2023 Hybrid Molten Salt Reactor (MSR) Workshop
Posted Presentations

Wednesday, October 25, 2023, Eastern Daylight Time (UTC-4:00)	
University Salt Irradiation Test Beds	
Molten Salt Reactor Test Bed with Neutron Irradiation	Charles Forsberg, Massachusetts Institute of Technology
DOE National Laboratory Advancements	
Overview of the Molten Salt Reactor Campaign	Patricia Paviet, Pacific Northwest National Laboratory (PNNL)
Molten Salt Research at Argonne National Laboratory	Mel Rose, Argonne National Laboratory
Overview of PNNL capabilities in support of MSR development	Praveen Thallapally, PNNL
Oak Ridge National Laboratory Foundational Studies to Support Molten Salt Reactor Development	Joanna Mcfarlane, ORNL
Actinide-Molten Salt Chemistry and Properties Research at Los Alamos National Laboratory	Marisa Monreal, Los Alamos National Laboratory
Working Lunch (provided)	
Molten Salt Reactor Analysis with SCALE 6.3.1	Donny Hartanto, ORNL

R&D Lightning Talks	
Laser-Induced Breakdown Spectroscopy: A Versatile Tool for MSR Applications	Hunter B. Andrews, ORNL
Usage of Surrogate Fluids for Optimization of Component Level Design for Heat Transport Systems within Molten Salt Reactors	Lane Carasik, Virginia Commonwealth University
Developing a Non-Destructive Method for Measuring Holdup in Liquid Fueled MSRs	Diego Jose Macias, University of Michigan
Graphite-Salt Interactions – an overview of research activities at ORNL	Nidia Gallego, ORNL
Safeguards and Security Recommendations	
International Safeguards by Design	Traci Newton, International Atomic Energy Agency
Novel strategies for Material Control and Accountancy of Liquid-Fueled MSRs	Nathan Shoman, Sandia National Laboratory (SNL)
A Material Control and Accountancy Approach for MSR License Applications	Nicholas Luciano, ORNL
Examples of Data-Driven Safeguards and Security by Design	Karen Hogue, ORNL

Thursday, October 26, 2023, Eastern Daylight Time (UTC-4:00)	
Advanced Reactor Demonstration Program Risk Reduction	
Molten Chloride Reactor Experiment	Dan Walter, TerraPower
Hermes Reactor Update	Anne Demma, Kairos Power
Industry Lightning Talks	
Development of Robust High-Temperature Reference Electrodes for Molten Salts	Jim Steppan, HiFunda LLC
Control Valve material combinations in 750C chloride molten salt	Jeff Parish, Flowserve
Overlays for Improved Corrosion Resistance During MSR Operation	Timothy Hall, Faraday Technology Inc.
Working Lunch (provided)	
MELCOR Advancements for MSRs	Matthew Christian, SNL
Developer Forum 1	
Flibe Energy	DJ Hanson, Flibe Energy
Seaborg Technologies	Federico Puente-Espel, Seaborg Technologies
TerraPower	Josh Walter, TerraPower
ThorCon	Dane Wilson, ThorCon
Developer Forum 2	
Copenhagen Atomics	Aslak Stubsgaard, Copenhagen Atomics
Kairos Power	Jake McMurray, Kairos Power
Natura Resources	Doug Robison, Natura Resources

Molten Salt Reactor Test Bed with Neutron Irradiation

Charles Forsberg
Massachusetts Institute of Technology
Cambridge, Massachusetts

ORNL Molten Salt Workshop

Oak Ridge National Laboratory
October 25-26, 2023
9:10 am

Charles Forsberg
cforsber@mit.edu

Massachusetts Institute of Technology

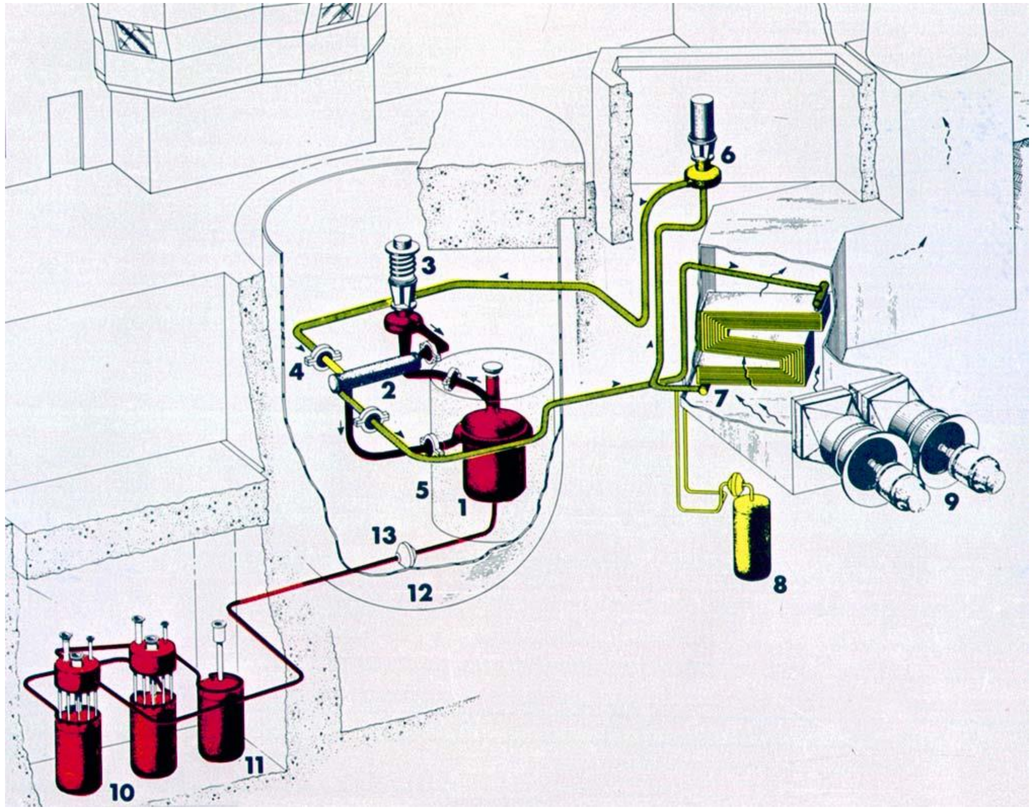
NC STATE UNIVERSITY

Berkeley UNIVERSITY OF CALIFORNIA

OAK RIDGE National Laboratory

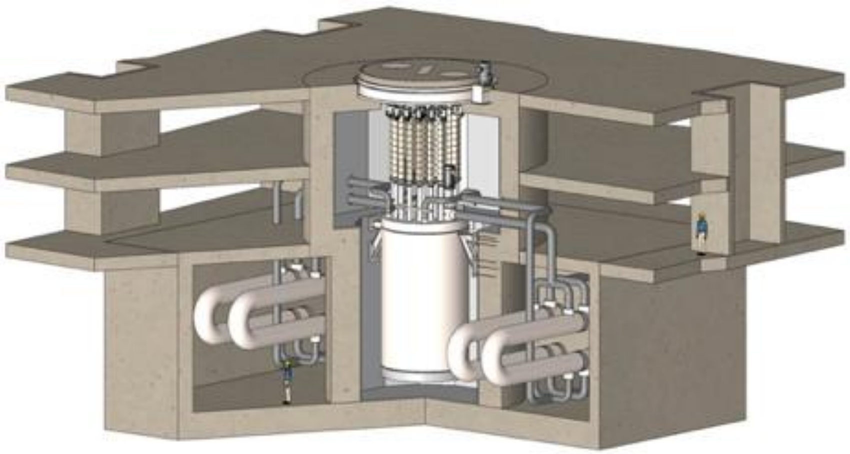
History

- Last flowing salt experiments in irradiation fields conducted more than 40 years ago
- Within the last decade MIT and others have conducted salt capsule irradiation experiments
- There has been a revolution in instrumentation and experimental techniques in those decades



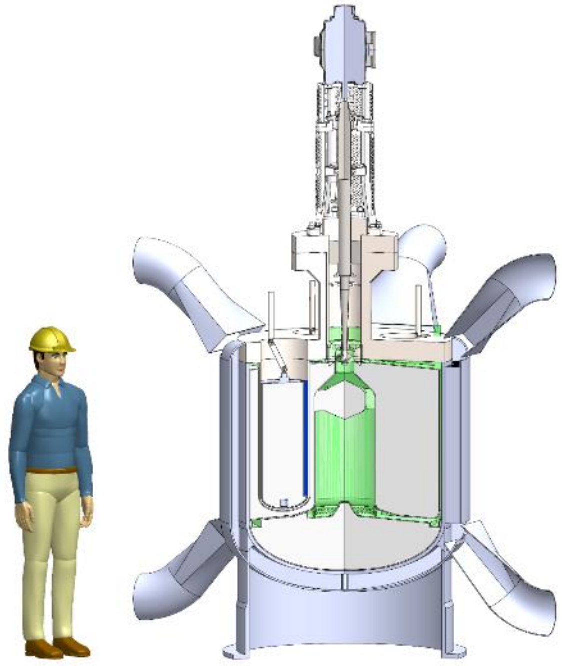
Molten Salt Reactor Experiment

Three Salt Reactors within the Next Several Years



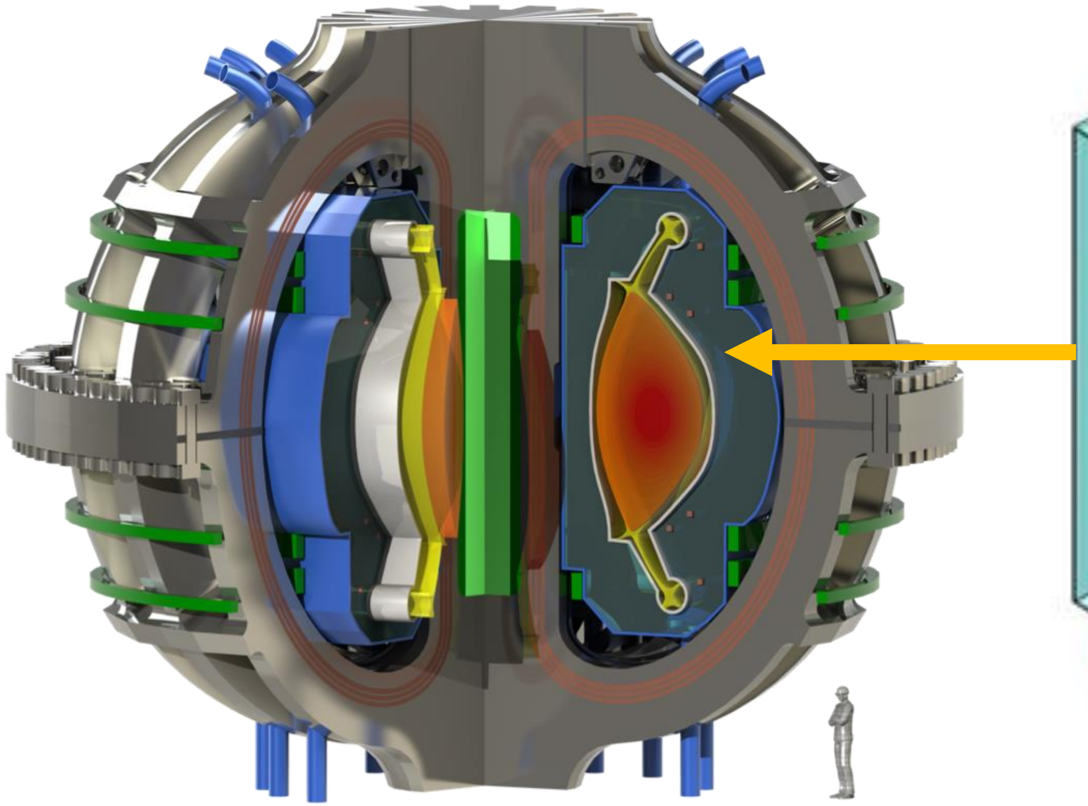
Kairos Power
35 MWt FHR, 2026
Hermes, Oak Ridge

Abilene Christian University /
Natura Resources 1-MWt
Molten Salt Research Reactor

