTDB-TP) Version 2 (Agca et al., 2021). Many of the thermophysical properties of eutectic NaCl-UCI₃ are unknown and some were estimated, as described below.

2.4.1 Estimating heat of fusion and melting temperature using thermodynamic database

The heat of fusion of FLiNaK (LiF-NaF-KF, 46.5-11.5-42 mol %) and eutectic NaCl-UCI₃ (66-34 mol %) were calculated using the thermodynamic properties in the Molten Salt Thermal Properties Database–Thermochemical Version 1.2 (MSTDB-TC V1.2) (Ard et al., 2022) by plotting the total enthalpy of the system (one mole of salt) as a function of temperature and identifying the phase transition from liquid to solid and the corresponding enthalpy change (Figure 3). This was done for FLiNaK to demonstrate how optimized thermodynamic data for a molten salt system can be used to estimate the heat of fusion of that system (Figure 3A). The estimated FLiNaK heat of fusion from the MSTDB-TC of 431 J g⁻¹ is similar to the measured value of 399 J g⁻¹ (Powers and Blalock, 1956). The heat of fusion of the eutectic composition of the NaCl-UCI₃ system has not been measured. The analysis shown in Figure 3B provides an estimate of 158 J g⁻¹ for the heat of fusion of eutectic NaCl-UCI₃, which is nearly three times lower than the estimated FLiNaK heat of fusion on a per gram basis. Although the values were calculated using thermodynamic data and the heat of fusion of NaCl-UCI₃ has not been measured, the differences in heat of fusion suggest FLiNaK and eutectic NaCl-UCI₃ will exhibit different heat transfer and cooling behavior during a salt spill accident.

![Figure 3](image1.png)

Figure 3: The total enthalpy of (A) FLiNaK and (B) eutectic NaCl-UCI₃ plotted as a function of temperature. The heat of fusion ($\Delta H_{fus}$) of the system is the difference in enthalpy between the solid and liquid phases near the melting point.

The thermodynamic information shown in Figure 3 can also be used to estimate the melting temperatures of the two salt compositions. The melting temperature of FLiNaK is calculated to be approximately 453 °C (726 K; Figure 3A) and the melting temperature of eutectic NaCl-UCI₃ is calculated to be approximately 520 °C (793 K; Figure 3B).
2.4.2 Estimating heat capacity using thermodynamic database

The heat capacities of FLiNaK (LiF-NaF-KF, 46.5-11.5-42 mol %) and eutectic NaCl-UCI₃ (66-34 mol %) were calculated using the MSTDB-TC V1.2. The calculated and measured heat capacities of FLiNaK are shown in Table 3. The measured and calculated heat capacity values of FLiNaK are very similar at 500 °C but deviate with increasing temperature. The calculated heat capacity values of eutectic NaCl-UCI₃ are approximately three times lower than the calculated and measured heat capacity values of FLiNaK at the same temperature (Table 3), which suggests that eutectic NaCl-UCI₃ and FLiNaK will exhibit different heat transfer and cooling behavior during a salt spill accident.

Table 3: Calculated and measured heat capacities (J K⁻¹ g⁻¹) of FLiNaK and eutectic NaCl-UCI₃

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>FLiNaK</th>
<th>eutectic NaCl-UCI₃</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calculated (MSTDB-TC)</td>
<td>Measured (MSTDB-TP)</td>
</tr>
<tr>
<td>500</td>
<td>1.72</td>
<td>1.79</td>
</tr>
<tr>
<td>600</td>
<td>1.72</td>
<td>1.90</td>
</tr>
<tr>
<td>700</td>
<td>1.72</td>
<td>2.01</td>
</tr>
<tr>
<td>800</td>
<td>1.72</td>
<td>2.11</td>
</tr>
</tbody>
</table>

2.4.3 Estimating radiation emissivity using IR camera measurements

The method to estimate the emissivity of FLiNaK described in Thomas and Jackson (2021) was applied to estimate the emissivity of eutectic NaCl-UCI₃. Briefly, an IR camera was used to measure the apparent temperature of the molten salt surface as it cooled to temperatures below the melting point. The temperature of an object measured by an IR camera (the “apparent” temperature) is less than the actual temperature when the emissivity of the object is less than one. The apparent temperature of an object measured by an IR camera is a function of the fraction of infrared radiation emitted by the object (emissivity, ε), reflected by the object (reflectivity, ρ), and transmitted through the object (transmissivity, τ), where ε + ρ + τ = 1. For objects that are not transparent, like eutectic NaCl-UCI₃, the relationship between the apparent temperature measured by the IR camera (T_app) and the object’s emissivity (ε) is simplified to the following equation:

\[ T_{\text{app}} = \varepsilon T_{\text{obj}} + (1 - \varepsilon)T_{\text{amb}} \]

Equation 2

where T_obj is the actual temperature of the object and T_amb is the effective ambient temperature of the room. To estimate the emissivity of eutectic NaCl-UCI₃, the known melting temperature of eutectic NaCl-UCI₃ (520 °C) was used as the T_obj and the effective ambient temperature of the room within which the cooling curve was measured was set to 28 °C. The maximum temperature measured by the IR camera during the phase transition from liquid to solid was used as the T_app at the melting point.

The apparent temperatures measured of cooling FLiNaK and cooling eutectic NaCl-UCI₃ over time are shown in Figure 4A and Figure 4B, respectively. The initiation of the phase transition from liquid to solid was marked by a supercooling feature in the cooling curves (Figure 4). Using Equation 2, the emissivity of eutectic NaCl-UCI₃ at the melting point is estimated to be 0.95. For FLiNaK, the maximum measured T_app during the phase transition of 451 °C is very close to the known melting point of FLiNaK of 462 °C (MSTDB-TP), so for simplicity, the emissivity of FLiNaK is estimated to be 1.0.
is assumed to be unity. Knowing the salt emissivity is essential to correct the temperature measurements made by the IR camera, which is done for the measurements presented within this report. Emissivity can depend on temperature and be sensitive to changes in material appearance. It is recommended that the emissivities of these two salt compositions be measured as a function of salt temperature and salt phase (liquid and solid). The results of measurements made by the IR camera reported herein can be corrected in the future when new emissivity measurements become available.

![Figure 4](image)

**Figure 4:** The apparent temperature measured by the IR camera of a pixel in a cooling pool of (A) FLiNaK and (B) eutectic NaCl-UCl₃. The maximum apparent temperature of the salt during the phase transition from liquid to solid was used to estimate the emissivity of the salt.

### 2.4.4 Summary of thermophysical properties of FLiNaK and eutectic NaCl-UCl₃

The thermophysical properties of FLiNaK are reported in Table 4 and the known or estimated thermophysical properties of eutectic NaCl-UCl₃ are shown in Table 5.

**Table 4:** Thermophysical properties of FLiNaK

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Applicable temp. range (K)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition (mol %)</td>
<td>(LiF)₀.₄₆₅(KF)₀.₄₂(NaF)₀.₁₁₅</td>
<td>–</td>
<td>MSTDB-TP</td>
</tr>
<tr>
<td>Molecular weight (g mol⁻¹)</td>
<td>41.29</td>
<td>–</td>
<td>MSTDB-TP</td>
</tr>
<tr>
<td>Melting point (K)</td>
<td>735</td>
<td>–</td>
<td>MSTDB-TP</td>
</tr>
<tr>
<td>Boiling point (K)</td>
<td>1843</td>
<td>–</td>
<td>MSTDB-TP</td>
</tr>
<tr>
<td>Liquid density (g cm⁻³)</td>
<td>2.6 − (6.2 × 10⁻⁴)T</td>
<td>933 − 1163</td>
<td>MSTDB-TP</td>
</tr>
<tr>
<td>Solid density (g cm⁻³)</td>
<td>2.199</td>
<td>–</td>
<td>Chapdelaine (2017)</td>
</tr>
<tr>
<td>Viscosity (mN s m⁻²) (T: K)</td>
<td>10⁰(0.21+⁻¹2×10⁻³) + 1.4×10⁶</td>
<td>770 - 970</td>
<td>MSTDB-TP</td>
</tr>
<tr>
<td>Property</td>
<td>Value</td>
<td>Applicable temp. range (K)</td>
<td>Reference</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>-----------------------------------------------------</td>
<td>----------------------------</td>
<td>------------------------------------</td>
</tr>
<tr>
<td>Liquid heat capacity (J K⁻¹ mol⁻¹) (T: K)</td>
<td>40 + (4.4 × 10⁻²)T</td>
<td>–</td>
<td>MSTDB-TP</td>
</tr>
<tr>
<td>Liquid thermal conductivity (W m⁻¹ K⁻¹) (T: K)</td>
<td>−0.35 + (1.3 × 10⁻³)T</td>
<td>773 – 973</td>
<td>MSTDB-TP</td>
</tr>
<tr>
<td>Latent heat of fusion (J g⁻¹)</td>
<td>399</td>
<td>–</td>
<td>Powers and Blalock (1956)</td>
</tr>
<tr>
<td>Surface tension (N m⁻¹)</td>
<td>0.2726 − (1.014 × 10⁻⁴)T</td>
<td>770 – 1040</td>
<td>Sohal et al. (2013)</td>
</tr>
<tr>
<td>Liquid volume expansion coefficient (K⁻¹)</td>
<td>3.4 × 10⁻⁴ (average value)</td>
<td>–</td>
<td>Anderson et al. (2015)</td>
</tr>
<tr>
<td>Radiation emissivity</td>
<td>Unknown. assume 1</td>
<td>–</td>
<td>Thomas and Jackson (2021)</td>
</tr>
</tbody>
</table>

Table 5: Thermophysical properties of eutectic NaCl-UCl₃

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Applicable temp. range (K)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition (mol %)</td>
<td>(NaCl)₀.₆₆(UCl₃)₀.₃₄</td>
<td>–</td>
<td>Rose and Thomas (2021)</td>
</tr>
<tr>
<td>Molecular weight (g mol⁻¹)</td>
<td>155.66</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Melting point (K)</td>
<td>793</td>
<td>–</td>
<td>MSTDB-TC (estimate)</td>
</tr>
<tr>
<td>Boiling point (K)</td>
<td>Data gap</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Liquid density (g cm⁻³) (T: K)</td>
<td>Data gap</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Solid density (g cm⁻³)</td>
<td>Data gap</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Viscosity (mN s m⁻²) (T: K)</td>
<td>Data gap</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Liquid heat capacity (J K⁻¹ mol⁻¹) (T: K)</td>
<td>102.9 − (5.4 × 10⁻³)T</td>
<td>–</td>
<td>MSTDB-TC (estimate, see Section 2.4.2)</td>
</tr>
<tr>
<td>Liquid thermal conductivity (W m⁻¹ K⁻¹) (T: K)</td>
<td>Data gap</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Latent heat of fusion (J g⁻¹)</td>
<td>158</td>
<td>–</td>
<td>MSTDB-TC (estimate, see Section 2.4.1)</td>
</tr>
<tr>
<td>Surface tension (N m⁻¹)</td>
<td>Data gap</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Liquid volume expansion coefficient (K⁻¹)</td>
<td>Data gap</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Radiation emissivity</td>
<td>0.95</td>
<td>–</td>
<td>Estimate (see Section 2.4.3)</td>
</tr>
</tbody>
</table>
3 Heat transfer behavior of static pool of molten salt

3.1 Methods

3.1.1 Design and description of test equipment

A method was developed to collect the temperature measurements required to develop and validate a heat transfer model of static molten salt, such as the one shown in Figure 5A. The model consists of a cylindrical container of known diameter that is insulated at the base and filled with molten salt to a known depth. Using a cylindrical container facilitates model development because temperature only needs to be tracked in 2 directions (radially from the center of the salt pool and vertically throughout the depth of the salt pool). Insulating the bottom of the container simplifies the model because it prevents heat loss from the bottom of the container. Insulating the walls of the container would further simplify the model but this was not done for the preliminary tests that are described in this report.

![Figure 5](image)

**Figure 5:** (A) Schematic of proposed heat transfer model for static pool of spilled molten salt. (B) Schematic of the setup to study heat transfer behavior of static pool of molten salt in stainless steel beaker.

Three 316 stainless steel beakers were fabricated with fixed inner dimensions (2" inner diameter and 3" depth) and varying wall and base thicknesses (T; Figure 5B). The beaker wall and base thicknesses were the same for each beaker and were either \(\frac{1}{16}\)" thick, \(\frac{1}{8}\)" thick, or \(\frac{1}{4}\)" thick. As a result, each beaker also had a different thermal mass, and the measured weight of the three beakers was 187 g, 394 g, and 856 g, respectively. The junction of butt-welded, K-type thermocouple lead wires was attached to the underside of the beaker with thermally conductive cement. The base of the beaker was insulated with three stacked layers of \(\frac{1}{4}\)"-thick alumina oxide ceramic fiber insulation (R value of 0.5).

The heat transfer tests were conducted within an argon atmosphere glovebox (O\(_2\) < 10 ppm, H\(_2\)O < 5 ppm). The salt was first heated in a custom nickel crucible within a furnace to the target temperature and then manually poured into the beaker using long crucible tongs. The two
thermocouples that were attached to the bottom of the beaker recorded the temperature of the beaker underside as a function of time at 1 second intervals. One IR camera positioned on a tripod above the beaker measured the temperature of the salt surface over time (Figure 5B). A second IR camera measured the temperature of the wall of the stainless steel beaker over time (Figure 5B). The temperature measurements from both IR cameras had a spatial resolution of approximately 1 mm² per pixel. The bottom 2 inches of the beaker wall was covered with high-temperature, high-emissivity tape (McMaster-Carr, item no. 1618N1) to facilitate correction of the IR camera temperature measurement of the beaker wall for emissivity. For some tests, a K-type thermocouple probe was immersed in the salt to a depth of a few millimeters above the beaker base. The thermocouple sheath diameter, sheath material and junction type (grounded vs. ungrounded) varied by test.

