Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

153-120200-001-000

MSR Research Activities at Canadian Nuclear Laboratories (CNL)

2024 Molten Salt Reactor Workshop

November 05-07

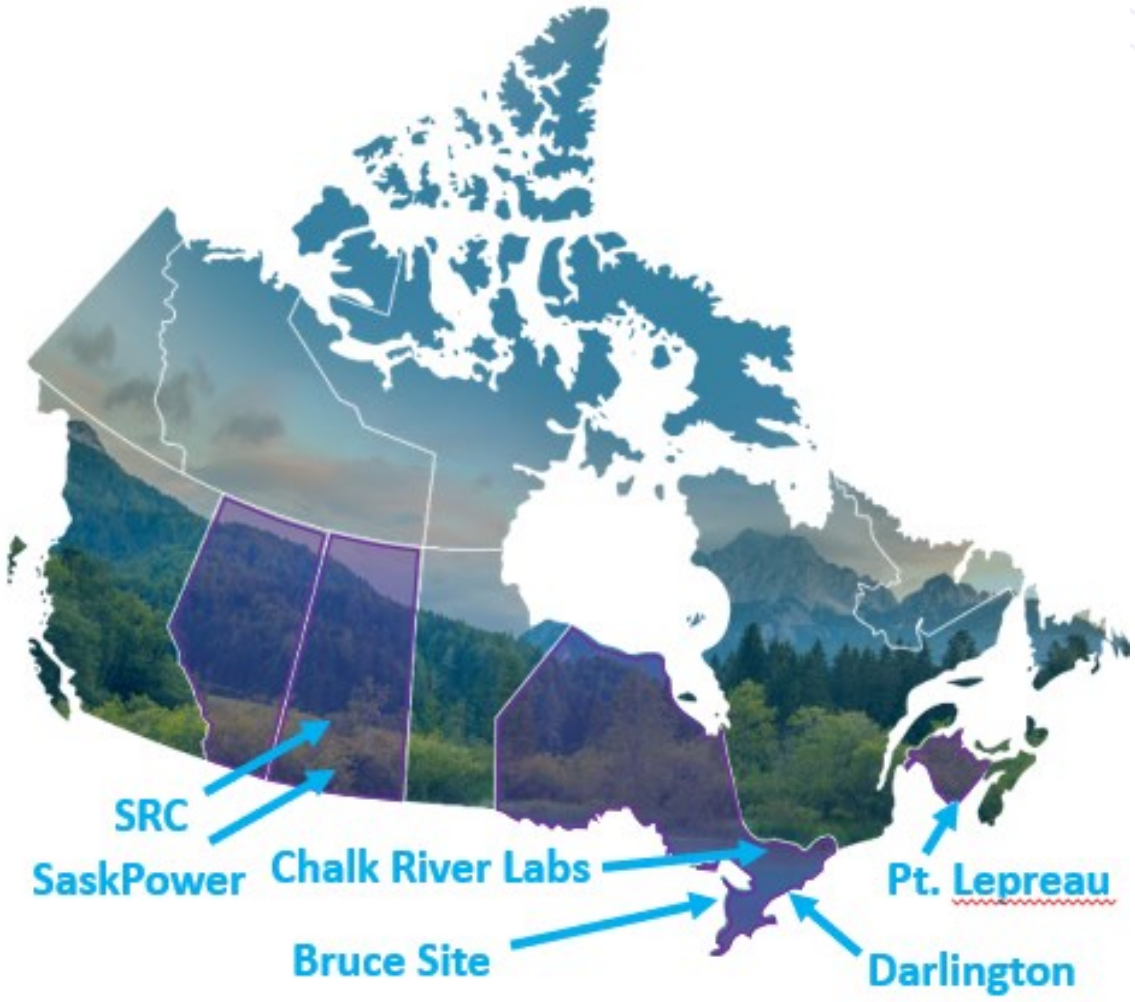
Mouna Saoudi

Knoxville, TN, USA

Update on 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

SMR Vendor	Design	Coolant type	Fuel type	Power (MWe)	Spectrum
GE-Hitachi	BWRX-300	Boiling water	Uranium oxide	300	Thermal
Westinghouse	eVinci	Sodium (heat pipe)	TRISO fuel	5	Thermal
Global First Power/USNC	MMR	Helium	TRISO fuel (prismatic)	3.5-15	Thermal
X-Energy	Xe-100	Helium	TRISO fuel (pebble)	80	Thermal
ARC Clean Technology	ARC-100	Sodium	Uranium alloy fuel	100-150	Fast
Moltex Energy	SSR-W	Molten chloride salt	Chloride fuel salt (static)	300	Fast
Terrestrial Energy	IMSR	Molten fluoride salt	Fluoride fuel salt (flowing)	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)
  - SK 4 units (2034-2042)
- Alberta
  - SMART MOU
  - OPG & Capital Power