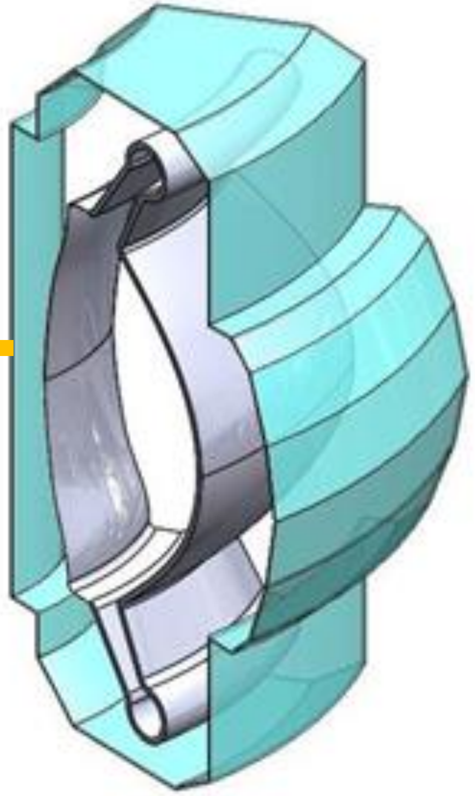


TerraPower/Southern
200 kW Molten Chloride
Reactor Experiment, INL

MIT/Commonwealth Fusion ($1.8 Billion Private Capital)
ARC Fusion with Liquid Flibe Salt Blanket



ARC



Flibe Salt Blanket

- Breed tritium fusion fuel from lithium in flibe salt
- Convert energy in 14-Mev neutrons to heat for power cycle
- Radiation Shielding

Flibe Coolant Becoming a Priority for Fusion Systems

Project Goals

- Design, build, and test a general-purpose instrumented molten-salt test loop at the MIT reactor where flowing salt is irradiated by neutrons with temperature variations around the loop to duplicate conditions in a salt reactor.
  - Experimental test bed for chemistry control, salt cleanup, tritium control and instrumentation
  - Experimental data on tritium and fission product retention, diffusion and transport properties (Loop initially clean flibe salt, capability for uranium salts).
- Provide learning experience (lessons learned) for future salt irradiations (loops at ATR, HFIR, and university reactors and reactors going critical in the next few years)
  - No flowing salt loops in reactors for over 40 years

C. Forsberg, "Future Salt Irradiations for Fission and Fusion Systems", American Nuclear Society Meeting, Washington D.C., November 12-15, 2023.

Massachusetts Institute of Technology (MIT) is Building a Flowing Liquid Salt Loop with Variable Temperatures and Neutron Irradiation of the Salt

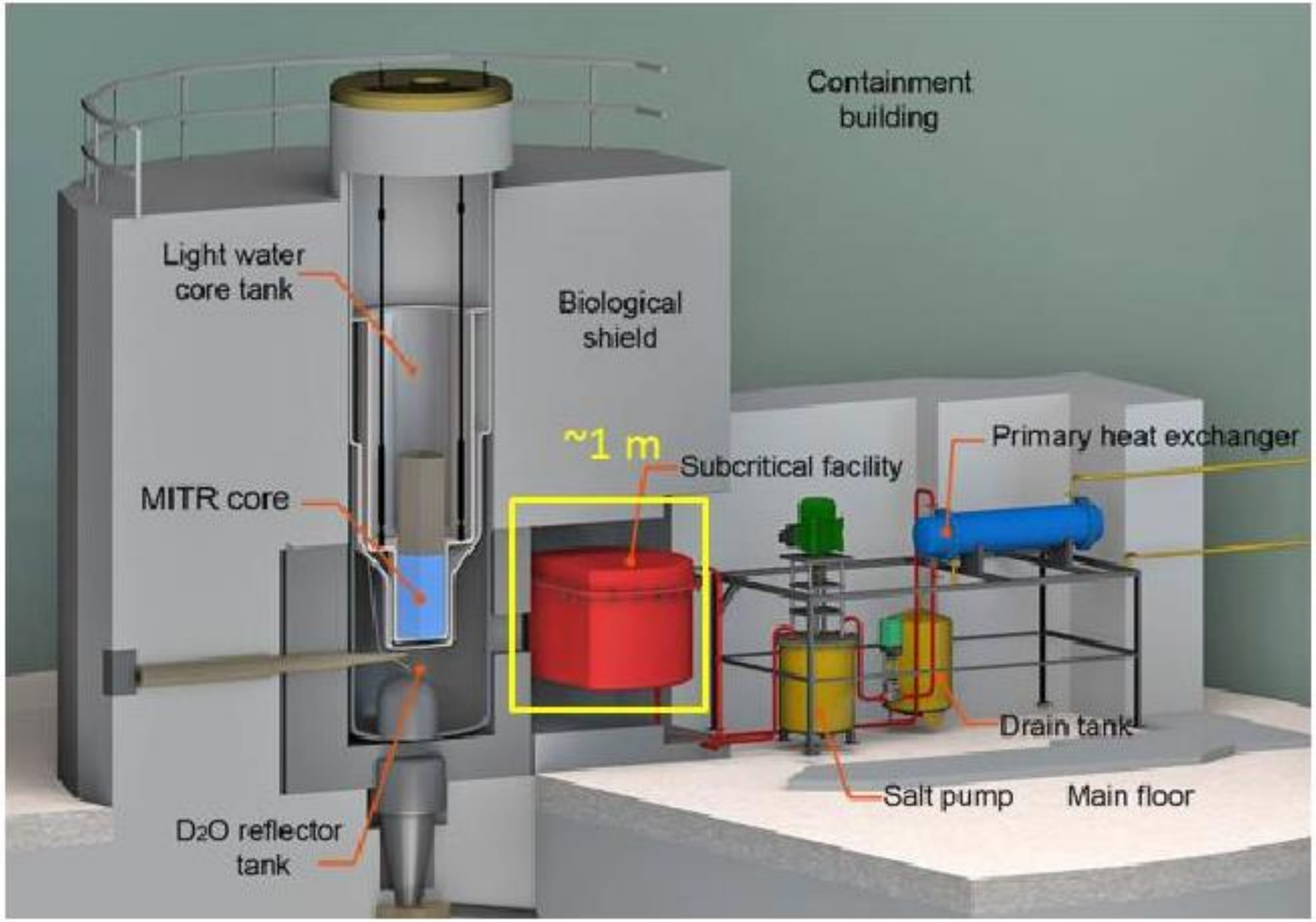
Department of Nuclear Science and Engineering

MIT Nuclear Reactor Laboratory

C. W. Forsberg, D. Carpenter

MIT Has Initiated Design and Construction of a Salt Loop at MIT Reactor

- MIT reactor: 6 Megawatts
- 24/7 operation, 1000 hour runs
- Forced circulation salt loop, heat and cool
  - High-temperature
  - Fully instrumented
- Salt loop operational mid 2024 (Reactor shutdown delay)

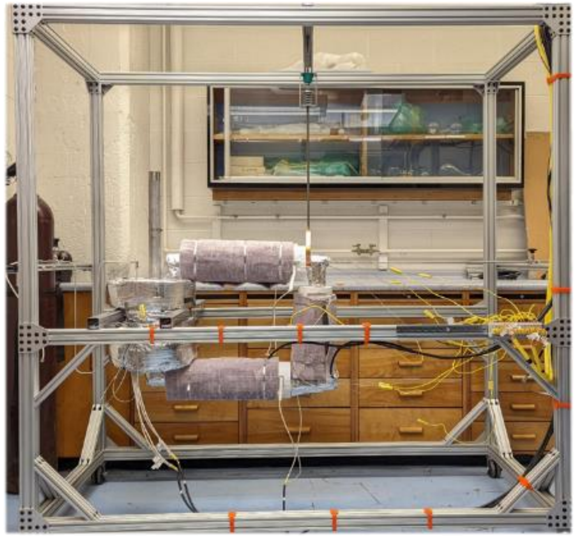


Project Strategy

- Build non-radioactive full loop with variable temperatures and salt circulation using flinak salt to develop and test full system
  - Smaller test loops for specific equipment tests such as seals and insulation
  - Integrate UC Berkeley sensors into system
- Second loop coupled to reactor with flowing flibe salt, variable temperature around the loop and neutron irradiation

MIT Is Working in Multiple Areas to Build Loop

Lowering CVD SiC-coated graphite crucible into the furnace



High temperature dry test facility for Insulation, Heaters and Flanges

Salt Pump System Testing

Modifying Interior of Hot Cell Next to Reactor for Salt Flow Loop

The IRP Held A Lessons-Learned on Neutron Salt Irradiations at ORNL in October 2022

- Emphasis on what to do and what not to do
- Included every group doing salt irradiations in the U.S. and Europe
- ANS summary distributed, lessons learned in quarterly reports, full report in preparation
- Biggest benefit may have been getting all the experimenters in the same room to talk to each other
- **Second "lessons learned" workshop next year day before or after ORNL molten salt reactor workshop**

C. W. Forsberg, D. M. Carpenter, R. O. Scarlat, R. Kevin and A. I. Hawari, "Lessons Learned In How to Conduct Irradiated Salt Experiments", Trans. American Nuclear Society Annual Meeting, Indianapolis, June 11-14, 2023.

North Carolina State University (NCSU) is Building A Molten Salt Off-gas Measurement System for Analysis of Fission Gases Exiting MSRs

Nuclear Reactor Program,

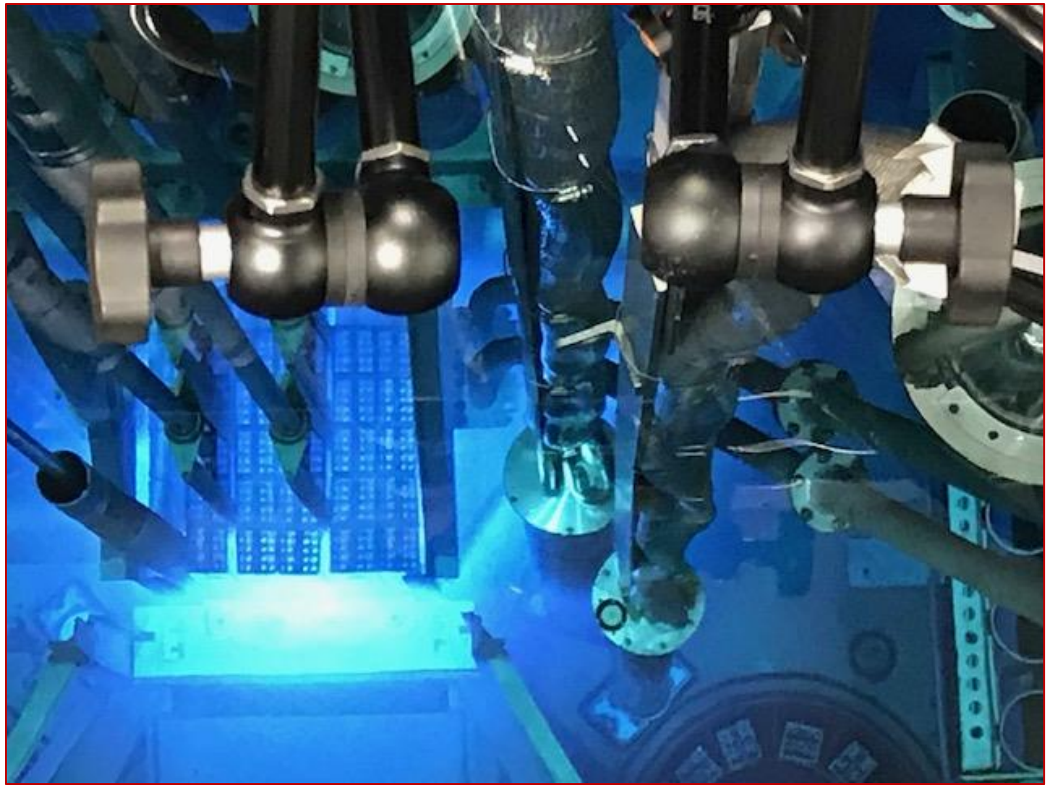
Department of Nuclear Engineering

Ayman Hawari (PI)

NC STATE UNIVERSITY

NCSU PULSAR Reactor Will Irradiate Capsule of Molten Uranium-Containing Salt to Provide Representative Off-Gas to Detector System

