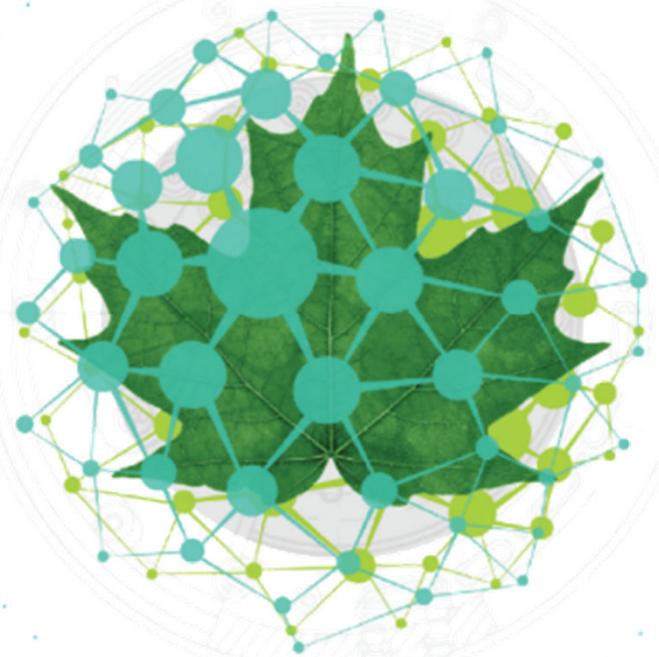
153-120200-001-000

Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

Molten Salt Research Activities at CNL

39th GIF MSR pSSC Meeting

2025 December 10th, PSI, Switzerland



Mouna Saoudi
Advanced Reactors Directorate

CNL Today

- ✓ $1.2B infrastructure investment
- ✓ Diverse & growing team of ~4,000; ~800 in Science & Technology
- ✓ Broadening portfolio supporting more industries and academia

Nuclear Landscape in Canada

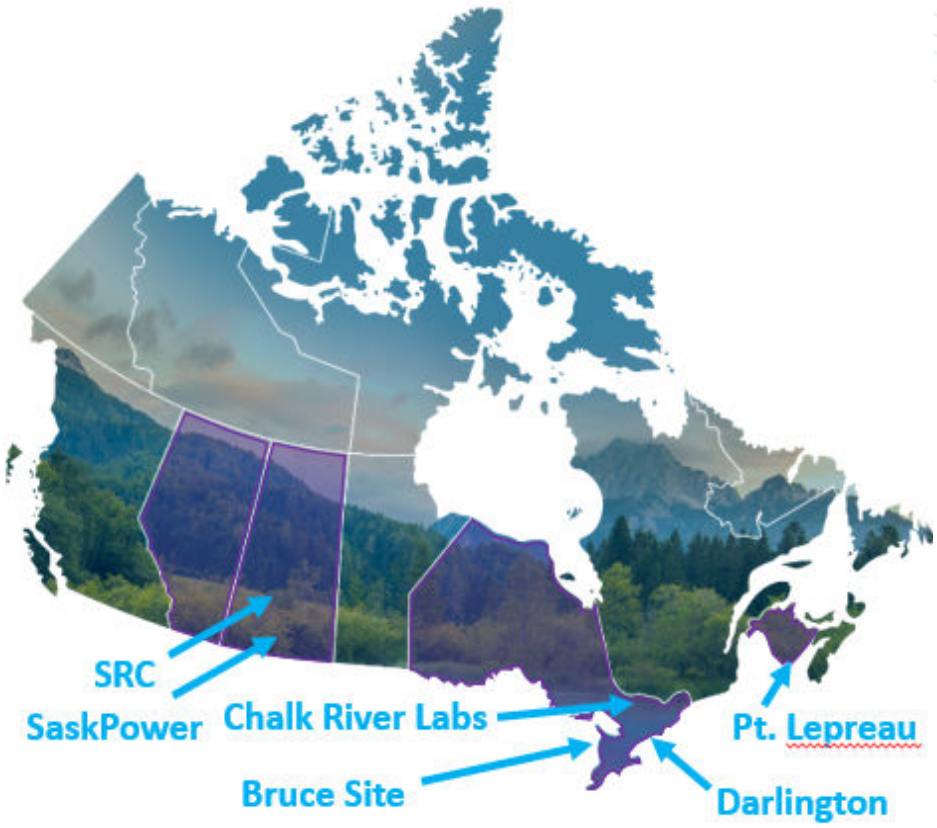
Large Nuclear

- Refurbs ahead of plan
- Pickering refurb
- Bruce Site 4800MWe pre-development
- AtkinsRéalis 1,000 MW CANDU® MONARK™

SMR Vendors Active in Canada and Aligned with a Utility or CNL

SMR Vendor	Design	Coolant type	Fuel type	Power (Mwe)	Spectrum
Ge-Hitachi	BWRX-300	Boiling water	Uranium oxide	300	Thermal
NANO Nuclear Energy Inc.	KRONOS MMR™	Helium	TRISO fuel (prismatic)	3.5 - 15	Thermal
X-Energy	Xe-100	Helium	TRISO fuel (pebble)	80	Thermal
ARC Nuclear	ARC-100	Molten sodium	Uranium alloy fuel	100	Fast
Moltex Energy	SSR-W	Molten salt	Chloride fuel salt	300	Fast
Terrestrial Energy	IMSR	Molten salt	Fluoride fuel salt	390	Thermal

