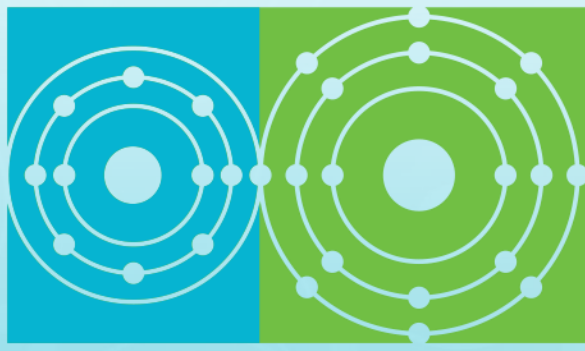




Molten Salt Reactor
P R O G R A M

Effect of Impurities on Fuel Salt Properties

Joint IAEA/NEA – EC/JRC Workshop on the Taxonomy and Related Terminology of Fuel Cycles for Molten Salt Reactors, November 3-7, 2025.

Melissa A. Rose, and Levi Gardner

Molten Salt Fuels

Molten salt fuel composition changes over the fuel lifetime and is susceptible to contamination from a variety of sources including:

- Corrosion of structural materials
- Fission of actinides
- Ingress of oxygen or moisture
- Synthesis processes

Used salt fuels can contain:

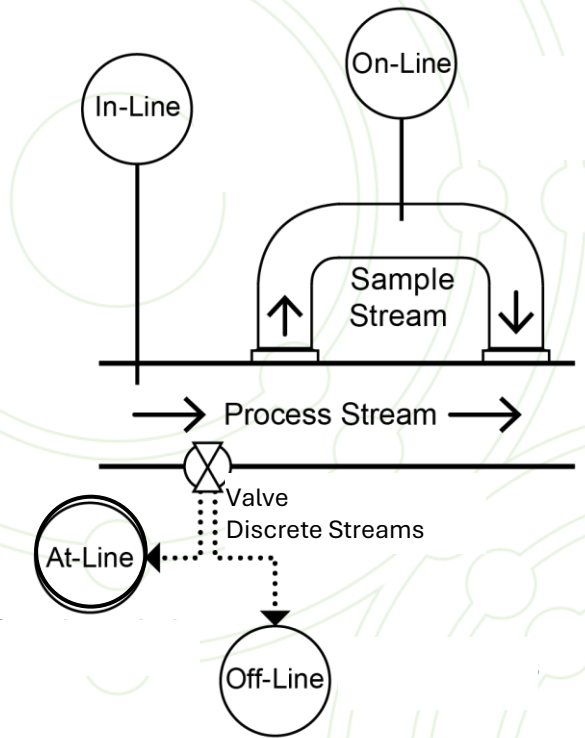
- **Fission products**
- **Reusable actinides**
- **Stable radioisotopes such as ^{37}Cl and ^7Li**
- **Corrosion products**
- **Contaminants due to oxygen and moisture ingress**

MSR fuels are uniquely suited for advanced fuel cycles:

- Enable on-line fuel conditioning
- Must be protected from contamination during synthesis, delivery, and use
- Online, at-line, in-line and offline processing options are all possible.

Limited conditioning with the goal of prolonging the life of fuels could include:

- Removal of oxides
- Recovery of FP and noble gases
- Recovery of noble metals
- Removal of soluble neutron poison FPs



Full recycling with the goal of maximizing reuse of molten salt fuels could include all of the above and:

- Actinide recovery
- Rare earth element extraction
- Recycling of the ^{37}Cl or ^7Li
- Repurification and reuse of the base salts

Motivation

Which impurities must be removed will be determined by the impact on fuel salt performance

Fuel salt performance is governed by thermal properties.

For example:

- Higher viscosity requires more pumping power
- Higher density impacts thermal convection and therefore fluid flow conditions
- Higher melting temperature could result in freezing of salt
- Change in thermal diffusivity will change heat removal rates

Determining how impurities impact fuel salt properties will provide insight into which impurities should be removed and help to set purity specifications

Impurities being investigated include

- Fission Products
- Oxides
- Corrosion Products

Effect of Fission Products

Determining the effect of fission products and on the properties of molten salt

- DSC was used to measure the thermal properties of the molten salts
- Laser flash analysis was used to determine the thermal diffusivity of the molten salts at several temperatures
- A rotational viscometer was used to determine the viscosity of the molten salts at several temperatures

¹ L. Gardner and M.A. Rose. "Uncertainty Analyses of Molten Salt Property Measurements". ANL/CFCT-25/5. March 2025.

Individual batches of doped FLiNaK salt with fission product concentrations representing low and high levels of burn up.