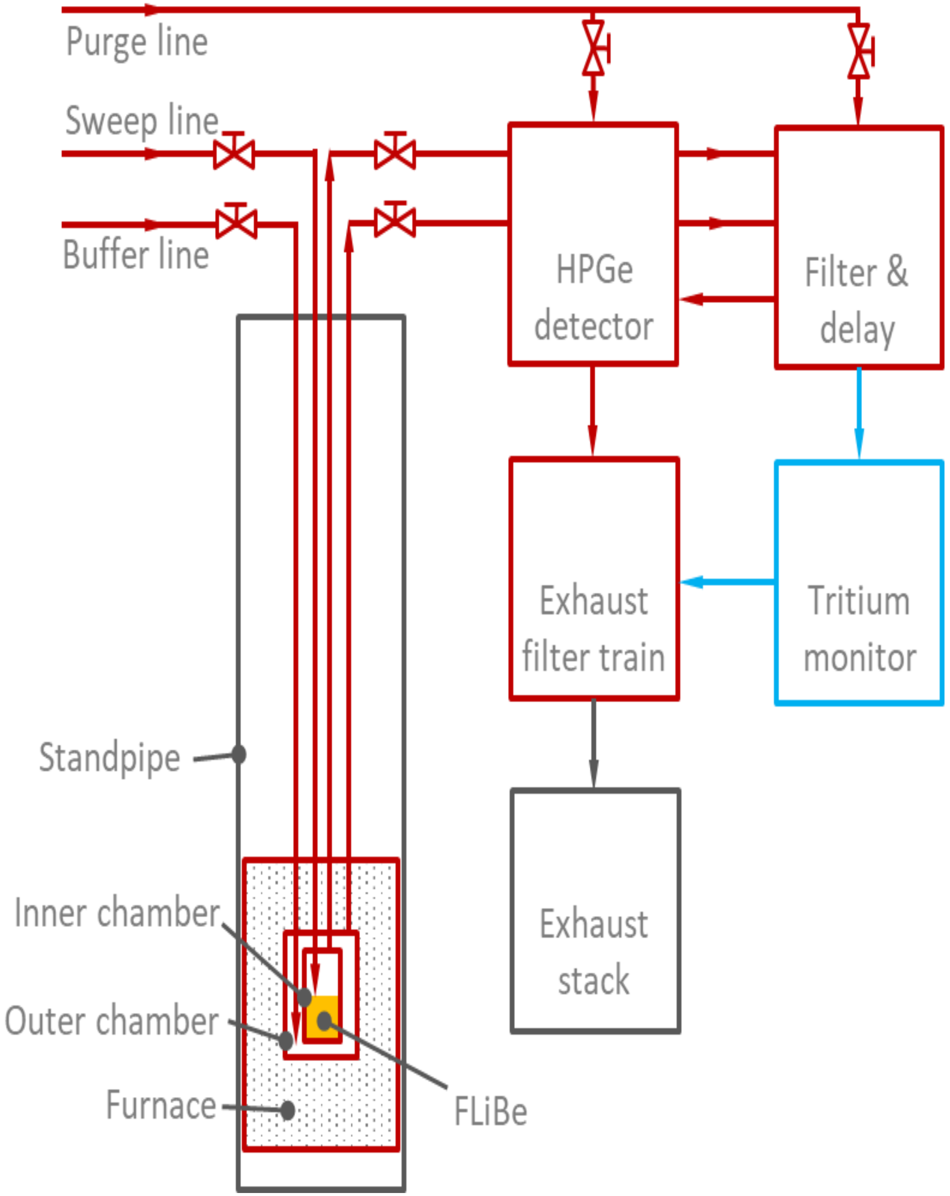
- Capsule at the edge of the reactor core (pool reactor)
- Heated piping to instrument system above reactor pool
- Provide modern instrument train to measure what is in fission gas stream
- Most instruments did not exist when MSRE was operated



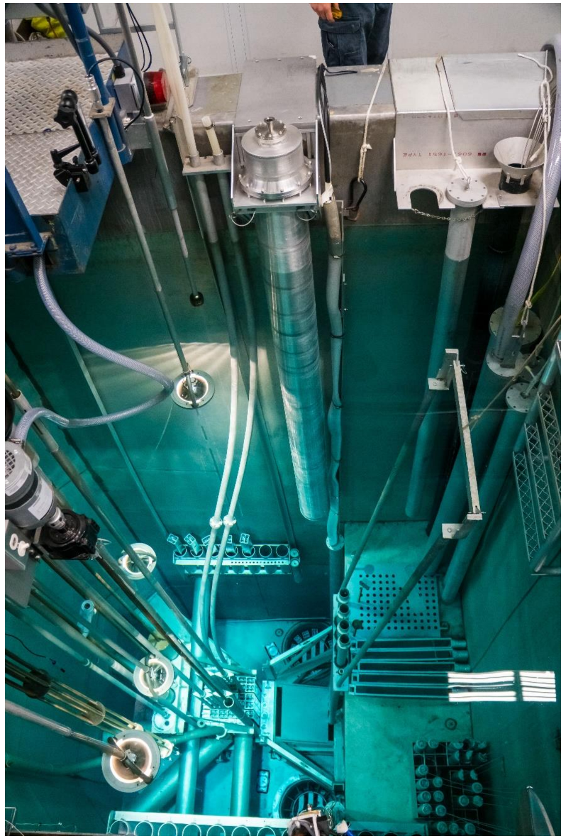
View of NCSU PULSTAR core

Multiple Sensors to Analyze Off-Gas with Fission Products

- On-line gamma spectroscopy for radionuclides
- On-line tritium analysis
- Off-line Laser Induced Breakdown Spectroscopy (LIBS) for chemical analysis

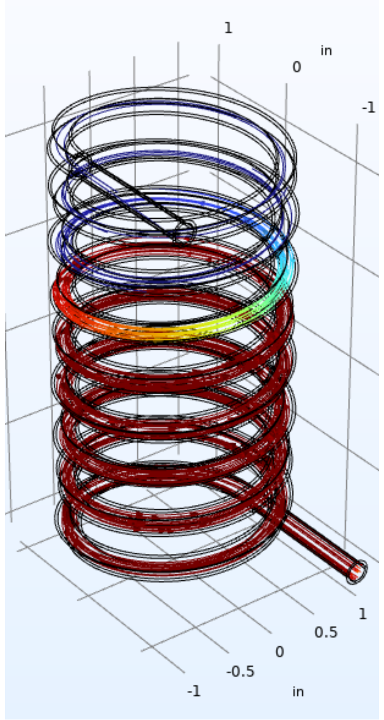


NCSU Experimental Equipment Testing



Pulsar Reactor with Vertical Port for Off-gas

Molten Salt Container & Heater



LIBS Measures Transport Properties

Gamma Spectroscopy for Fission Products

The University of California at Berkeley (UCB) is Developing Chemical Control Strategies for Salt Systems and On-line Redox Measurements

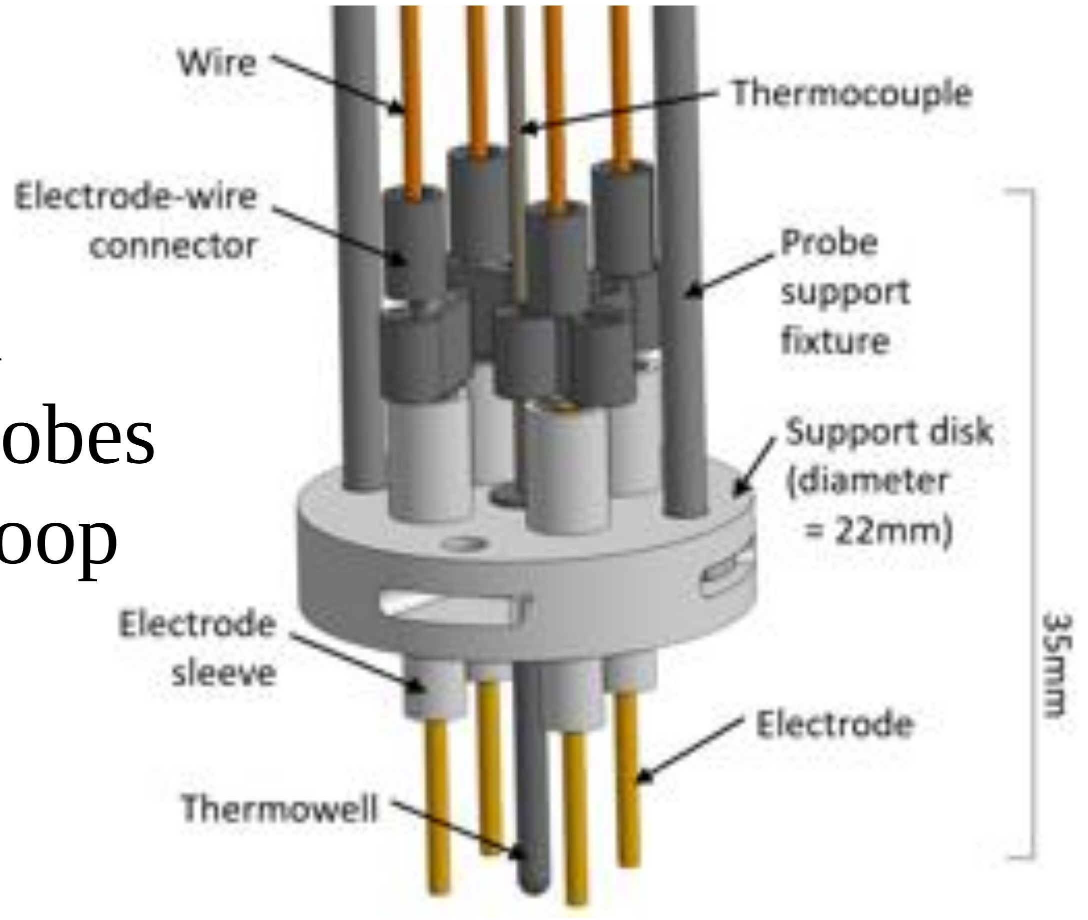
Department of Nuclear Engineering

R. O. Scarlat (Co-PI)

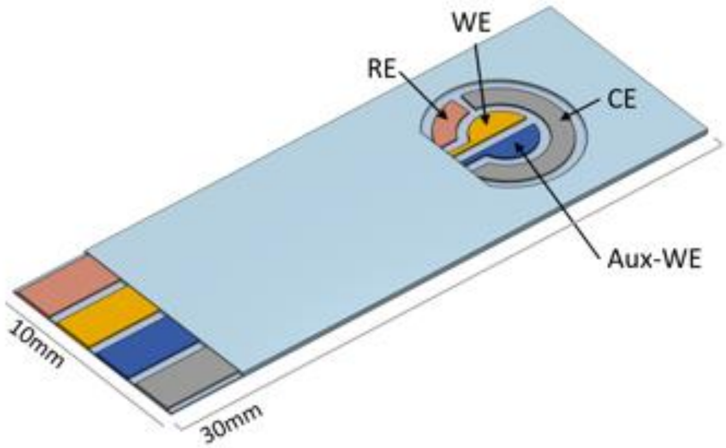
Chemical Redox Determines Corrosion Rates and What Fission Products are Metals versus Fluorides: Need On-line Redox Instrumentation

- Tritium and fission product transport experiments
- Development of redox measurement probes for loop
- Development of redox control strategies
- Incorporate sensors into the MIT loop

Sensor Development at U.C Berkeley



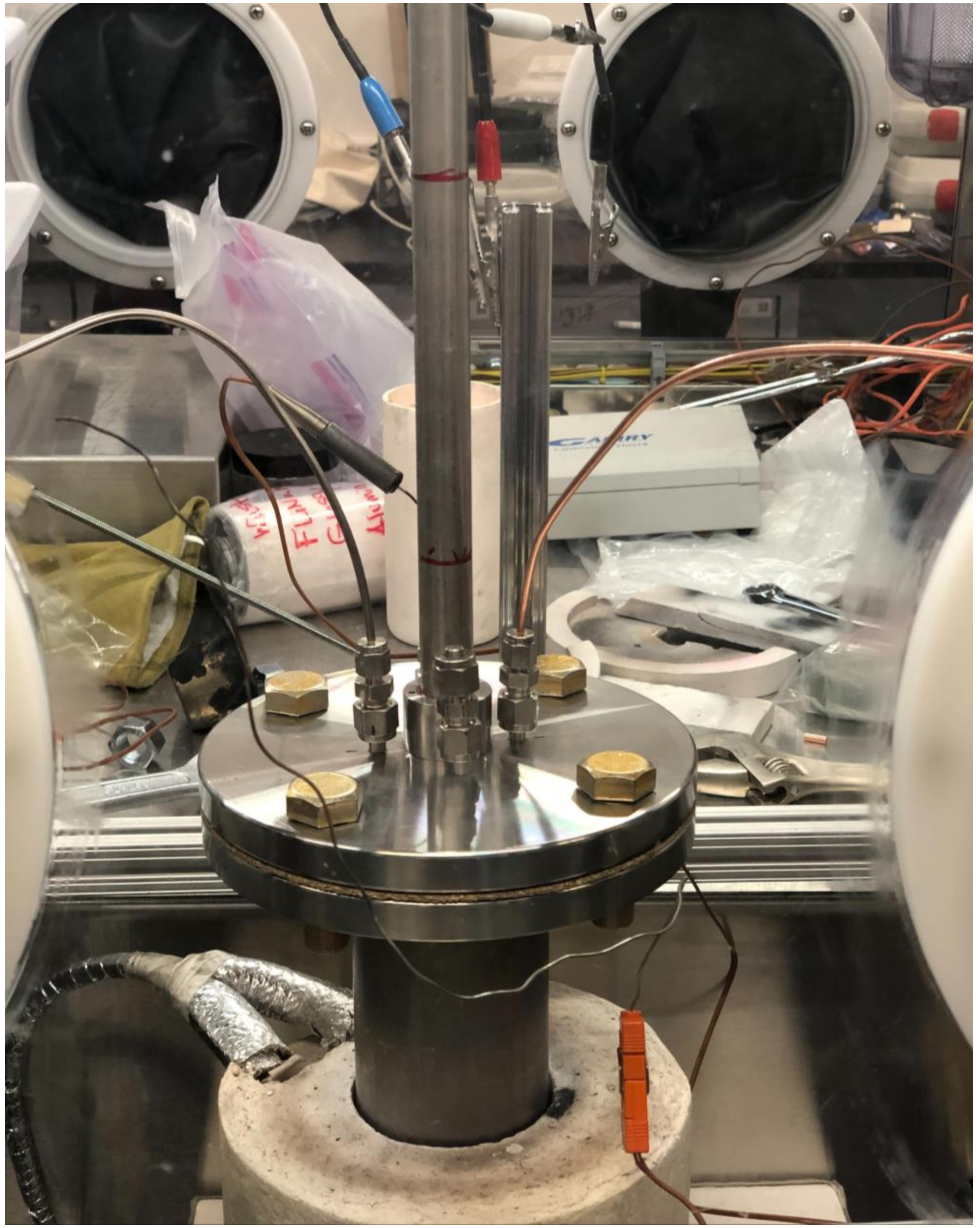
Electrochemical probe for standard molten salt electrochemical cell. The probes will be inserted in the MIT irradiated loop