← Liquid fuelled MSRs



Three Streams of SMR Development in Canada

Illustration of GE Hitachi BWRX-300 - https://bindustry.eu/

Stream 1: On-Grid, ~300 MW_e

- Ontario Power Generation & SaskPower select GE-Hitachi BWRX-300
  - Darlington 4 units (2028 first unit)
  - SK 4 units (2034-2042)
- Alberta
  - SMART MOU (2023)
  - OPG & Capital Power (2025 feasibility study complete)

Illustration of Moltex SSR-W – moltexenergy.com

Stream 2: Advanced Reactors

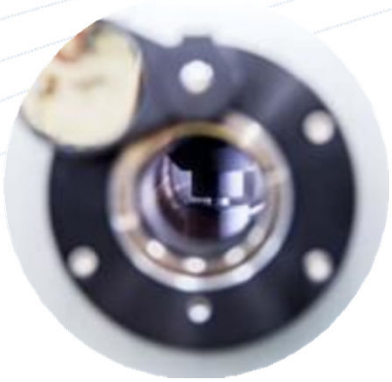
- New Brunswick Power, Point Lepreau
  - ARC Nuclear ARC-100, LTPS submitted, VDR Phase 2 complete
  - Moltex SSR-W
- OPG + X-Energy framework agreement
- Alberta
  - Terrestrial Energy MOU
  - X-Energy Study
  - Cenovus Oil Sands Study

Illustration of McMaster's Net Zero Community Project

Stream 3: Off-Grid, <15 MW_e

- Development of a pan-Canadian Framework to inform the safe deployment of SMR microreactors
  - CNL's Siting Clean Energy Siting Program
  - McMaster's Net Zero Community Project
  - Saskatchewan Research Council (SRC) Nuclear
  - Bruce Power Feasibility Study

How CNL is **Enabling SMRs / Advanced Reactors**



Federal Nuclear Science & Technology Program

Helping to build a framework for SMR development & deployment in Canada

Canadian Nuclear Research Initiative

Working with commercial companies to apply our nuclear capabilities to technical challenges

Clean Energy Invitation

Hosting a demonstration SMR or other clean energy projects on a CNL-managed site

Microreactor Framework

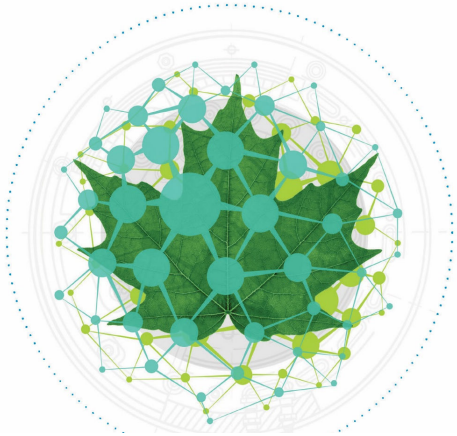
Enabling a national approach to deployment of microreactors

New Nuclear Energy Technologies (N2ET) Program (Link)

Canadian Federal Nuclear Science & Technology Program on MSR Systems

Molten Salts Research Activities- Mission & Objectives

- Mission:
  - To support regulatory positions and decisions for novel nuclear fuel
  - To reduce uncertainties regarding safety, security and environmental issues
  - To generate knowledge and information to identify and address emerging issues related to molten salt technology



- Objectives:
  - Develop modelling capabilities and experimental facilities to generate data for validation required to support molten salt SMRs
  - Engage with federal stakeholders and industry to address gaps and reduce risk associated with MSR technology
  - Actively seek collaborations with national and international partners to leverage resources and conduct focused R&D targeted to specific outcomes

Active Federal S&T Projects related to MSR Technologies

Fuel & Coolant Salt Properties

- Fuel salt synthesis & purification
- Thermophysical properties measurements of molten salts
- Structural characterization
- Atomistic modelling
- Thermochemical modelling
- Fuel salt behaviour under accident conditions

Corrosion in Molten Salts

- Corrosion test loops
- Static corrosion tests on various materials:
  - SS 316
  - Grade 91 steel
  - Hastelloy N
  - Alloy 242
- Activity transport
- Electrochemistry & redox control

Multiphysics Modelling for Safety Performance

- Coupled CFD-Neutronics MSR transient simulation tools
- Passive decay heat removal
- Self-heating fluid testing
- Exploring ZED-2 reactor measurements
- Beyond-design basis modelling capabilities for MSRs

Evaluation of Waste Streams

- Evaluation of waste streams from MSRs considered for deployment in Canada
- Exploring of salt waste treatment methods

