

C440 Overview presentation

July 2023

John P Carter





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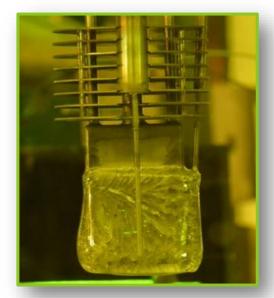
"Accelerating Molten Salt Technologies to our Customers"

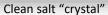
John P. Carter, PhD



Agenda

- Mission: support on-going advanced MSR demonstration, basic science research, novel salt synthesis, materials recovery and advanced thermal energy storage system development.
- Research Team
- Activities & Capabilities
- Interests
- Facility Access
- Example Activities and Interests
 - High-purity Salt Synthesis
 - Salt
 - Thermophysical Properties
 - Chemical Monitoring
 - Flow-Loops
 - First-ever NaCl-PuCl₃ loop
 - MSTEC

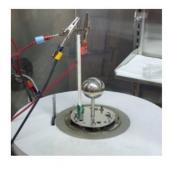












High-temperature Spectroscopy Setup

Advanced Technologies of Molten Salts (AToMS) Department - Fuel Cycle Science & Technology Division – Nuclear S&T Directorate

- 18 Full-Time Staff
 - 8 Scientists
 - 2 Design & experiment engineers
 - Technician (lab operations, I&C, light machining)
 - 4 Post-Doctoral
 - Project Coordinator
- We are growing
 - post-doctoral candidates



World Class Team of Experts focused on Molten Salts

Molten Salt Activities

High-quality Synthesis

- Support Industry and Vendor needs
- Actinide (U/Pu) and TRU salts

Irradiation and Examination

- MRTI materials, corrosion, source term
- First-time demonstration
- MSTEC post-irradiation examinations

Flow-Loop Studies

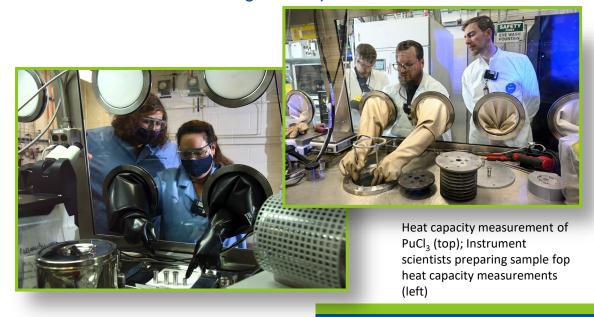
- Safeguards
- Materials
- Sensors
- ModSim validation
- Redox control systems

Basic Science Research

- Thermophysical Properties
- Structure and Speciation
- Purification
- Corrosion

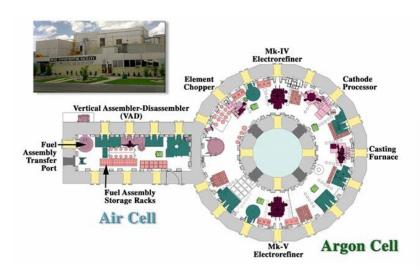
Support to Molten Salt Reactors

- Sensors for molten salt reactor applications (redox measurement, moisture, corrosion species)
- Online purification (e.g., key fission product species)
- Salt irradiation behavior fused & solid
- Corrosion control under flowing conditions
- UCl₃ and PuCl₃ salt synthesis
- Thermophysical properties of actinoid-bearing salts and measurement method development
- Waste form strategies and processes