Thin film sensor for high-throughput electrochemical experimentation

Engineered Sensor System to Measure Multiple Salt Properties In the MIT Loop

Open circuit potential (OCP) and cyclic voltammetry (CV) for redox measurement and corrosion product detection, and square-wave voltammetry (SWV) for oxide quantification



Proposed Phase II

Add Uranium to MIT Flowing Salt Loop

Massachusetts Institute of Technology

Berkeley UNIVERSITY OF CALIFORNIA

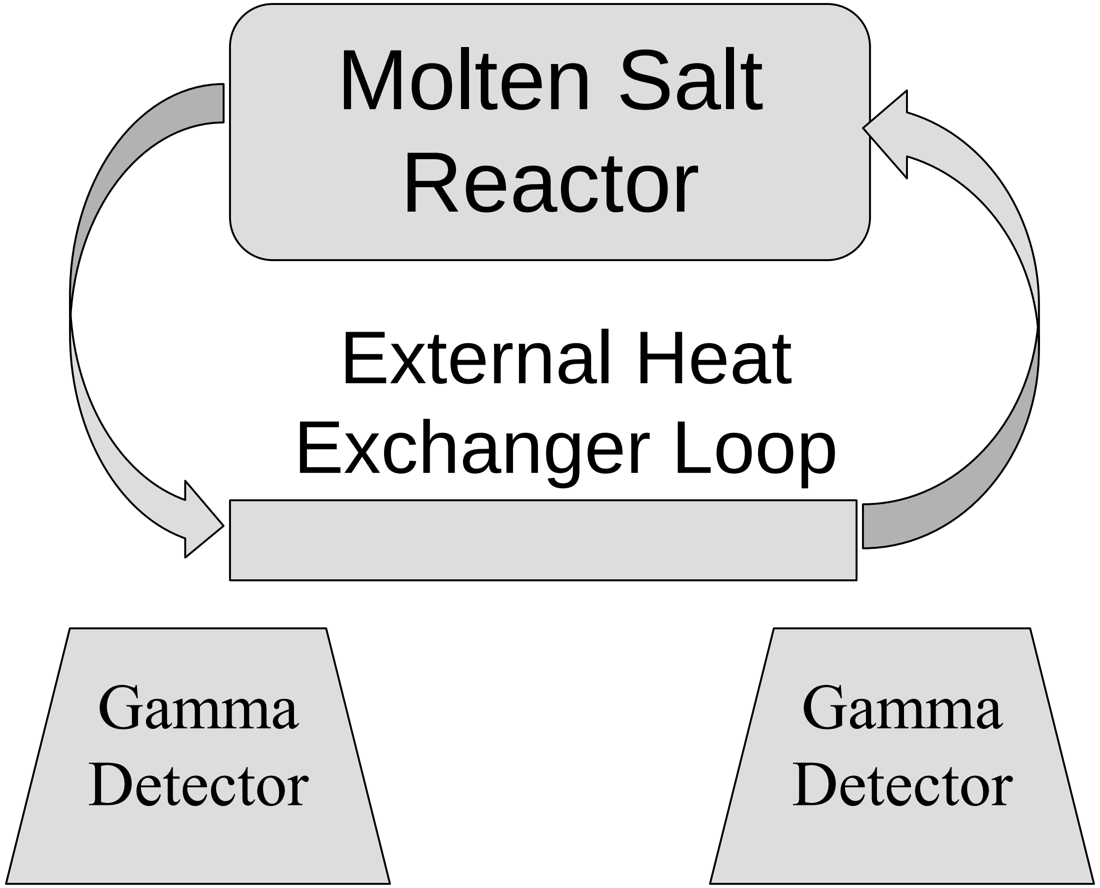
The University of Texas at Austin

Applications for Flowing Loop with Uranium

- Traditional: Corrosion testing, etc.
- "New" capabilities not available when the Molten Salt Reactor Experiment was built at ORNL
    - Understanding noble metal plate out and decay product re-entry into salt (MIT)
    - Flowing salt instrumentation (all)
    - Digital Twin of loop, basis for digital twin of future molten salt reactors (U. of Texas)

With Flowing Fissile Salt, Gamma Detectors May Measure Flow Velocity, Mass Flow and Kr/Xe Content

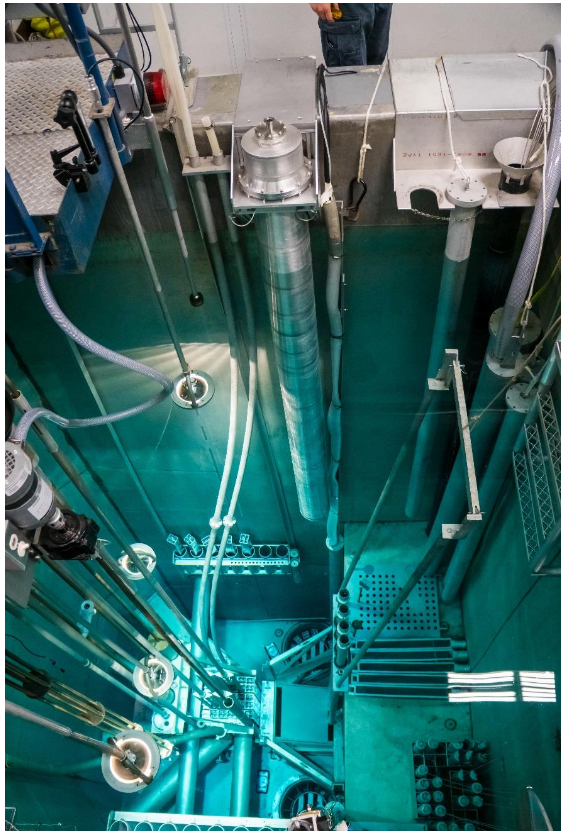
- Velocity and Mass Flow
  - Decay gamma rapidly decreases with time since leaving reactor core
  - More time out of core, less gamma.
- Short-lived nuclides may enable measuring dissolved Xe and Kr in the fuel salt
- Non-uniform flow in core with variable power density



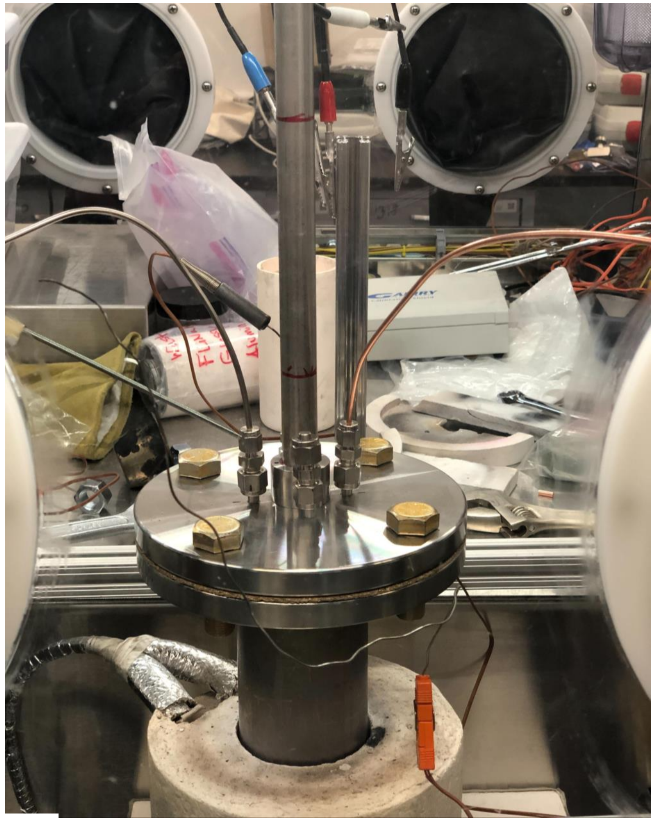
Can Measure Flow in Clean Salt with 11 Second F-20, 1633 KeV

Questions

MIT: Flowing Salt Loop with Neutron Irradiation & Variable Temperature



NCSU: Off-gas Measurement System



UCB: Redox Measurement & Control

Added Information

Biography: Charles Forsberg

Dr. Charles Forsberg is a principal research scientist at MIT. His current research areas include Fluoride-salt-cooled High-Temperature Reactors (FHRs), hybrid energy systems, utility-scale 100 GWh heat storage systems and nuclear biofuels systems. He is one of the three inventors of the FHR. He teaches the fuel cycle and energy systems classes. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory. Earlier he worked for Bechtel Corporation and Exxon.

He is a Fellow of the American Nuclear Society (ANS), a Fellow of the American Association for the Advancement of Science, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding chemical engineering contributions to nuclear energy, including his work in waste management, hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design and is a former Director of the ANS. Dr. Forsberg earned his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. He has been awarded 12 patents and published over 300 papers.

Team Members and Responsibilities

Massachusetts Institute of Technology

NC STATE UNIVERSITY

Berkeley UNIVERSITY OF CALIFORNIA

OAK RIDGE National Laboratory

- MIT. Design, build, and test a general-purpose instrumented molten-salt test loop at the MIT reactor
- NCSU. Develop, design, build and test off-gas sensor system capable of measuring tritium, fission products and actinides (not installed in MIT loop in this IRP)
- University of California at Berkeley: Develop, design and build instrumentation for measurement and control of redox salt chemistry to be installed in loop
- Oak Ridge National Laboratory. Supporting Role

Workshop on lessons learned in how to conduct salt irradiation experiments

Second workshop being planned

C. W. Forsberg, D. M. Carpenter, R. O. Scarlat, R. Kevin and A. I. Hawari, "Lessons Learned In How to Conduct Irradiated Salt Experiments", *Transactions of the American Nuclear Society Annual Meeting*, Indianapolis, June 11-14, 2023.