Doped FLiNaK Compositions (mol %)

Component	Composition 1 (low burnup)	Composition 2 (high burnup)
FLiNaK	99.65	98.23
ZrF ₄	0.05	0.25
Mo	0.05	0.25
NdF ₃	0.05	0.25
CeF ₃	0.05	0.25
CsF	0.05	0.25
CsI	0.005	0.025
SrF ₂	0.05	0.25
Ru	0.05	0.25
Na ₂ Te	0.005	0.025

Measured property values are compared with those of eutectic FLiNaK base salt to assess the impact of impurities

Uncertainty quantification¹ based on principles outlined in the Guide to the Expression of Uncertainty in Measurement

Thermal Analyses

Thermal transitions of three samples each of FLiNaK, FLiNaK-L, and FLiNaK-H were measured by using DSC

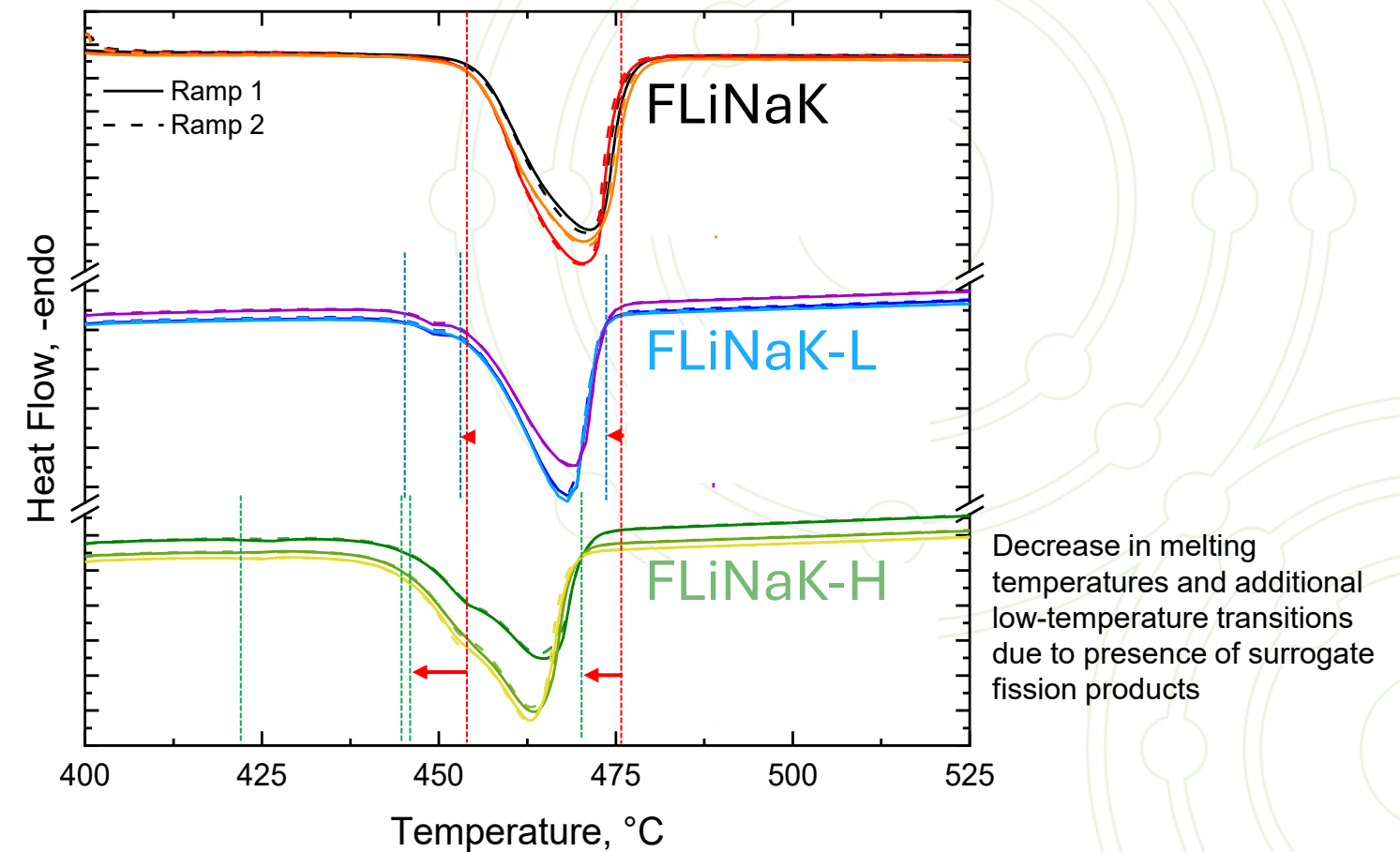
Heating cycle performed for each sample:

- One 20 °C min⁻¹ pre-melting ramp
- Two 5 °C min⁻¹ measurement ramps

Consistency of transition temperatures measured in duplicate ramps of the same sample indicates measurement conditions were stable

Consistency of the transition temperatures measured with different samples indicates compositional uniformity of salt mixtures

¹L.D Gardner, K.A. Chamberlain and M.A. Rose. Property Measurements of LiF-NaF-KF Molten Salts Doped with Surrogate Fission Products. ANL/CFCT-24/23. September 2024.