Safeguards of MSRs

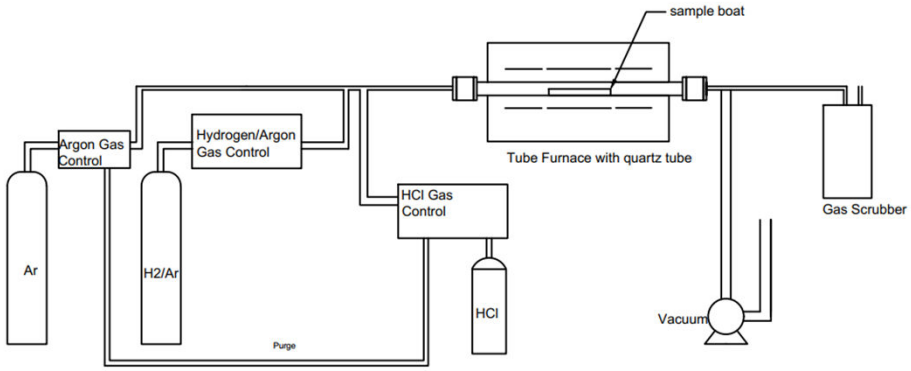
- Evaluation and improvement of safeguards approaches and methods for
- Proliferation Resistance & Physical Protection

Synthesis and Purification of Actinide Salts

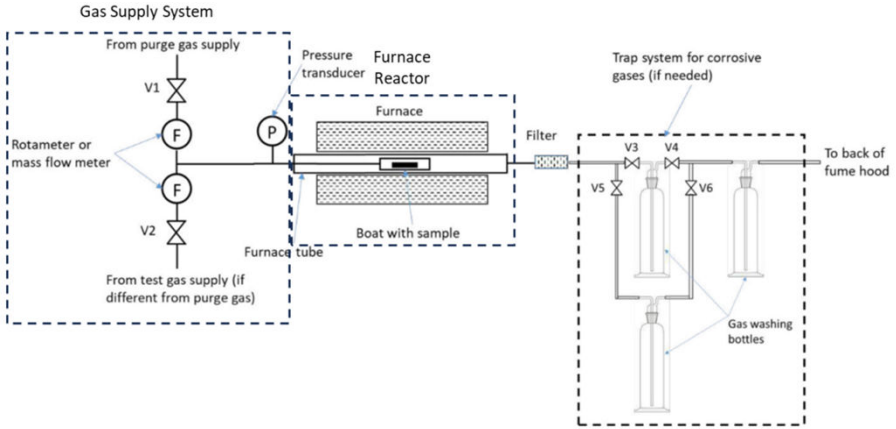
Selected Halogenating Agents for Synthesizing actinide salts

Halogenating Agent	Target Actinide Salt
HCl (gas)	UCl_3
NH_4HF_2 (solid)	UF_4
HF (gas)	UF_4

NH_4HF_2 (s) → NH_3(g)+2HF (g) @ 150-200 °C



Gas-solid Hydrochlorination setup with hydrogen chloride (HCl)

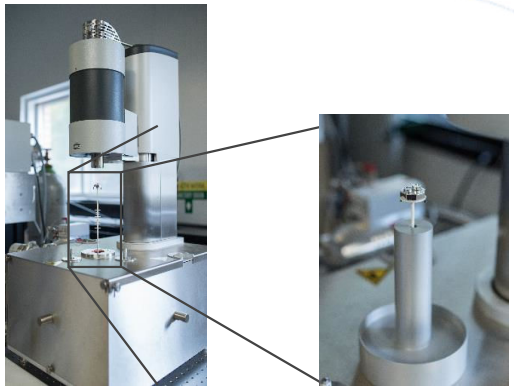


Fluorination setup with ammonium bifluoride (NH_4HF_2) or HF gas

Molten salt thermophysical properties (1/2)

- Establish experimental procedures:
  - Molten salt encapsulation
  - High temperature DSC (T_m, C_p, …)
  - Laser flash apparatus (thermal diffusivity)
  - XRD for phase identification
  - TGA for thermal stability
  - ICP-OES for composition
  - Oxygen analysis

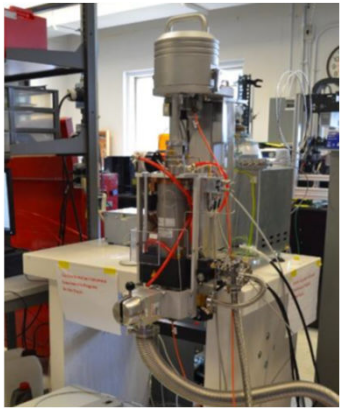
Laser Flash Apparatus (LFA)



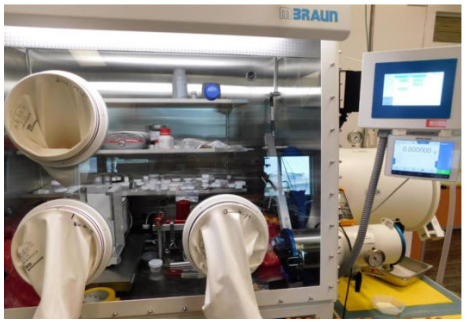
Differential Scanning Calorimeter (DSC)

Custom hermetic sample holder to enable XRD measurements of molten salts under inert atmosphere

Inert Gas Fusion (IGF) for oxygen analysis (LECO O836)



Thermogravimetric Analyser (TGA)



Ar Glovebox (O_2 < 2 ppm; H_2O < 5 ppm)