Workshop Participants by Organization

- **MIT (Two earlier IRPs with capsule salt irradiations)**
- U. of California, Berkeley
- North Carolina State University
- Texas A&M
- Abilene Christian University
- Ohio State University
- Virginia Tech
- Vanderbilt
- **Oak Ridge National Laboratory (Earlier salt capsule irradiation)**
- Westinghouse
- U.S. Department of Energy
- Idaho National Laboratory
- Pacific Northwest National Laboratory
- Sandia National Laboratory
- Moltex
- **Petten (Netherlands): (Earlier salt irradiation)**
- Canadian National Laboratory
- **Kairos Power (Salt irradiation with MIT)**
- Natura Resources

Lessons Learned Workshop Agenda: 1 of 2

What is Similar and What is Different Relative to Unirradiated Salt Loops and Capsules	Charles Forsberg (MIT)
MIT Lessons Learned in Salt Irradiations	Dave Carpenter (MIT)
SALIENT experiments lessons learned (Netherlands)	Ralph Hania (Petten), Dennis Boomstra, Konstantin Kottrup
Experimental Capabilities at NC State University in Support of Molten Salt Reactor Development and Deployment	Ayman Hawari (NCSU)
Electrochemical Sensors and Techniques for Redox Potential and Tritium Transport in a Neutron-Irradiated Molten FLiBe Salt Loop	Raluca O. Scarlat (UCB)
Kairos Power Flibe Irradiation Testing – Lessons Learned and Future Work	Kieran Dolan (Kairos Power)

Lessons Learned Workshop Agenda: 2 of 2

Flibe Fusion Blankets and LIBRA Experiment:	Kevin Woller (MIT)
Design of a Molten Salt Containment System for Capsule Heating and Off-Gassing	Matthew Van Zile (Ohio State)
Mining MSRE Experience	Steven Krahn (Vanderbilt)
Molten Salt R&D Capabilities	Kenneth Armijo (Sandia National Laboratory)
Molten Salt Irradiation – ORNL Experiences	Kevin Robb (Oak Ridge National Laboratory)

Key Workshop Conclusions

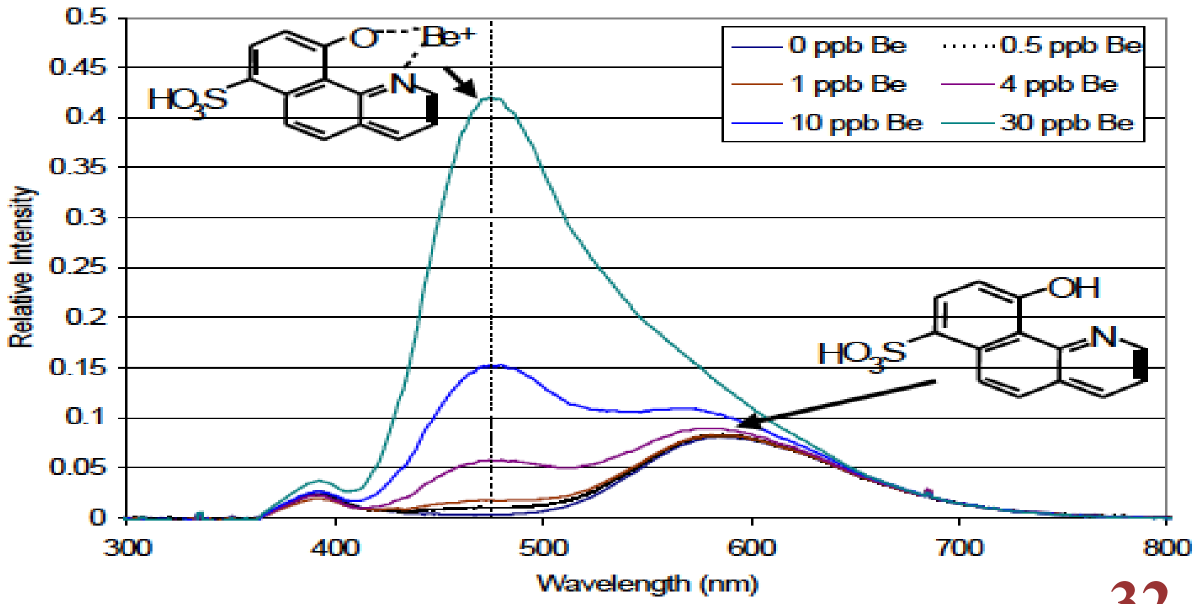
1. Keep salt hot until it is out of the irradiation zone to avoid generation of fluorine and other gases
2. Care must be taken to assure no freezing of salt including: sloped tubes to enable draining after loss of heating, multiple heating and insulation systems, and test systems in non-radioactive environments before using in irradiative environments
3. Need for on-line redox measurements and potentially redox control to relate results of investigations to the chemical state
4. Conduct parallel irradiated and un-irradiated salt experiments
5. Use of forensic analysis to learn from experience.
6. Avoid and report non-metallic impurities (O, H, S) affecting wetting behaviour and corrosion results.

Example 1: Keep salt hot until it is out of the irradiation zone to avoid generation of fluorine and other gases

- Gamma radiolysis occurs in cold frozen salt releasing fluorine and, if uranium in salt, uranium hexafluoride
  - Fluorine destroys samples and corrodes equipment
  - No radiolysis if keep salt warm
- Test reactors traditionally use reactor gamma heating to heat test loops—simple to implement
- Decay gamma after reactor shutdown and salt freezing can result in radiolysis with fluorine / other releases
- **Need to heat sample inside reactor core after reactor shutdown—major experimental complication**.

Example 2 (MIT): Fast Beryllium Swipe Analysis

- Traditional beryllium safety protocol using swipes and chemical analysis is slow
- Standard safety protocol causes major delays in building and maintaining equipment
- Qualified fast analysis using beryllium detection in the fluorometer



Quarterly Reports Are Widely Distributed

- Reports include both successes and lessons learned
- Current distribution
  - Industry: **Kairos, TerraPower, Moltex, Terrestrial, Commonwealth Fusion, EPRI, Flibe Energy**
  - National Laboratories: **ORNL ANL, INL, PNNL, SRNL, Petten, Canadian National Laboratory**
  - Universities: **MIT, UCB, NCSU UML, OSU, TAMU, UTK, Illinois, ACU, UTEXAS, Georgia Tech, Vanderbilt, Wisconsin, BYU, Virginia Tech**

Molten Salt Futures

Multiple Applications Drive the Need for Cooperation Between Salt Programs

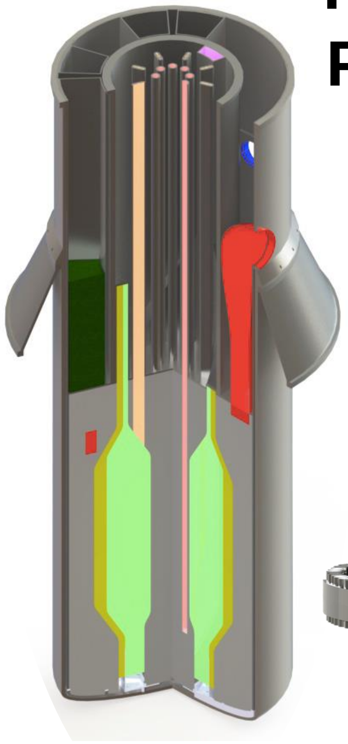
Economic Basis for Salt Reactors (Fission, Fusion, Solar): Higher-Temperature Heat to Power Cycles and Industry

Coolant	Average Core Inlet Temperature (°C)	Average Core Exit Temperature (°C)	Ave. Temperature of Delivered Heat (°C)
Water	270	290	**280**
Sodium	450	550	**500**
Helium	350	750	**550**
Salt	**600**	**700**	**650**

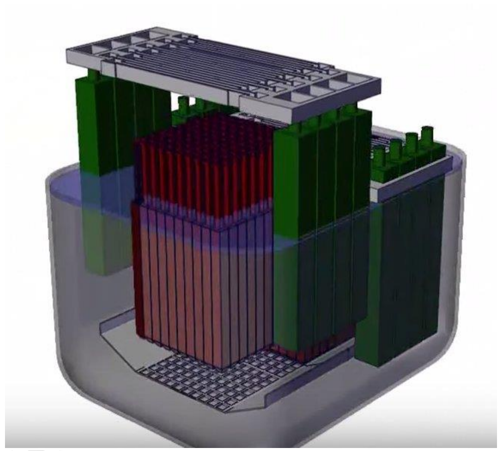
C. W. Forsberg. Market Basis for Salt-Cooled Reactors: Dispatchable Heat, Hydrogen, and Electricity with Assured Peak Power Capacity, *Nuclear Technology*, 206 (11), 1659-1685, November 2020. https://doi.org/10.1080/00295450.2020.1743628

Multiple Technologies Dependent on Salt Technology

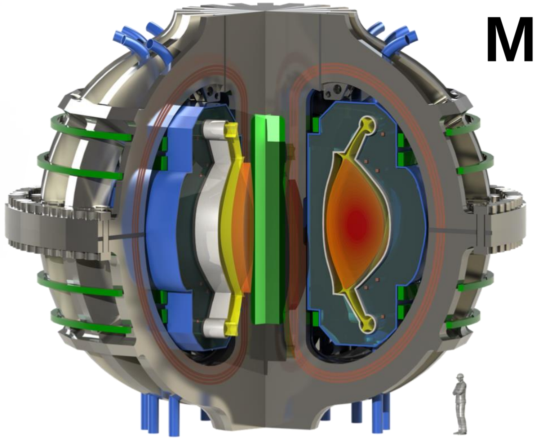
Clean Fluoride Salt Coolant



Kairos Power FHR



Moltex



Commonwealth Fusion

Fuel in Fluoride Salt

MSR: Many variants

Molten Fluoride Salt Fast Reactor (Europe)

Fuel in Chloride Salt

Molten Chloride Fast Reactor

Fuel Salt in Tubes with clean salt coolant (Moltex)

Clean Chloride Salt

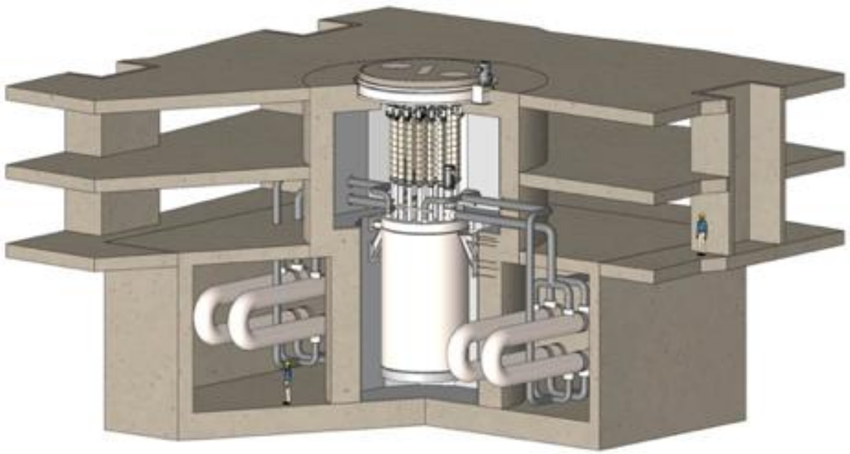
Concentrated Solar Power

High Temperature Heat Storage

Fast-Spectrum Fission ?

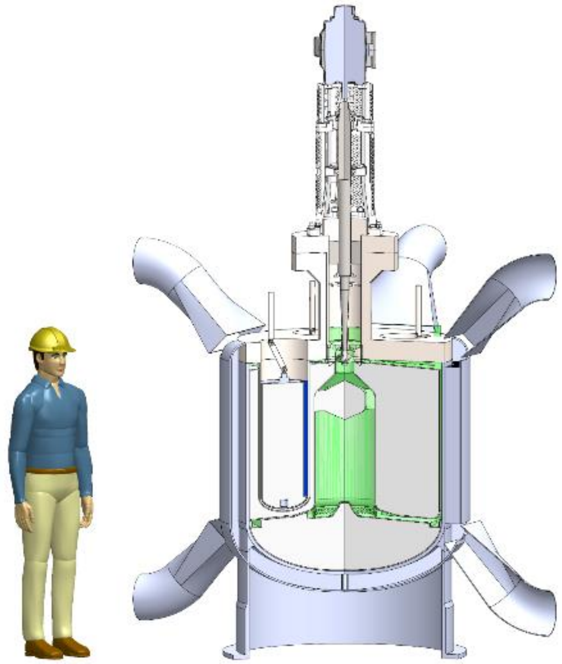
Applications: Fission, *Fusion*, Solar, Heat Storage

Three Salt Reactors within the Next Several Years



Kairos Power
35 MWt FHR, 2026
Hermes, Oak Ridge

Abilene Christian University / Natura Resources 1-MWt Molten Salt Research Reactor