A description of the IR camera, data logger for thermocouple measurements, and furnace is provided in Appendix A.

3.1.2 Measurements and calculations

3.1.2.1 Temperature

Temperature was measured at three or four locations depending on the test. A thermocouple attached to the bottom of the beaker recorded the temperature of the beaker underside surface at one second intervals throughout the test. This surface temperature measurement method using thermocouples was previously demonstrated to provide a quick and accurate temperature response (Thomas and Jackson, 2021).

The temperature of the beaker wall was measured at 10 second intervals by using an IR camera. The beaker wall was covered with high-emissivity tape to facilitate emissivity correction (see Section 3.1.1). The beaker wall temperature measurements were corrected for emissivity using the emissivity of the high-emissivity tape as a function of temperature measured previously (Thomas and Jackson, 2021). The temperature of the molten salt surface in the stainless steel beaker was recorded by using a separate IR camera. The emissivity of FLiNaK is assumed to be unity, as described in Section 2.4.3. However, results discussed in Section 2.4.3 indicate that the emissivity of eutectic NaCl-UCl₃ is less than 1. The temperature measurements of the eutectic NaCl-UCl₃ surface were corrected for emissivity by using an estimated emissivity of 0.95 at all temperatures and Equation 3.

\[
T_{\text{actual}} = \frac{T_{\text{app}} - (1 - \varepsilon) \cdot T_{\text{amb}}}{\varepsilon}
\]  

\text{Equation 3}

where \( T_{\text{actual}} \) is the actual temperature of the salt surface, \( T_{\text{app}} \) is the apparent temperature of the salt surface measured by the IR camera, \( T_{\text{amb}} \) is the effective ambient temperature of the room, and \( \varepsilon \) is the emissivity of the salt at \( T_{\text{actual}} \). The effective ambient temperature of the room was assumed to be 28 °C. The temperature measurements taken by the IR camera of the eutectic NaCl-UCl₃ surface can be corrected with more comprehensive emissivity values for this salt composition (i.e., emissivity as a function of temperature) if they become available.

A thermocouple immersed in the salt with the probe approximately five millimeters above the base of the beaker and one to two centimeters from the beaker wall was used to measure the temperature of the salt pool. This immersed thermocouple was only employed during tests with FLiNaK.
The furnace temperature was used to estimate the molten salt temperature immediately before it was poured. The initial salt temperature in the crucible was determined by using the IR camera to provide a more accurate value because the temperature of the furnace is determined by a thermocouple in the furnace liner and may not reflect the actual salt temperature.

A thermocouple positioned in the glovebox more than two feet away from test apparatus was used to measure the ambient temperature of the glovebox atmosphere prior to and during the test.

3.1.2.2 Height and mass of frozen salt in beaker

The salt that froze in the beaker during the heat transfer tests was easily removed as a single solid "puck". The mass of the frozen salt puck was recorded, and calipers were used to measure the height of the puck at three locations so that an average salt depth in the beaker could be determined.

3.1.2.3 Glovebox conditions

The temperature, O₂ content, and H₂O content of the argon atmosphere glovebox was recorded before and after pouring molten salt for each test.

3.2 Results from preliminary tests with FLiNaK

The methodology to provide data for heat transfer models of static molten salt pools was developed as part of this work, and preliminary tests were initially conducted with FLiNaK. The results and main findings from these tests with FLiNaK are presented in this section. Full datasets are available from the authors in the data package associated with this report and their availability is indicated in the following sections. Table 6 provides a summary of the conditions for each test using FLiNaK. A small amount of FLiNaK was used for each test so that the results could be comparable to tests with eutectic NaCl-UCl₃, which were limited by the amount of salt available. A summary of the conditions of the glovebox atmosphere for each test is provided in Appendix B.

Table 6: Summary of test conditions to study heat transfer of molten FLiNaK

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Target initial salt temp. (°C)a</th>
<th>Max salt temp. (°C)b</th>
<th>Beaker wall thickness (in)</th>
<th>Avg. salt depth (mm)</th>
<th>Salt mass recovered (g)c</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>650</td>
<td>587</td>
<td>1/8&quot;</td>
<td>12.9 ± 0.3</td>
<td>59.2</td>
</tr>
<tr>
<td>2</td>
<td>650</td>
<td>n/a</td>
<td>1/8&quot;, 607</td>
<td>12.7 ± 0.5</td>
<td>59.8</td>
</tr>
<tr>
<td>3</td>
<td>650</td>
<td>607</td>
<td>1/8&quot;, 603</td>
<td>12.0 ± 0.5</td>
<td>57.4</td>
</tr>
<tr>
<td>4</td>
<td>650</td>
<td>603</td>
<td>1/8&quot;, 603</td>
<td>12.7 ± 0.4</td>
<td>59.0</td>
</tr>
</tbody>
</table>

a The actual salt temperatures may have slightly differed from the target temperature.
b The maximum temperature of the salt measured by the IR camera (assumed salt emissivity of 1) provided an estimate of the actual salt temperature as it was poured.
c All tests had a target salt mass of 60 g added to the crucible but not all poured out of the crucible.
d IR camera did not capture salt temperature in the crucible before the pour.

3.2.1 Salt surface temperature measurements by using an infrared camera

Figure 6 presents still frames taken by the IR camera of the FLiNaK salt surface temperature in the stainless steel beaker at different times after first pouring the molten salt into the beaker. The salt-immersed thermocouple obstructed the view in some of the frames, and black circles mark
the interface of the salt and inner diameter of the beaker (Figure 6). An analysis of the images in Figure 6 reveals that the salt nearest the beaker walls cools faster than the salt at the center due to conductive heat transfer from the salt to the beaker walls. This heat loss to the beaker walls is likely observed because the walls are not insulated. In addition, the salt that was poured into the beaker with ¼" thick walls cools faster than the salt in the beakers with thinner walls (Figure 6). The cooling time is inversely proportional to the beaker wall thickness due to the correlation between wall thickness and thermal mass. The IR video frames that report the salt surface temperatures of FLiNaK for heat transfer Tests 1, 3, and 4 have been exported to .csv files and are available in the data package associated with this report. Salt surface temperature measurements are not available for Test 2 because the IR video failed during that test.

![Figure 6: The surface temperature (°C) of FLiNaK in stainless steel beakers of different wall thicknesses over time during Tests 1, 3, and 4. The indicated time is the relative time after pouring the molten salt into the beaker. The black circle in each frame marks the edge of the salt in the beaker. A thermocouple and thermocouple holder obstructed the view of some frames.](image-url)
Figure 7: Radial distribution of FLiNaK surface temperature (°C) in stainless steel beakers with wall thicknesses of (A) $\frac{1}{16}$", (B) $\frac{1}{8}$", and (C) $\frac{1}{4}$" as a function of distance from center of the beaker and the time after the salt was poured for Tests 1, 3, and 4. The image in the inset shows the location of the assessed pixels. The center is pixel 0.

The effect of distance from the center of the beaker and time on the FLiNaK surface temperature for beakers of different wall thicknesses is shown in Figure 7. The inset in Figure 7 identifies the pixels that were analyzed (black arrow), where the center pixel is labeled pixel 0. The surface temperature of the salt near the beaker wall is consistently lower than the surface temperature of the salt at the center of the beaker for all tests regardless of beaker wall thickness (Figure 7). This indicates the presence of a temperature gradient along the surface of the salt pool. The radial distribution plots of the salt surface temperature also show the times at which the salt underwent a phase transition from liquid to solid, as indicated by the temperature plateau at the freezing point of FLiNaK (approximately 450 °C). The phase transition from liquid to solid was slowest for the salt in the beaker with $\frac{1}{16}$" thick walls because that beaker had the lowest thermal mass and lowest total heat capacity (Figure 7A). Accordingly, the salt in the beaker with the highest thermal mass and highest total heat capacity cooled the fastest (Figure 7C). The salt surface temperature was lower at the center of the beaker than it was 5 to 7 pixels away from the center of the beaker at 4.167 minutes after pouring the salt into the beaker with $\frac{1}{4}$" thick walls due to a heat-sink attributed to the immersed thermocouple located nearer to the beaker center (light green curve, Figure 7C).
Analyses of the salt surface temperatures measured by the IR camera revealed that the local salt surface temperature near the immersed thermocouple was consistently lower than the surface temperature of the bulk salt by 10 °C to 15 °C. Figure 8 illustrates this by showing the surface temperature measurements along a linear path of 13 pixels adjacent to the immersed thermocouple at different time points after the salt was poured into the beaker for Test 3. The temperature curves (solid lines in Figure 8A) dip right at the location of the immersed thermocouple (pixel 7). The IR image of the salt surface in Figure 8B shows the location of the temperature measurements (black arrow) relative to the thermocouple position (black dot). The markers in Figure 8A indicate the temperature of the salt measured by the immersed thermocouple. The thermocouple junction was located approximately 5 mm from the base of the beaker; the thermocouple measured the temperature of the salt near the base of the beaker and not the salt-atmosphere interface where the IR camera measurements were made. The employed thermocouple (K-type) was a ¼" diameter, 316 stainless steel-sheathed probe with a grounded junction. This comparison shows how the temperature measurements near the two interfaces (salt-beaker base and salt-atmosphere) at the same radial distance from the beaker center can vary over time (Figure 8A).

### 3.2.2 Temperature measurements by salt-immersed thermocouple

A thermocouple was immersed in the salt with the junction approximately 5 mm above the beaker base and used to measure the salt temperature at one second intervals during each test. The measured temperatures are plotted as a function of time for each test in Figure 9. Thermocouples of different diameters, sheath material, and junction types were employed: the thermocouple used in Test 1 had an ungrounded junction and a ¼"-diameter Super OMEGACLAD™ XL sheath, the thermocouple used in Test 2 had an ungrounded junction and a ¼₆"-diameter Super
OMEGACLAD™ XL sheath, and the thermocouple used in Test 3 and Test 4 had a $\frac{1}{16}$"-diameter 316 stainless steel sheath with a grounded junction. The highest temperatures were measured in Test 3 and Test 4 (inset, Figure 9), which is attributed to the faster temperature response of grounded junctions compared to ungrounded junctions. The temperature measurement plateaued at the melting point of FLiNaK (approximately 450 °C) for the tests conducted using beakers with $\frac{1}{16}$"-thick and $\frac{3}{8}$"-thick walls (Figure 9). This temperature plateau (i.e., phase transition) lasted longest in the beaker with $\frac{1}{16}$"-thick walls (Test 1) because the least amount of heat was lost to the beaker due to its low thermal mass and low total heat capacity. The data files of the temperature measurements by the salt-immersed thermocouple are available in the data package associated with this report.

![Figure 9](image-url)

**Figure 9:** The salt temperature as measured by the salt-immersed thermocouple plotted as a function of time for each test.

Thermocouples were not immersed in the salt in subsequent tests with eutectic NaCl-UCi3 performed at the same scale (Section 3.3) because it was observed to be a heat sink (as described in Section 3.2.1), and the utility of that measurement is low relative to the other temperature measurements taken during each test. The sheath of the salt-immersed thermocouple that was exposed to the glovebox atmosphere was not insulated for any test, which likely contributed to the thermocouple being a heat sink in the salt. Future tests that use salt-immersed thermocouples to measure the temperature of the salt should employ grounded thermocouples for faster response time and the thermocouple sheath exposed to the atmosphere should be insulated to minimize the heat sink effect in the salt.

### 3.2.3 Beaker wall temperature measurements

Figure 10 presents still frames taken from IR video that provide the surface temperature of the outer beaker wall after approximately 60 g of FLiNaK at an initial temperature of approximately 650 °C was poured into beakers with different wall thicknesses (Test 1, 3, and 4). The depth of the salt in the beaker was approximately 12.5 mm (0.5") for each test, as presented in Table 8 and indicated by the dotted red line in each image in Figure 10. This was determined by recovering the
frozen salt from the beaker after cooling to room temperature and measuring the height of the intact piece of salt using calipers. Only the bottom 2 inches of the beaker that is covered with the high-emissivity tape are shown in the IR video frames. The overall surface temperature of the outer beaker wall was highest for the beaker with \( \frac{1}{16} \)"-thick walls and decreased with increasing wall thickness. The IR video frames that contain the beaker outer wall temperatures for heat transfer tests 1, 2, 3, and 4 have been exported to .csv files and are available in the data package associated with this report. The temperatures reported in those data files have been adjusted to account for the emissivity of the tape coating the beaker outer wall.

Figure 10: Still frames from video taken by the IR camera that show the surface temperature (°C) of the outer wall of the stainless steel beakers with different wall thicknesses from Tests 1, 3, and 4. The height of the high-emissivity tape that covered the outer beaker wall was 2" and the red dotted line shows the approximate height of the salt in the beaker. The frames were taken between 0.167 minutes and 5.168 minutes after the salt was first poured into the beaker.
The pixel in the IR video frames of the beaker outer wall indicating the maximum temperature was identified for each test, and the temperature indicated by those pixels over time is plotted Figure 11A. The maximum temperature of the beaker outer wall that was reached during the test decreases with beaker wall thickness (Figure 11B). The time to reach the maximum outer wall temperature was approximately 2 minutes for the beaker with \( \frac{1}{16} \)"-thick walls and approximately 4 minutes for the beakers with \( \frac{1}{8} \)"-thick walls (Test 2 and Test 3) and the beaker with \( \frac{1}{4} \)"-thick walls (Test 4).

