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Molten Salt Spill Testing

Experiments to support accident progression analysis for MSR licensing

MSR Campaign Review Meeting

26 & 27 April 2022

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Molten Salt Reactor PROGRAM

Motivation and Objectives

Motivation

- Analysis of the effects of postulated accidents on safety is required to obtain NRC license for new nuclear reactors
- There is a lack of experimental data on processes that determine the consequences of potential molten salt reactor (MSR) accidents
  - Experimental data are needed by vendors preparing for the licensing process
  - Experimental data are needed by modelers to guide and advance model development

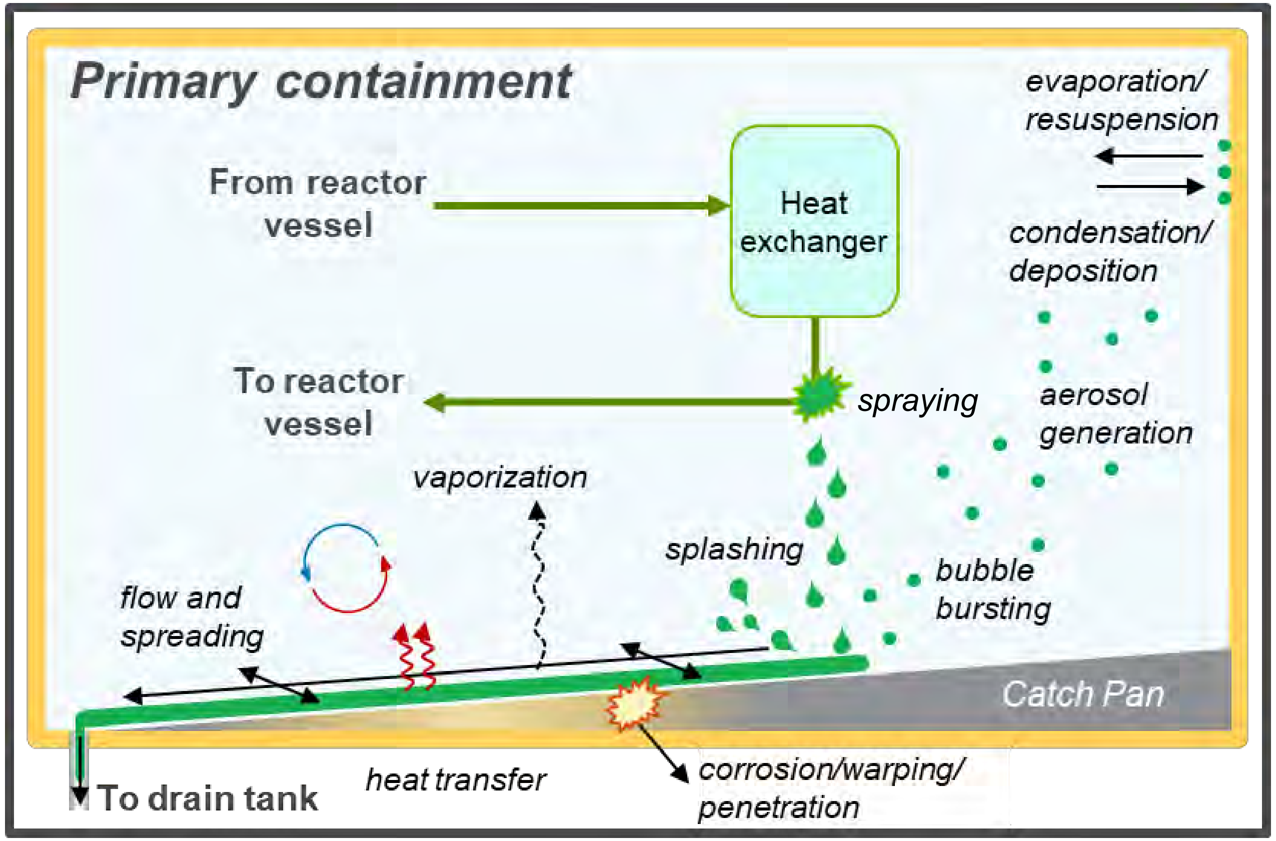
Objectives and Approach

- Provide technical bases for key processes included in mechanistic source term and accident progression models by conducting various laboratory-scale tests designed to highlight key processes
- Perform analyses using existing models to compare results with experimental data and to plan for large-scale integrated molten salt spill tests
  - e.g., MELTSPREAD to model molten salt spreading and heat transfer and perform sensitivity analysis on thermophysical properties

Molten Salt Spill Accident

- Common postulated accident scenario for many MSR concepts involves a rupture within the primary loop that leads to hot fuel salt spilling onto the primary containment floor

For MSR: salt spilling onto primary containment floor



Processes for which experimental data are needed to develop and validate models

- Spreading and flowing
  - On containment floor and through tubing into drain tank
- Heat transfer
  - Convection, conduction, radiation
- Interactions with structural materials
  - Warping, corrosion
- Vaporization and condensation
- Aerosol formation
  - Due to splashing, spraying, bubble bursting, and vapor nucleation