TerraPower/Southern
200 kW Molten Chloride Reactor Experiment, INL

Fusion Salt Systems

MIT Develops ARC Fusion Concept with Flibe Salt Blanket

MIT Spin-out ($2 billion) Commonwealth Fusion to Commercialize Technology

Major Player in Development of Salt Systems Going Forward

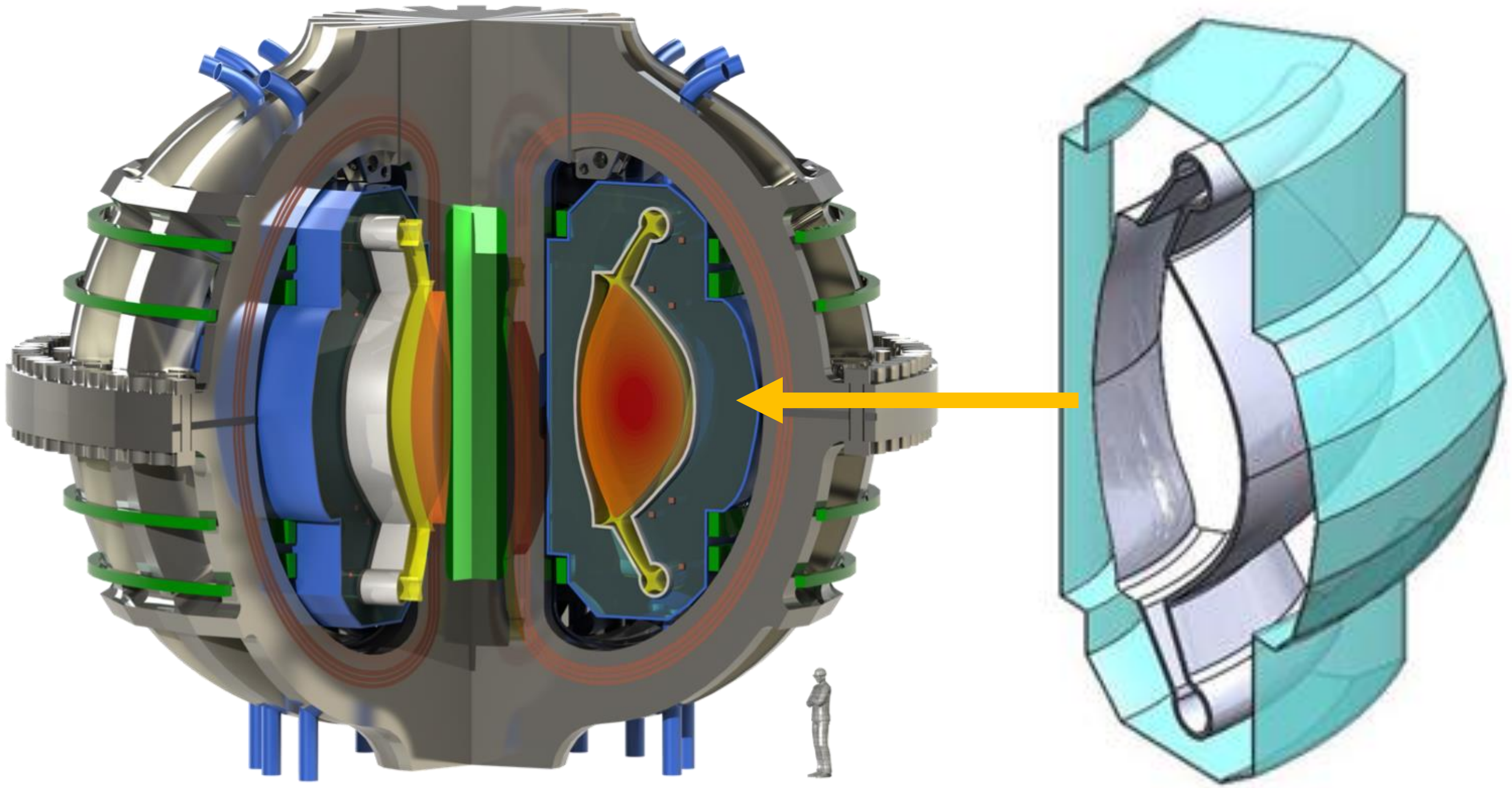
Break-Though In Magnetic Fusion with REBCO Superconducting Magnets

- The size of a fusion system varies as one over the fourth power of the magnetic field strength
- **Manufacturing breakthrough with REBCO superconductors enabled doubling magnetic field**
- Reduces fusion machine size by up to a factor of 16
  - Power density in fusion blanket increases by order of magnitude and makes it very difficult to cool solid blankets
  - Higher magnetic fields create large incentives to have a coolant with low electrical conductivity to avoid coolant/magnetic field interactions
- Solution: Liquid flibe blanket (Flibe blanket is not new concept)

First Large-Scale Magnet Test in September 2021

- MIT develops ARC fusion system based on REBCO superconductor
- MIT and Commonwealth Fusion (spin-out company from MIT) start development
- Demonstrated the key magnet technology at scale
- Creates the incentives to develop flibe salt blankets for fusion

ARC Fusion with Liquid Flibe Salt Blanket

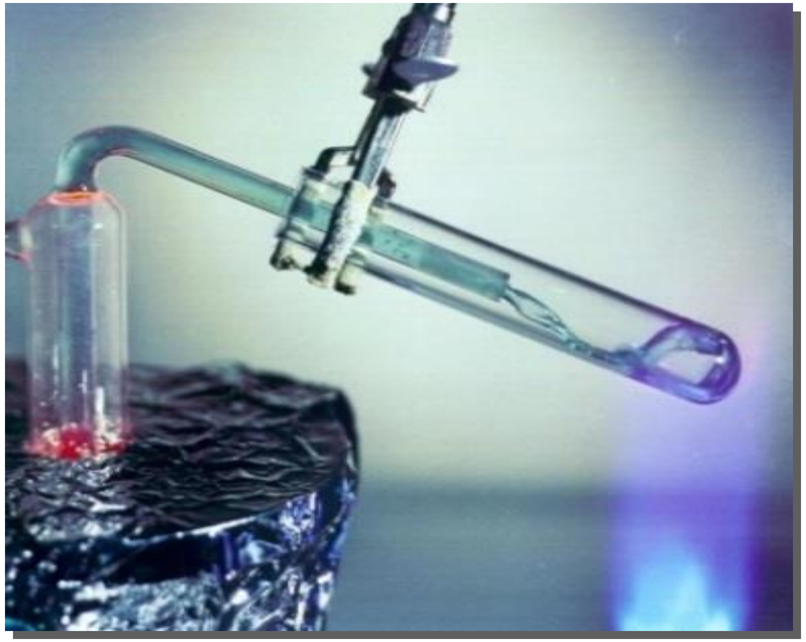


ARC Flibe Salt Blanket

- Fusion generates 14-MeV neutrons that is the heat for the power cycle. Heat deposited in the salt blanket with high power density
- Neutrons adsorbed in lithium in salt generating tritium—fusion fuel

https://www.newyorker.com/magazine/2021/10/11/can-nuclear-fusion-put-the-brakes-on-climate-change

Why Flibe (Li_2BeF_4) Salt Blanket



No limit on power density with liquid blanket from slowing down fast neutrons

Maximize tritium production (90% Li-6) to produce sufficient tritium for self-sustaining fusion machine

- Beryllium (n, 2n) reaction generates more neutrons
- Lithium plus neutron yields tritium

Excellent heat transfer relative to other salts

Same Salt as Kairos Power and Many Fission MSRs

Progression: Magnets, SPARC and ARK

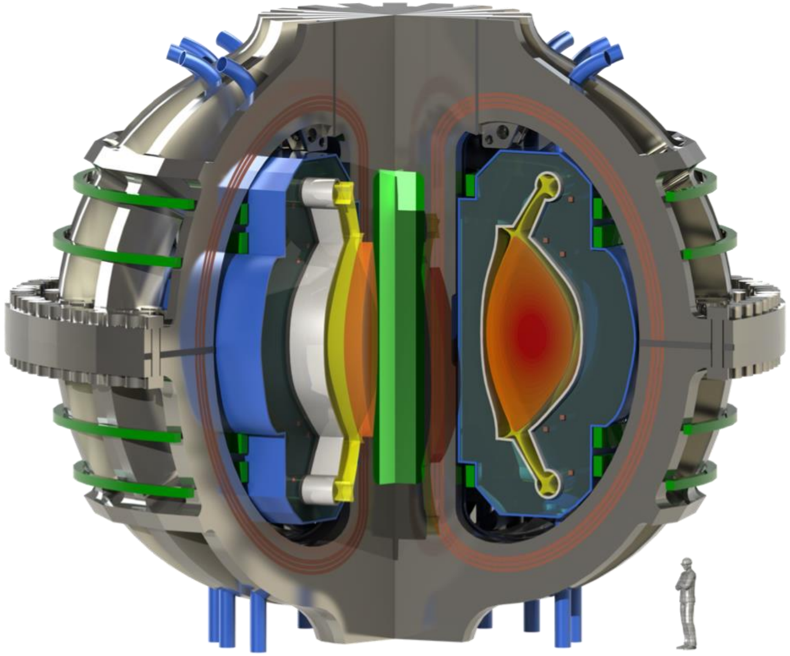
Super-Conducting Experiments: Done

2025 SPARC Plasma Breakeven Experiment:

No Breeding Blanket

ARC: Engineering Demonstration

2030s



SPARC Startup in 2025

Courtesy of Commonwealth Fusion Systems

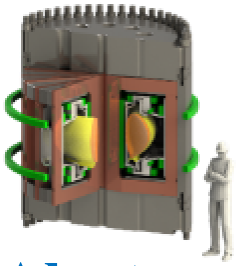
Using high-field superconducting magnets to accelerate fusion energy

High-field fusion science

Phase 1: Technology R&D

Phase 2: Demonstration

Phase 3: Commercialization

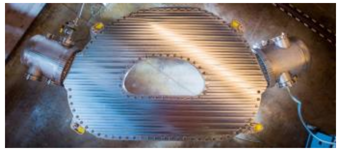


Alcator C-Mod (MIT)

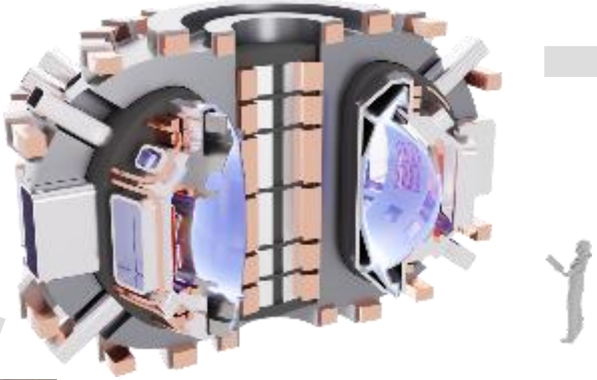
REBCO CICC cable concepts

No-insulation REBCO concepts

REBCO magnet R&D



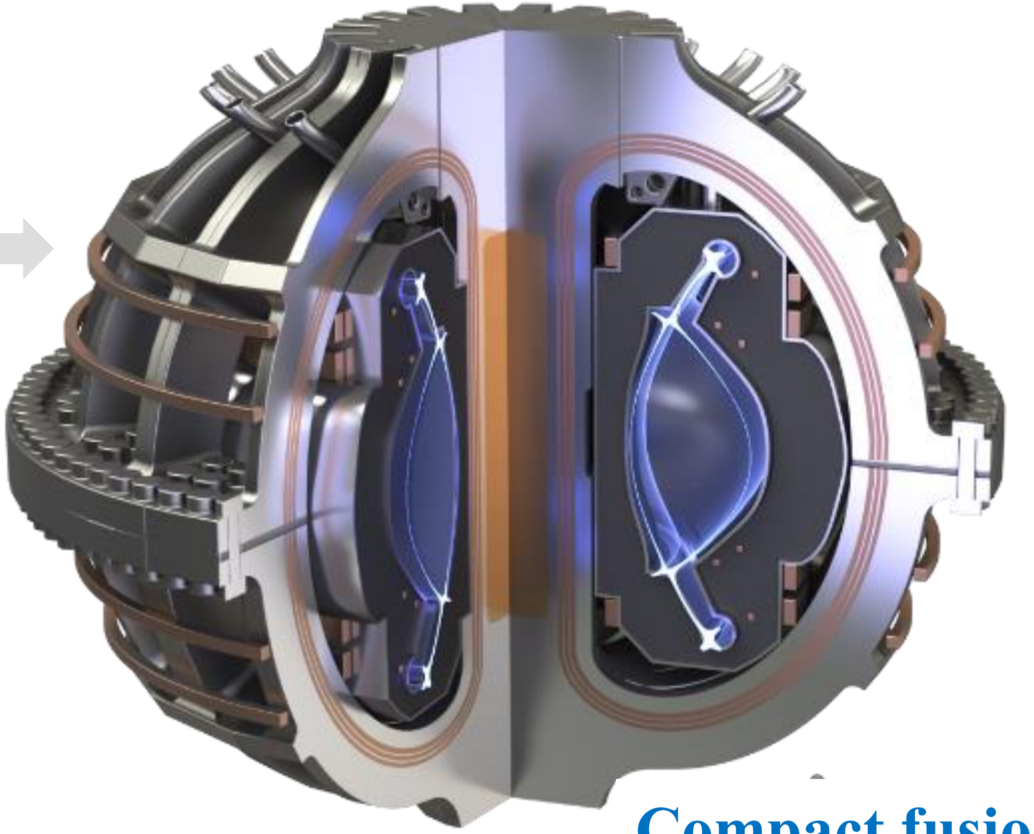
TF model coil (2019-2021)