Lower onset of melting and liquidus point temperatures were measured for both low-burnup FLiNaK and high-burnup FLiNaK compared to those of pure FLiNaK, for which the onset of melting and liquidus point temperatures were 455 °C and 476 °C , respectively

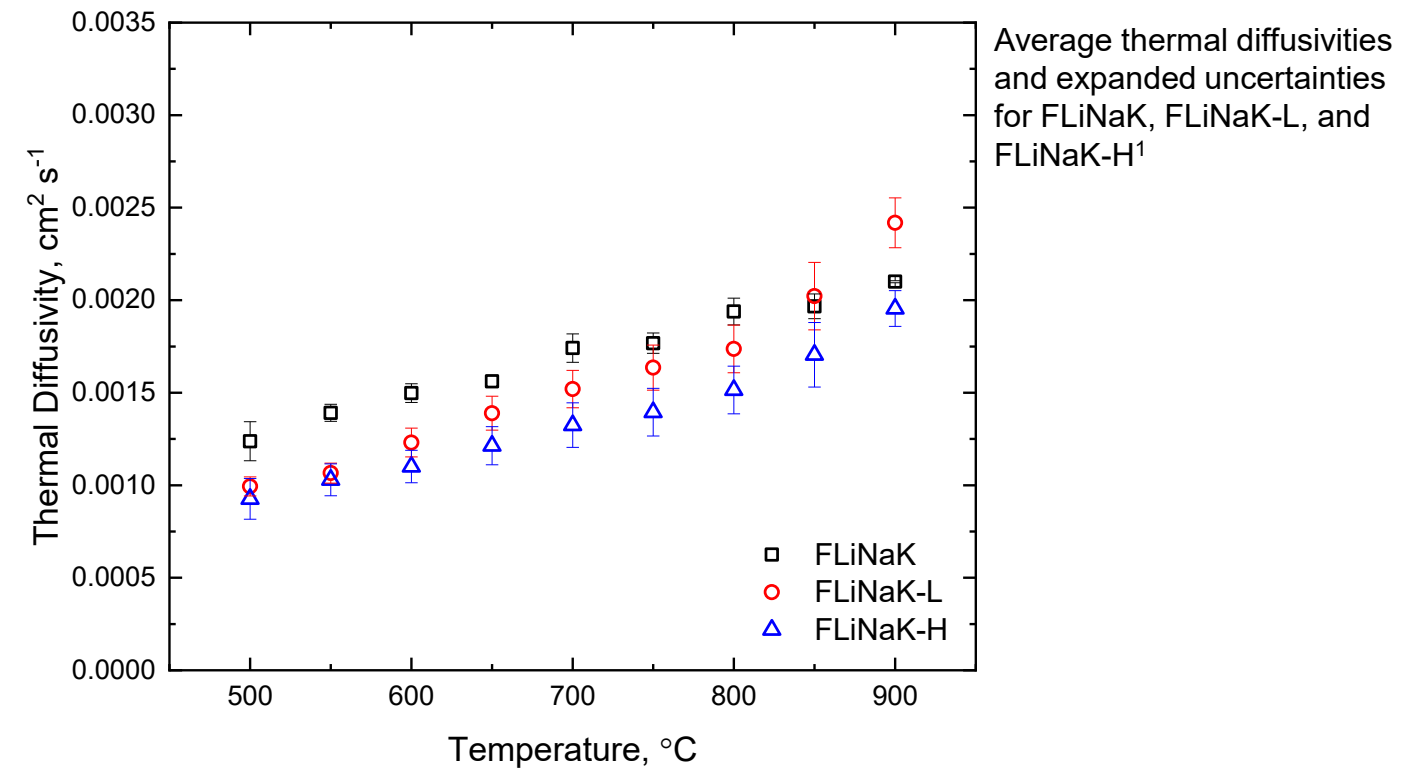
- A small peak detected with an onset at 445 °C in analyses with both doped FLiNaK salts
- Additional pre-peak with an onset near 419 °C is observed in high-burnup FLiNaK measurements

Differences in melting onset temperatures exceed the measurement uncertainty

Thermal Diffusivity

- Uncertainties in thermal diffusivity measurements by laser flash analysis (LFA) are primarily due to:
 - LFA timer resolution
 - Variance in multiple measurements
 - Random error
 - Distortion in salt layer thickness during heating
 - Thermocouple uncertainty
- Relative uncertainties at each temperature are on the order of 10%

¹L.D Gardner, K.A. Chamberlain and M.A. Rose. Property Measurements of LiF-NaF-KF Molten Salts Doped with Surrogate Fission Products. ANL/CFCT-24/23. September 2024.