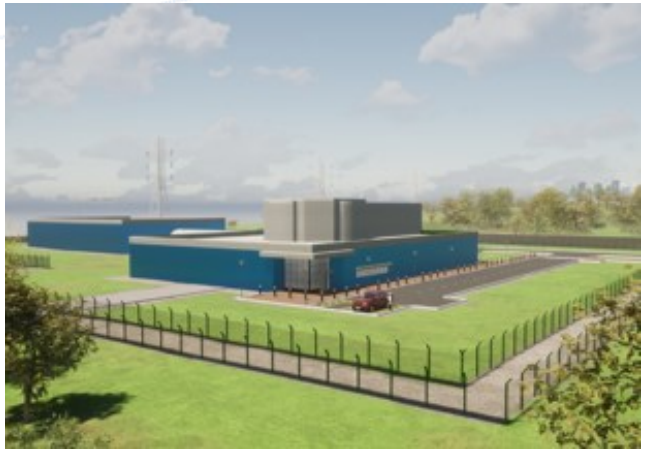


Illustration of Moltex SSR-W – moltexenergy.com

Stream 2: Advanced Reactors

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

Illustration of Westinghouse eVinci – brucepower.com

Stream 3: Off-Grid, <15 MW_e

- Development of a pan-Canadian Framework to inform the safe deployment of SMR microreactors
  - CNL's Siting Invitation Process
    - Hosting a clean energy demonstration on a CNL-managed site (e.g. GFP MMR)
  - McMaster's Net Zero Community Project
    - USNC/GFP MOU
  - Saskatchewan Research Council (SRC) Nuclear
    - Westinghouse eVinci
  - Bruce Power Feasibility Study
    - Westinghouse eVinci

CNL is a National Lab Focused on National Priorities

Restore and protect the environment

Conducting the largest and most complex environmental remediation in Canada, spanning three provinces

Clean energy for today and tomorrow

Supporting our current nuclear fleet and advancing the future ones while also leveraging vast expertise to support Canada's growing hydrogen economy, fusion research and industry's clean energy transition

Improve the health of Canadians

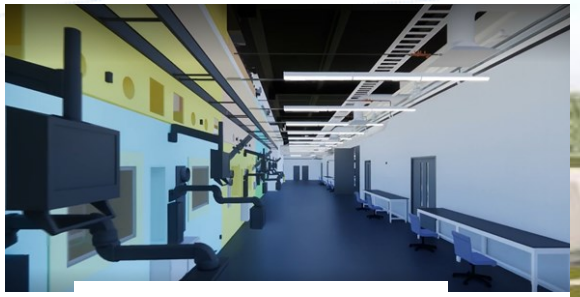
Advancing R&D in radiobiology and commitment to advancing Targeted Alpha Therapy

CNL Today

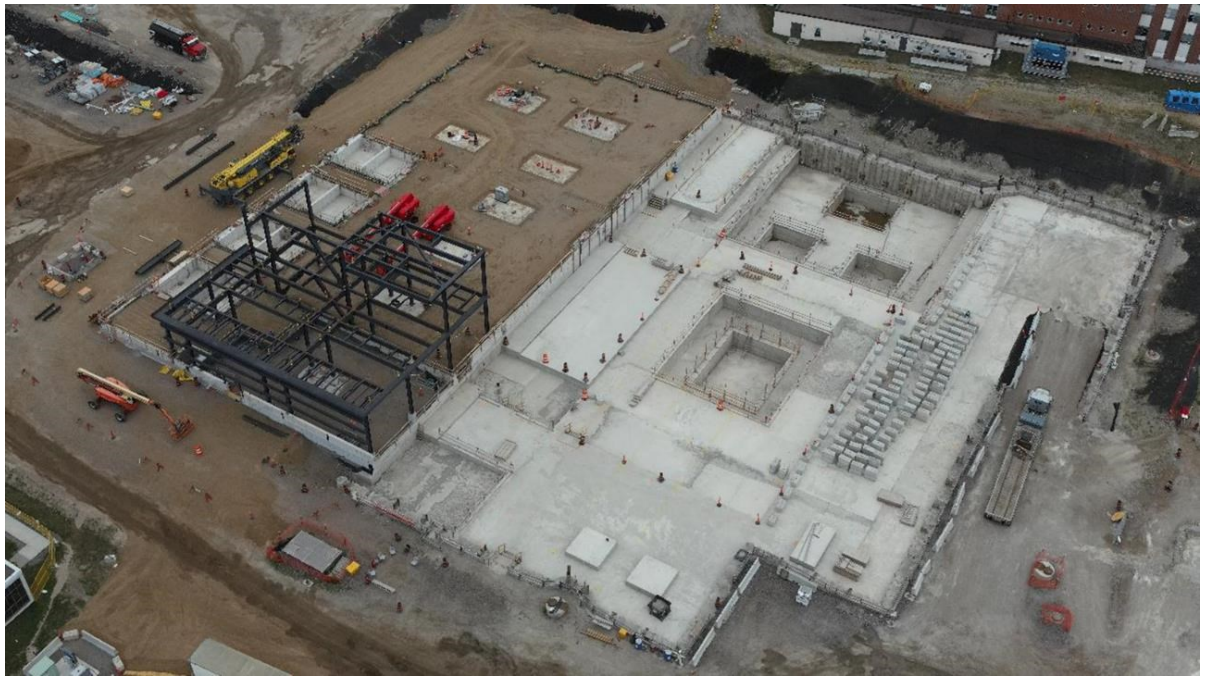
- ✓ $1.2B infrastructure investment
- ✓ Diverse & growing team of ~4,000; ~800 in Science & Technology
- ✓ Broadening portfolio supporting more industries and academia

Advanced Nuclear Materials Research Centre (ANMRC)