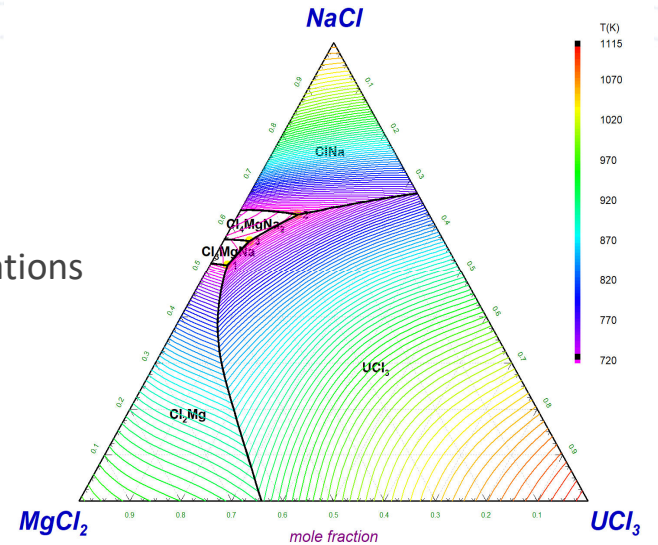
Handling of non-active and active salts

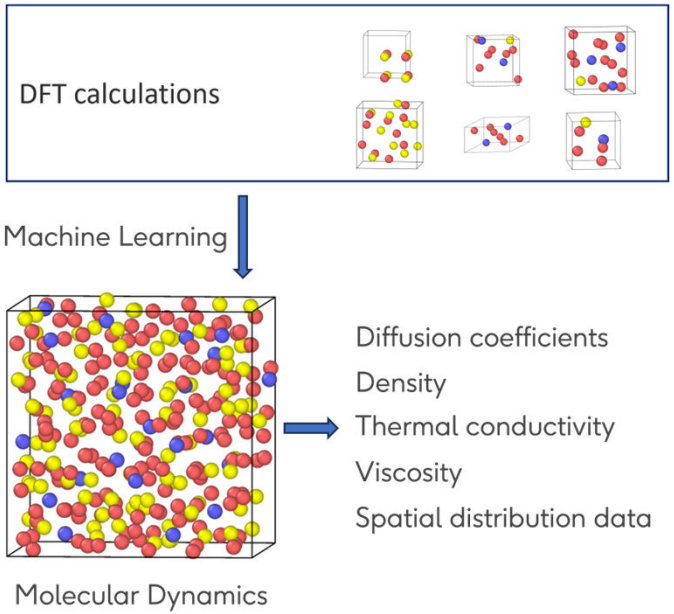
Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

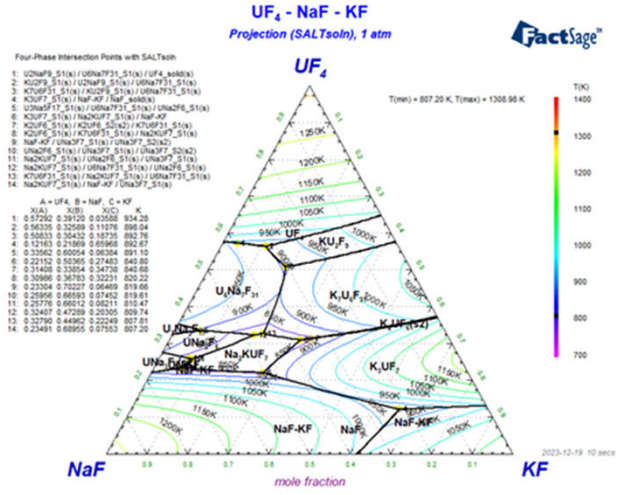
Molten salt thermophysical properties (2/2)

- Modelling of molten salt thermophysical properties:
  - Thermochemical modelling
  - Atomistic simulations
  - DFT calculations
  - Finite Element Analysis

Calphad calculations

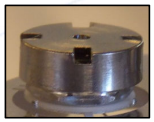




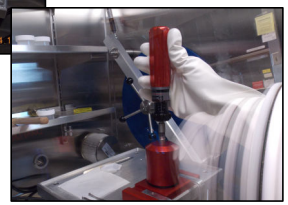


Differential Scanning Calorimetry (DSC) Measurements

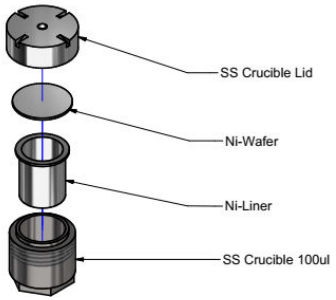
Salt encapsulation for DSC

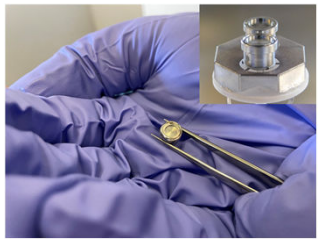


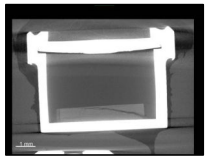
CrNi steel crucible



Modified in-house hermetically sealed CrNi steel crucible

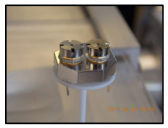






Customized Ni crucible Laser welded to maintain hermetic seal for high temperatures DSC measurements