![Figure 11: (A) The outer surface temperature of the beaker wall plotted as a function of time as measured by the IR camera for Tests 1, 2, 3, and 4. The temperatures of the pixel that yielded the highest temperature during the test are plotted. (B) The maximum temperature of the beaker wall outer surface plotted as a function of beaker wall thickness. (C) The time after pouring salt into the beaker at which the beaker outer surface reached the maximum temperature.](image)

3.2.4 Temperature of the underside of the stainless steel beaker

The temperature of the underside of the stainless steel beaker was measured over the duration of each test at one second intervals using a thermocouple, and the results are plotted in Figure 12A. The measured beaker underside temperature profiles resemble the profiles of the measured temperatures of the beaker outer walls for the same test. The maximum temperatures attained at the beaker underside are slightly higher than those of the beaker outer wall for the same beaker wall or base thickness (compare Figure 11B and Figure 12B), likely because the base is insulated and the outer wall is not. In addition, the beaker underside temperatures measured for replicate tests 2 and 3 are highly similar, indicating that the surface temperature measurements are repeatable using the thermocouple method. Like the maximum temperatures of the outer surface of the beaker wall, the maximum temperatures of the beaker underside decrease with the beaker base thickness (Figure 12B). The time required to reach the maximum temperature at the beaker underside increases with the beaker base thickness (Figure 12C). The data files of the beaker underside temperature measurements are available in the data package associated with this report.
Figure 12: (A) The beaker underside temperature plotted as a function of time as measured by a thermocouple attached to the surface for Tests 1, 2, 3, and 4. The beaker underside was insulated. (B) The maximum temperature of the beaker underside was plotted as a function of beaker base thickness. (C) The time after pouring salt into the beaker at which the beaker underside reached the maximum temperature.

3.3 Results from tests with eutectic NaCl-UCl₃

The methodology that was developed to provide data for heat transfer models of static molten salt pools using FLiNaK was employed to investigate the heat transfer behavior of eutectic NaCl-UCl₃, except a thermocouple was not immersed in the salt. The results and main findings from these tests with eutectic NaCl-UCl₃ are presented in this section. Some full datasets are available in the data package associated with this report and their availability is indicated in the following sections. Table 7 provides a summary of the conditions for each test using eutectic NaCl-UCl₃. Tests were conducted with between 65 g and 80 g NaCl-UCl₃. A summary of the conditions of the glovebox atmosphere for each test is provided in Appendix B.

Table 7: Summary of test conditions to study heat transfer of molten eutectic NaCl-UCl₃

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Target initial salt temp. (°C)a</th>
<th>Max salt temp. (°C)b</th>
<th>Beaker wall thickness (in.)</th>
<th>Avg. salt depth (mm)</th>
<th>Salt mass recovered (g)c</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>700</td>
<td>662</td>
<td>1/16&quot;</td>
<td>10.2 ± 0.5</td>
<td>71.8</td>
</tr>
<tr>
<td>2</td>
<td>700</td>
<td>n/a</td>
<td>1/16&quot;</td>
<td>10.4 ± 0.4</td>
<td>72.1</td>
</tr>
<tr>
<td>3</td>
<td>700</td>
<td>658</td>
<td>1/8&quot;</td>
<td>10.4 ± 0.2</td>
<td>71.6</td>
</tr>
<tr>
<td>4</td>
<td>700</td>
<td>648</td>
<td>5/8&quot;</td>
<td>8.5 ± 0.3</td>
<td>59.1</td>
</tr>
<tr>
<td>5</td>
<td>700</td>
<td>662</td>
<td>1/4&quot;</td>
<td>10.7 ± 0.2</td>
<td>72.8</td>
</tr>
</tbody>
</table>

a The actual salt temperatures may have slightly differed from the target temperature.
b The maximum temperature of the salt measured by the IR camera (assumed salt emissivity of 0.95) provided an estimate of the actual salt temperature as it was poured.
c Tests 1, 2, 3, and 5 had a target salt mass of 80 g and Test 4 had a target mass of 65 g.
d IR camera did not capture salt temperature in the crucible before the pour.
3.3.1 Salt surface temperature measurements by using an infrared camera

Figure 13 presents still frames taken by the IR camera of the NaCl-UCl$_3$ salt surface temperature in the stainless steel beaker at different times after first pouring the molten salt into the beaker. The black circle in each still frame marks the interface of the salt and the inner beaker wall (Figure 13). Like what was observed in tests with FLiNaK, the eutectic NaCl-UCl$_3$ salt in the beaker cools fastest near the walls of the beaker, and the salt that was poured into the beaker with $\frac{1}{4}$"-thick walls cools faster than the salt that was poured into beakers with thinner walls (Figure 13). The IR video frames that recorded the salt surface temperatures for heat transfer Tests 1, 3, 4, and 5 with eutectic NaCl-UCl$_3$ have been exported to .csv files and are available in the data package associated with this report. Results for Test 2 do not include salt surface temperature measurements because the IR video failed during that test. Files that have and have not been corrected for the emissivity of the salt are available. The frozen salt typically had non-uniform surface topography and voids within the salt, as shown in example images in Figure 14.

![Figure 13: The surface temperature (°C) of eutectic NaCl-UCl$_3$ in stainless steel beakers of different wall thicknesses over time during Tests 1, 3, and 5. The indicated time is the relative time after pouring the molten salt into the beaker. The black circle in each frame marks the edge of the salt in the beaker.](image-url)
**Figure 14:** Examples of the frozen NaCl-UCl₃ salt after it had cooled to room temperature and was removed from the stainless steel beaker. (A) Aerial view of salt from Test 1 and (B) cross section of salt from Test 2.

**Figure 15:** Radial distribution of NaCl-UCl₃ surface temperature (°C) in stainless steel beakers with wall thicknesses of (A) 1/16", (B) 1/8", and (C) 1/4" as a function of distance from center of the beaker and the time after the salt was poured for Tests 1, 3, and 5. The image in the inset shows the location of the assessed pixels. The center is pixel 0.

The effect of distance from the center of the beaker and time after the salt was poured on the NaCl-UCl₃ surface temperature for beakers of different wall thicknesses is shown in Figure 15. The inset in Figure 15 identifies the pixels that were analyzed (black arrow), where the center pixel is labeled pixel 0. The surface temperature of the salt near the beaker wall is lower than the surface temperature of the salt at the center of the beaker for all tests and time points regardless of beaker wall thickness, indicating a temperature gradient along the salt surface. The lack of insulation around the beaker walls likely amplifies this radial temperature gradient because the beaker walls
are a heat sink due to natural convection in the glovebox atmosphere that cools the outer walls. The duration of the phase change from liquid to solid at which the salt surface temperature remains at the melting point (450 °C) is much shorter in tests with NaCl-UCl₃ salt than in tests with FLiNaK (compare Figure 7 with Figure 15). This can be attributed to a heat of fusion of eutectic NaCl-UCl₃ being much lower than that of FLiNaK (on a per gram basis; Section 2.4.4). In addition, the salt surface temperatures between pixel 0 and pixel 20 for the first few time points presented in Figure 15 are not as uniform as the same pixels for the tests with FLiNaK (see Figure 7), likely because eutectic NaCl-UCl₃ cooled faster than FLiNaK and presented non-uniform surface topography (e.g., Figure 14).

3.3.2 Beaker wall temperature measurements

Figure 16 presents still frames taken from IR video that provide the surface temperature of the outer beaker wall after approximately 60 g to 70 g of eutectic NaCl-UCl₃ at an initial target temperature of 700 °C was poured into beakers with different wall thicknesses (Test 1, 3, and 5).

![Figure 16: Still frames from video taken by the IR camera that show the surface temperature (°C) of the outer wall of the stainless steel beaker with different wall thicknesses from Tests 1, 3, and 5. The height of the high-emissivity tape that covered the outer beaker wall was 2" and the red dotted line shows the approximate height of the salt in the beaker. The frames were taken between 0.166 minutes and 3 minutes after the salt was first poured into the beaker.](image-url)
The depth of salt in the beaker was approximately the same for these tests (i.e., approximately 10.5 mm) and the values are presented in Table 7. The approximate depth of the salt in the beaker is indicated in each still frame in Figure 16. The overall surface temperature of the outer beaker wall was highest for the beaker with 1/16"-thick walls and decreased with increasing wall thickness. The IR video frames that provide the beaker outer wall temperatures for heat transfer Tests 1, 2, 3, 4, and 5 have been exported to .csv files and are available from the authors in the data package associated with this report. The reported temperatures in those data files have been adjusted to account for the emissivity of the tape coating the beaker outer wall.

The pixel in the IR video frames of the beaker outer wall that reached the maximum temperature was identified for each test, and the temperature that was measured at that pixel is plotted over time for each test in Figure 17A. The maximum temperature of the beaker outer wall for the tests with eutectic NaCl-UCl₃ decreases with increasing beaker wall thickness (Figure 17B). The maximum outer wall temperatures that were reached in Tests 1 and 2 using the beaker with 1/16"-thick walls was approximately 315 °C, whereas the maximum outer wall temperature for the same test conditions with FLiNaK was approximately 410 °C. The masses of FLiNaK and eutectic NaCl-UCl₃ used in the static molten salt heat transfer tests were slightly different (i.e., between 65 g and 80 g of NaCl-UCl₃ and approximately 60 g of FLiNaK; compare Table 6 and Table 7). In addition, the time to reach the maximum outer wall temperature for the tests with eutectic NaCl-UCl₃ increases with the beaker wall thickness (Figure 17C).

**Figure 17:** (A) The outer surface temperature of the beaker wall plotted as a function of time as measured by the IR camera for Tests 1, 2, 3, 4, and 5 using eutectic NaCl-UCl₃. The temperatures of the pixel that yielded the highest temperature during the test are plotted. (B) The maximum temperature of the beaker wall outer surface plotted as a function of beaker wall thickness. (C) The time after pouring salt into the beaker at which the beaker outer surface reached the maximum temperature.

### 3.3.3 Temperature of the underside of the stainless steel beaker

The temperature of the underside of the stainless steel beaker was measured over the duration of each test at one second intervals using a thermocouple, and the results are plotted in Figure 18A.
Test 1 and Test 2 were conducted using a beaker with \(\frac{1}{16}\)"-thick walls and approximately the same mass of NaCl-UCl₃, and the temperature measurements are repeatable (Figure 18A). In addition, the measured beaker underside temperatures profiles resemble those of the beaker outer wall for the same test conditions (compare Figure 17A and Figure 18A). The maximum temperatures of the beaker underside are slightly higher than those of the beaker outer wall for the same beaker wall or base thickness (compare Figure 17B and Figure 18B). This is likely because the base is insulated and the outer wall is not. The maximum temperatures reached by the beaker underside decrease with increasing beaker base thickness (Figure 18B), and the time to reach the maximum temperature for the beaker underside increases with beaker base thickness (Figure 18C). The data files with results of the beaker underside temperature measurements are available in the data package associated with this report.

Figure 18: (A) The beaker underside temperature plotted as a function of time as measured by a thermocouple attached to the surface for Tests 1, 2, 3, 4, and 5. Test 4 used a different amount of salt than the other tests (approximately 59 g in beaker versus approximately 72 g for the other tests). The beaker underside was insulated. (B) The maximum temperature of the beaker underside plotted as a function of beaker base thickness. (C) The time after pouring salt into the beaker at which the beaker underside reached the maximum temperature.

4 Molten salt spreading

4.1 Methods

4.1.1 Design and description of test equipment

The objective of these tests was to measure the flow and spreading behavior of spilled molten salt on a sloped catch pan. Molten NaCl-UCl₃ was poured onto a 316 stainless steel sheet (McMaster-Carr, item no. 88885K24) that was 22 in. long, 10 in. wide, and 0.06 in. thick with a 1-in. lip on three sides to prevent spillover (Figure 19). The top end of the catch pan was elevated to create a tilt angle of 2.5° for these measurements. The salt was heated to the target temperature in a
furnace using a custom nickel crucible and then manually poured onto the top end of the catch pan using long crucible tongs. The spreading and heat transfer tests were conducted within an argon atmosphere glovebox (O<sub>2</sub> < 10 ppm, H<sub>2</sub>O < 5 ppm). An IR camera and a visible camera mounted on a tripod and positioned approximately three feet above the catch pan were used to record video of molten salt spreading as it was poured (Figure 19). The IR camera was used to measure the surface temperatures of the salt as a function of time. Several thermocouples were attached to the top surface and underside of the catch pan and placed in the atmosphere above the catch pan to record temperatures throughout the tests. These thermocouples were butt-welded, K-type lead wires that were attached to the surface with thermally conductive cement. A description of the IR camera, data logger for thermocouple measurements, visible camera, and furnace is provided in Appendix A. Technical aspects of temperature measurements and calibrations for the IR camera and surface thermocouples are described in a previous report (Thomas and Jackson, 2021).

Figure 19: (A) Schematic of the molten salt spreading and heat transfer test. (B) Photograph of the setup in the glovebox.

Figure 20 shows the thermocouple layout at the underside of the stainless steel catch pan. The salt was poured down the center of the catch pan with the intention that it would flow directly over most of the thermocouples attached to the underside of the catch pan.

Figure 20: The thermocouple layout at the underside of the catch pan. The diagram shows the layout as viewed looking down on the catch pan upper surface. The top end of the diagram is on the left side of the diagram and salt flows from left to right. Thermocouple 1 and Thermocouple 9 were positioned approximately 0.5 in. from the top and bottom of the sheet, respectively.
4.1.2 Measurements and calculations

4.1.2.1 Temperature

Thermocouples attached to the underside of the catch pan were used to measure the temperature at one second intervals during each test (see Figure 20 for thermocouple locations). This surface temperature measurement method using thermocouples was previously demonstrated to provide a quick and accurate temperature response (Thomas and Jackson, 2021).