Experimental Approach

Five modular laboratory test methods were designed to:

- Quantify individual processes important to accident progression modeling
- Provide data that can be used in individual process models
- Identify key factors and priorities for model development and future integrated tests

Test method descriptions:

1. Spreading and heat transfer of molten salt on sloped stainless steel sheets
2. Heat transfer of static molten salt pool contained in stainless steel
3. Aerosol generation due to splashing and vapor nucleation during a molten salt spill
4. Flowing and freezing of molten salt in stainless-steel tubing
5. Corrosion kinetics of stainless steel in molten salt

Salt compositions:

FY22

- $NaCl-UCl_3$ (eutectic composition)

FY21

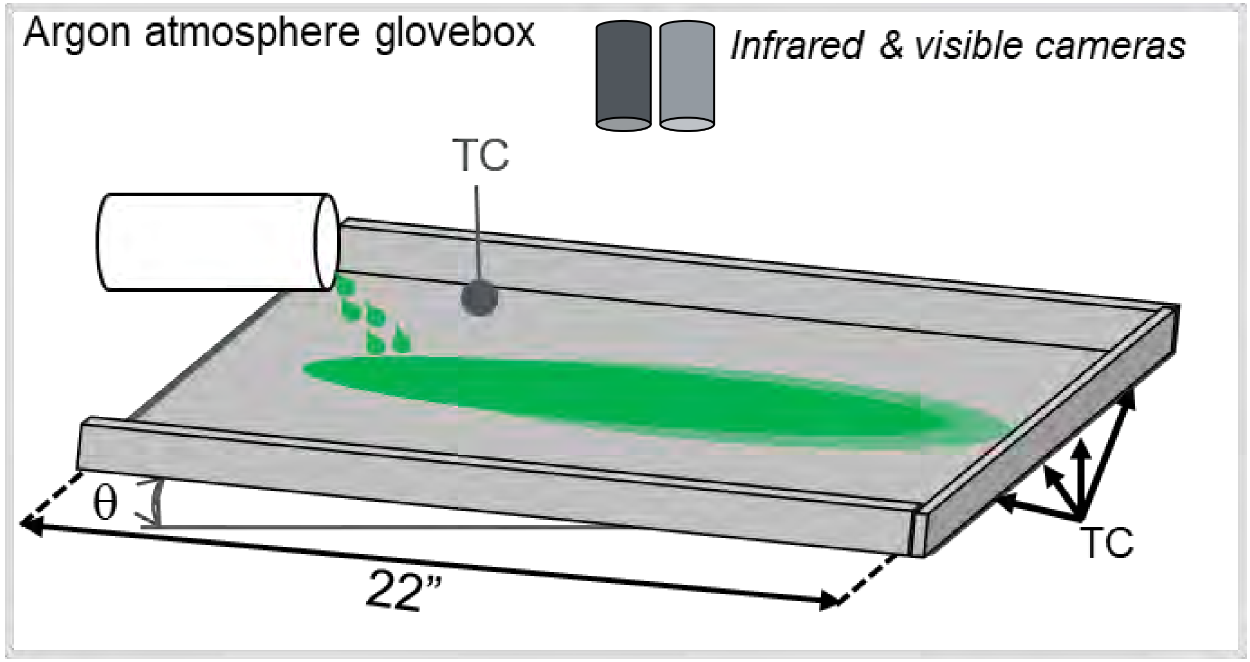
- Pure FLiNaK
- FLiNaK doped with cesium and iodine as surrogate fission products (0.9 mol % CsF, 0.099 mol % CsI)