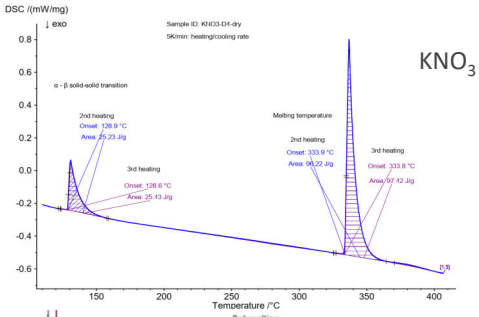
Validation of the encapsulation methods

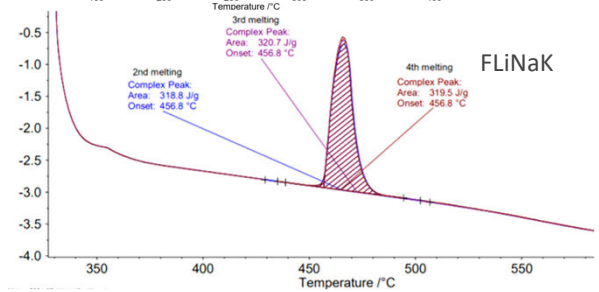


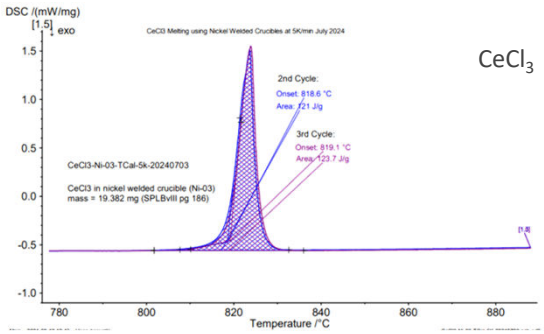
CrNi steel crucible

Modified CrNi with Ni liner tested and benchmarked using FLiNaK

Hermetically sealed Ni capsule for high temperatures DSC measurements



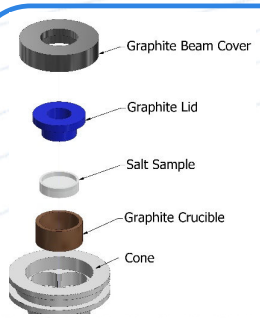


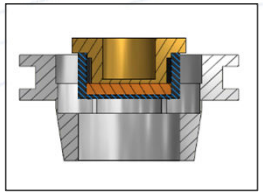


Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

Thermal Conductivity of Molten Salts

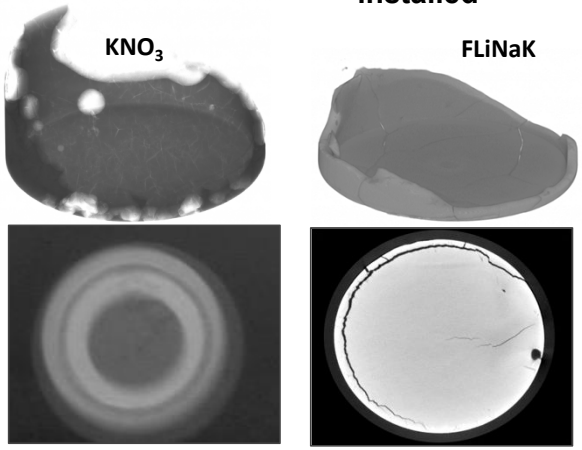
Salt encapsulation





Cross section of a sample installed

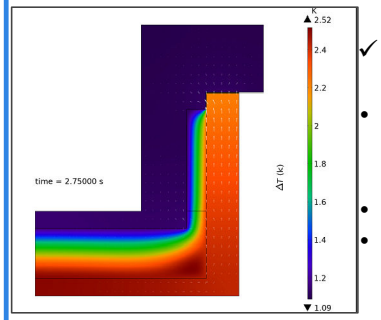
KNO_3 **FLiNaK**



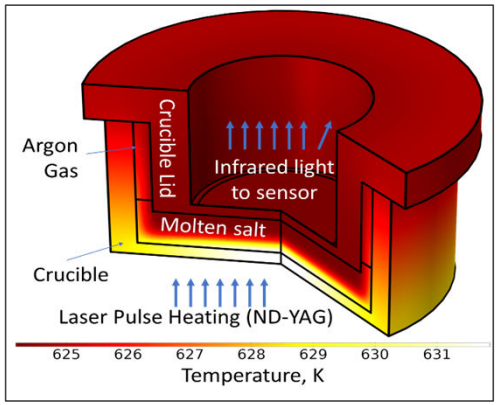
XCT imaging of the encapsulated salt before and after LFA measurements

Finite Element Analysis

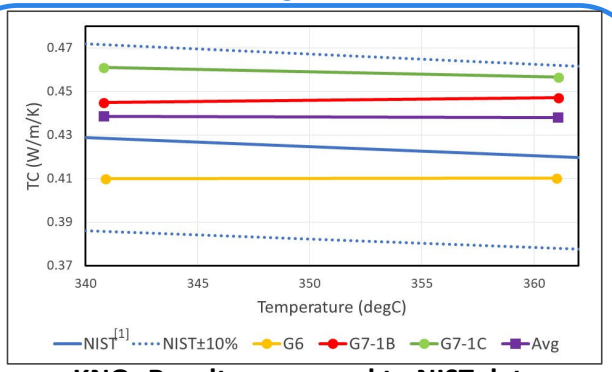
Evaluate effect of the container on measured thermograms