Facilities

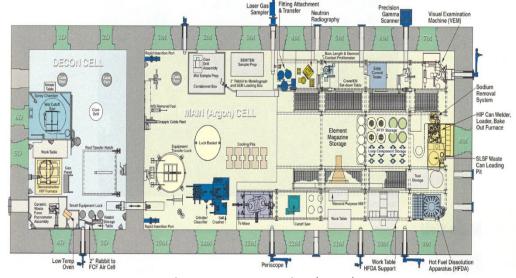
- Non-radiological laboratory space
 - 5000 ft² in three primary lab spaces
 - Includes 8 inert-atmosphere gloveboxes
- Radiological laboratory space (U, Th, & minor quantities of other radioisotopes)
 - Fuel Cycle Glovebox, 26 ft length (FCF)
 - Pyrochemistry Glovebox, 46 ft length (FASB)
 - Includes four built-in furnace systems
- Nuclear facilities
 - Air and inert atmosphere hot cells
 - Table space, generic signal/power feedthroughs
 - Custom installations for longer term programs
 - Transuranic Gloveboxes
 - Fresh Fuels glovebox (<50 g Pu)
 - AFCI glovebox (<200 g Pu)



Fuel Conditioning Facility (FCF)



Pyrochemistry glovebox in FASB



Hot Fuel Examination Facility (HFEF)

Capabilities

Non-radiological laboratories

- Electrochemistry & corrosion studies
- High temperature furnaces (1800°C)
- DSC, TGA, high temperature viscosity, and density
- UV-vis, Raman and LIBS spectroscopy
- Spectro-electrochemistry
- Vapor and Aerosol phase Spectroscopy
- Raman microscope
- Light machining and I&C
- Safeguards instrumentation development
- Gamma irradiation

Radiological laboratories

- Electrochemistry, vacuum separations
- MSR fuel demonstrations processing, cleaning, purification, and storage
- Full-scale equipment demonstration
- Lab & large-scale UCl₃ synthesis (10 g-10 kg)
- SEM, XRD
- Gamma irradiation

Synthesized PuCl₃ binary salt





Setting up experiments for a phase diagram study (top) and an off-gas system study (right)



Nuclear facilities

- Electrochemistry & corrosion studies
- Laboratory-scale molten salt furnace in HFEF for gram to ~100 g scale testing (used for several GAIN projects)
- Research access to Pu, Am, irradiated LWR and other fuels, other irradiated materials (e.g., electrorefiner salts)
- Safeguards testbed for fuel cycle applications, including input accountancy, bubbler, and voltammetry
- Furnaces for sintering, hydriding, synthesis of transuranic metals & salts, and vacuum separations
- Neutron and gamma irradiation
- DSC, TGA, LFA, SEM, TEM, EPMA, Hardness testing
- Isotopic and elemental analysis

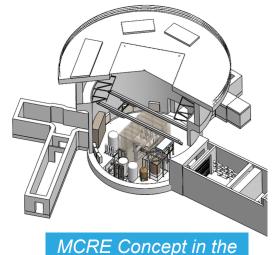
Molten Chloride Reactor Experiment (MCRE)

- DOE Advanced Reactor Demonstration Program-Risk Reduction award
 - Led by Southern Company with TerraPower, INL,
 Orano, CorePower, 3M, and EPRI as partners
- MCRE endeavors to design, construct, and operate a fast spectrum liquid chloride salt fueled critical experiment at INL
 - To measure key reactor physics phenomena and test hypotheses about Molten Chloride Fast Reactor (MCFR) behavior, to reduce uncertainty and provide foundational knowledge to support the development of the MCFR Demonstration Reactor (MCFR-D)

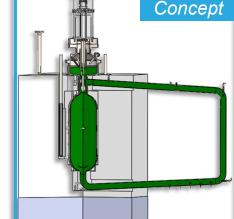
INL Scope

- Provide support for fuel salt synthesis and storage and development of MCRE
- Integrate reactor into an NRIC-LOTUS test bed for operation, testing and decommissioning

INL is leveraging unique capabilities at MFC to synthesize fuel salt and operate MCRE