Test method 1: Molten salt spreading and heat transfer

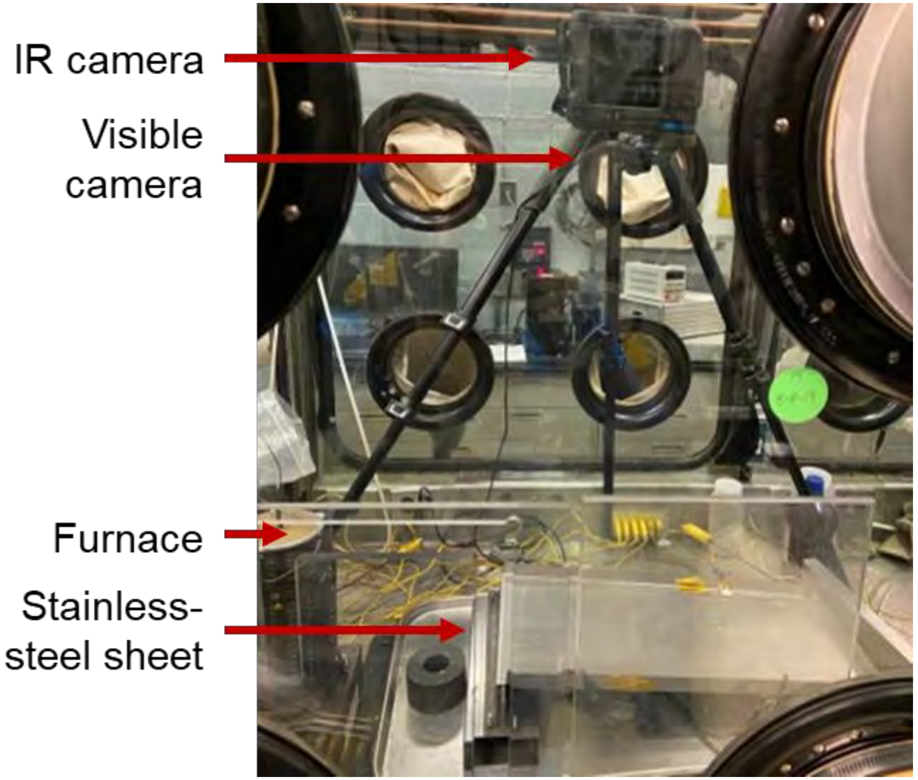
- Significance of molten salt spreading and heat transfer to consequences of a molten salt spill accident:
  - Determines extent of radionuclide-bearing molten salt dispersal
  - Determines surface area of salt in contact with atmosphere (radionuclide vaporization)
  - Determines duration surface stays molten (radionuclide vaporization & substrate integrity)
  - Determines surface area of salt in contact with substrate (substrate integrity)
- Experiments were designed to quantify NaCl-UCl_3 spreading and provide temperature data to calculate heat loss from the salt

Test method 1: Molten salt spreading and heat transfer

Schematic of test apparatus



Apparatus in glovebox



Measurements

- Visible video of salt spreading
- Leading edge and covered area of salt on substrate vs. time (IR camera)
- Temperature of substrate underside, substrate surface, salt surface, and atmosphere
- Thickness of frozen salt collected after spreading

Variables tested

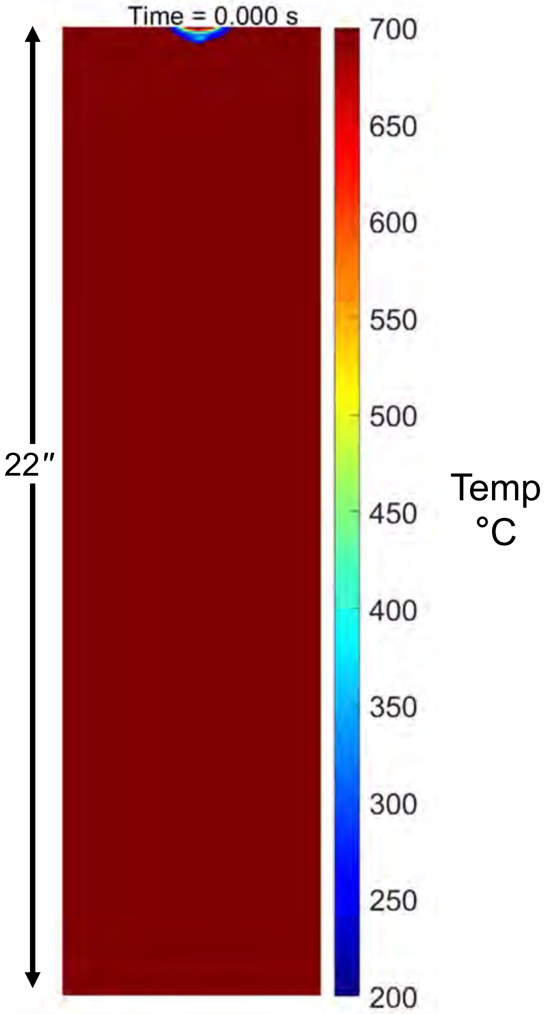
- Initial salt temperature (550 °C – 750 °C)
- Pour mass

Quantifying molten NaCl-UCl_3 spreading for model validation

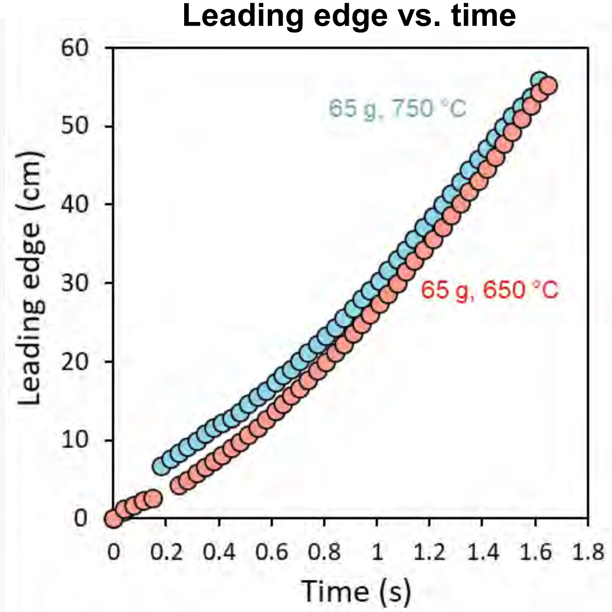
Initial salt temp: 750 °C, Mass salt poured: 65 g