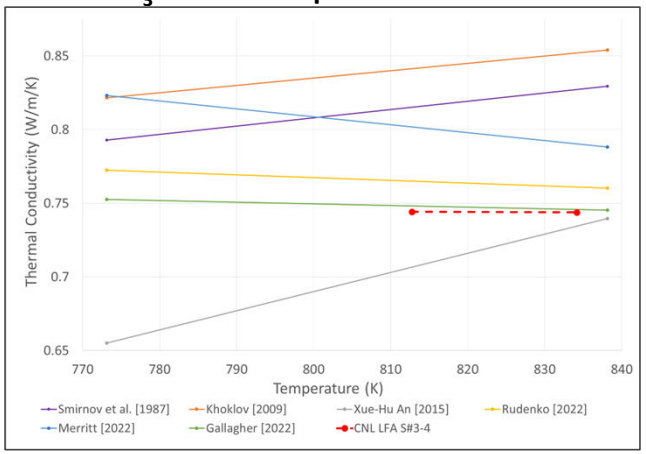
- ✓ **Insignificant radiative heat loss at low T (350 °C)**
- **Two conduction modes with different timescales:**
- **Across-molten salt**
- **Around crucible sides**



Validation using benchmark salts



KNO_3 Results compared to NIST data

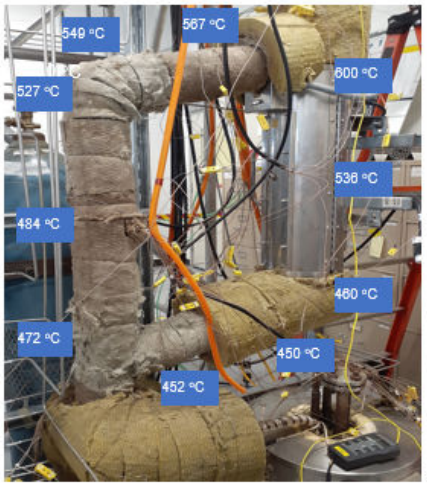


FLiNaK thermal diffusivity results compared to literature data

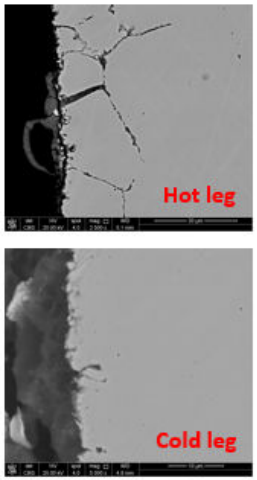
Materials Corrosion and Degradation in Molten Salt (1/2)

- High temperature molten salt corrosion test capability long-term Demonstration Natural Corrosion Loop (DNCL) operation with controlled salt chemistry (SS 316L exposed to chloride binary salt mixture)
- Salt and metal samples are collected for post-experiment characterization.
- After each experiment, main components are harvested from the loop to evaluate their design and the material selection.
- Static corrosion testing of candidate alloys (SS 316L, Alloy 242, and Alloy N in molten salts are on-going.