Graphite cells used to contain salt during measurements are designed to maintain a known uniform thickness of salt

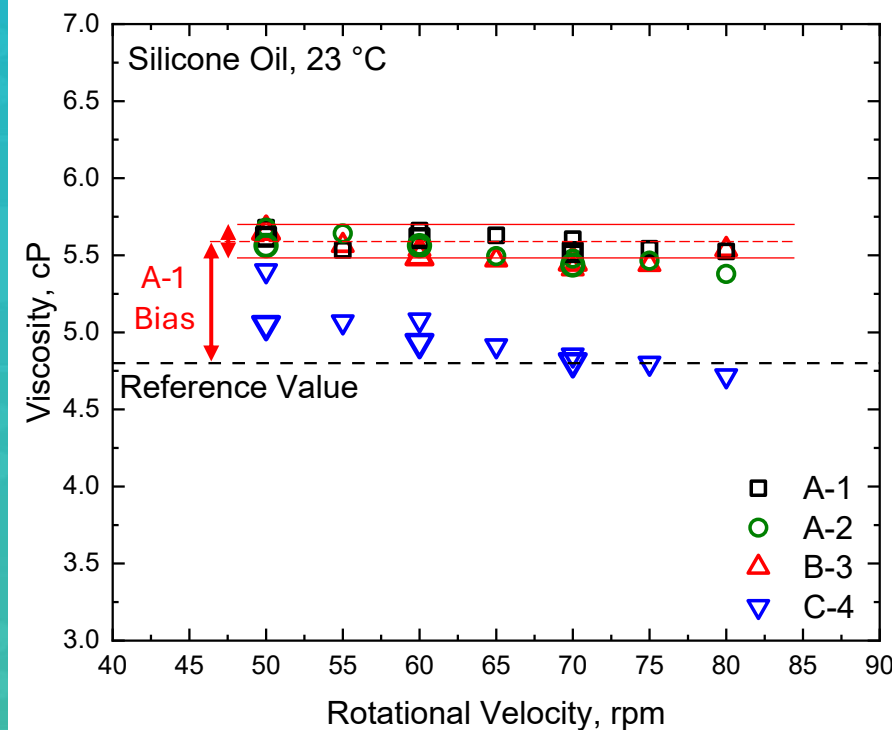
Periodic instrument response checks with a certified reference material provide confidence that various instrument effects are controlled.

Differences between the responses of salts with and without dopants are greater than the measurement uncertainty