The temperatures of the entire molten salt surface were monitored with an IR camera with 42° lens. The wide lens was chosen so that the field of view of the camera included the entire catch pan. The emissivity of eutectic NaCl-UCl₃ was assumed to be 0.95 at all temperatures (as estimated in Section 2.4.3), and this value was used in Equation 3 to adjust the measurements made by the IR camera and determine the salt surface temperature. The IR camera measured the apparent temperature of the stainless steel catch pan surface, but adjustments for this low emissivity material (estimated to be between 0.1 and 0.3; Thomas and Jackson, 2021) were not made due to the high uncertainty associated with temperature adjustments for low emissivity materials.

The furnace temperature, as measured by a thermocouple positioned in the furnace liner, provided an estimate of the initial molten salt temperature. The initial salt temperature in the crucible before it was poured was measured using the IR camera.

A sheath-type thermocouple (ungrounded, K type) positioned in the atmosphere approximately 2 feet above the substrate and directly above the molten salt pool that formed at the end of the catch during the spreading test provided the temperature of the atmosphere as a function of time.

4.1.2.2 Average pour rate

The average pour rate was determined by dividing the mass of salt that was poured by the duration of the pour. The mass of salt poured was determined by collecting and weighing all of the salt that had been poured onto the catch pan. The duration of the pour was determined by using footage from the visible camera, which showed the time when the salt first hit the catch pan and the time when the salt ceased flowing from the crucible. The time when salt ceased flowing from the crucible was taken as the time at which the salt stream stopped flowing, so that the final drips of salt leaving the crucible were excluded from the pour duration but included in the poured mass.

4.1.2.3 Leading edge and covered area as a function of time

The IR camera records video at a rate of 30 frames per second and provides detailed information on the leading edge and covered area of the salt spreading on catch pan as a function of time. The leading edge and covered area of the molten salt flowing on the catch pan was determined for each still frame of the IR video. The raw IR video for each molten salt spreading measurement was uploaded to the software FLIR ResearchIR (Version 4.40.11.35) and the dataset (matrix of temperature values per pixel at each frame of the video) was exported into a MATLAB®-readable format. The difference between the apparent temperatures of the salt and the catch pan measured in the IR images provides sufficient contrast to distinguish the two materials due to the significant difference in their emissivity. The Image Processing Toolbox™ in MATLAB® was used to distinguish between the two materials in the temperature matrix of each still frame so that each pixel could be identified as representing salt or stainless steel to create a binary image. Specifically, the “imbinarize” function was employed to identify the pixels in each IR video frame
that were salt and those that were the catch pan. The temperatures of the pixels identified to be salt were adjusted for the estimated emissivity of the salt using the methods described in Section 3.1.2.1.

Figure 21A provides a raw IR image of salt spreading on the catch pan (approximately two seconds after the salt first exited the crucible and touched the catch pan). The top-most part of the image was cropped to remove the crucible from the field of view so that the crucible surface did not interfere with image processing. Figure 21B provides a binary image of the salt (white) on a black background (the substrate), and Figure 21C provides the processed image showing the temperature of just the salt after correcting the IR camera measurements for the estimated emissivity of the salt.

The leading edge and covered area were determined from the corresponding binary image in units of pixels for each still frame recorded by the IR camera. The dimensions of each pixel were determined by using the known length and width of the catch pan and then used to convert the leading edge and covered area from numbers of pixels to units of centimeters and square centimeters, respectively.

![Figure 21](image)

**Figure 21:** (A) Raw image measured by IR camera, (B) binary image showing the salt (white) on the stainless steel background (black), and (C) processed image showing the temperature of just the salt.

4.1.2.4 Video and images obtained by visible camera

A visible camera mounted on a tripod filmed visible video of the molten salt spreading and freezing on the catch pan. Photographs of the frozen salt were also taken to show the morphology and freezing behavior.
4.1.2.5 Glovebox conditions

The temperature, O₂ content, and H₂O content of the atmosphere of the argon glovebox was recorded before and after pouring molten salt for each test.

4.2 Results

Table 8 provides a summary of the conditions used in each spreading test conducted using eutectic NaCl-UCl₃. A summary of the conditions of the glovebox atmosphere for each test is provided in Appendix B. This section provides examples of the results and summarizes key findings. Full datasets for some of the measurements are available in the data package associated with this report and their availability is indicated.

Table 8: Summary of test conditions to study spreading of eutectic NaCl-UCl₃

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Target initial salt temp. (°C)</th>
<th>Max temp. (°C)</th>
<th>Mass of salt poured (g)</th>
<th>Average pour rate (g s⁻¹)</th>
<th>Spreading behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>700</td>
<td>643.6</td>
<td>67.1</td>
<td>31.8</td>
<td>Single stream</td>
</tr>
<tr>
<td>2</td>
<td>800</td>
<td>736.6</td>
<td>65.2</td>
<td>27.2</td>
<td>Single stream</td>
</tr>
<tr>
<td>3</td>
<td>600</td>
<td>561.2</td>
<td>51.5</td>
<td>21.8</td>
<td>Split stream</td>
</tr>
<tr>
<td>4</td>
<td>600</td>
<td>550.0</td>
<td>64.8</td>
<td>26.8</td>
<td>Split stream</td>
</tr>
<tr>
<td>5</td>
<td>700</td>
<td>644.3</td>
<td>51.6</td>
<td>20.0</td>
<td>Split stream</td>
</tr>
<tr>
<td>6</td>
<td>800</td>
<td>729.4</td>
<td>48.2</td>
<td>18.6</td>
<td>Split stream</td>
</tr>
<tr>
<td>7</td>
<td>800</td>
<td>729.8</td>
<td>66.6</td>
<td>23.1</td>
<td>Split stream</td>
</tr>
</tbody>
</table>

a All tests were conducted using a catch pan tilt angle of 2.5°

b Tests 1, 2, 4, and 7 had a target pour mass of 80 g and Tests 3, 5, and 6 had a target pour mass of 65 g.

c The actual salt temperature may have differed from the target temperature.

d The maximum temperature of the salt measured by the IR camera (emissivity = 0.95) provides an estimate of the actual salt temperature as it was poured.

4.2.1 Visible and IR images from tests of molten salt spreading and freezing on a stainless steel catch pan

Figure 22 and Figure 23 show still frames taken from video recorded by the visible and IR cameras of eutectic NaCl-UCl₃ spreading on the stainless steel catch pan at initial salt temperatures of approximately 740 °C (Test 2) and 550 °C (Test 4), respectively. The molten NaCl-UCl₃ is a brown-black color and is not optically transparent. At the initial contact location between the spilling molten salt and the catch pan, the salt spreads laterally to widths greater than the diameter of the stream pouring from the crucible (Figure 22 and Figure 23). This indicates that this salt wets the stainless steel catch pan to some extent, unlike FLiNaK which did not appear to wet the stainless steel sheet during previous tests (Thomas and Jackson, 2021). Other atmospheric conditions (i.e., in air) or catch pans with different surface roughness may affect the molten salt wetting and spreading behavior (Grosu et al., 2019).

The molten NaCl-UCl₃ displayed two types of spreading behavior, as summarized in Table 8. One type of spreading behavior was flowing as a single stream down the length of the catch pan, as shown in Figure 22. This salt spread out initially at the location of impact on the catch pan and then coalesced into a single narrow stream that remained intact until it pooled at the bottom of the
catch pan (Figure 22E). The other type of spreading behavior involved splitting into two streams at the location of impact, as shown in Figure 23. The IR still frames of the molten salt on the catch pan at the location of impact provide insight into this behavior (Figure 23A, Figure 23B, and Figure 23C). The salt surface reaches temperatures below the melting point of 520 °C at the impact zone. This frozen salt forms a salt dam that forces the fresh molten salt spilling from the crucible to flow around the dam. The salt in Test 4 bypassed the impact zone and formed two streams that flowed separately to the end of the substrate (Figure 23). Notably, the salt at the impact zone of Test 2 also appeared to reach temperatures below the freezing point of 520 °C and form a frozen salt dam, but the molten salt that flowed around both sides of the dam recombined into one stream as it flowed to the bottom of the catch pan (Figure 22).

**Figure 22:** Still frames from video taken by the visible and IR camera at the same time point that show approximately 65 g of eutectic NaCl-UCl₃ at an initial temperature of approximately 740 °C flowing and spreading onto a stainless steel catch pan tilted at an angle of 2.5° (Test 2). The frames were taken (A) 0.3, (B) 0.5, (C) 0.9, (D) 1.4, and (E) 2.0 seconds after the molten salt first contacted the catch pan.
Figure 23: Still frames from video taken by the visible and IR camera at the same time point that show approximately 65 g of eutectic NaCl-UCI₃ at an initial temperature of approximately 550 °C flowing and spreading onto a stainless steel catch pan tilted at an angle of 2.5° (Test 4). The frames were taken (A) 0.3, (B) 0.4, (C) 0.7, (D) 1.5, and (E) 2.6 seconds after the molten salt first contacted the catch pan.

Whether the molten salt flowed as a single stream or split into two streams as it spread appears to be related to the initial salt temperature and the total amount of salt that was spilled (Table 8). Molten salt at a lower initial temperature and smaller initial pour mass split most frequently. However, initial salt temperature and pour mass do not determine spreading behavior because Test 2 and Test 7 had nearly identical initial conditions but displayed different spreading behavior (Table 8). To compare, molten FLiNaK never split into two streams during prior testing using similar salt volumes and initial temperatures (Thomas and Jackson, 2021). This is likely because the
The molten NaCl-UCI₃ salt flowed quickly down the length of the stainless steel catch pan and pooled at the bottom during all tests. The spreading behavior was not limited by salt freezing, similar to previous observations during tests using FLiNaK (Thomas and Jackson, 2021). In addition, a crust formed at the salt-catch pan interface in all tests, which left a trail of frozen salt the entire length of the flow path. Similar crust formation was observed previously with tests with FLiNaK (Thomas and Jackson, 2021), although the NaCl-UCI₃ crusts were much thinner than the FLiNaK crusts. The average thickness of the NaCl-UCI₃ crust that formed near the top of the substrate (upstream) is provided in Table 9 for each test. The upstream crust thickness was around 1 mm in each test with NaCl-UCI₃ and around 2.5 mm in previous tests using FLiNaK (Thomas and Jackson, 2021). The reason for this difference in crust thickness between NaCl-UCI₃ and FLiNaK for similar test conditions is unknown but is likely due to a difference in thermophysical properties of these salts. The mass fraction of salt that pooled at the end of the substrate and the mass fraction of salt that remained as a crust on the substrate are presented in Table 9 for each test. The amount of salt that pools at the end of the substrate is highly dependent on the total mass of salt poured and the initial temperature of the salt. Tests 1, 2, and 7 all had a total pour mass of approximately 65 g of salt and target initial salt temperatures between 700 °C and 800 °C, and all had a similar distribution of salt by mass (Table 9). The tests with salt at an initial target temperature of 800 °C (Tests 2 and 7) had more salt pooled at the bottom of the catch pan than Test 1 that used salt at an initial target temperature of 700 °C, likely because 800 °C is farther from the freezing point of the salt. Likewise, Test 3 and Test 4 that used salt at an initial target temperature of 600 °C had significantly less salt form a pool at the bottom of the catch than tests conducted with salts at higher initial temperatures (Table 9).

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Target initial salt temp. (°C)</th>
<th>Mass of salt poured (g)</th>
<th>Mass fraction of salt pooled</th>
<th>Mass fraction of salt crust</th>
<th>Avg. pool thickness (mm)</th>
<th>Avg. crust thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>700</td>
<td>67.1</td>
<td>0.48</td>
<td>0.52</td>
<td>3.9 ± 0.1</td>
<td>1.2 ± 0.2</td>
</tr>
<tr>
<td>2</td>
<td>800</td>
<td>65.2</td>
<td>0.54</td>
<td>0.46</td>
<td>4.2 ± 0.1</td>
<td>1.1 ± 0.3</td>
</tr>
<tr>
<td>3</td>
<td>600</td>
<td>51.5</td>
<td>0.09</td>
<td>0.91</td>
<td>3.9 ± 0.3</td>
<td>1.0 ± 0.1</td>
</tr>
<tr>
<td>4</td>
<td>600</td>
<td>64.8</td>
<td>0.16</td>
<td>0.84</td>
<td>4.3 ± 0.1</td>
<td>1.4 ± 0.1</td>
</tr>
<tr>
<td>5</td>
<td>700</td>
<td>51.6</td>
<td>0.31</td>
<td>0.69</td>
<td>4.0 ± 0.2</td>
<td>1.1 ± 0.1</td>
</tr>
<tr>
<td>6</td>
<td>800</td>
<td>48.2</td>
<td>0.31</td>
<td>0.69</td>
<td>4.3 ± 0.2</td>
<td>0.9 ± 0.1</td>
</tr>
<tr>
<td>7</td>
<td>800</td>
<td>66.6</td>
<td>0.56</td>
<td>0.44</td>
<td>3.9 ± 0.1</td>
<td>1.3 ± 0.2</td>
</tr>
</tbody>
</table>

Another notable feature of the spreading NaCl-UCI₃ that was identified by the IR camera measurements was that the surface temperature of the salt that was spreading appeared to be below the freezing point. This is clear in Figure 23D where the salt leading edge appears to be at a temperature between 350 °C and 400 °C, which is well below the freezing point. The fact that the spreading salt is thin (approximately 1 mm thick) likely affects the apparent temperature of the salt surface that is measured by the IR camera. Although the temperature measurements made by the IR camera in Figure 22 and Figure 23 were corrected for the estimated emissivity of the salt (see Section 2.4.3), the transmissivity of the salt to IR radiation was assumed to be negligible. The transmissivity of the salt when it is very thin is likely not negligible; the transmission of IR radiation from the underlying catch pan through the salt is likely affecting the apparent salt surface.
temperature measured by the IR camera. This hypothesis is supported by the fact that the salt surface temperature (as measured by the IR camera) is higher for the thicker layer of pooled salt at the bottom of the catch pan than the thinner layer of spreading salt shown in previous IR video frames (compare Figure 23D and Figure 23E). As such, the surface temperatures of thin layers of eutectic NaCl-UCl$_3$ measured by using an IR camera that have not been adjusted to account for the transmissivity of the salt probably do not represent the actual salt temperature. Future studies to determine the maximum thickness of eutectic NaCl-UCl$_3$ (and other salt compositions) at which the salt transmissivity to IR radiation is negligible are recommended.