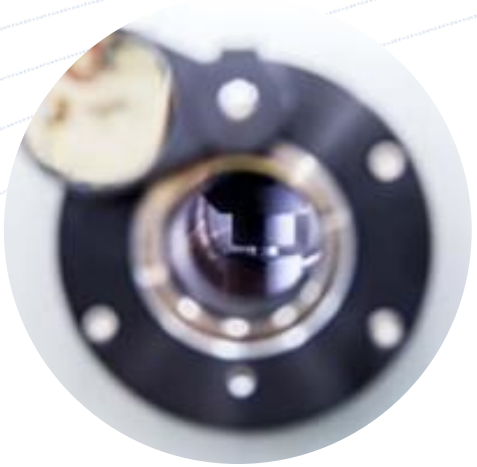
- Advanced Nuclear Materials Research Centre (ANMRC) is designed to meet nuclear material research needs for the next 50 years
- 125,000 square foot space
- 12 hot cells and 23 laboratories
- Will replace current hot cells facilities dating back to the 1950s
- Provides research capabilities to support the life extension and long-term reliability of existing reactors and future advanced reactors
- Ground breaking occurred in Sept. 2022
- Operation expected in 2028-2029



Hot cells



How CNL is **Enabling SMRs**



Federal Nuclear Science & Technology Program

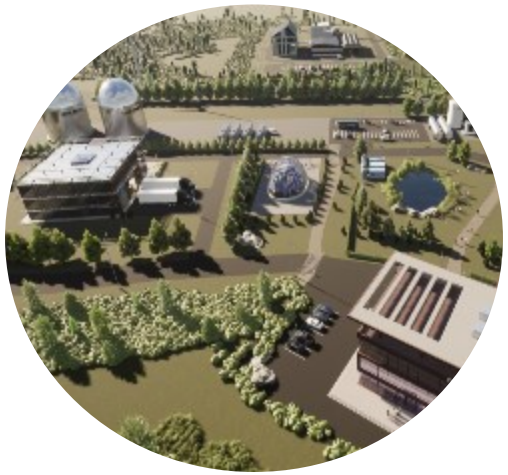
Helping to build a framework for SMR development & deployment in Canada

Canadian Nuclear Research Initiative

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

SMR Demonstration Siting

Hosting a demonstration SMR on a CNL-managed site



Clean Energy Demonstration, Innovation & Research (CEDIR)

Phase 1: Advancing research on clean energy and hybrid energy systems

Phase 2: Demonstrate technologies with an SMR – CEDIR Park

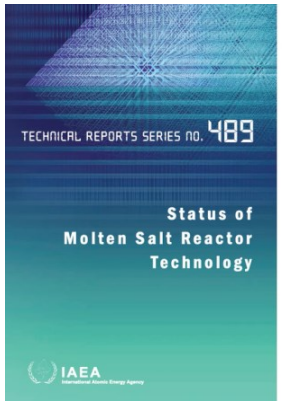
New Nuclear Emerging Technologies (N2ET) Program N2ET Program

International Collaborations on MSRs

GIF MSR provisional System Steering Committee (pSSC)

- Fuel salt thermophysical and thermochemical properties
- Materials and components
- Reactor physics
- System integration

- Participation in CRPs and preparation of TECDOCs
- Co-Author of Technical Report issued in November 2023



Working Groups

- Economic Modelling
- Proliferation Resistance and Physical Protection,
- Risk and Safety
- Advanced Manufacturing and Material Engineering
- Non-Electric Applications of Nuclear Heat Task Force

Bi-Lateral Cooperations

- Canada-US
- Canada-UK
- AECL and CNL MOUs with laboratories and academia

Canadian Federal Nuclear Science & Technologies Research on MSR Systems

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 of Materials 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

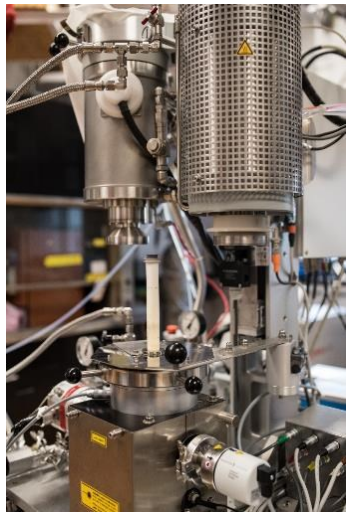
- Evaluation of waste streams from MSRs considered for deployment in Canada
- Exploring of salt waste treatment methods

Safeguards of MSRs

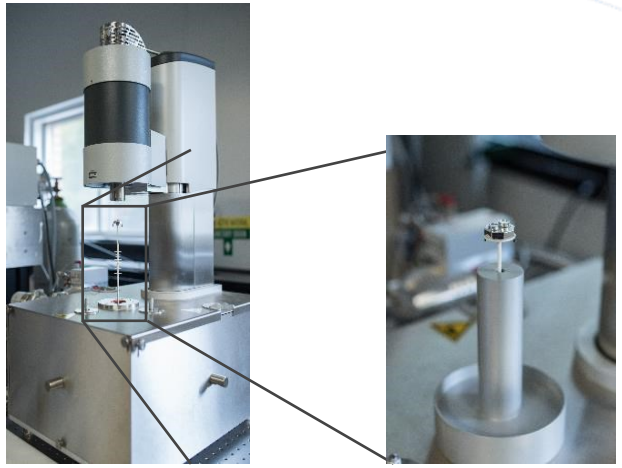
- Evaluation and improvement of safeguards approaches and methods
- Proliferation Resistance & Physical Protection

Molten salt thermophysical properties (1/2)

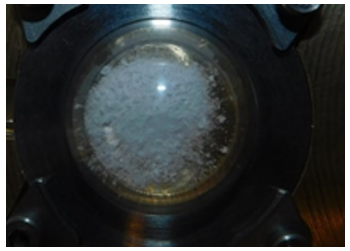
- Establish experimental procedures:
  - Fuel-salt synthesis
  - Molten salt encapsulation
  - High temperature DSC (T_m, C_p, …)
  - Laser flash apparatus (thermal diffusivity)
  - XRD for phase identification
  - TGA for thermal stability
  - ICP-OES for composition
  - Oxygen analysis