LOTUS testbed



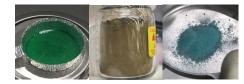
MCRE

Thermophysical Properties

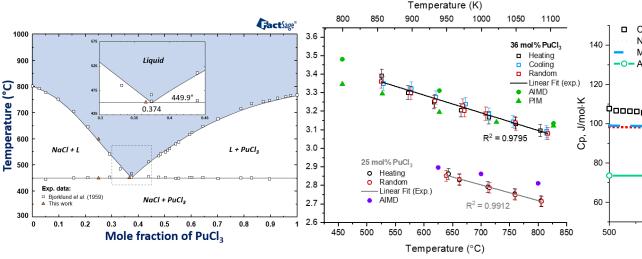
- Robust line of characterization and related equipment
 - Capabilities in place for non-radiological to transuranic fuel salts
 - Continually adding and developing new techniques for high temperature property measurements
 - Property measurements on high purity salts and compositions with O₂, H₂O, fission, and corrosion products

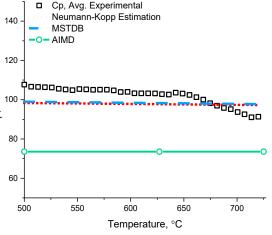


Researchers loading salt sample for measurement



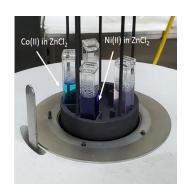
UF₄ (left), UCl₃ (middle), PuCl₃ (right)



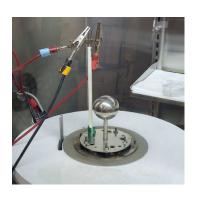


Task Name	Method
Salt Synthesis	Gloveboxes, furnaces
Electrochemistry, Separations	electrochemistry
Elemental Analysis	ICP-OES, ICP-MS, etc.
Density (solid)	Gas Displacement Pycnometer
Density (liquid)	Archimedean hydrostatic Method
Viscosity	INL modified viscometer
Specific Heat	DSC
Melting Point	TG-DSC, STA
Enthalpy of Fusion	STA & DSC
Salt Stability	TGA
Vapor Pressure/Boiling Point	STA-Skimmer – in process
Thermal Conductivity	Derive from thermal diffusivity (LFA), density, heat capacity (DSC); 3-Omega
Corrosion	Static tests and flow loops
Speciation and Chemical Monitoring	Raman, UV-vis, LIBS
Off-gas analysis	UV-Vis and LIBS

Molten Salt Spectroscopy Capabilities - INL





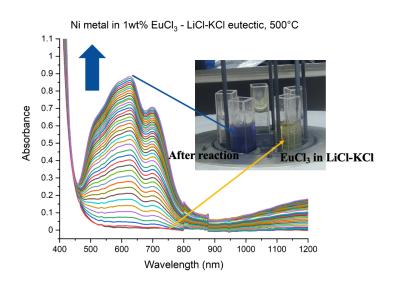


Instrumentation and Capabilities:

- Optical Spectroscopy (UV-VIS-NIR)
 - Gold coated fiber optics cables, 195-2300 nm spectral range
- Custom cuvette holder for fluoride salts
 - Metal body with sapphire windows and gold O-rings
- Terahertz Raman Probe Spectroscopy
 - 100mW 532nm laser, ~5 to 200 cm-1 spectral range
- Unique optical cell for Spectroscopy of Vapor and Aerosol Phase
 - Combination of LIBS and UV-VIS spectroscopy
- In-situ Spectro-electrochemistry
 - Redox potential study

Focus Areas:

- Chemical structure and Speciation
- Molten Salt Radiolysis
- Off-gas analysis
- In-line Chemical monitoring
- Safeguards and Process monitoring