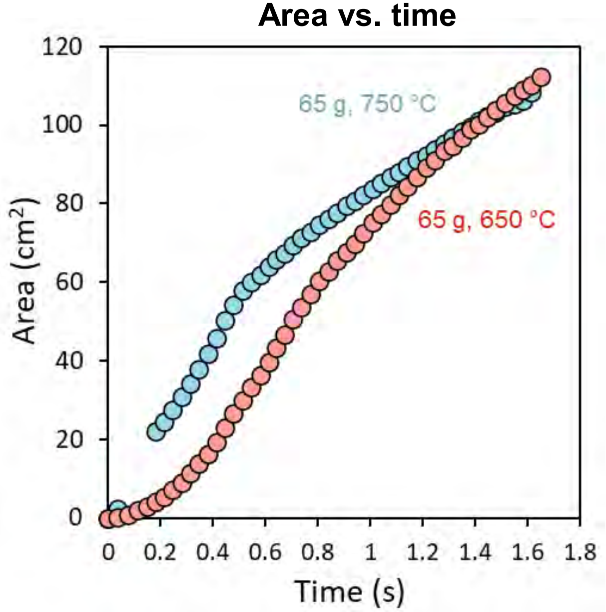
Visible video

Processed IR video



- Results from IR video analysis provide data that can be directly compared with results from spreading and heat transfer models
  - Leading edge vs. time
  - Area vs. time
  - Salt surface temperature at each pixel vs. time



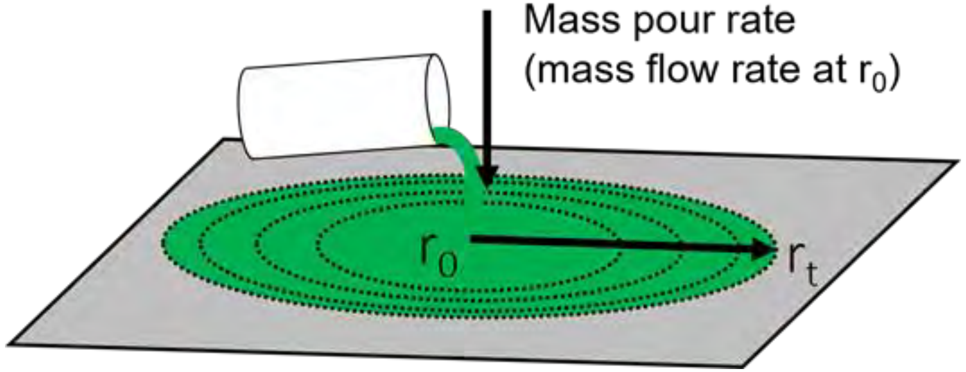


Modeling molten salt spreading and freezing using MELTSPREAD

- MELTSPREAD was developed at Argonne to model the one-dimensional flowing and freezing of molten corium
- MELTSPREAD was used to model molten salt spreading for the first time during FY21
- FY22 work is building upon the molten FLiNaK MELTSPREAD model developed during FY21 to incorporate processes identified in FLiNaK spreading experiments (i.e., crust formation at the salt/substrate interface) and to model a larger FLiNaK spill
  - Objective 1: to identify thermophysical properties that have the greatest effect on spreading behavior
  - Objective 2: to inform design of large scale salt spill tests

Spill conditions of model:

radial spreading of FLiNaK poured onto flat sheet

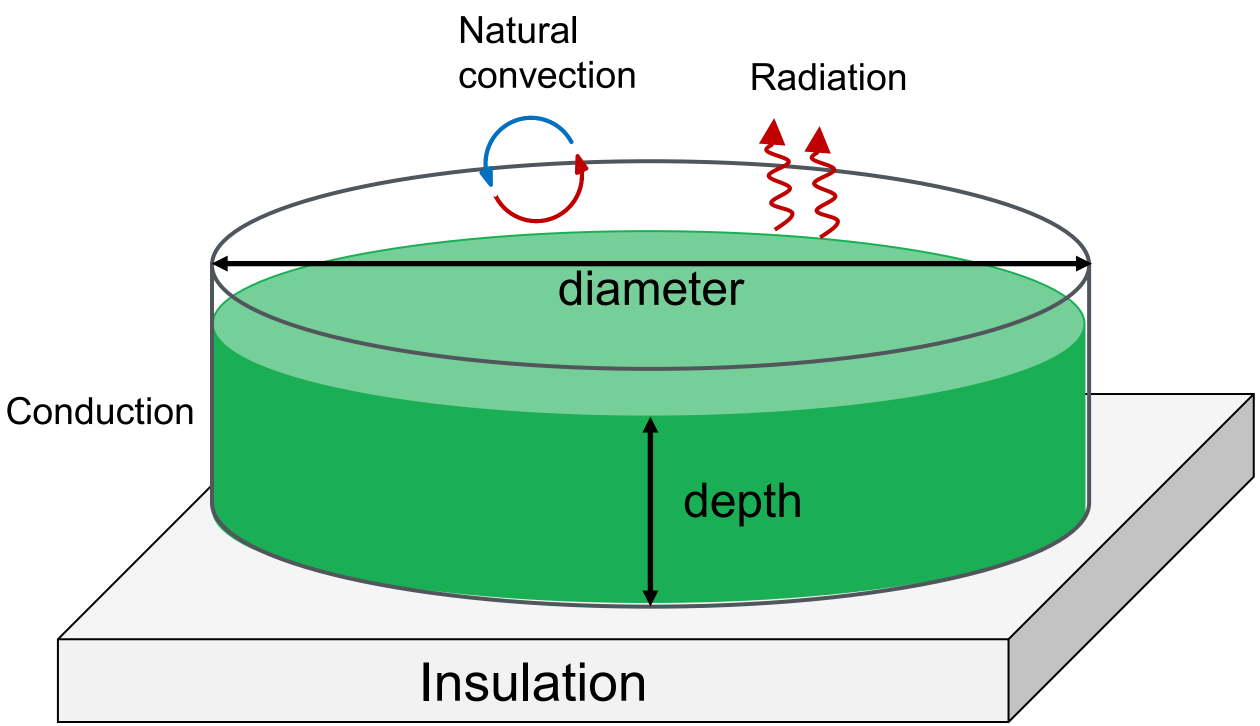


Thermophysical properties and initial conditions to vary for sensitivity analysis

- Pour mass
- Pour rate
- Surface tension
- Viscosity
- Density
- Emissivity
- Thermal conductivity
- Heat capacity
- Heat of fusion

Test method 2: Heat transfer from static pool of molten salt

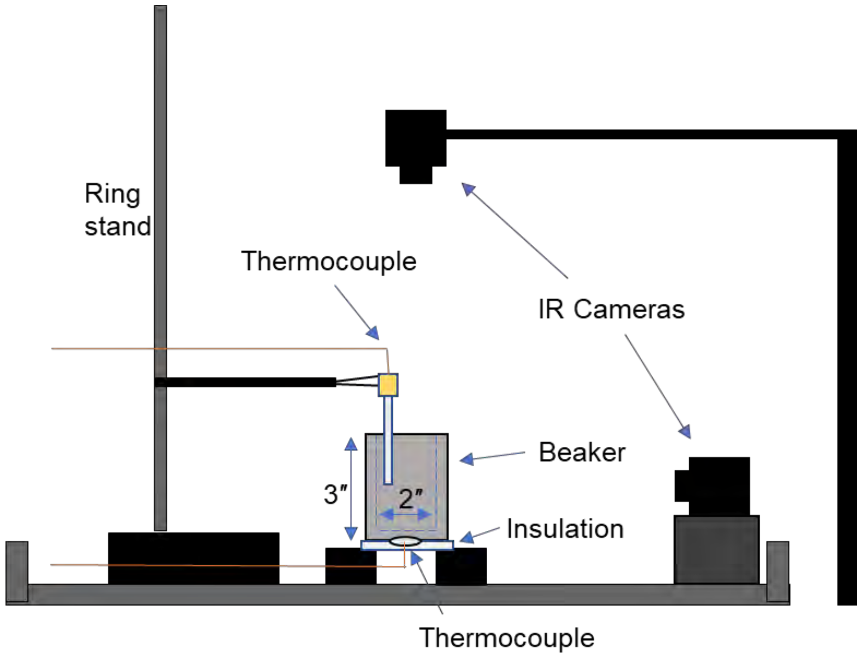
- Postulated accident scenario involves molten salt spilling onto the containment floor and forming a static pool
- Significance of heat transfer from static pool to consequences of molten salt spill accident:
  - Determines duration surface stays molten (radionuclide vaporization)
  - Determines substrate temperature (substrate integrity)
  - Determines duration molten salt is in contact with substrate (substrate corrosion)
- Experiments were designed to provide temperature data to calculate heat loss from the salt and the rate of conduction through the walls
  - Insulation minimizes cooling of substrate bottom
  - Natural convection cools the substrate walls
- Multiple variables can be tested systematically to determine their influence on the cooling behavior of the salt