Visible video taken of the frozen crust on the catch pan as it cooled consistently captured the salt raise off the stainless steel surface and shrink and break into pieces at the end of all tests. Figure 24 shows an example of the salt behavior and appearance as it cools on the stainless steel catch pan. Visible videos and the IR video frames (uncorrected for emissivity) from each test are available in the data package associated with this report. The IR video frames have been cropped to show just the stainless steel catch pan, and the hot crucible appears in the first few frames of each test as the salt is being poured onto the catch pan.

![Figure 24](image)

**Figure 24:** Still frames from video taken by the visible camera that show approximately 65 g of eutectic NaCl-UCl$_3$ at an initial temperature of approximately 550 °C cooling on the stainless steel substrate (Test 4). The frames were taken 3, 8, 14, and 46 seconds after the molten salt was poured onto the catch pan.

### 4.2.2 Temperature of substrate underside

Figure 25A and Figure 26A show the layout of the thermocouples attached to the underside of the stainless steel catch pan overlaid on a still frame of video collected by using the IR camera for Tests 1 and 4 at initial salt temperatures of approximately 644 °C and 550 °C, respectively. The
positions of Thermocouple 1 and Thermocouple 9 were approximately 0.5 in. from the top and bottom of the catch pan, respectively, for all tests. These images show the positions of the salt after spreading ceased relative to the locations of the thermocouples. The temperatures recorded by each thermocouple are provided in subplots B and C of Figure 25 and Figure 26. The thermocouples at positions 4 and 7 failed for all tests and temperatures for those positions are not reported. The images of the thermocouple locations overlaid on still frames of the salt on the catch pan after spreading had ceased for Tests 2, 3, 5, 6, and 7 are reported in Appendix B.

![Image](image.png)

**Figure 25:** Results for salt spreading Test 1: (A) Location of thermocouples attached to the underside of the catch pan overlaid on an image of the salt spreading path, (B) the temperature profiles measured by Thermocouples 1, 2, 3, 6, and 9 along the center of the catch pan, and (C) the temperature profiles measured by Thermocouples 5 and 8. Thermocouples 4 and 7 failed during this test.

The spreading behavior of eutectic NaCl-UCl₃ was different than the salt composition that was tested previously (i.e., FLiNaK) in that it frequently split into two streams as it flowed to the bottom of the catch. Therefore, the molten NaCl-UCl₃ did not always flow directly over the thermocouples attached to the catch pan underside, which were all located near the center of the substrate (Figure 20). The temperature underneath the static salt pool that formed at the bottom of the catch pan (recorded by Thermocouple 9) was typically the highest recorded temperature as long as the salt pooled directly above Thermocouple 9. This is because the pooled salt layer was thicker than the salt that formed a crust upstream of the pool (i.e., around 4 mm versus around 1 mm; Table 9). The maximum temperature recorded at the catch pan underside of all tests was approximately 170 °C, which was made by Thermocouple 9 during Test 6. For this test, the salt had a high initial temperature (approximately 730 °C) and pooled directly over Thermocouple 9 at the bottom of the catch pan.
Figure 26: Results for salt spreading Test 4: (A) Location of thermocouples attached to the underside of the catch pan overlaid on an image of the salt spreading path, (B) the temperature profiles measured by Thermocouples 1, 2, 3, 6, and 9 along the center of the catch pan, and (C) the temperature profiles measured by Thermocouples 5 and 8. Thermocouples 4 and 7 failed during this test.

4.2.3 Leading edge and covered area

The leading edge of the molten salt stream that flowed down the catch pan and the area of the catch pan covered by salt was determined for each spreading test as a function of time. Test 7 was not analyzed for leading edge or total covered area because the salt touched the side walls of the catch pan before pooling at the bottom. The leading edge position and covered area of the salt on the catch pan for tests with an approximate pour mass of 65 g are shown in Figure 27A and Figure 27B, respectively. The leading edge position and covered area of the salt on the catch pan for tests with an approximate pour mass of 50 g are shown in Figure 27C and Figure 27D, respectively. The area of the catch pan covered by the salt was only assessed until the leading edge first touched the bottom wall so that the salt that pools at the end of the catch pan was not included in the area analysis. In general, molten NaCl-UCl₃ salt at lower initial temperatures took longer to reach the end of the catch pan and had a larger total covered area when it reached the end of the catch pan than molten NaCl-UCl₃ salt at higher initial temperatures (Figure 27).
Figure 27: (A,C) The leading edge of the flowing salt and (B,D) the area of the catch pan covered by salt as a function of time for tests with a pour mass of approximately (A,B) 65 g and (C,D) 50 g. The initial salt temperatures and average pour rates are provided in the legend.

A correlation between the spreading duration and the pour rate was observed for the entire dataset shown (Figure 28A). This is likely because the inertia of the poured salt contributes to the spreading velocity. Also, salt with initial temperatures of 550 °C and 561 °C (Test 3 and Test 4) took longer to reach the end of the substrate than the salts with substantially higher initial temperatures of 729 °C and 737 °C (Figure 28A). The spreading duration also correlated slightly with the total mass poured due to the fact that the total mass poured and the average pour rate are correlated. A correlation between the initial (maximum) salt temperature and the total area of the catch pan covered by salt when the leading edge first reached the bottom of the catch pan was observed for the entire dataset (Figure 28B). Salts at lower initial salt temperatures spread to larger areas than those with higher initial salt temperatures (Figure 28B). The observed effect of temperature on the total spreading area can likely be attributed to differences in thermophysical
properties as a function of temperature, although many thermophysical properties of eutectic NaCl-UCI₃ are currently unknown (Section 2.4.4).

Figure 28: (A) The time it took for the leading edge of the spreading salt to reach the bottom of the catch pan (spreading duration) plotted as a function of the average pour rate for 6 tests. (B) The total area of salt covering the catch pan when the leading edge first reached the bottom of the catch pan plotted as a function of the initial (maximum) temperature of salt that was poured.

5 Molten salt splashing and aerosol formation

5.1 Methods

5.1.1 Design and description of test equipment

The objective of the tests discussed in this section is to quantify the splatter and aerosols that are generated due to splashing of molten salt onto a catch pan surface. The molten salt can be doped with surrogate fission products to gain insight into the distribution of key radionuclide species after a salt spill accident. A 12 in. × 12 in. × 12 in. (L × W × H) stainless steel “spill containment box” was constructed to study molten salt splashing and aerosol formation (Figure 29A). The purpose of the box is to contain the splatter and aerosols that form within so that they can be collected and analyzed. The top of the box includes a 2.5 in. × 2.5 in. × 3 in. (L × W × H) opening through which molten salt is poured manually. The pour inlet is wide enough so that the stream of molten salt does not contact the inlet walls while it is being poured into the box. A catch pan with dimensions of 10.375 in. × 6.375 in. × 6 in. (L × W × H) and a wall thickness of 0.03125 in. was placed inside the spill containment box to collect the molten salt that is poured through the inlet. A removable acrylic window was placed on one side of the box to provide access to the inside of the box. The edges of the window were lined with a foam rubber seal to ensure a snug fit when the window is in place. A 2-in. diameter hole cut into the top of the box was used as a viewport for a visible camera (Figure 29A). All molten salt splashing and aerosol generation tests were conducted within an argon atmosphere glovebox (O₂ < 10 ppm, H₂O < 5 ppm).
Figure 29: (A) Schematic of the spill containment box for the molten salt splashing and aerosol collection test. (B) Photograph of the spill containment box that identifies the various measurement components including thermocouples, coupons to collect molten salt splatter, a filter to collect aerosols, and the visible camera.

Tubing was passed through a small hole in the wall of the spill containment box farthest from the pour inlet and attached to a filter in an aerosol cassette to collect aerosols (Figure 29A). The other end of the tubing was connected to a sampling pump (Buck Elite™) to pull gas through the filter. Figure 29B shows an image of the spill containment box and identifies the various measurement components. Nickel coupons (1 in. × 1 in.) covered with double-sided copper tape (3M) on one side were hung on the catch pan walls to retain splatter contacting the adhesive during the test for future analysis. Thermocouples cemented to the underside of the catch pan (directly under the spill zone) and threaded through tube fittings on the spill containment box walls were used to measure the temperature of the catch pan underside and the temperature of the atmosphere, respectively (Figure 29B).

A description of the data logger for thermocouple measurements, visible camera, and furnace is provided in Appendix A.

5.1.2 Measurements and calculations

5.1.2.1 Average pour rate

The average pour rate was determined by dividing the mass of salt that was poured by the duration of the pour. The mass of salt poured was determined by collecting and weighing all of the salt that had been poured into the catch pan. The duration of the pour was determined by using footage from the visible camera, which showed the time when the salt first contacted the catch pan and the time when the salt ceased pouring onto the catch pan. The final few drips of salt contacting the catch pan were excluded from the pour duration but included in the poured mass.

5.1.2.2 Temperature

The temperature of the underside of the stainless steel catch pan that collected the molten salt that was poured into the spill containment box was recorded with butt-welded thermocouple lead wires with the junction attached to the surface with thermally conductive cement. This surface temperature measurement method has a quick and accurate temperature response (Thomas and
The thermocouple probes were attached to the catch pan directly under the anticipated spill zone location.

Sheath-type thermocouples (ungrounded, K type, ½” diameter) were inserted into the spill containment box at three locations through tube fittings to gauge temperature gradients and the evolution of the temperature of the atmosphere after the spill.

The furnace temperature provided an estimate of the initial molten salt temperature immediately before it was poured.

5.1.2.3 Video and images obtained by visible camera

A visible camera mounted on a tripod and positioned above the camera viewport of the spill containment box (Figure 29A) was used to generate a video of the molten salt splashing into the stainless steel catch pan. The video was collected at a rate of 240 frames per second and was slowed down by a factor of 20 to achieve slow motion footage of molten salt splashing. Photographs were also taken after the splashed salt had cooled to show the distribution of salt particles that had stuck to the walls of the catch pan and the coupons.

5.1.2.4 Glovebox conditions

The temperature, O₂ content, and H₂O content of the argon atmosphere in the glovebox was recorded before and after pouring molten salt for each test.

5.1.2.5 Composition of splatter by ICP-OES and ICP-MS

Samples of splattered salt that froze on the walls of the stainless steel catch pan and salt that froze in a pool on the catch pan floor were collected and analyzed for major cations (sodium and uranium) by using ICP-OES according to the methods reported in Section 2.3. The concentrations of trace metals (cesium, copper, iron, nickel, chromium, calcium, magnesium, potassium, lithium, and zinc) and iodine in the salt were determined by using ICP-MS according to the methods reported in Section 2.3.

5.1.2.6 Aerosol composition

Aerosols that formed in the spill containment box during the test were collected on a 37-mm diameter PTFE filter (0.45 μm pore size) that was connected to a sampling pump. The pump was set to a constant flow rate of 4 L min⁻¹ and was turned on approximately 30 seconds before pouring molten salt into the spill containment box to achieve a steady flow of argon gas from the glovebox through the filter. The pump was run for approximately 10 minutes after the salt was first poured into the box. The total mass of particles collected on the filter was determined by weighing the sampling cassettes before and after the tests; the efficiency of particle collection is unknown.

After the test, the aerosol sampling cassette with PTFE filter was carefully removed from the spill containment box so that the collected particulates could be washed off the filter and analyzed to determine elemental composition. The concentrations of total iodine, cesium, sodium, and uranium in the wash solutions were analyzed by using ICP-MS as described in Section 2.3. The concentrations of metals iron, nickel, chromium, magnesium, calcium, and zinc were also measured in the wash solution by using ICP-MS to provide a composition of the glovebox background particulates.
Nickel coupons were hung on the walls of the catch pan surrounding the spill zone and on the wall furthest from the spill zone just below the aerosol collection filter to collect splatter for the determination of particle abundance and size distribution. The coupons were covered with double-sided copper tape to improve the adhesion of particles to the coupons. Copper tape was intentionally selected as the adhesive material so that the dark salt particles would be visible on the light-colored tape in visible images. A photograph was taken of each coupon that collected salt splatter using a visible camera so that the image could be analyzed for total particle abundance and particle size. The pixel dimensions of the image were determined using the known dimensions of the nickel coupon. The image was then cropped to include only the region of interest for analysis and the total area of the region of interest was determined using the known pixel dimensions. Figure 30 provides an example of a raw image, cropped image, and processed binary image of salt particles collected on a coupon from a molten salt splashing test.

![Figure 30](Image)

**Figure 30**: An example of a raw image, cropped image, and processed binary image of NaCl-UCl₃ salt particles collected on a coupon from a molten salt splashing test. The horizontal line on the coupon in the raw and cropped image is the joint between two pieces of 0.5 in. wide copper tape.

The Image Processing Toolbox™ in MATLAB® was used to identify the black salt particles on the copper tape background. The contrast of the dark particles on the light background facilitated image processing. Image processing of a cropped raw image consisted of the following procedure:

- Convert to grayscale image.
- Perform background correction (for non-uniform illumination).
- Convert to binary image (particles are white, background is black).
- Define a particle as a group of 10 or more contiguous white pixels.
- Count particles and determine the number of pixels occupied by each particle.
- Convert particle area in pixels to mm² using known pixel dimensions.