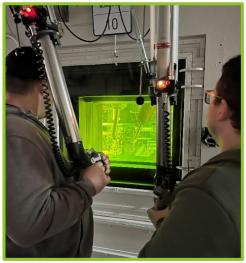


First-of-a-Kind Plutonium 'Microloop' Experiment

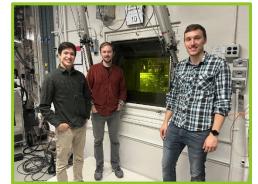




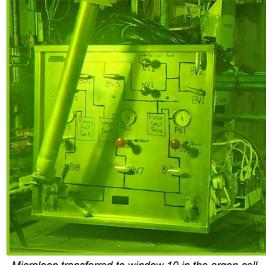
- Supporting TerraPower's Molten Chloride Fast Reactor (MCFR) R&D, the microloop experiment is a collaboration between TerraPower and INL designed to examine the corrosion of structural material when exposed to molten flowing salt PuCl₃-NaCl.
 - TerraPower has operated more than 50 microloops, this is the first to use plutonium salt... ever!
 - The project team and FCF staff worked through the mock-up procedures, the transfer of the salt, and the installation of the flowloop in the hotcell.
 - TerraPower staff visited INL to assist the INL project team with flush salt operations and fuel loading.
 - The flowloop operated for >1000 hours before disassembly and examination.



Tyler Rigoulot and Skyler Pettengill attaching the salt pod to the microloop



TerraPower Staff after the salt began circulating Left to right (Ivan Mitchell, Sean Gagnon, Cody Falconer)



Microloop transferred to window 10 in the argon cell



Photo of the microloop shortly after salt began circulating

Flow-Loop Testbed for Instrumentation Development and Corrosion Control

- MSR deployment requires increased understanding
 - Corrosion under reactor relevant conditions, including flow, redox buffering and thermal gradients
 - Development and demonstration of functional sensors to monitor (and control) salt chemistry and conditions important to corrosion control
- Goal is to develop a testbed design at ~25mm diameter scale for deployment into a radiological facility
 - System is designed to operate in open air, allowing for a large system to be set up outside of a glovebox
 - Flexible design to adapt to experiment needs
 - Insertion capability in hot and cold legs
 - Instrumentation and corrosion sample insertion capability in hot and cold legs.
 - Able to be removed or inserted while loop remains operational



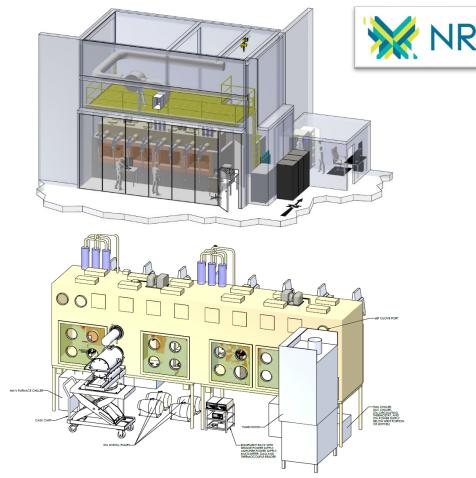


INL thermal convection loop in Energy Innovation Lab



Molten Salt Thermophysical Examination Capability (MSTEC)

- A post-irradiation examination capability focused on fused salts at high temperature
 - Shielded capability for high-actinide and irradiated salts
 - Thermophysical properties
 - Self-irradiation behaviors (including off-gas)
 - Versatile workspace for users (academia, industry, etc.) to test equipment on irradiated or actinide-bearing salts
- Capability to address major experimental gaps for actinide and irradiated salts
 - Includes DSC, STA, TMA, rheometer, thermal hotwire, pycnometer, densitometer, electrochemistry, salt synthesis
 - Capability for CI, F, Be, irradiated, and actinide-bearing salts
 - Open work area
- Online in FY24
- Multi-purpose: fuel cycle, batteries, space fuels and safeguards



MSTEC Facility installation (top) and north view of the containment structure (lower)

Opportunities

Invest in Future Expertise

- Talent pipeline for SMEs to support US Reactor Deployment and Safeguards
- Preserve and transfer knowledge
- Engage and mentor early career researchers
- Rotational assignments, sponsored PhD students (educate future workforce)
- Enhance domestic and international collaborations

Collaborate

- NRIC
- GAIN Voucher
- NEUP
- ARPA-E calls
- Others?
- Areas of Interest
 - Critical Materials, Carbon Capture, Energy Storage



More Information

- Several Factsheets are available
 - https://factsheets.inl.gov





Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy. INL is the nation's center for nuclear energy research and development, and also performs research in each of DOE's strategic goal areas: energy, national security, science and the environment.