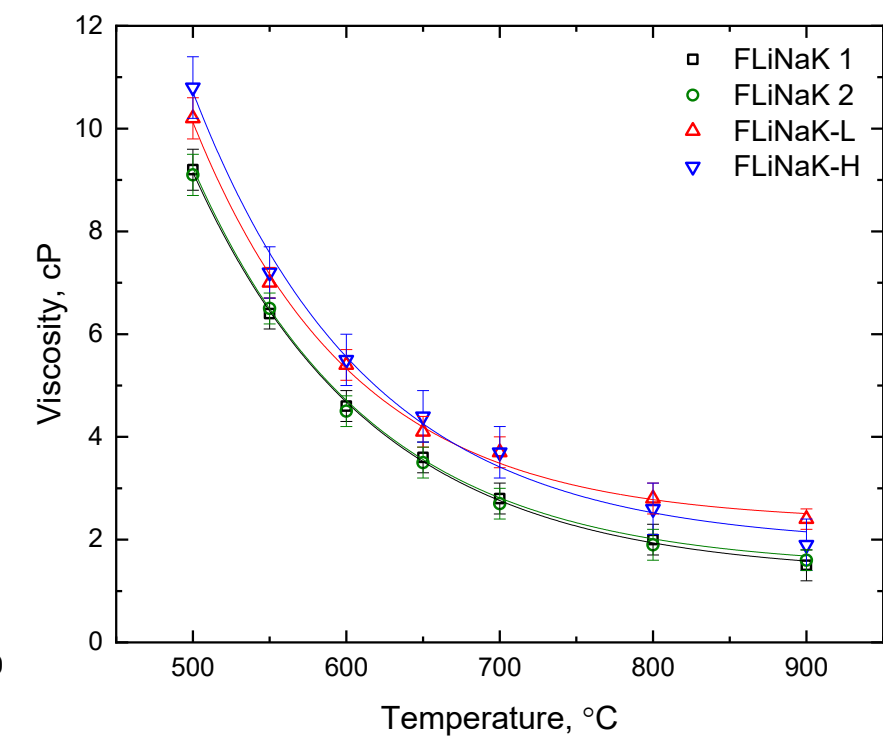
Viscosity

- Uncertainties in viscosity measurements are primarily due to:
 - Resolution of calipers, bore gauge
 - Viscometer torque calibration
 - Variance in multiple measurements
 - Uncertainty in salt temperature stability and control
- Relative uncertainties at each temperature are on the order of 10%
- Draft standard test method is being circulated for comment

¹L.D Gardner, K.A. Chamberlain and M.A. Rose. Property Measurements of LiF-NaF-KF Molten Salts Doped with Surrogate Fission Products. ANL/CFCT-24/23. September 2024.



Viscosities of silicone reference oil measured using three different viscometers (A, B, and C) at room temperature



Average bias-corrected viscosities and expanded uncertainties for FLiNaK 1, FLiNaK 2, FLiNaK-L, and FLiNaK-H¹

A long drive shaft is needed to avoid heating the viscometer head, which increases gyration

Effects of gyration and bearing wear on measured values can be determined by performing measurements with a reference fluid using the same viscometer, drive shaft, and spindle size used for measurements of molten salts to determine a bias correction factor

- Viscometer calibration is performed by using a commercial silicone reference oil
- Bias factor determined from measurements with silicone oil is applied to measurements made in a molten salt

Differences in viscosities of salts with and without dopants are greater than the measurement uncertainty

Effect of Corrosion Products on Thermal Analyses

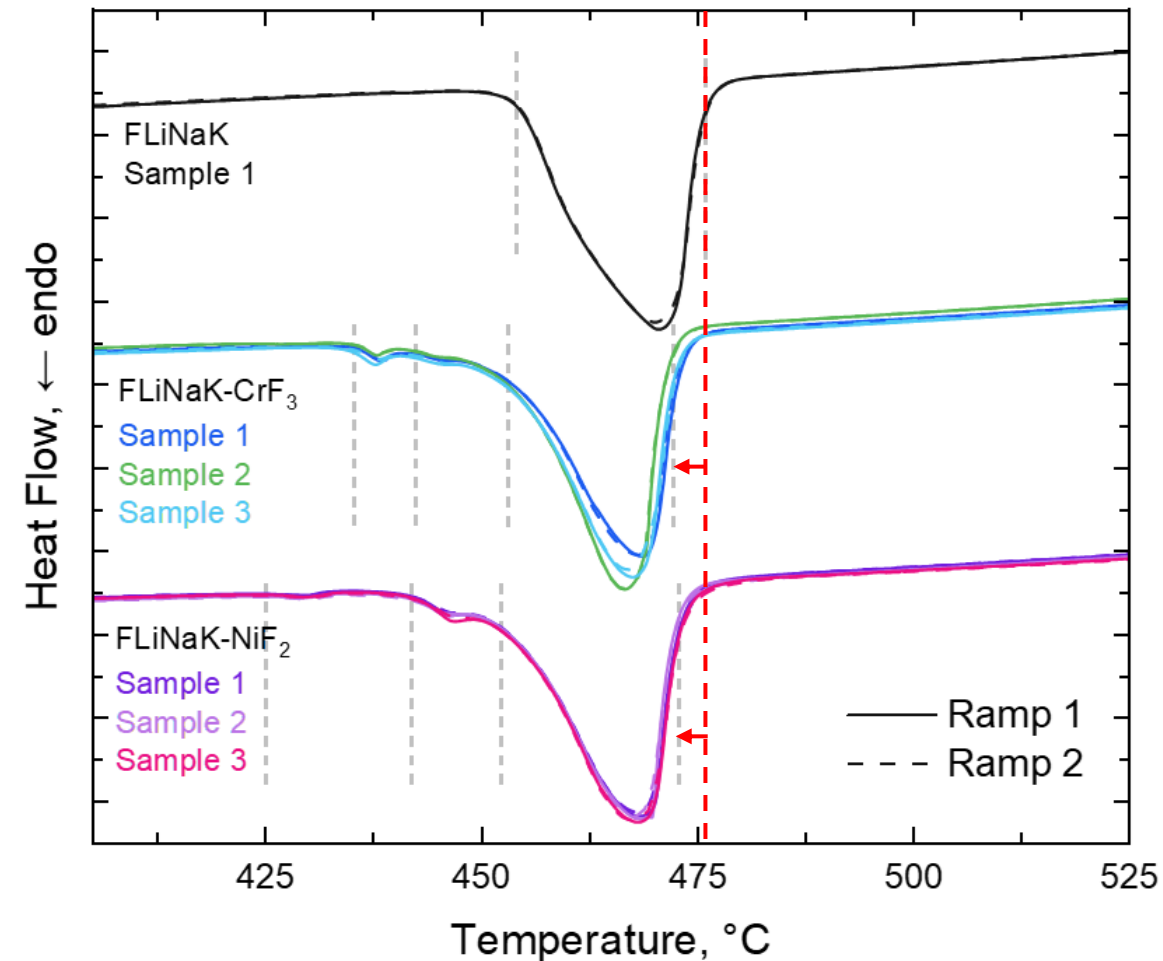
DSC used to measure thermal transitions of individual batches of FLiNaK salt doped with:

- 0.9 wt % NiF_2
- 0.9 wt % CrF_3

Heating cycle performed for each sample:

- One $20\text{ }^\circ\text{C min}^{-1}$ pre-melting ramp
- Two $5\text{ }^\circ\text{C min}^{-1}$ measurement ramps

¹L.D Gardner, E. Dowding, J. Rojas and M.A. Rose. Property Measurements of LiF-NaF-KF Molten Salts Doped with Corrosion Products and Oxygen. ANL/CFCT-25/22. September 2025.



Decrease in melting temperatures and presence of low-temperature transitions due to addition of corrosion products

Presence of nickel and chromium fluoride shift liquidus temperatures lower and introduce lower temperature transitions

Effect of Uranium Oxide on Thermal Analyses

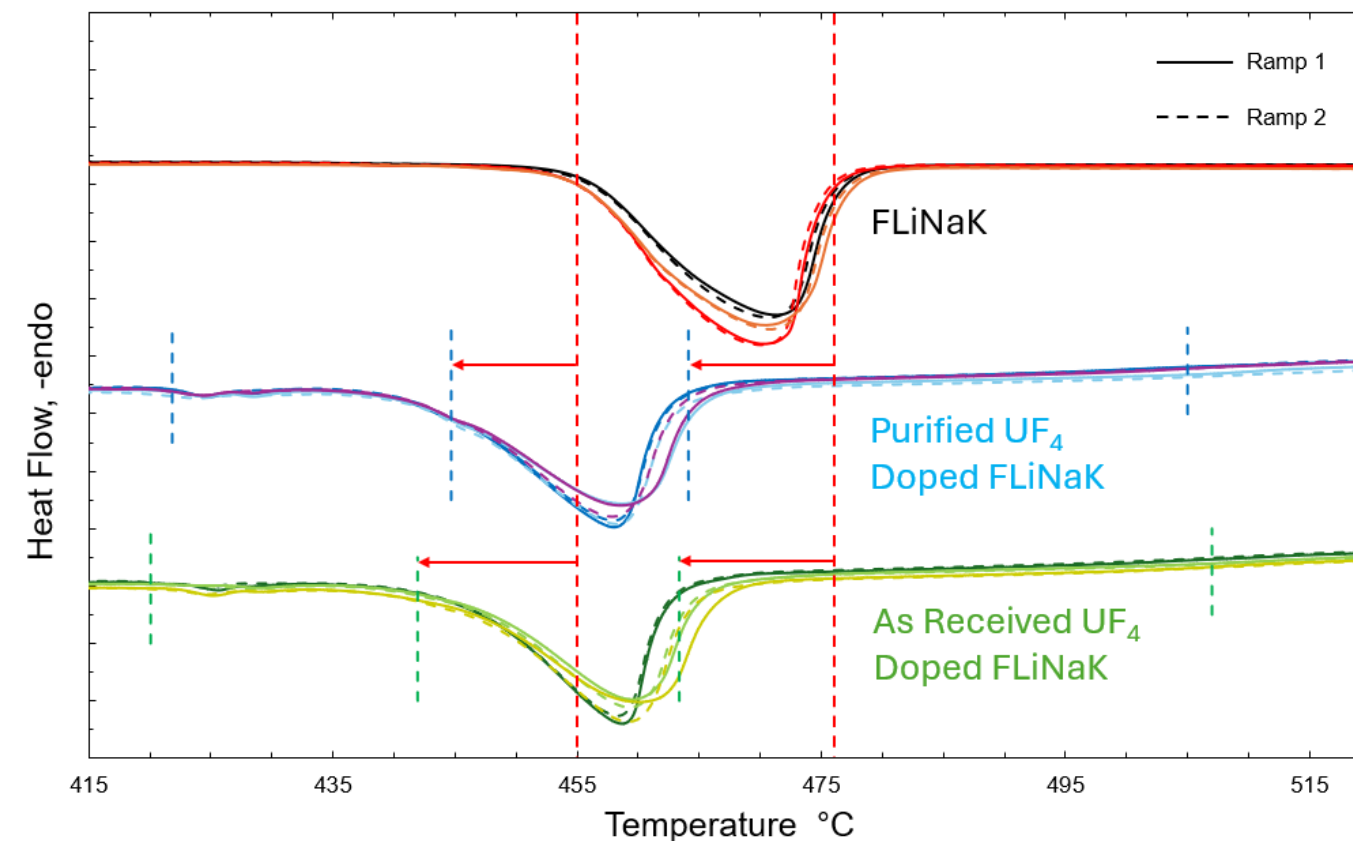
DSC was used to measure thermal transitions of three samples each of FLiNaK doped with ~12 wt % UF_4 from two sources:

- As-received UF_4 containing ~10 wt % UO_2
- Purified UF_4 containing < 1.5 wt % UO_2

Heating cycle performed for each sample:

- One $20^\circ\text{C min}^{-1}$ pre-melting ramp
- Two 5°C min^{-1} measurement ramps

¹L.D Gardner, E. Dowding, J. Rojas and M.A. Rose. Property Measurements of LiF-NaF-KF Molten Salts Doped with Corrosion Products and Oxygen. ANL/CFCT-25/22. September 2025.



Decrease in melting temperature and presence of low-temperature transitions due to addition of UF_4

Addition of UF_4 to FLiNaK:

- Lowers melting temperature
- Introduces low temperature features
- Produces extended shouldering of liquidus

The lack of consistency of the transition temperatures ($> 2^\circ\text{C}$) measured with different samples of FLiNaK doped with UF_4 from both sources indicates compositional non-uniformity of salt mixtures

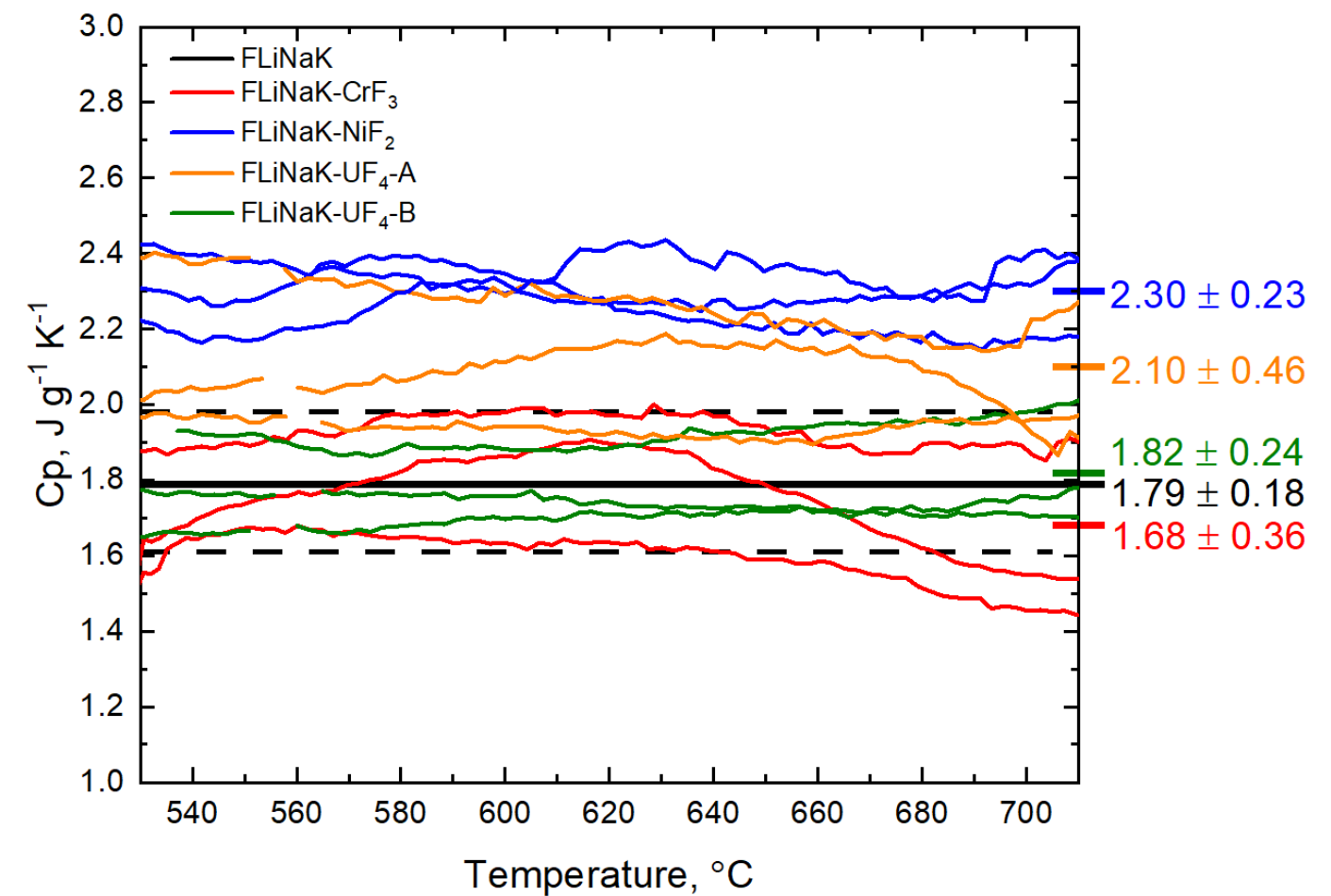
- Effect is more pronounced in salt with higher oxide content
- Oxide is not soluble in salt and is likely not distributed homogeneously