SPARC (CFS)

$Q_{physics} > 2$

$P_{fusion} > 100$ MW



Compact fusion power plant

$Q_{physics} > 10$

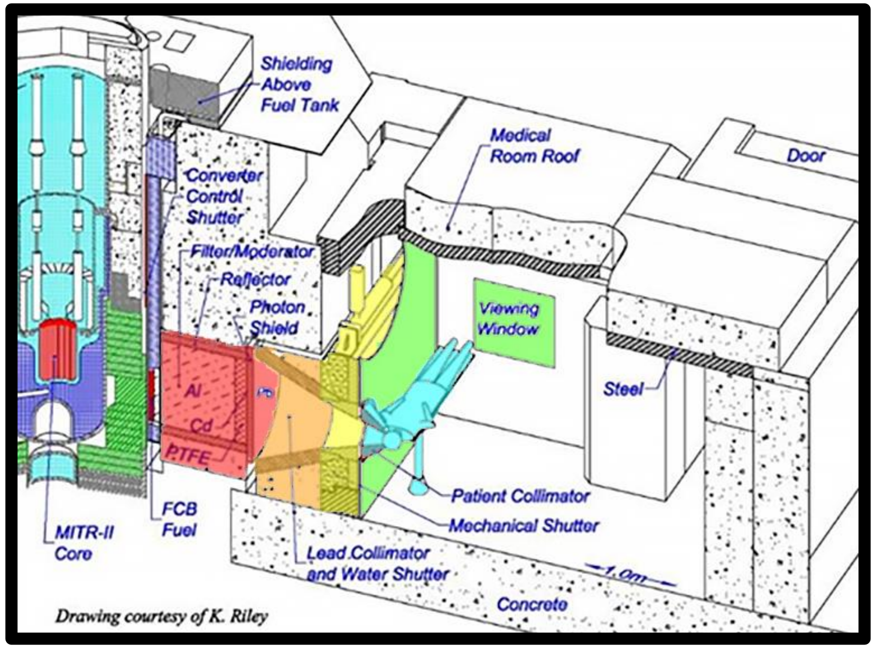
$P_{electric} > 200$ MWe

2016 **2021** **2025** **2030s**

Massachusetts Institute of Technology

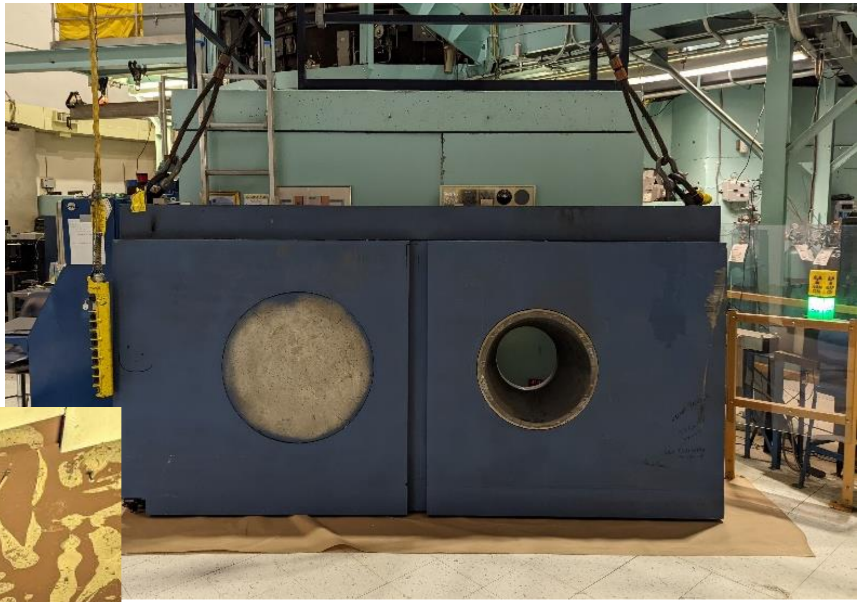
The Fusion Program Is Having a Major Impact on the Fission IRP at MIT and Elsewhere with Shared Facilities

MIT shared salt laboratories and major facilities such as M3



Remodel Hot Cell Next to MIT Reactor for IRP Flowing Salt Loop and Fusion Experiments

Construct Ceiling Access Hatch to Hot Cell for Crane Access



Remove Old Radiation Shutters

MIT Has Multiple Salt Projects that Share Facilities, Personnel, Results and Experience

- IRP salt loop (Initially clean salt)
- MIT/Commonwealth Fusion salt systems
- Kairos Power tritium experiments
- ARPA-E materials transport in salt with uranium

↕ Large Programs; Commercial Machines Use Clean Flibe Salt

Likely Model for Larger Salt Programs

There is Potentially a Massive Market for Separated Lithium Isotopes

- Existing: Li-7 for chemistry control in pressurized water reactors
- Salt Energy Systems: Fission (Li-7) and Fusion (Li-6)
- High performance lithium ion batteries where Li-6 increases power output per unit weight by 10% (faster diffusion of Li-6 ion). Space & aircraft where peak power demand controls battery size (deploy solar array, engine restart, etc.)

C. W. Forsberg, "Future Cost of Isotopically Separated Lithium for PWRs, Fluoride-salt-cooled High-Temperature Reactors (FHRs), and Lithium Batteries", Paper 8712, Transactions 2013 American Nuclear Society Winter Meeting, Washington D.C., Nov. 10-14, 2(

Experimental Capabilities at NC State University in Support of Molten Salt Reactor Development and Deployment

A. Bauyrzhan, N. Poole, M. Schweitzer

M. Liu, A. Wells, C. Fleming, A. I. Hawari

Nuclear Reactor Program, Department of Nuclear Engineering

North Carolina State University, Raleigh, North Carolina, USA

2023 MSR Workshop
Oak Ridge National Laboratory, Oak Ridge, Tennessee
October 25-26, 2023

Motivation

NEUP Nuclear Energy University Program

U.S. Department of Energy

Molten Salt Reactor Test Bed with Neutron Irradiation

PI: Charles Forsberg
Massachusetts Institute of Technology (MIT)

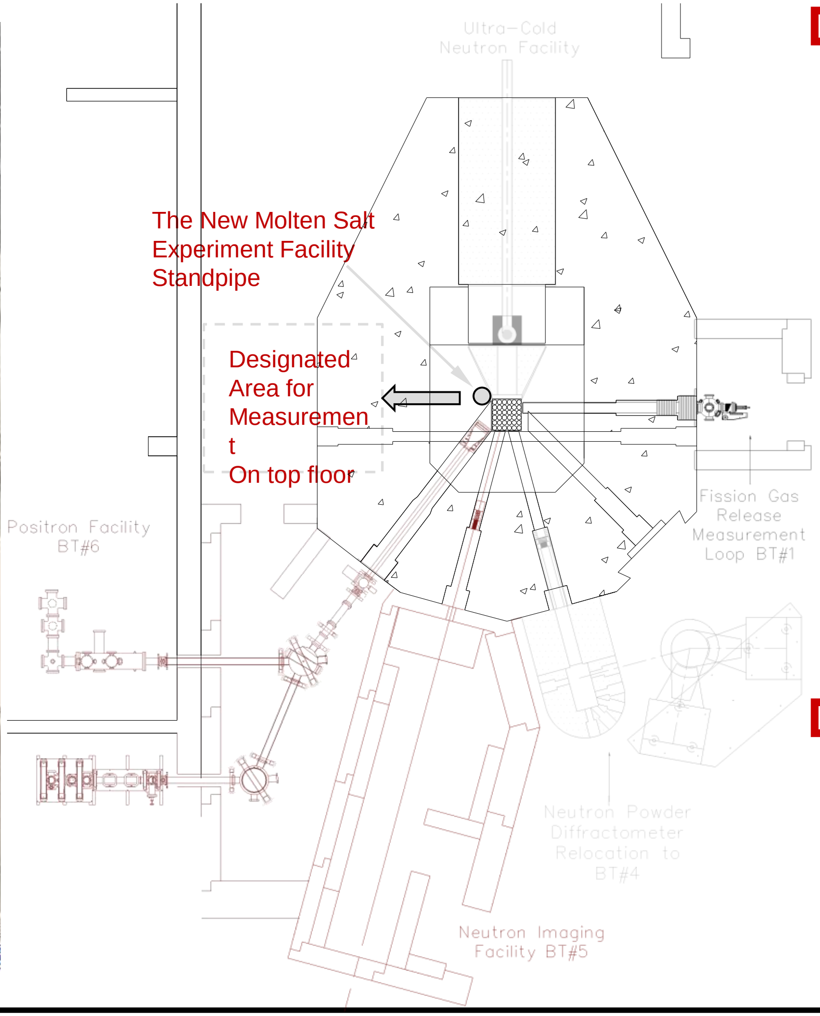
Program: Reactor Concepts

Collaborators:
David M Carpenter—MIT
Ayman Hawari—North Carolina State University
Raluca O. Scarlat—University of California at Berkeley
Kevin Robb—Oak Ridge National Laboratory

- **Molten Salt Irradiation Experiment (MSIE) –** monitor various species production and release under neutron irradiation and with active temperature control

- **Develop, implement and test pre and post irradiation capabilities –** e.g., using samples irradiated in a salt environment

Molten Salt Irradiation Experiment (MSIE)



- Floor Planning of the Molten Salt Experiment
  - 8"ID vertical Al dry port near BT#6
  - Measurement stations at the pool top level
  - Umbilical connecting the vertical port and the measurement stations
- Nominal Flux at test location:
  - > $2\text{x}10^{12}$ Thermal
  - 10^{12} Fast n/cm^2·s

Design Based on Detection and Safety Limits

Production

- Fission gases (Xe, Kr)
- Nobel Metal fluorides, aerosols
- Tritium
- Others (I_2, chemicals)
- FLiBe, FLiNaK

Transport

- Transport in molten salt, liquid/gas interface, and gas.
- Transport of gases, vapors, and aerosols

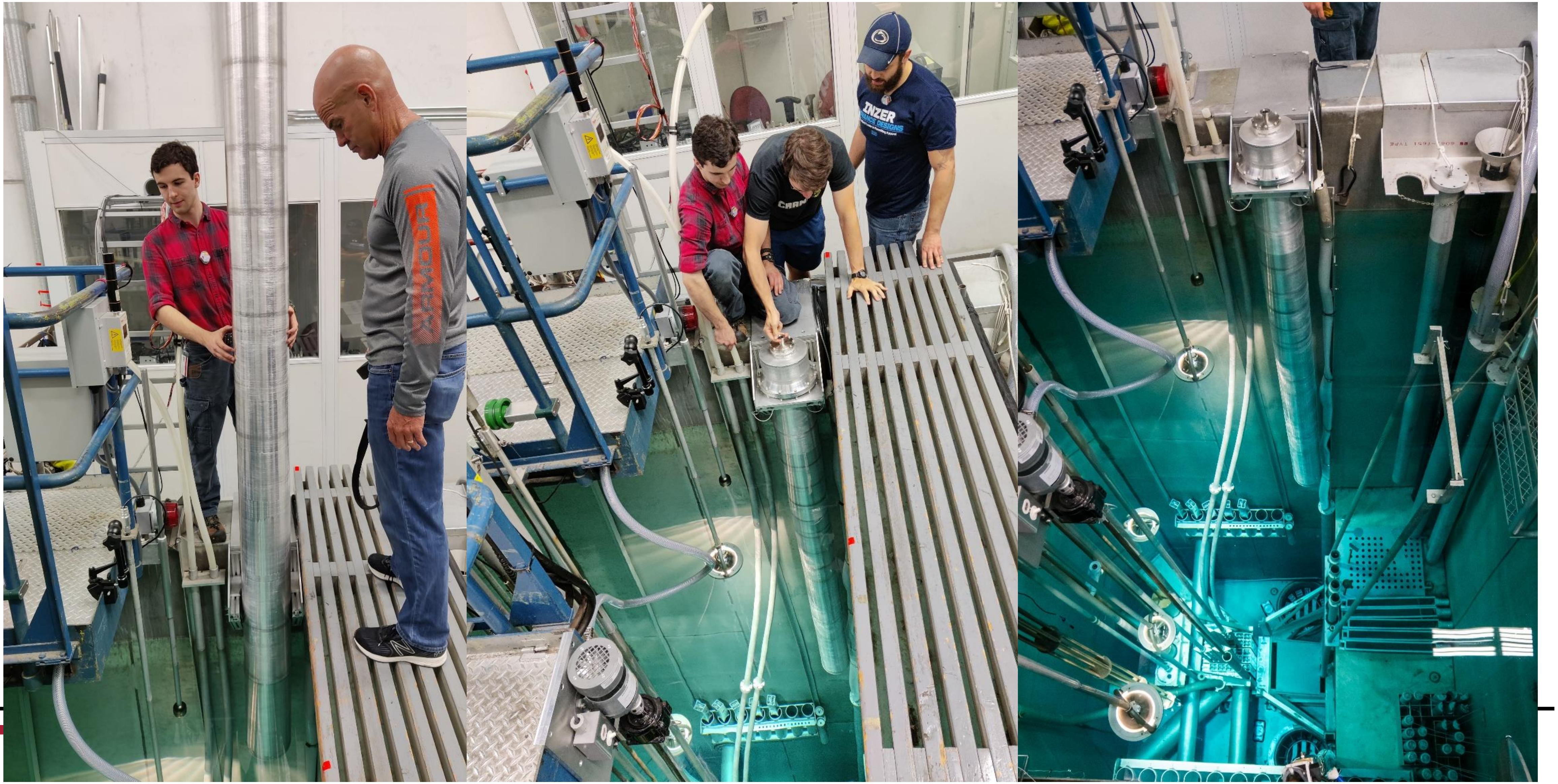
Detection

- Gamma spectroscopy
- Tritium monitor
- Laser induced breakdown spectroscopy (LIBS)