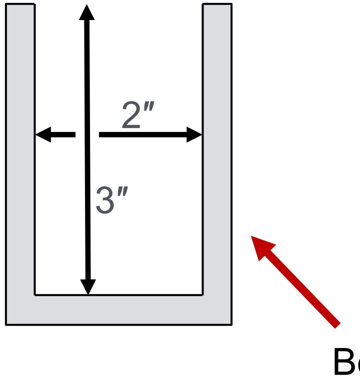


Schematic of salt pool for model

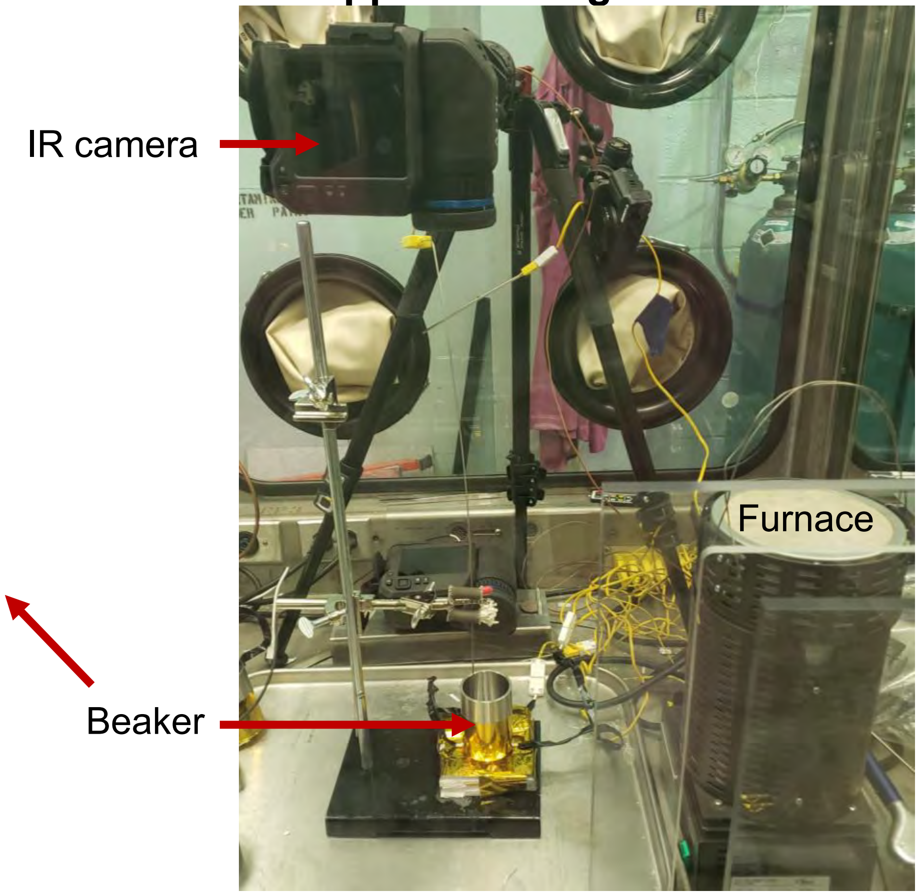
Test method 2: Heat transfer from static pool of molten salt

Argon atmosphere glovebox





Apparatus in glovebox



Measurements

- Temperature of salt surface (IR camera)
- Temperature of salt (immersed thermocouple)
- Temperature of substrate underside (thermocouple)
- Temperature of substrate wall (IR camera)
- Thickness and mass of salt in beaker

Variables tested

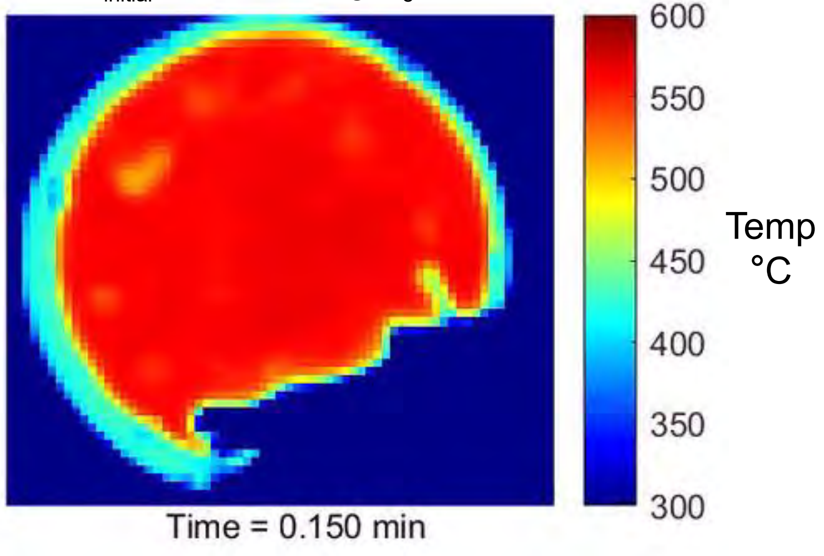
- Beaker wall & bottom thickness (¼″, ⅛″, $^1/_{16}$″)
- Beaker thermal mass (proportional to wall thickness)

Quantifying heat transfer from $NaCl\text{-}UCl_3$ for model validation

- Temperature of the salt surface was measured using an IR camera
- Tests with FLiNaK and $NaCl\text{-}UCl_3$ showed that salt near walls cools fastest and that FLiNaK is more efficient at retaining heat
- Spatially resolved salt surface temperature measurement can be used to create and validate heat transfer models for static pools of molten salt