Effect of Corrosion Products and oxides on Heat Capacity

Heat capacities were measured by using DSC by the ratio method of three samples each of salt¹:

- FLiNaK
- FLiNaK + 0.9 wt % NiF₂
- FLiNaK + 0.9 wt % CrF₃
- FLiNaK + 12 wt % UF₄ As received (A)
- FLiNaK + 12 wt % UF₄ Purified (B)

¹L.D Gardner, E. Dowding, J. Rojas and M.A. Rose. Property Measurements of LiF-NaF-KF Molten Salts Doped with Corrosion Products and Oxygen. ANL/CFCT-25/22. September 2025.



Addition of NiF₂ (blue) raises heat capacity beyond the uncertainty of the measurement.

Additions of CrF₃, and UF₄ with oxygen contamination do not change the heat capacity beyond the uncertainty of the measurements

Summary

Affects of key fission products, corrosion products and oxides have been investigated.

- Impacts on thermal transition temperatures, viscosity, density and heat capacity are measurable.

Additional measurements are needed to provide data which can be used to determine which impurities must be removed to maintain acceptable fuel salt properties

- Effect of other impurities (Fe, moisture, noble metals)
- Different concentrations of impurities to set purity standards

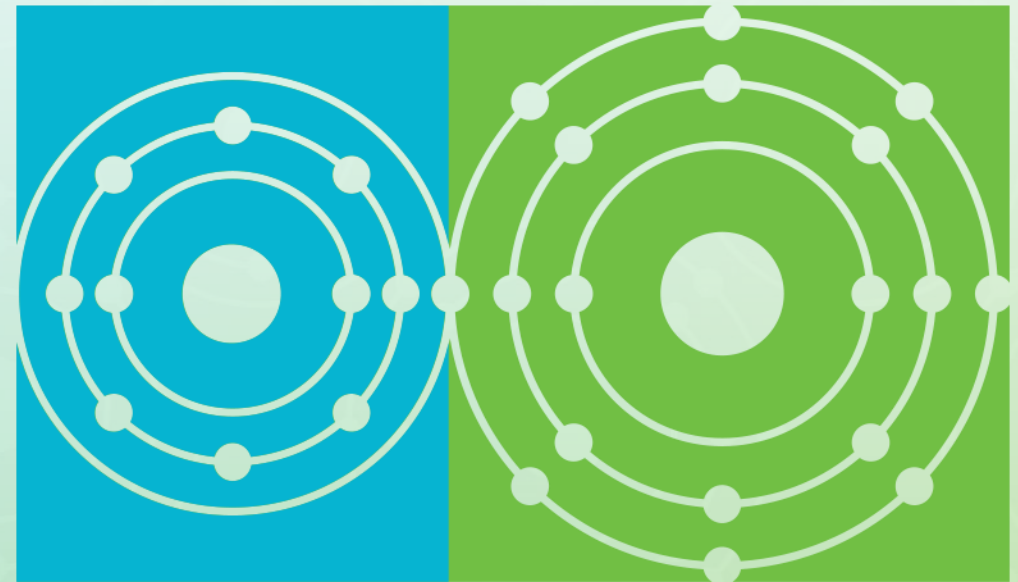
Knowing which impurities should be removed and setting purity standards will enable developers to define their fuel cycle strategy.

Acknowledgements

- Financial support provided by U.S. Department of Energy, Office of Nuclear Energy
- Government License Notice -the manuscript has been created by UChicagoArgonne, LLC, Operator of Argonne National Laboratory (“Argonne”). Argonne, a U.S. Department of Energy Office of Science laboratory, is operated under Contract No. DE-AC02-06CH11357.

Thank you

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