The measured particle area was used to determine the equivalent diameter, which is defined as the diameter of the particle assuming the projected area on the coupon is a perfect circle. The number of particles and the size distribution of particles for the known area analyzed were obtained in this manner and used to quantify the splashing behavior in individual tests. The minimum detectable equivalent diameter of a particle using this method was approximately 100 μm for this specific salt composition and background combination. It was more difficult to detect these dark NaCl-UCl₃ salt particles on the copper background than it was to detect white FLiNaK particles on a black background, which is why the minimum detectable equivalent diameter is larger for this
analysis than what it was in previous tests using FLiNaK (which was 50 μm; Thomas and Jackson, 2021). NaCl-UCl₃ salt particles with diameters less than 100 μm can be seen on coupons with the naked eye; using adhesive that provides better contrast with dark NaCl-UCl₃ particles would improve particle detection using image analysis techniques.

Splatter formation was also quantified by collecting and weighing the frozen splatter particles and the frozen salt pool in the catch pan after the test had concluded.

5.2 Results

Table 10 provides a summary of the conditions of each splashing and aerosol generation test that was conducted with eutectic NaCl-UCl₃. A summary of the conditions of the glovebox atmosphere for each test is provided in Appendix B. This section provides examples of the results and summarizes key findings. Full datasets are available for some of the measurements in the data package associated with this report and their availability is indicated in the following sections.

Table 10: Summary of splashing and aerosol generation test conditions for tests using molten eutectic NaCl-UCl₃ with and without surrogate fission products

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Initial salt temp. (°C) estimate b</th>
<th>Avg. pour rate (g s⁻¹)</th>
<th>Total mass poured (g)</th>
<th>CsCl and CsI addition?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>650</td>
<td>15.9</td>
<td>24.2</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>650</td>
<td>16.5</td>
<td>23.6</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>800</td>
<td>16.2</td>
<td>24.0</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>800</td>
<td>18.4</td>
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<td>No</td>
</tr>
<tr>
<td>5</td>
<td>800</td>
<td>20.1</td>
<td>23.1</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>650</td>
<td>16.3</td>
<td>24.0</td>
<td>Yes</td>
</tr>
<tr>
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<td>650</td>
<td>17.8</td>
<td>24.4</td>
<td>Yes</td>
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</tr>
<tr>
<td>9</td>
<td>800</td>
<td>19.0</td>
<td>22.6</td>
<td>Yes</td>
</tr>
</tbody>
</table>

a The pour height was 15 in. for all tests. b The initial salt temperature was estimated by using a thermocouple placed in the furnace liner in which the salt was heated.

5.2.1 Splashing behavior

The slow-motion video of molten NaCl-UCl₃ pouring into the spill containment box revealed that the liquid salt poured into the catch pan as a continuous stream when the initial salt temperature of the salt was approximately 650 °C (Figure 31A) and as droplets when the initial temperature of the salt was approximately 800 °C (Figure 31B). This difference in salt behavior during spilling is likely attributable to temperature-dependent thermophysical properties including surface tension, viscosity, and density. Similar temperature-dependent behavior was observed previously with FLiNaK (Thomas and Jackson, 2021). The duration of the spill for all tests discussed in this section was approximately one second. The splashing behavior of eutectic NaCl-UCl₃ was similar to that observed for FLiNaK, where the salt that impinged on the floor of the catch pan broke up into smaller particles that adhered to the walls of the catch pan. The splatter that hit the walls of the catch pan appeared to freeze upon impact. Most splatter particles adhered on the walls of the catch pan temporarily, indicating that the splatter did not freeze prior to contacting the catch pan walls. The splatter that adhered to the catch pan walls eventually fell off during the test due to gravity or after the test when moving the catch pan to collect the coupons with salt splatter. Figure 32 provides still frames taken by the visible camera that capture the spilled NaCl-UCl₃
impinging onto the catch pan floor at different time points after the salt first touched the catch pan floor. After each test, small splatter particles were observed still adhered to the catch pan walls, adhered to the coupons, and on the catch pan floor (Figure 32). The particles on the catch pan floor appear to have fallen from the catch pan walls and collected at the base of the walls.

Visible video of the spilled molten NaCl-UCl₃ splashing in the spill containment box is available from the authors in the data package associated with this report. The available files include video that plays in real time as well as slow motion video that plays at a rate 20 times slower than the real time video.

![Figure 31](image)

**Figure 31:** Still frames from the video taken of molten NaCl-UCl₃ at an initial temperature of approximately (A) 650 °C and (B) 800 °C pouring into the catch pan. Each still frame was taken approximately 0.02 seconds after the salt first touched the catch pan.
Figure 32: Still frames from the video taken of eutectic NaCl-UCl₃ at an initial temperature of approximately 650 °C pouring into the catch pan. The still frames were taken approximately (A) 0.03 seconds, (B) 0.13 seconds, (C) 0.33 seconds, and (D) 0.53 seconds after the salt first touched the catch pan floor.

5.2.2 Splashing quantification

Figure 33 provides the layout and labels of nickel coupons that were hung on the walls of the catch pan surrounding the spill zone (Coupons 1 – 6) to collect splatter for the determination of particle abundance and size distribution. A coupon on the wall furthest from the spill zone was positioned just below the aerosol collection filter (Coupon 7) to collect aerosol particles that were suspended in the gas stream that flowed towards the filter.

Figure 34A shows photographs of the wall nearest to the spill zone (supporting Coupon 2 and Coupon 5), and Figure 34B shows photographs of the wall furthest from the spill zone (supporting Coupon 7) after spilling approximately 24 g of eutectic NaCl-UCl₃ at an initial temperature of approximately 650 °C into the spill containment box. Some black salt particles remain adhered to
the catch pan wall after the spill, with most particles concentrated towards the bottom half of the wall (Figure 34). A few small particles were detected on the upper portion of the walls, including two smaller particles adhered to Coupon 7 with approximate diameters between 400 and 500 μm (Figure 34B).

**Figure 33:** The coupon labels and locations in the catch pan relative to the salt spill zone. The filter for aerosol collection is positioned directly above Coupon 7 on the far wall from the spill zone and is connected to a pump set to a constant flow rate of 4 L min⁻¹.

(A) | (B)
--- | ---

**Figure 34:** Images of the wall supporting (A) Coupon 2 and Coupon 5 and (B) Coupon 7 after spilling approximately 24 g of eutectic NaCl-UCl₃ at an initial temperature of approximately 650 °C into the spill containment box (Test 1). The coupon dimensions are 1 in. × 1 in. The center of Coupon 2 was approximately 2 in. above the catch pan floor and the center of Coupon 5 was approximately 2 in. above the center of Coupon 2.
The abundance and size distribution of particles adhered to coupons were determined from visible images taken of each coupon. This was achieved by converting each raw image into a binary image using the Image Processing Toolbox™ in MATLAB® (as described in Section 5.1.2.7). Figure 35 and Figure 36 provide examples of the raw and processed images of particles adhered to coupons collected after pouring eutectic NaCl-UCl₃ at an initial temperature of approximately 650 °C and 800 °C, respectively, into the spill containment box. The minimum detectable equivalent diameter of a particle for this salt on the copper background was approximately 100 μm; the image analysis software was not able to consistently detect smaller particles although some could be seen with the naked eye.

**Figure 35:** Examples of the raw and processed visible images of (A) Coupon 2, (B) Coupon 4, and (C) Coupon 7 after approximately 24 g of eutectic NaCl-UCl₃ spiked with CsCl and CsI at an initial temperature of approximately 650 °C was poured into the spill containment box (Test 6). The images were cropped prior to analysis. The total areas analyzed for each of the cropped images were (A) 695.2 mm², (B) 583.7 mm², and (C) 600.6 mm².
Figure 36: Examples of the raw and processed visible images of (A) Coupon 1, (B) Coupon 5, and (C) Coupon 7 after approximately 23 g of eutectic NaCl-UCl₃ spiked with CsCl and CsI at an initial temperature of approximately 800 °C was poured into the spill containment box (Test 9). The images were cropped prior to analysis. The total areas analyzed for each of the cropped images were (A) 614.7 mm², (B) 572.0 mm², and (C) 536 mm².

The equivalent diameter (i.e., the diameter of the particle assuming it projects a perfect circle on the coupon) was determined from the particle area in mm² and was the parameter used to compare particle size distributions generated in different tests. The total number of particles collected on the three coupons on the lower section of the walls near the spill zone (Coupons 1, 2, and 3), on the three coupons on the upper section of the walls near the spill zone (Coupons 4, 5, and 6), and on Coupon 7 were normalized to the total area analyzed and averaged to compare the results from tests performed using initial salt temperatures of 650 °C and 800 °C. The results for the three regions are plotted as a function of particle size range in Figure 37. Significantly more particles were collected on Coupons 1, 2, and 3 near the spill zone on the lower section of the walls.
(Figure 37A) than on the Coupons 4, 5, and 6 near the spill zone on the upper section of the walls (Figure 37B) for all temperatures evaluated. Particles with an equivalent diameter greater than 100 μm reached the upper coupons in all tests and reached Coupon 7 in most tests. The initial salt temperature appears to have no effect on particle abundance or size distribution at any coupon location (Figure 37). This behavior was also observed for FLiNaK in previous tests (Thomas and Jackson, 2021).

The raw, cropped, and processed images of the particles on coupons for each test are available from the authors as part of the data package that is associated with this report.

![Figure 37](image)

**Figure 37:** The number of particles within defined size ranges per 1000 mm² that were collected on (A) the lower coupons near the spill zone (sum of Coupons 1, 2, and 3), (B) the upper coupons near the spill zone (sum of Coupons 4, 5, and 6), and (C) Coupon 7 on the far wall from the spill zone. The results are averages from four to five replicate tests at each initial salt temperature and the error bars represent one standard deviation.

The molten salt splashing behavior was also quantified as a function of initial salt temperature by determining the mass fractions of spilled salt recovered in the catch pan that had pooled at the bottom and that had formed splatter particles (Figure 38). There was no significant effect of initial salt temperature on the mass fraction of salt that formed splatter particles; the splatter made up approximately 25% of the total mass of recovered salt in the catch pan for tests with initial salt temperatures of 650 °C and 800 °C (Figure 38B). This observation is different than what was previously observed in tests using FLiNaK, where the fraction of salt that formed splatter was negatively correlated with initial salt temperature (Thomas and Jackson, 2021). Eutectic NaCl-UCl₃ has a much lower heat capacity and heat of fusion per gram of salt than FLiNaK (see Section 2.4.4), which could explain why the initial salt temperature of eutectic NaCl-UCl₃ did not affect the salt breakup as it impacted on the catch pan floor. It is possible that the heat of fusion and heat capacity of eutectic NaCl-UCl₃ are too low for the initial temperature of this salt to affect the breakup behavior.
Figure 38: The fraction of the total mass of salt recovered in the catch pan that was (A) collected as the pooled salt at the bottom of the catch pan and (B) collected as splatter particles. The results are averages from four to five replicate tests at the two initial salt temperatures evaluated and the error bars are one standard deviation.

5.2.3 Temperatures measured in the spill containment box

Figure 39 provides an example of the temperatures measured in the spill containment box after spilling approximately 24 g of eutectic NaCl-UCl$_3$ at an initial temperature of approximately 650 °C (Test 1). Two adjacent surface thermocouples were attached to the underside of the catch pan and located directly below the inlet of the spill containment box (i.e., TC1 and TC2), and three additional sheath-type thermocouples were placed at different locations within the spill containment box to monitor the temperature of the atmosphere (i.e., TC3, TC4, and TC5; Figure 39). The maximum temperature that was recorded at the underside of the catch pan within the salt spill zone among all tests was approximately 220 °C for Test 1 (Figure 39A). The thickness of the salt pool at the bottom of the catch pan was 1.9 ± 0.4 mm for Test 1. The temperature of the atmosphere of the spill containment box remained near the initial ambient temperature after pouring molten salt for all tests (see results from Test 1 in Figure 39B). The initial ambient temperature of the glovebox atmosphere was between 26 °C and 30 °C, depending on the test. Low temperatures in the spill containment box atmosphere were observed previously during similar tests using FLiNaK (Thomas and Jackson, 2021). The maximum temperature recorded at the filter inlet by Thermocouple 5 (TC5) was 32.6 °C during Test 4 with an initial salt temperature of approximately 800 °C and an initial ambient glovebox atmosphere temperature of approximately 29.5 °C.

The temperatures of the catch pan underside and the spill containment box atmosphere as well as the average thickness of the pooled salt at the bottom of the catch pan for each test are available from the authors as part of the data package that is associated with this report.
Figure 39: The temperature recorded at (A) the underside of the catch pan by two adjacent surface thermocouples and (B) various locations in the spill containment box atmosphere after spilling approximately 24 g of eutectic NaCl-UCl$_3$ at an initial temperature of approximately 650 °C (Test 1). (C) Photograph showing the thermocouple locations within the spill containment box. TC5 recorded the temperature of the atmosphere near the filter inlet.

5.2.4 Salt composition analysis by ICP-OES and ICP-MS

Table 11 and Table 12 provide the concentrations of major salt components (NaCl, UCl$_3$, CsCl, and CsI) and trace metals (lithium, magnesium, nickel, zinc, potassium, calcium, chromium, iron, and copper), respectively, that were measured in the salt after spilling as a function of initial salt temperature. Only the salt samples collected from Tests 6, 7, 8, and 9 using eutectic NaCl-UCl$_3$ salt spiked with CsCl and CsI were analyzed for composition. The concentrations of sodium and uranium were determined by using ICP-OES and the concentrations of the trace metals, cesium, and iodine were determined by using ICP-MS (as described in Section 2.3). The concentrations were averaged for duplicate samples taken from two independent experiments with the same target initial salt temperature and sampling location (i.e., the presented results are averages of four samples). The sampling locations included the salt that pooled at the bottom of the catch pan (pool) and the splatter particles that dispersed within the catch pan (splatter). The concentrations presented in Table 11 show that the salt that formed splatter particles due to spilling does not have a significantly different composition than the salt that pooled at the bottom of the catch pan. A relatively large standard deviation of the mean iodine concentration was observed for each result presented in Table 11 (reported as mol % CsI). This is likely because iodine was not as homogeneously distributed in the salt as were the cations sodium, uranium, and cesium.