Laser Flash Apparatus (LFA)

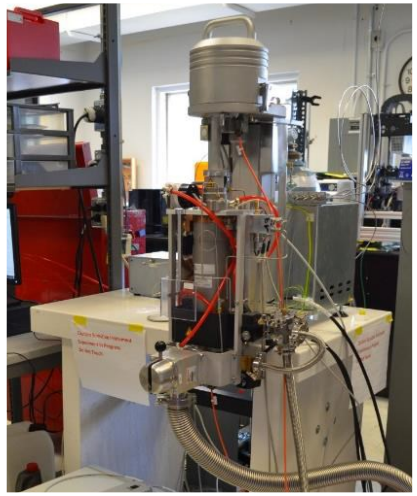


Differential Scanning Calorimeter (DSC)

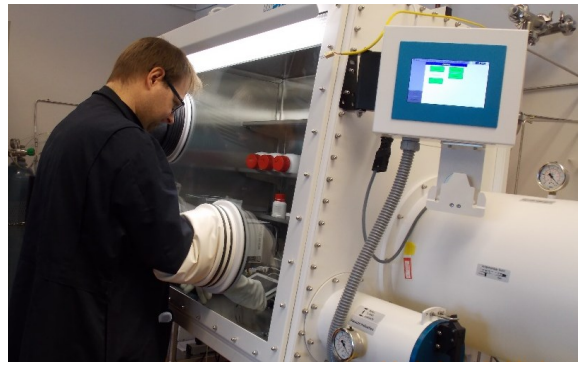


Custom hermetic sample holder to enable XRD measurements of molten salts under inert atmosphere

Oxygen Analyser (LECO O836)



Thermogravimetric Analyser (TGA)



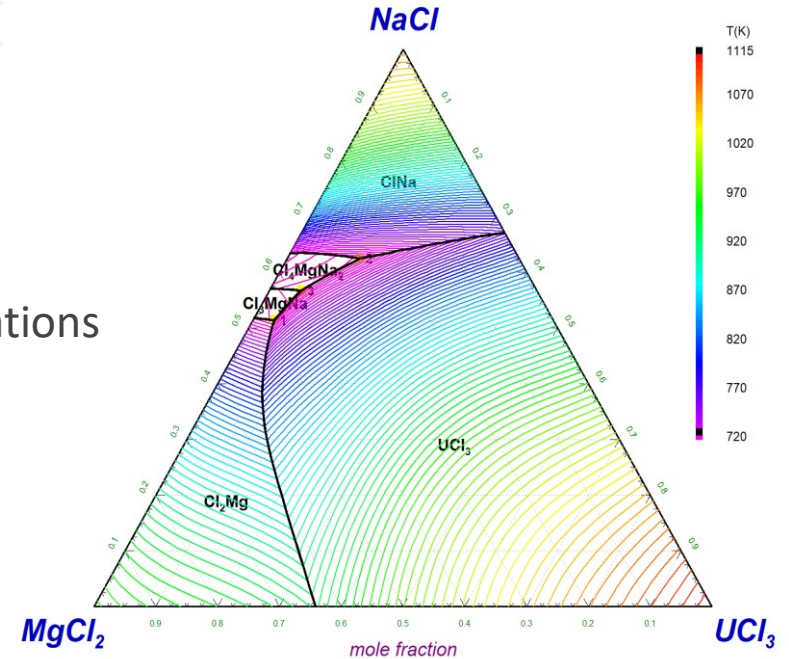
Ar Glovebox (O_2 < 2 ppm; H_2O < 5 ppm)

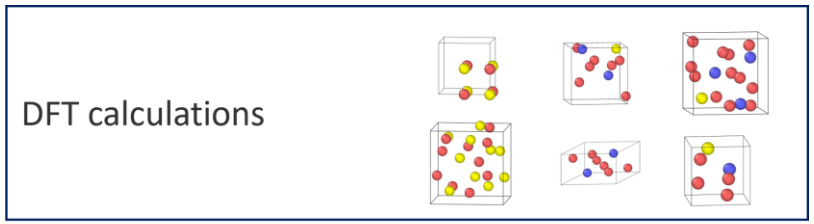
Handling of non-active and active salts

Molten salt thermophysical properties (2/2)

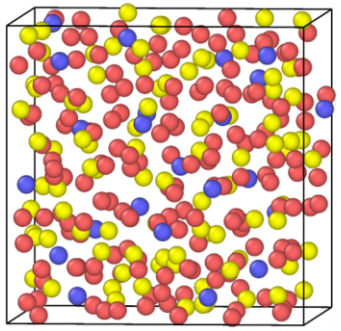
- Modelling of molten salt thermophysical properties:
  - Thermochemical modelling
  - Atomistic simulations
  - DFT calculations
  - Finite Element Analysis