FLiNaK

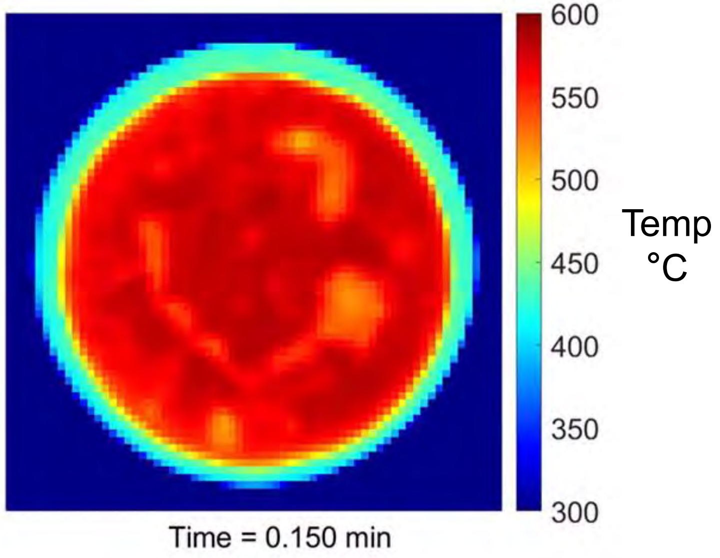
$T_{initial}$ = 650 °C, 60 g, ⅛″ wall beaker



$C_{p,liquid}$ = 1.72 J K^{-1} g^{-1}
ΔH_{fus} = 434 J g^{-1}

$NaCl\text{-}UCl_3$

$T_{initial}$ = 650 °C, 70 g, ⅛″ wall beaker

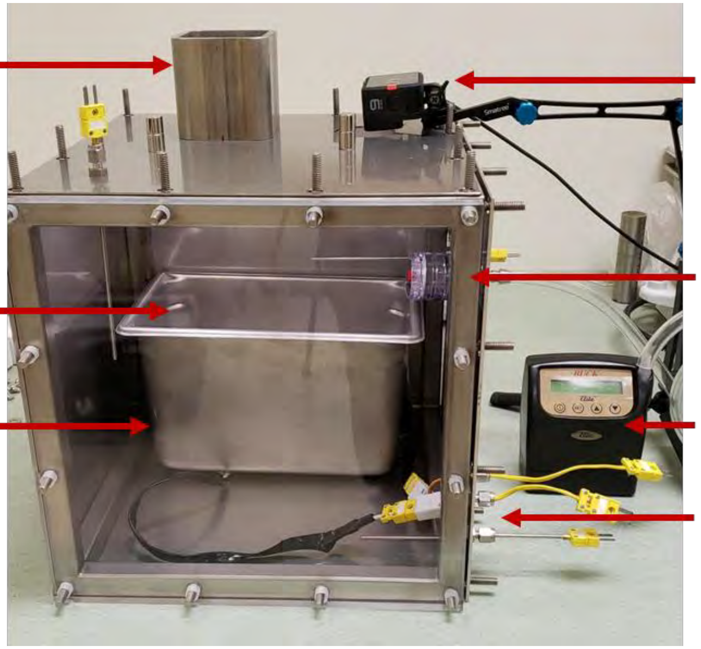


$C_{p,\ liquid}$ = 0.63 J K^{-1} g^{-1}
ΔH_{fus} = 158 J g^{-1}

Test method 3: Molten salt aerosol and splatter generation due to spilling

- Significance of aerosol and splatter formation to consequences of molten salt spill accident:
  - Determines dispersal of radionuclides (source term)
    - Radionuclide-bearing splatter
    - Radionuclide-bearing aerosols
  - Determines human health hazard if radionuclide-bearing aerosols are within respirable range
- Demonstrated technique during FY21 with FLiNaK
- Molten salt aerosol generation due to spilling $NaCl-UCl_3$ into a stainless steel catch pan is being tested in FY22

Test apparatus



Measurements

– Visible video of molten salt splashing (slow motion)

– Splatter abundance, size distribution, and composition

– Temperature of atmosphere within spill containment box and at underside of catch pan

– Aerosol composition collected on filters (0.45 μm) by ICP-MS and collected on adhesive tape by SEM-EDS