Trace metals lithium, magnesium, nickel, and zinc were detected in some frozen salt samples of eutectic NaCl-UCl$_3$ salt spiked with CsCl and CsI, while potassium, calcium, chromium, iron, and...
copper were all below the detection limit of the measurement technique (Table 12). The concentrations of lithium and magnesium were uniformly distributed among the samples collected from the pooled salt and the splatter, indicating a homogenous distribution of these elements within the salt before it was poured into the spill containment box (Table 12). Nickel was detected in samples of the pooled salt and splatter and zinc was only detected in samples of the splatter (Table 12). The source of nickel is likely the nickel crucible in which the salt was heated prior to pouring and the zinc is likely a remnant from the salt synthesis process. Metallic nickel and zinc would not likely be homogeneously distributed in the salt, which would explain the large standard deviation of their mean concentrations in the splatter reported in Table 12.

**Table 11: Composition of frozen salt samples collected from splash tests**

<table>
<thead>
<tr>
<th>Target initial temp. (°C)</th>
<th>CsCl and CsI added?</th>
<th>Sample type</th>
<th>NaCl (mol %)</th>
<th>UCl₃ (mol %)</th>
<th>CsCl (mol %)</th>
<th>CsI (mol %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>650</td>
<td>Yes</td>
<td>Splatter</td>
<td>63.0 ± 1.9</td>
<td>35.9 ± 1.9</td>
<td>1.0 ± 0.08</td>
<td>0.05 ± 0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pool</td>
<td>64.8 ± 0.6</td>
<td>34.1 ± 0.6</td>
<td>1.0 ± 0.06</td>
<td>0.05 ± 0.05</td>
</tr>
<tr>
<td>800</td>
<td>Yes</td>
<td>Splatter</td>
<td>65.4 ± 0.4</td>
<td>33.6 ± 0.4</td>
<td>1.0 ± 0.1</td>
<td>0.06 ± 0.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pool</td>
<td>65.8 ± 0.1</td>
<td>33.2 ± 0.1</td>
<td>1.0 ± 0.06</td>
<td>0.05 ± 0.04</td>
</tr>
</tbody>
</table>

*a Only tests using salts spiked with CsCl and CsI were analyzed for composition (Tests 6, 7, 8, & 9).

*b The reported values are the mean ± one standard deviation.

*c Mol % of CsI was calculated assuming all detected iodine was present as CsI.

**Table 12: Concentration of significant trace metals in frozen salt samples collected from splash tests**

<table>
<thead>
<tr>
<th>Target initial temp. (°C)</th>
<th>CsCl and CsI added?</th>
<th>Sample type</th>
<th>Li (ppm)</th>
<th>Mg (ppm)</th>
<th>Ni (ppm)</th>
<th>Zn (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>650</td>
<td>Yes</td>
<td>Splatter</td>
<td>92 ± 8</td>
<td>240 ± 10</td>
<td>410 ± 300</td>
<td>26 ± 30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pool</td>
<td>96 ± 4</td>
<td>240 ± 30</td>
<td>150 ± 100</td>
<td>n.d.</td>
</tr>
<tr>
<td>800</td>
<td>Yes</td>
<td>Splatter</td>
<td>100 ± 5</td>
<td>240 ± 10</td>
<td>70 ± 60</td>
<td>150 ± 300</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pool</td>
<td>100 ± 4</td>
<td>240 ± 20</td>
<td>32 ± 4</td>
<td>n.d.</td>
</tr>
</tbody>
</table>

*a The concentrations of K, Ca, Cr, Fe, and Cu in all samples were below the detection limits of approximately 700 ppm, 300 ppm, 8 ppm, 100 ppm, and 4 ppm, respectively.

*b The reported values are the mean ± one standard deviation.

*c “n.d.” means not detected.

### 5.2.5 Aerosol collection on filters

Aerosol cassettes with 0.45-μm pore size PTFE filters connected to a sampling pump set to a constant flow rate of 4 L min⁻¹ were used to sample the spill containment box atmosphere for suspended particulates (e.g., aerosols generated due to splashing or vapor nucleation and condensation). The aerosol cassettes were weighed before and after sampling using an analytical balance (Mettler Toledo Balance XPR226DR), and the total mass of particulates collected on each filter is presented in Figure 40.
The two Controls in Figure 40 represent samples of the glovebox atmosphere within the spill containment box collected for 10 minutes prior to spilling any eutectic NaCl-UCl₃ to provide a background analysis of the glovebox atmosphere. Each control filter collected a similar mass of particles as the sample filters, suggesting that the glovebox atmosphere contains dust that was likely collected concurrently with molten salt aerosols. The compositional analyses of the particulate material collected on filters during each spill test provides more insight into the origin of the collected particulate material to distinguish between background dust and salt. A filter blank that had not sampled the glovebox atmosphere was also weighed at the same time as the control filters and sample filters to confirm the accuracy of the balance. The bar marked with an asterisk in Figure 40 represents a filter that contained a visible NaCl-UCl₃ particle, explaining why the mass of collected particulates was significantly greater than the others.

![Figure 40: Mass of particles collected on filters for tests conducted with pure NaCl-UCl₃ salt and salt doped with cesium and iodine (NaCl-UCl₃-CsI) at initial temperatures of 650 °C and 800 °C. The bar marked with an asterisk represents a filter that collected a NaCl-UCl₃ salt particle that was visible to the naked eye.](image)

The results of compositional analyses of particulates collected on the filters during each test in this section are provided in Table 13. The iodine concentration was below the detection limit for all tests (Table 13). Cesium was detected on the filters of Tests 3, 6, 7, and 9, but the amounts of cesium detected did not follow a clear trend with initial salt temperature as had been observed in tests with FLiNaK doped with CsF and CsI (Thomas and Jackson, 2021). A significant amount of cesium was detected on the filter of Test 6, which contained a visible salt splatter particle and was from a test that used NaCl-UCl₃ salt doped with CsCl and CsI. Much smaller amounts of cesium were detected for Tests 3, 7, and 9, where similar amounts of cesium were detected regardless of initial salt temperature or whether the salt was spiked with CsCl and CsI. Mist formation above the spilled salt pool was not observed during any test conducted with NaCl-UCl₃, whereas mist was observed to form over spilled pools of FLiNaK doped with the same mole fraction of cesium and iodine species in previous tests (Thomas and Jackson, 2021). The amount of sodium detected on the test filters was not significantly different than the amount of sodium on the two control filters. In contrast, the amount of uranium detected on the test filters was significantly larger than the
amount of uranium on the control filters. The masses of sodium and uranium detected on the control and test filters are presented as a function of test condition in Figure 41A and Figure 41B, respectively.

Table 13: Elemental composition of particulates collected on 0.45 μm filters

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Initial salt temp. (°C)</th>
<th>CsCl and CsI added?</th>
<th>Total particulate mass (mg)</th>
<th>Na (µg)</th>
<th>U (µg)</th>
<th>Cs (µg)</th>
<th>I (µg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blankc</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>0.61</td>
<td>0.012</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Control 1d</td>
<td>n/a</td>
<td>n/a</td>
<td>1.455</td>
<td>3.0</td>
<td>0.016</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Control 2d</td>
<td>n/a</td>
<td>n/a</td>
<td>1.465</td>
<td>1.4</td>
<td>0.003</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>1</td>
<td>650</td>
<td>No</td>
<td>1.845</td>
<td>1.4</td>
<td>0.83</td>
<td>&lt; 0.003</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>2</td>
<td>650</td>
<td>No</td>
<td>0.295</td>
<td>0.74</td>
<td>0.17</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>3</td>
<td>800</td>
<td>No</td>
<td>0.590</td>
<td>1.0</td>
<td>0.84</td>
<td>0.04</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>4</td>
<td>800</td>
<td>No</td>
<td>1.315</td>
<td>3.1</td>
<td>1.3</td>
<td>&lt; 0.01</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>5</td>
<td>800</td>
<td>No</td>
<td>1.455</td>
<td>2.4</td>
<td>1.4</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>6e</td>
<td>650</td>
<td>Yes</td>
<td>4.505</td>
<td>66</td>
<td>330</td>
<td>4.4</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td>7</td>
<td>650</td>
<td>Yes</td>
<td>2.095</td>
<td>1.8</td>
<td>1.6</td>
<td>0.03</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>8</td>
<td>800</td>
<td>Yes</td>
<td>0.905</td>
<td>2.9</td>
<td>2.2</td>
<td>&lt; 0.01</td>
<td>&lt; 0.03</td>
</tr>
<tr>
<td>9</td>
<td>800</td>
<td>Yes</td>
<td>1.600</td>
<td>2.4</td>
<td>1.8</td>
<td>0.01</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

a The number following the < is the detection limit.
b The initial salt temperature was estimated by a thermocouple placed in the furnace liner in which the salt was heated.
c The composition of the blank filter was measured directly after removal from its packaging.
d The control filter sampled the background glovebox atmosphere for 10 minutes before any NaCl-UCl₃ splash tests were conducted.
e This sample has significantly more Na and U that the others because the filter contained a visible NaCl-UCl₃ particle.

It is clear from Figure 41B that the uranium collected on the filters during the spill tests originated from the spilled molten salt and not the background dust present in the glovebox atmosphere. There appears to be a slight dependence on initial salt temperature, where slightly more uranium was collected on the filters for tests with an initial salt temperature of approximately 800 °C than during tests with an initial salt temperature of approximately 650 °C. The exception is the significant amount of uranium (330 µg) detected on the filter for Test 6, which is attributed to the visible NaCl-UCl₃ particle on the filter and not aerosol collection. The average amount of uranium collected on the filters was approximately 0.9 µg for tests conducted with salt at an initial temperature of 650 °C and 1.5 µg for tests conducted with salt at an initial temperature of 800 °C (excluding the result from Test 6). The amount of uranium that became aerosolized and was collected on the filters is approximately seven orders of magnitude lower than the total uranium content of the poured salt (approximately 13 g). At larger scales, such as those that will be considered for MSR licensing, a uranium mass fraction of 10⁻⁷ of the total uranium in the spilled pool that becomes aerosolized could be significant for the source term of an MSR. Future tests are planned at larger scales to provide insight on the effect of the total salt volume spilled on aerosol formation. Larger spilled salt pools will remain molten for longer durations, and this is expected to promote aerosol formation due to vapor condensation and nucleation.
Figure 41: The mass of (A) sodium and (B) uranium detected on the aerosol collection filters for the control and test conditions. Each bar represents an individual test. The filter that had a visible NaCl-UCl$_3$ salt particle for Test 6 contained significantly more sodium (66 μg) and uranium (330 μg) than the other tests.

6 Conclusions and recommendations

Tests were conducted using eutectic NaCl-UCl$_3$ to provide the data needed to model processes that are expected to have the greatest impact on radionuclide release and the overall fate of the reactor after a salt spill accident. The major accomplishments from this work include:

- Generating data that is needed to develop process models on molten salt heat transfer, spreading, and splatter and aerosol generation due to a salt spill accident for a chloride salt composition of interest to fast spectrum MSR developers.

- Demonstrating that the methods and measurement techniques that were developed previously to assess molten salt spreading, splatter formation, and aerosol generation are applicable to chloride and fluoride-based salt compositions (e.g., eutectic NaC-UCl$_3$ and FLiNaK).
• Developing a new test method to provide the data needed for process models on the heat transfer behavior of static pools of molten salt and applying it to FLiNaK and eutectic NaCl-UCl₃.

• Safely simulating salt spill accidents at a laboratory scale using a uranium-bearing salt.

The insights gained regarding the behavior of spilled eutectic NaCl-UCl₃ and disposition of the radionuclides within (both actual and surrogate) are summarized in Section 6.1. These proven test methods can be applied in integrated process tests that simulate a salt spill accident at a larger scale using 10 to 100 times more spilled salt than the tests described herein. Suggestions for improvements and considerations for the future integrated process tests are discussed in Section 6.2.

6.1 Summary of key findings

The key findings from the tests that provided temperature measurements to use to develop models on static pools of molten salt are as follows:

• A temperature gradient was observed at the salt surface as the molten salt (both FLiNaK and eutectic NaCl-UCl₃) cooled in cylindrical stainless steel beakers due to conductive heat transfer to the uninsulated and initially room temperature beaker walls.

• The temperature of the bottom beaker surface was higher than the temperature of the outer beaker walls for all tests conducted because the beaker bottom was insulated but the walls were not.

• The eutectic NaCl-UCl₃ salt cooled much faster than similar masses of FLiNaK under similar test conditions because eutectic NaCl-UCl₃ has a much lower heat capacity and heat of fusion than FLiNaK (on a per gram basis).

• The molten salt cooled faster in beakers with thicker walls for all tests conducted due to the increased thermal mass that corresponds to beaker wall thickness.

• Supercooling of eutectic NaCl-UCl₃ and FLiNaK was observed during heat transfer tests. Non-equilibrium freezing may influence the behavior of spilled molten salt during an accident.

The key findings from the tests on molten NaCl-UCl₃ spreading on a tilted stainless steel catch pan are as follows:

• The molten eutectic NaCl-UCl₃ wet the surface of the catch pan (i.e., spread laterally into a thin layer of approximately 1 mm at the location of impact on the catch pan) as it spread down the length of the catch pan due to gravity. FLiNaK was not observed to wet the surface of the stainless steel in previous tests.