Calphad calculations



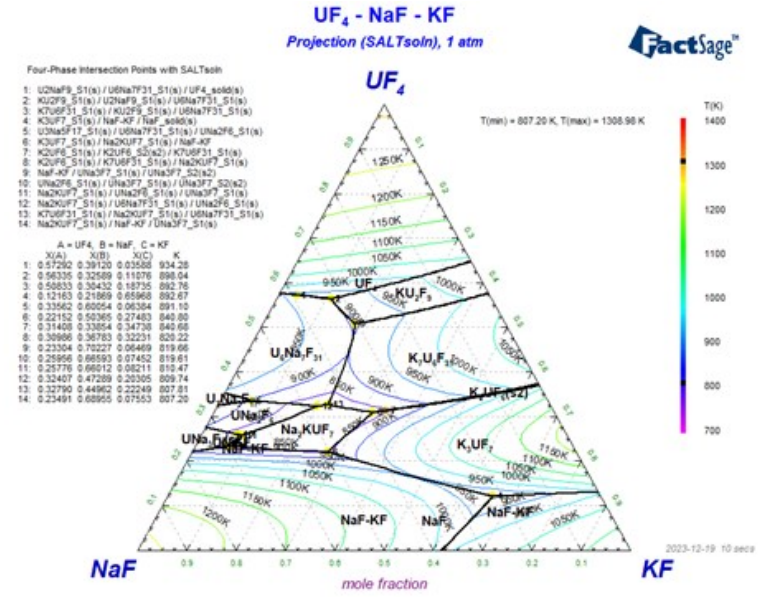


Machine Learning



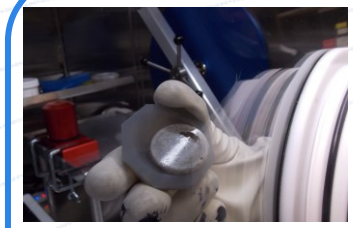
Molecular Dynamics

- Diffusion coefficients
- Density
- Thermal conductivity
- Viscosity
- Spatial distribution data



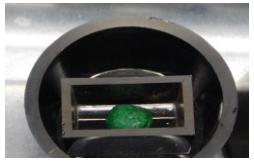
Differential Scanning Calorimetry (DSC) Measurements

Salt mixtures preparation

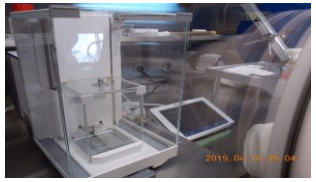


Eutectic salt mixture
$KCl-MgCl_2$ (68–32 mol%)

Furnace pre-melt FLiNaK sample
LiF-NaF-KF (46.5-11.5-42.0 mol%)
Expected $T_{m,\ Eutectic}$ ~ 454 °C)



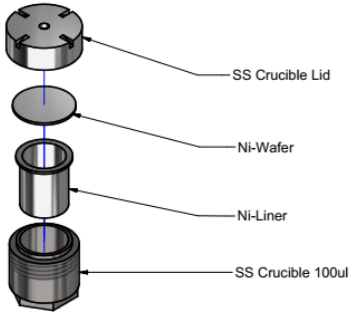
FuNaK ($NaF-KF-UF_4$)



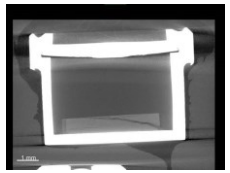
High precision analytical balance in dry argon atmosphere dry-box

Salt encapsulation for DSC

CrNi steel crucible



Modified in-house hermetically sealed CrNi steel crucible

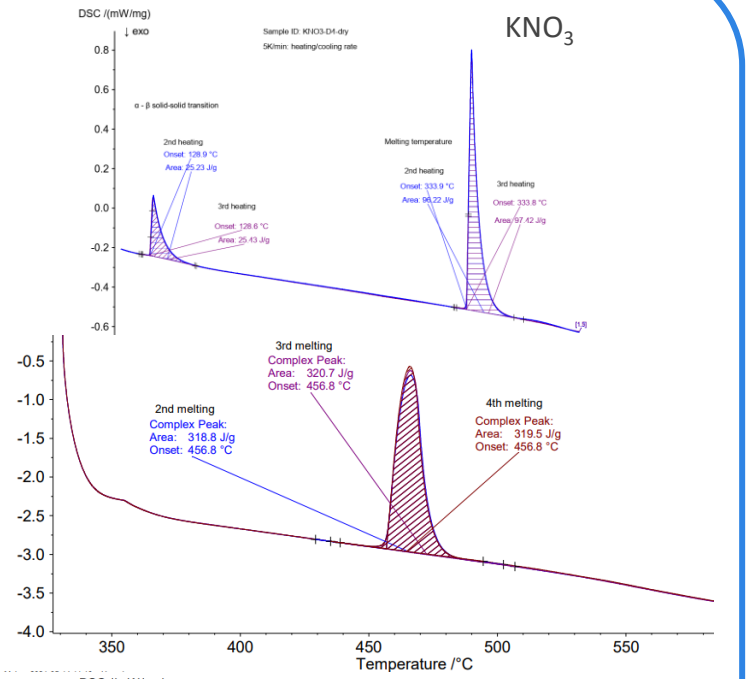


Customized Ni crucible
Laser welded to maintain hermetic seal

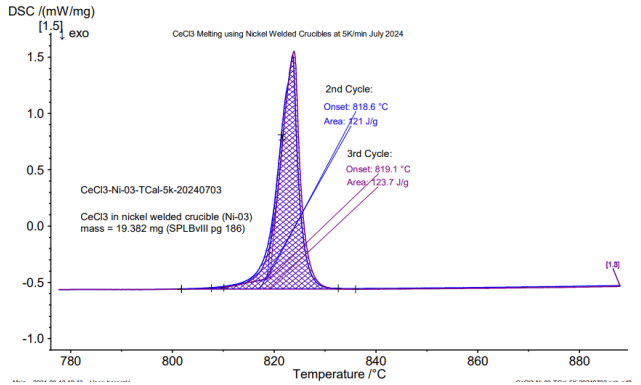
Validation of the encapsulation methods

CrNi steel crucible

Modified CrNi with Ni liner tested and benchmarked using FLiNaK

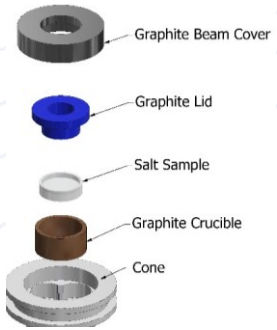


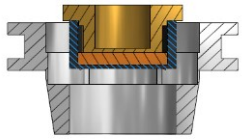
Hermetically sealed Ni capsule for high temperatures DSC measurements