Temperature profile during DNCL experiment



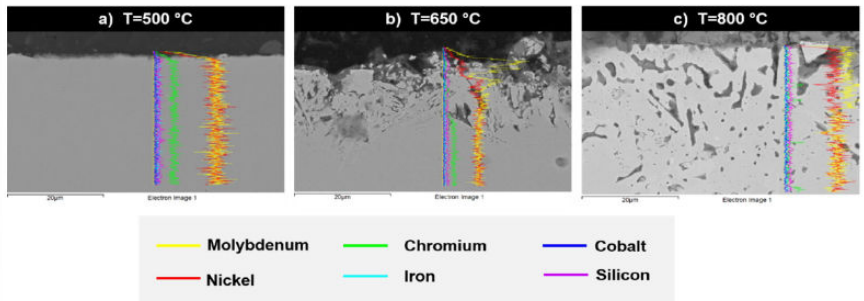
SEM micrographs of loop sections



Setup for static corrosion experiments

Characterization of freeze valve

Alloy 242 after static corrosion experiments

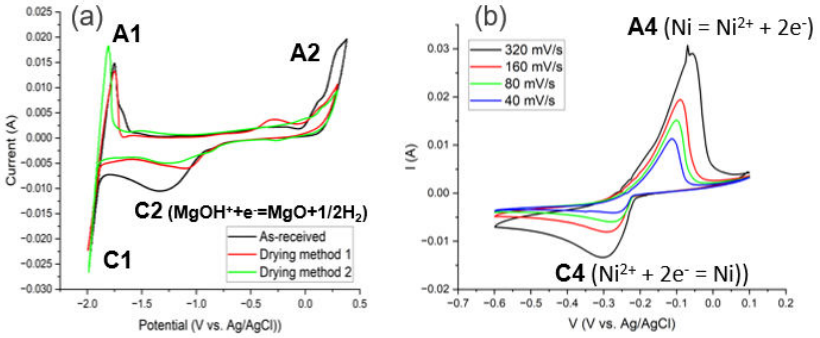


Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

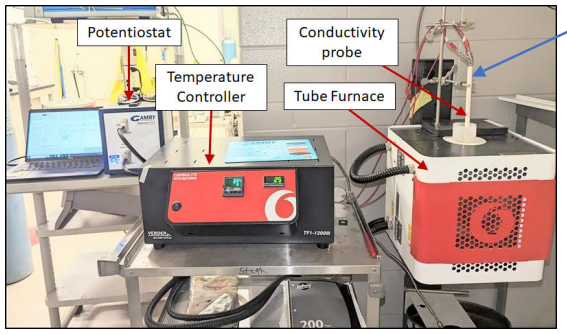
Materials Corrosion and Degradation in Molten Salt (2/2)

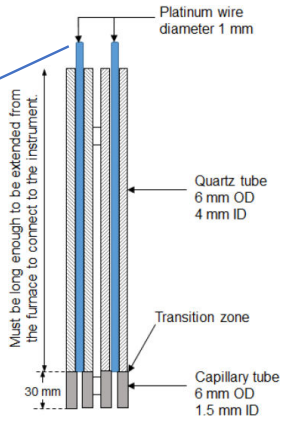
- Develop electrochemical methods for impurity detection in salts
- A glovebox with integrated furnace has been delivered. Lab preparation to install the glovebox is ongoing
- Development of electrical conductivity equipment using Pt-wire probe as electrodes and testing at 550 °C in KCl-LiCl (41-59 mol%)

Electrochemical methods for characterization of molten salts



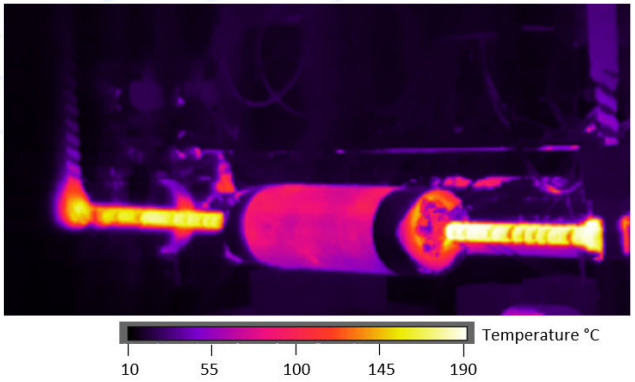
Electrical conductivity equipment

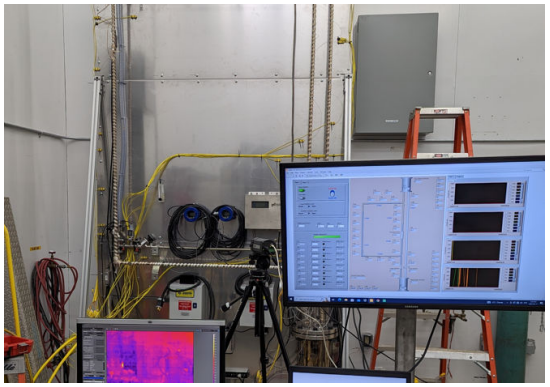




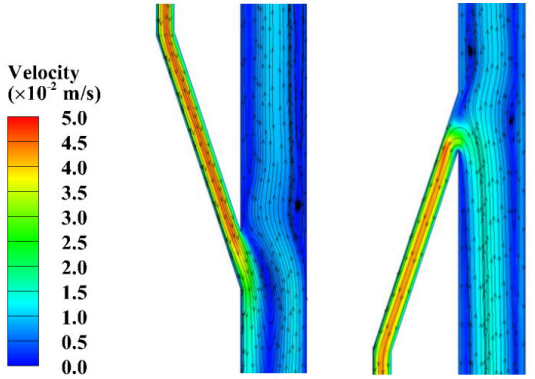
Pt wire-probe

Passive Safety Molten Salt Natural Circulation Heat Transfer Loop





Assembled loop undergoing dry testing



Phenomena to Study

- Heat transfer
- Salt freezing
- Loop geometry
- Salt temperature

Construction

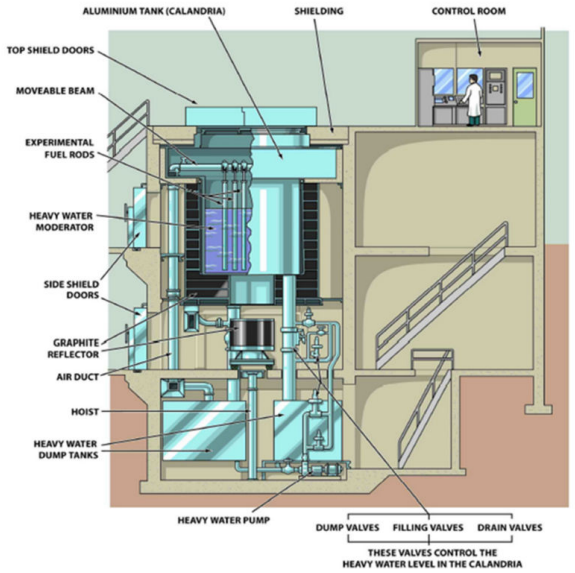
- 316 Stainless steel
- Main loop is 2 m tall
- Operate at ~550°
- Instrumented with fibre-optic sensors, capacitance sensors, thermocouples, ultrasonic flow sensors