• A crust of eutectic NaCl-UCl₃ formed at the salt-catch pan interface and left a trail along the entire spreading path. This was observed previously in tests with FLiNaK.
• The spreading of eutectic NaCl-UCl₃ was not completely hindered by freezing and the salt pooled at the bottom of all tests conducted for this work. A frozen salt layer did form at the location of impact on the catch pan, which impeded salt spreading and led to the spreading salt to split into two streams for some tests.

• The poured NaCl-UCl₃ that had lower initial salt temperatures took longer to spread to the bottom of the catch pan and covered a larger area of the catch pan than salt with higher initial salt temperatures.

• The time required for the poured NaCl-UCl₃ to spread to the bottom of the catch pan (spreading duration) was shorter for tests that had higher pour rates.

• The transmissivity of the salt to IR radiation likely needs to be taken into account when using an IR camera to measure the temperature of thin layers of eutectic NaCl-UCl₃.

The key findings from the tests on molten NaCl-UCl₃ splashing and splatter and aerosol generation are summarized as follows:

• The initial salt temperature had no effect on the mass fraction, particle size, or collection location of molten salt splatter that was produced due to splashing. Significantly more splatter particles were collected near the spill zone on coupons that were positioned on the lower half of the catch pan wall than those positioned on the upper half of the catch pan wall.

• The temperature of the spill containment box atmosphere remained nearly constant during the splashing tests with NaCl-UCl₃. The maximum atmospheric temperature recorded near the filter inlet was 32.6 °C for a test that poured approximately 23 g of molten NaCl-UCl₃ at an initial temperature of approximately 800 °C.

• The composition of frozen NaCl-UCl₃ doped with CsCl and CsI that was collected after splashing was not significantly different in samples of splatter particles and pooled salt or among tests conducted at different initial salt temperatures.

• Aerosols containing uranium were detected on the 0.45 μm pore size filters that were used to sample the spill containment box atmosphere for all tests that were conducted with NaCl-UCl₃. The amount of uranium detected on the filters was generally greater for the tests conducted with salt at an initial temperature of approximately 800 °C than those with salt at an initial temperature of approximately 650 °C.

• No aerosol particles containing iodine were detected on the 0.45 μm pore size filters for any test with NaCl-UCl₃. Cesium-bearing aerosol particles were detected on the filters for some tests, but the cesium concentrations did not follow a clear trend with initial salt temperature and particulate cesium appeared to originate from the background glovebox atmosphere for one test.
6.2 Suggested improvements and considerations for future tests

The lessons that were learned while conducting laboratory-scale tests with eutectic NaCl-UCl₃, suggestions to improve the measurements of certain processes, and considerations for future integrated process tests at larger scales are discussed in this section.

All tests using the methods described in this report were conducted by pouring the salt manually from a nickel crucible using tongs to simulate a salt spill. An automated pouring system would improve the reproducibility of the pour rate and the pour direction and provide an unbiased measure of pour rate. The pour rate (i.e., flow rate of the spill) is an initial condition of the spill and is a key variable to evaluate in simulated salt spill tests because it may have significant effects on the accident consequences. For tests using large salt volumes, an automated pouring system would be required for safety and practicality reasons so that the test could be run remotely. An automated pouring system should be designed in the future for employment in scaled up, integrated tests. A method to calculate the salt pour rate of the automated pouring system would also need to be employed, which will likely involve using a data-logging scale to record a change in the mass of the catch pan over time. The scale would preferably record mass at intervals of one second or less.

Improvements to the temperature measurement techniques can also be employed. When measuring the temperature of a salt pool using an immersed thermocouple, it is recommended that the thermocouple sheath exposed to the atmosphere be insulated to minimize the heat sink effect in the salt. The heat sink effect of thermocouples immersed in salt in tests that are conducted at larger scales with larger salt volumes will not likely be as apparent as in the tests described in this report. In addition, using grounded, sheath-type thermocouples is recommended for all future tests due to their faster response time than ungrounded thermocouples. Grounded thermocouples can be subject to electrical interference, and this should be tested prior to employment.

The tests that assessed the spreading of eutectic NaCl-UCl₃ revealed that the transmissivity of thin layers of this salt to IR radiation may not be negligible. The transmissivity of salt compositions would have to be quantified to use an IR camera to measure the temperature of thin salt layers. Tests to determine the maximum thickness of eutectic NaCl-UCl₃ (and other salt compositions) at which the salt transmissivity to IR radiation is negligible are recommended. In addition, the emissivity of salt compositions relevant to MSR developers need to be measured as a function of temperature for liquid and solid salt. This is also important for heat transfer model development.

The aerosol particle detection methods could be expanded to include techniques that provide real-time particle size distributions, although commercial instrumentation for real-time aerosol quantification have never been applied to aerosols produced from molten salts. The observation that the atmosphere does not heat up significantly during the spill tests conducted thus far indicates that commercial aerosol quantification instrumentation could be employed. The temperature of the atmosphere should be monitored in larger scale spill tests to confirm that real-time aerosol detection techniques could be used for tests with larger spill volumes. In addition, for tests that employ coupons to collect splatter and aerosol particles suspended in the atmosphere, adhesive material that has good visible contrast with the salt composition of interest should be identified to improve image processing so that smaller size distributions of adhered particles can be quantified.

The test methods and measurement techniques developed to date can be used to quantify the effects of additional variables to account for the wide range of conditions that are possible during a salt spill accident. Different conditions that should be tested in the future are described below.
• The laboratory tests described herein were conducted with a small volume of salt doped with conservatively high concentrations of cesium and iodine to facilitate detection. These results indicate that future tests using larger volumes of salt can be conducted using salts with lower concentrations of surrogate fission products that are more representative of actual fuel salts. Many more surrogate fission products could also be added to the salt to track their distribution in a defined containment geometry after a salt spill. In addition, future tests using larger salt volumes will generate heat transfer data that is more representative of a larger molten salt spill accident.

• Oxidizing conditions (e.g., the presence of air and humidity) may also be considered in an accident scenario for MSR licensing and be significant to the consequences of a molten salt spill accident. For example, oxidizing conditions may accelerate the corrosion of the catch pan and introduce corrosion products (e.g., chromium, manganese, and iron) into the salt. The presence of an air atmosphere also might affect the wetting behavior of salt on stainless steel. Finally, the absorption of O_2 and H_2O from air can greatly affect salt chemistry. Fluoride and chloride salts are hygroscopic and may produce hazardous gases (e.g., HF and HCl) from reactions with the moisture in air. Future tests in the presence of an air atmosphere are recommended. Special consideration will be needed to ensure the safety of the design so that hazardous gases that are produced, if any, are contained.

• The tests on spreading were performed on stainless steel sheets that were not insulated at the underside while the tests on heat transfer from a static pool of molten salt employed beakers that were only insulated on the bottom. Performing tests that do and do not insulate structures should be conducted to provide relevant data for all reactor designs and potential heat transfer models.
References


Appendix A: Common equipment

This appendix provides descriptions of the common equipment that was used in two or more of the experiments in this report.

A.1. Infrared camera

Two FLIR T540 infrared (IR) cameras with a 42° lens were used to measure the temperatures of the salt and steel surfaces for the spreading and heat transfer tests and the flowing and freezing tests. The IR camera has three calibration ranges: 0 °C to 120 °C, 0 °C to 650 °C, and 300 °C to 1500 °C. The IR camera detects infrared wavelengths within the range of 7.5 to 14 μm and has a resolution of 348 × 464 pixels. The IR cameras were operated in video mode during the tests described herein, which provides a radiometric data file (temperature of each pixel in the field of view) for each frame at a default collection rate of 30 frames per second.

A.2. Data logger for thermocouple measurements

Several thermocouples were used to measure the temperatures of surfaces and the vapor space in the experiments described in this report. A groov Edge Programmable Industrial Controller (EPIC) from Opto 22 was used to record the temperatures from every thermocouple used in the different tests. The thermocouples were attached to the groov EPIC using GRV-ITMI-8 analog input modules. Each module allows 8 isolated thermocouple connections so that multiple grounded thermocouples can be employed without interference. The groov EPIC was programmed using the PAC Control software to record the temperature of each thermocouple connected at one second intervals.

A.3. Visible camera

A Canon PowerShot SX740 HS Wi-Fi 4K digital camera was used to record the visible video for the spreading and heat transfer tests and the flowing and freezing tests. A GoPro HERO9 black 5K video streaming camera was used to record video at 240 frames per second for the splashing and aerosol generation tests.

A.4 Furnace

The furnace used to heat the salt in these experiments was a KERR Electro-Melt furnace with a 100 oz capacity. An external J-Kem 270 controller was used to control the furnace at the desired target temperature.
Appendix B: Additional test conditions and measurements

B.1 Conditions of the glovebox atmosphere during testing

The measured temperature, O\textsubscript{2} content, and H\textsubscript{2}O content of the argon atmosphere glovebox recorded before and after each test are provided in this section. The atmospheric conditions of the heat transfer tests using FLiNaK (Section 3.2), the heat transfer tests using eutectic NaCl-UCl\textsubscript{3} (Section 3.3), and the spreading tests (Section 4) are provided in Table B-1, Table B-2, and Table B-3, respectively. The O\textsubscript{2} content and H\textsubscript{2}O content of the argon atmosphere glovebox that was recorded before and after each molten salt splashing test (Section 5) are provided in Table B-4. The temperatures recorded at different locations over time within the spill containment box for each splashing test are available from the authors in the data package associated with this report.

<table>
<thead>
<tr>
<th>Test</th>
<th>( \text{O}_2 ) content (ppm) Before</th>
<th>( \text{O}_2 ) content (ppm) After</th>
<th>( \text{H}_2\text{O} ) content (ppm) Before</th>
<th>( \text{H}_2\text{O} ) content (ppm) After</th>
<th>Temperature (°C) of atmosphere Before</th>
<th>Temperature (°C) of atmosphere After</th>
<th>Temperature (°C) of atmosphere Max.</th>
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<td>&lt;1</td>
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<td>30.2</td>
<td>30.4</td>
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<tr>
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<td>29.4</td>
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<table>
<thead>
<tr>
<th>Test</th>
<th>( \text{O}_2 ) content (ppm) Before</th>
<th>( \text{O}_2 ) content (ppm) After</th>
<th>( \text{H}_2\text{O} ) content (ppm) Before</th>
<th>( \text{H}_2\text{O} ) content (ppm) After</th>
<th>Temperature (°C) of atmosphere Before</th>
<th>Temperature (°C) of atmosphere After</th>
<th>Temperature (°C) of atmosphere Max.</th>
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</thead>
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<td>4.6</td>
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Table B-3: The O$_2$ content, H$_2$O content, and temperature of the glovebox atmosphere measured before and after each molten salt spreading test using eutectic NaCl-UCl$_3$

<table>
<thead>
<tr>
<th>Test</th>
<th>O$_2$ content (ppm)</th>
<th>H$_2$O content (ppm)</th>
<th>Temperature (°C) of atmosphere</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>Before</td>
<td>After</td>
<td>Before</td>
</tr>
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<td>&lt;1</td>
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</tr>
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<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>7</td>
<td>2.0</td>
<td>2.0</td>
<td>&lt;1</td>
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</tbody>
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Table B-4: The O$_2$ content and H$_2$O content of the glovebox atmosphere measured before and after each molten salt splashing test using eutectic NaCl-UCl$_3$

<table>
<thead>
<tr>
<th>Test</th>
<th>O$_2$ content (ppm)</th>
<th>H$_2$O content (ppm)</th>
</tr>
</thead>
<tbody>
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<td>Before</td>
<td>After</td>
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<td>5.0</td>
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<tr>
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<td>2.7</td>
</tr>
<tr>
<td>9</td>
<td>5.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>

B.2 Locations of and temperature measurements by thermocouples attached to catch pan underside for spreading tests

The layout of the thermocouples attached to the underside of the stainless steel catch pan overlaid on a still frame of video collected by using the IR camera is presented for Test 2, Test 3, Test 5, Test 6, and Test 7 in Figure B-1, Figure B-2, Figure B-3, Figure B-4, and Figure B-5, respectively.
Figure B-1: Results for salt spreading Test 2: (A) Location of thermocouples attached to the underside of the catch pan overlaid on an image of the salt spreading path, (B) the temperature profiles measured by Thermocouples 1, 2, 3, 6, and 9 along the center of the catch pan, and (C) the temperature profiles measured by Thermocouples 5 and 8. Thermocouples 4 and 7 failed during this test.
Figure B-2: Results for salt spreading Test 3: (A) Location of thermocouples attached to the underside of the catch pan overlaid on an image of the salt spreading path, (B) the temperature profiles measured by Thermocouples 1, 2, 3, 6, and 9 along the center of the catch pan, and (C) the temperature profiles measured by Thermocouples 5 and 8. Thermocouples 4 and 7 failed during this test.
Figure B-3: Results for salt spreading Test 5: (A) Location of thermocouples attached to the underside of the catch pan overlaid on an image of the salt spreading path, (B) the temperature profiles measured by Thermocouples 1, 2, 3, 6, and 9 along the center of the catch pan, and (C) the temperature profiles measured by Thermocouples 5 and 8. Thermocouples 4 and 7 failed during this test.
Figure B-4: Results for salt spreading Test 6: (A) Location of thermocouples attached to the underside of the catch pan overlaid on an image of the salt spreading path, (B) the temperature profiles measured by Thermocouples 1, 2, 3, 6, and 9 along the center of the catch pan, and (C) the temperature profiles measured by Thermocouples 5 and 8. Thermocouples 4 and 7 failed during this test.
Figure B-5: Results for salt spreading Test 7: (A) Location of thermocouples attached to the underside of the catch pan overlaid on an image of the salt spreading path, (B) the temperature profiles measured by Thermocouples 1, 2, 3, 6, and 9 along the center of the catch pan, and (C) the temperature profiles measured by Thermocouples 5 and 8. Thermocouples 4 and 7 failed during this test.