Laser Flash Analysis (LFA) Applied to Molten Salts

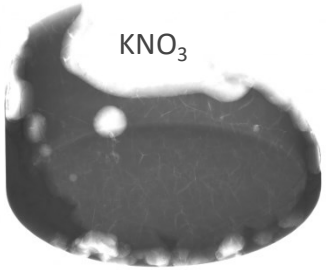
Salt encapsulation



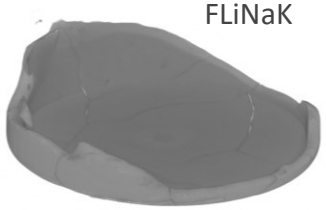


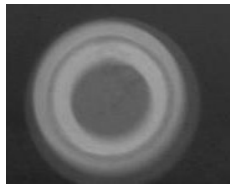
Cross section of a sample installed

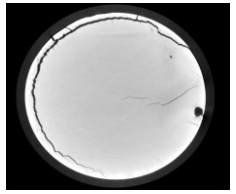
KNO_3



FLiNaK



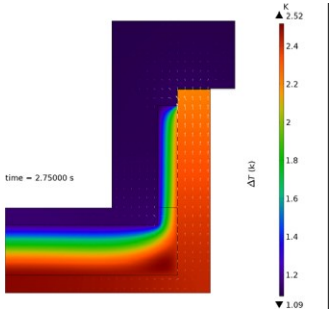




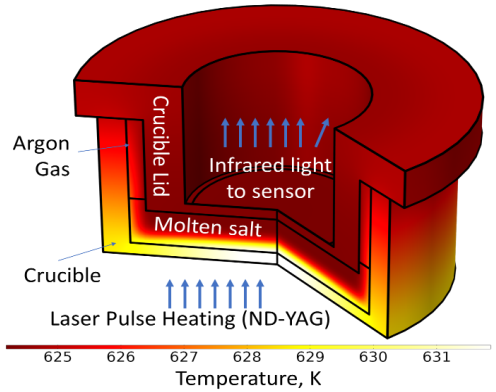
XCT imaging of the encapsulated salt before and after LFA measurements

Finite Element Analysis

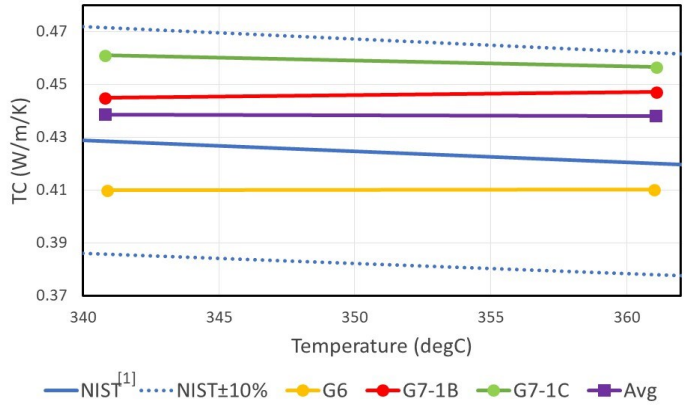
Evaluate effect of the container on measured thermograms



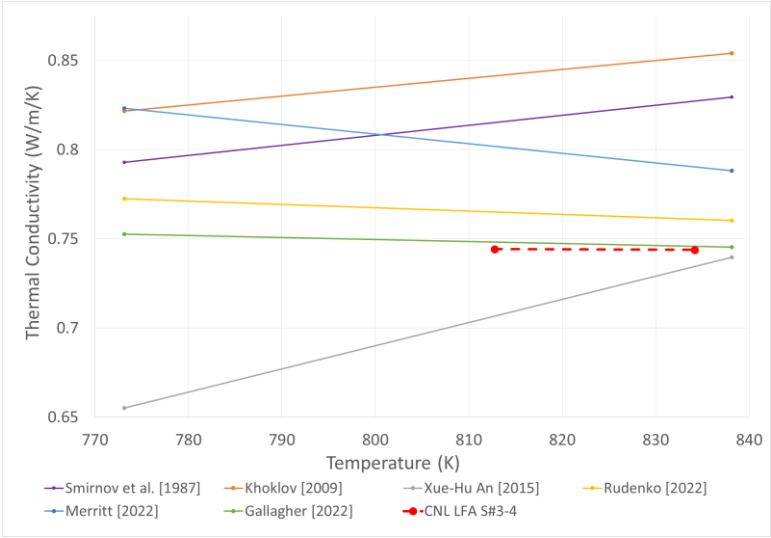
- ✓ Insignificant radiative heat loss at low T (350 °C)
- ✓ Two conduction modes with different timescales:
  - Across-molten salt
  - Around crucible sides