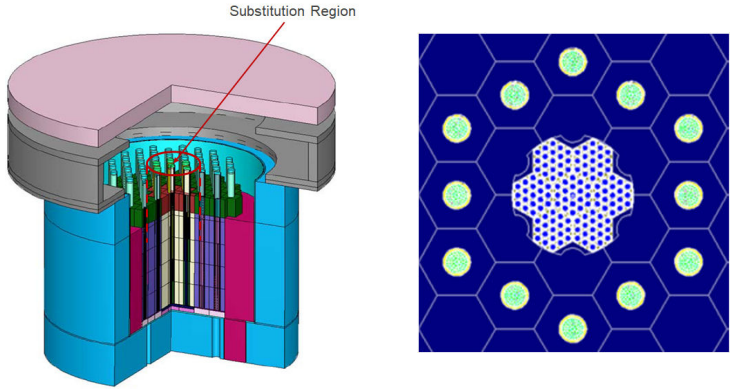
Testing

- Instrumentation effectiveness
- Changes in geometry due to aging
- Data for benchmarking models e.g., CFD and System Code simulations

MSR Reactor Physics Measurements in ZED-2 Reactor

- Zero Energy Deuterium (ZED-2) reactor
  - ➢ Versatile tank type, heavy water moderated low power research reactor.
  - ➢ Variable pitch, ease of access to the core, and instrumentation ideal for performing reactor physics measurements and fuel studies.
- Typically ~10^9 n/cm^2/s thermal and 10^8 n/cm^2/s fast neutron (core middle).
- Initial simulations indicate that the results of ZED-2 reactor experiments will support the validation of SMR physics codes.

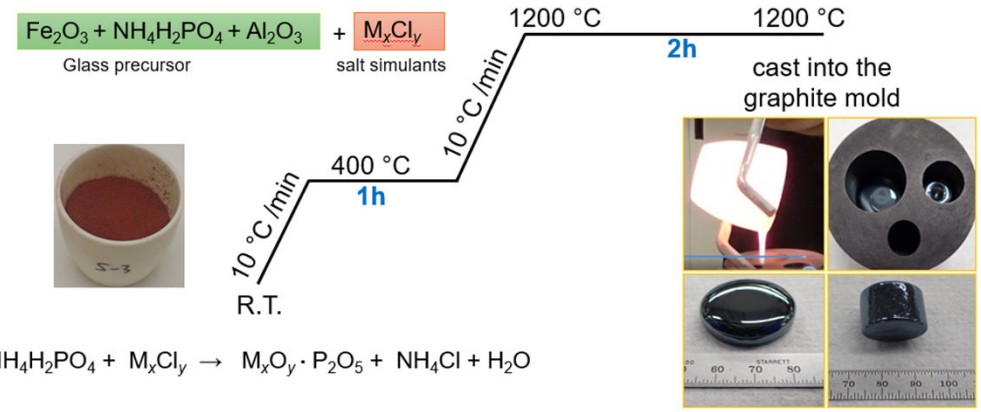




Evaluation of Waste Streams from MSRs

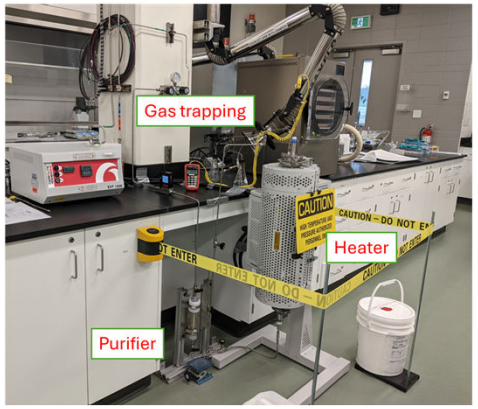
Immobilizing Radioactive Waste

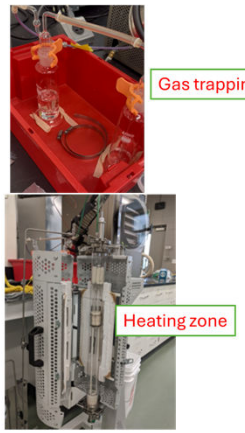
- The melt quenching technique was used to prepare the glass samples.



- Dehalogenation of salt-based wastes
- Developing iron phosphate matrices
- Dissolution testd to be conducted in water at 90 °C to evaluate the chemical durability of the glass.

Separation of Fission Products (FPs) from High-Level Waste Salt





Experimental Setup for Zeolites Selective Sorption

- To separate Cs and Sr in molten chloride salts
- Evaluate HLW inventories from a small modular molten salt reactor (MCSR) with closed fuel cycle.
- Determine chemical state of fission products at end-of-life using equilibrium thermodynamics calculations.
- Prototype and assess methods for spent chloride fuel salt waste management.

This work was supported by Atomic Energy of Canada Limited's Federal Nuclear Science & Technology Work Plan.

Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

www.cnl.ca