Variables to test

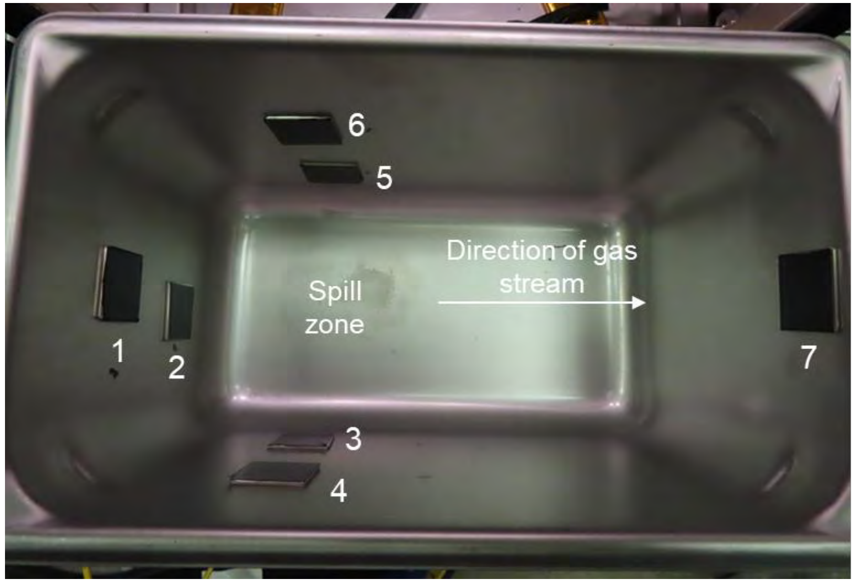
– Initial salt temperature (550 °C, 650 °C, 750 °C)

– (Potentially) presence of CsCl and CsI surrogate fission products

Test method 3: Molten salt aerosol and splatter generation due to spilling

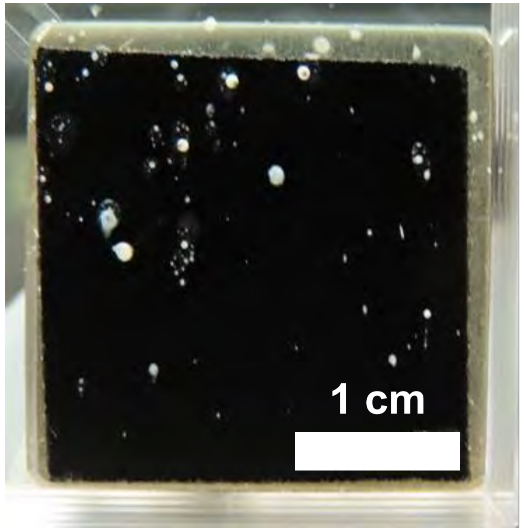
- Coupons with adhesive are effective at collecting splatter on the walls of the catch pan for analysis
  - Abundance and size distribution is determined by analyzing images taken by visible camera
  - Composition is determined by using SEM-EDS
- PTFE filter and Coupon 7 (below filter) are effective at collecting aerosol particles for analysis
  - Composition of aerosol particles on filter is determined by using ICP-MS and composition of aerosol particles on Coupon 7 is determined by using SEM-EDS
  - Size of individual aerosol particles on Coupon 7 is determined by using SEM-EDS

Coupon layout

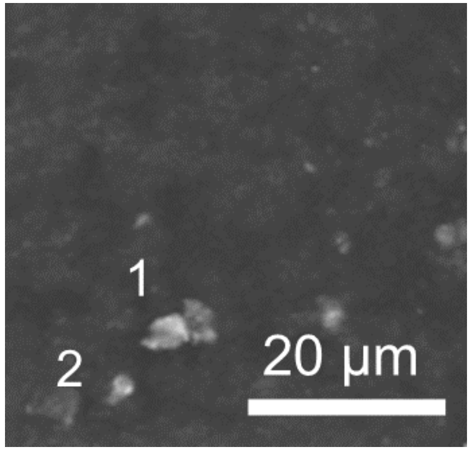


PTFE filter

FLiNaK splatter collected on coupon



SEM image of cesium and iodine containing particles on Coupon 7



Summary of accomplishments and milestones

Summary of accomplishments

- Methods developed to quantify individual processes are being employed with a representative chloride salt ($NaCl\text{-}UCl_3$) to provide data for model development
  - Conducted molten salt spreading tests on a stainless steel sheet to quantify spreading behavior
  - Conducted molten salt heat transfer tests in a stainless steel beaker to provide temperature measurements with high spatial and temporal resolution
  - Tests on splatter and aerosol generation are in progress
- MELTSPREAD model of the radial spreading of FLiNaK on stainless steel is being developed to:
  - Incorporate crust formation at the salt/substrate interface
  - Perform a sensitivity analysis of thermophysical properties and initial conditions for a large scale FLiNaK spill

Upcoming milestones – on schedule

Milestone Number	Title	Due
M4RD-22AN0602092	MELTSPREAD modeling report	6/24/22
M3RD-22AN0602091	Report and data package of results from spill tests	9/23/22

Future Work

Future work (near term)

- Conduct individual process tests at laboratory scale, including those that emphasize:
  - Molten salt aerosol studies
  - Complex salt compositions (i.e., those containing surrogate fission products) and environmental conditions (i.e., presence of humidity and oxygen)
  - Irradiated salts
- Integrate ongoing MSR campaign work (e.g., sensors for off gas components) in experiments to understand consequences of MSR salt spill accidents
- Design large scale integrated tests with input from MSR campaign participants, modelers, and MSR developers

Future work (long term)

- Construct large scale integrated salt spill test facility and conduct tests using representative fluoride and chloride salts

Questions

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