Validation using benchmark salts



KNO_3 Results compared to NIST data

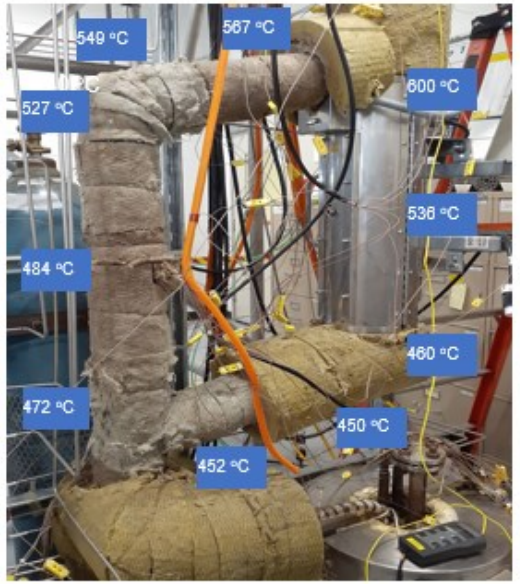


FLiNaK thermal diffusivity results compared to literature data

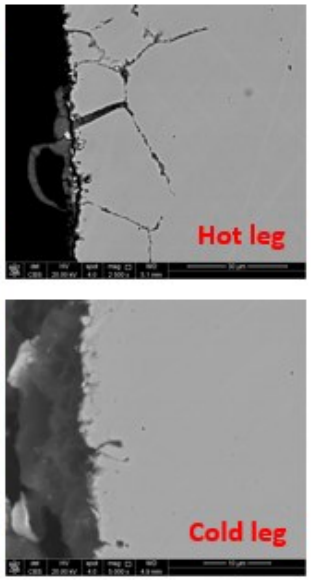
Materials Corrosion and Degradation in Molten Salt (1/2)

- High temperature molten salt corrosion test capability long-term Demonstration Natural Corrosion Loop (DNCL) operation with rigorously 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.

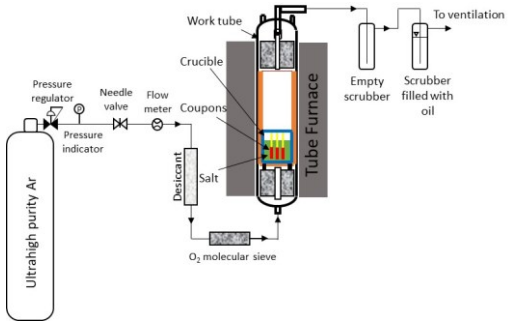
Temperature profile during DNCL experiment



SEM micrographs of loop sections

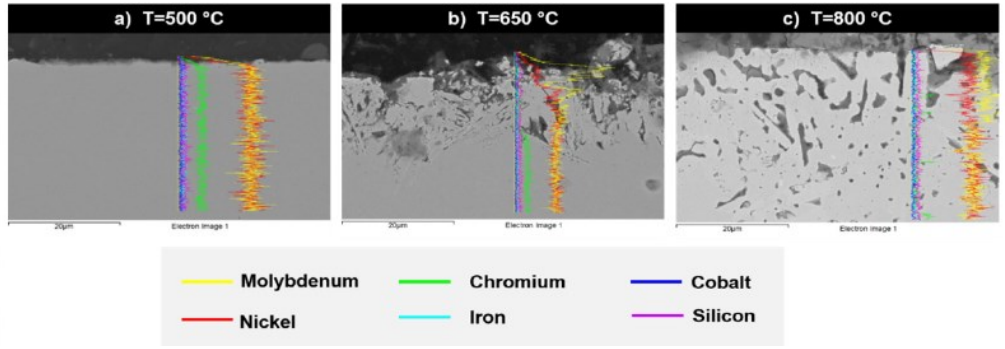


Setup for static corrosion experiments



Characterization of freeze valve

Alloy 242 after static corrosion experiments



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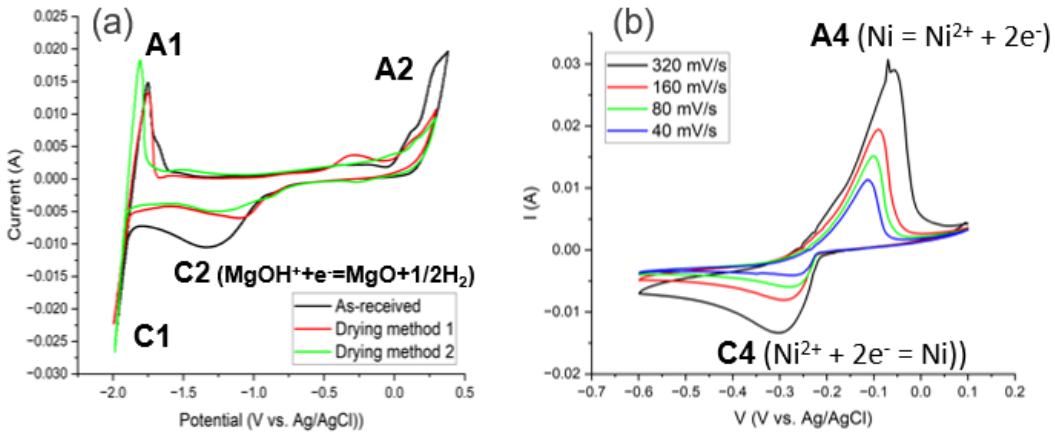
Materials Corrosion and Degradation in Molten Salt (2/2)

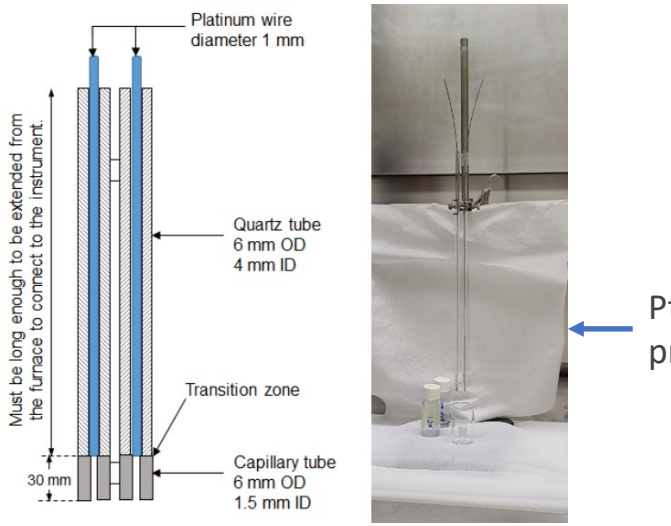
- Develop electrochemical methods for impurity detection in salts
- A glovebox with integrated furnace has been delivered. Lab preparation to install the glovebox is on-going
- Development of electrical conductivity equipment using Pt-wire probe as electrodes and testing at 550 °C in KCl-LiCl (41-59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

Electrochemical methods for characterization of molten salts

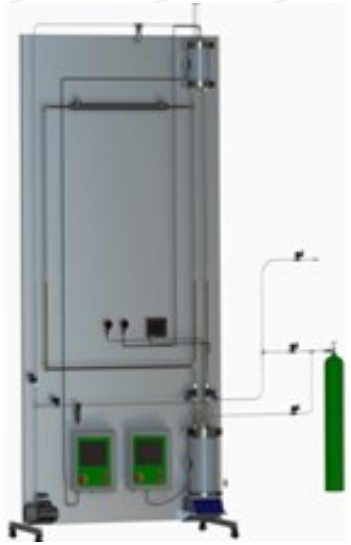


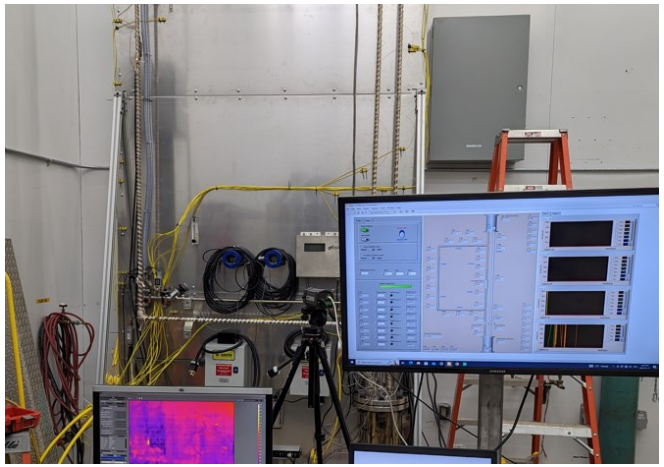
Setup of an Ar Glovebox with integrated furnace

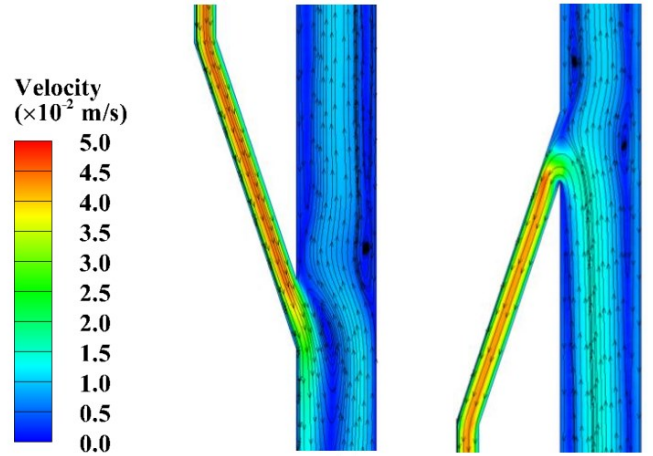
Electrical conductivity equipment



Passive Safety Molten Salt Natural Circulation Heat Transfer Loop







Design

- Simplification of a single loop in the Direct Reactor Auxiliary Cooling System
- Main loop is 2 m tall
- Operate at ~550°C

Construction

- 316 Stainless steel
- 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

Summary

- CNL role is:
  - To support regulatory positions and decisions for novel nuclear fuel (e.g. fuel salt)
  - 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
- Focus areas
  - Develop modelling and experimental facilities to support MSRs
  - Engage with federal stakeholders and industry to address gaps and reduce risk associated with MSR technology
  - Actively seek collaboration with national and international partners to leverage resources and conduct focused R&D targeted to specific outcomes

CNL's Canadian Nuclear Research Initiative (CNRI)

December 20, 2024: Deadline for proposal submission

Supporting Technology Developers

- Program enables collaborative advanced reactor development and research projects
- The goal is to accelerate the deployment of safe, secure, clean, and cost effective SMRs in Canada and make CNL's technical capabilities and expert knowledge available and accessible to the SMR community
- Projects underway with several participants
- www.cnl.ca/CNRI

Participants Including:

USNC ULTRA•SAFE•NUCLEAR

moltex clean energy

TERRESTRIAL ENERGY

Kairos Power

generalfusion

ARC CLEAN ENERGY

Thank You

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mouna.saoudi@cnl.ca

www.cnl.ca