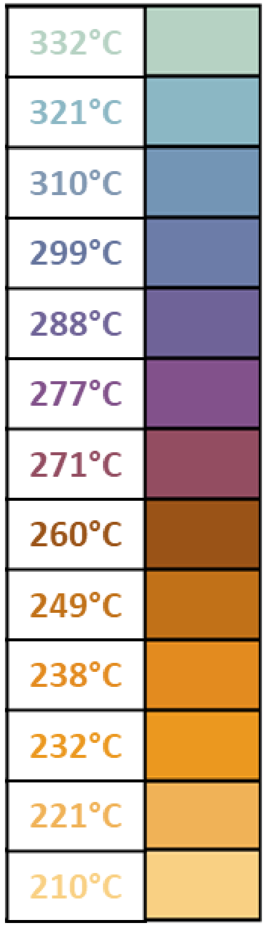
Exhaust

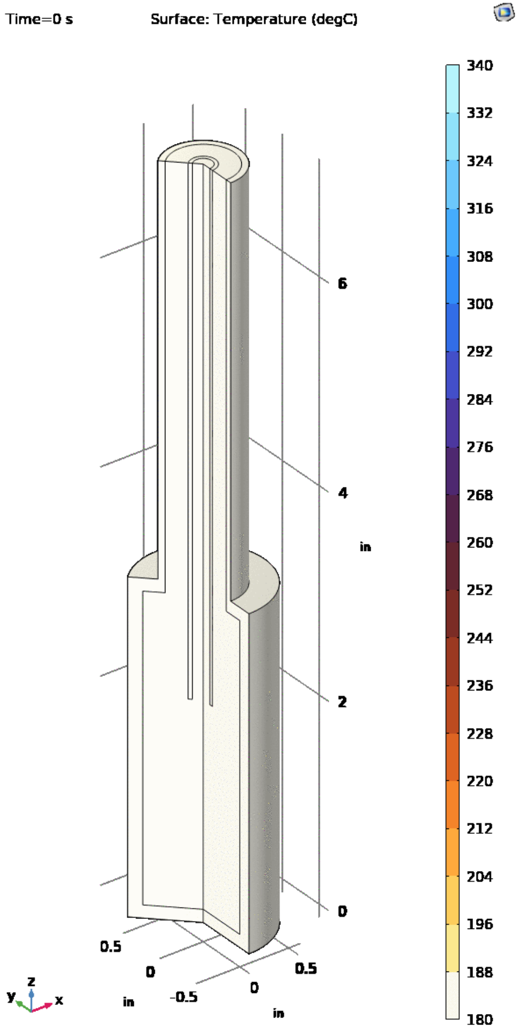
- Safety limits
- Different filters for various components
- Delay tank for short-lived isotopes

Testing of MSIE Vertical Port



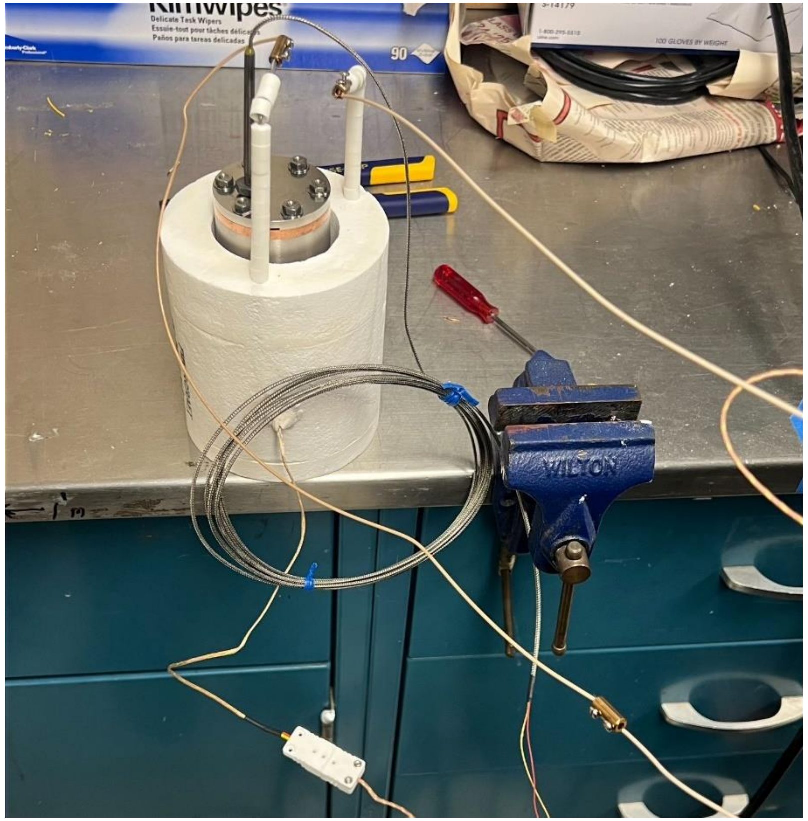
Testing of the Molten Salt Container & Heater

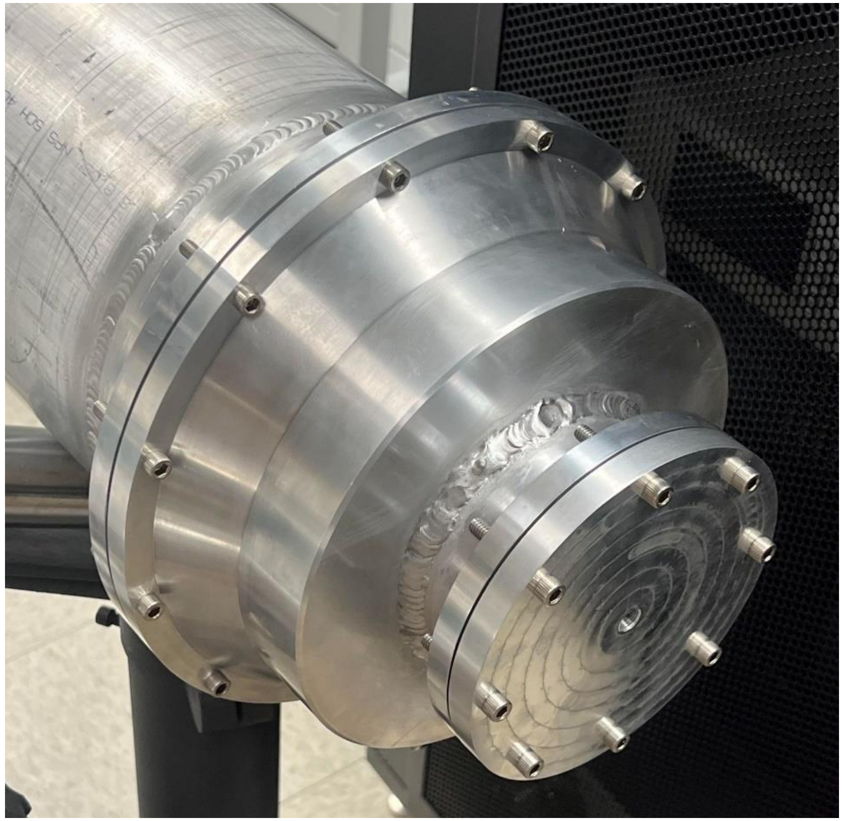




- COMSOL simulations of thermal properties
- Sample heater tested to 760°C in vacuum
  - Temperature gradient identified with heat tint (tempering) color between 200-330°C
  - Coincide with the range of most fluorides boiling temperature

Testing of the Salt Irradiation Chamber

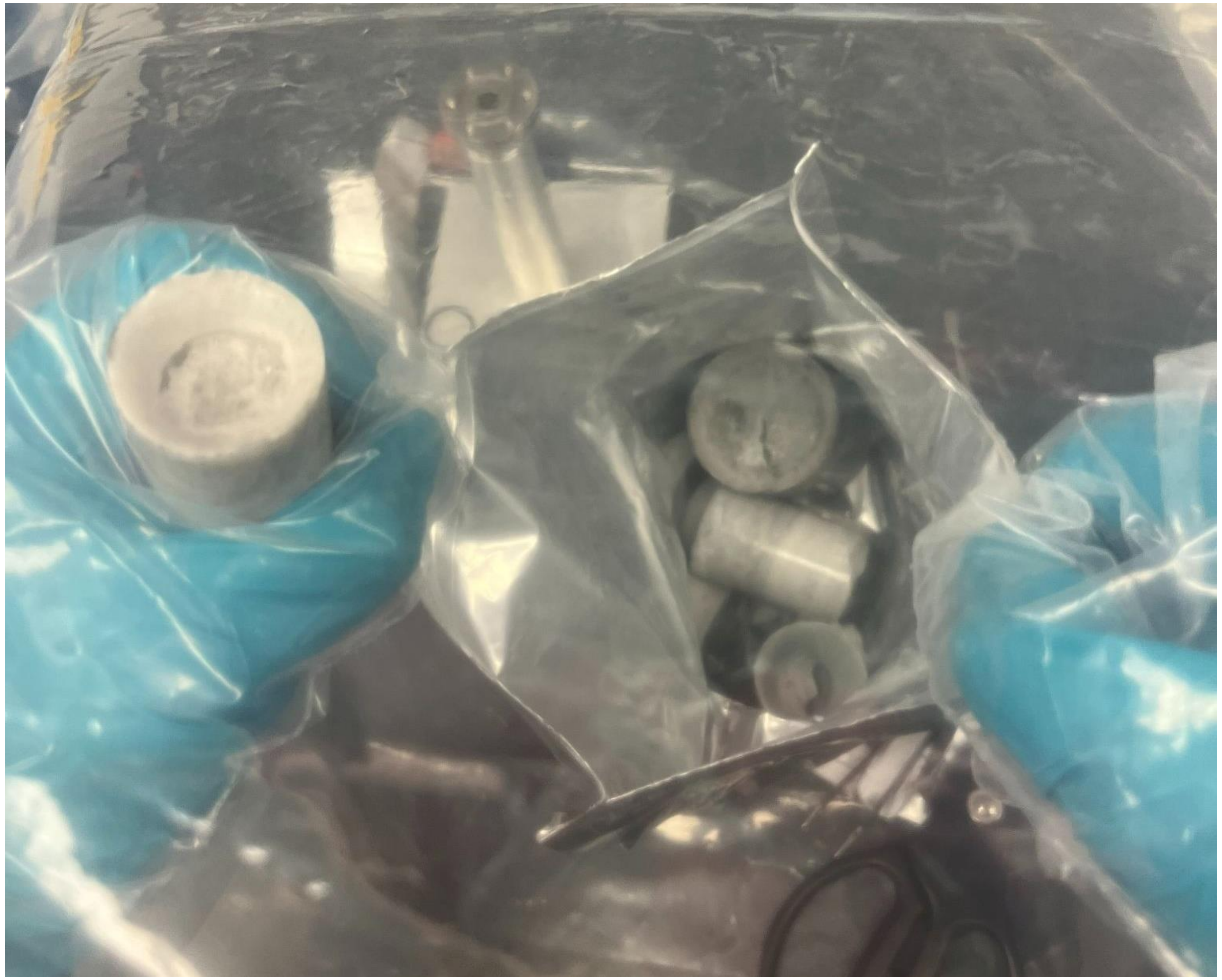




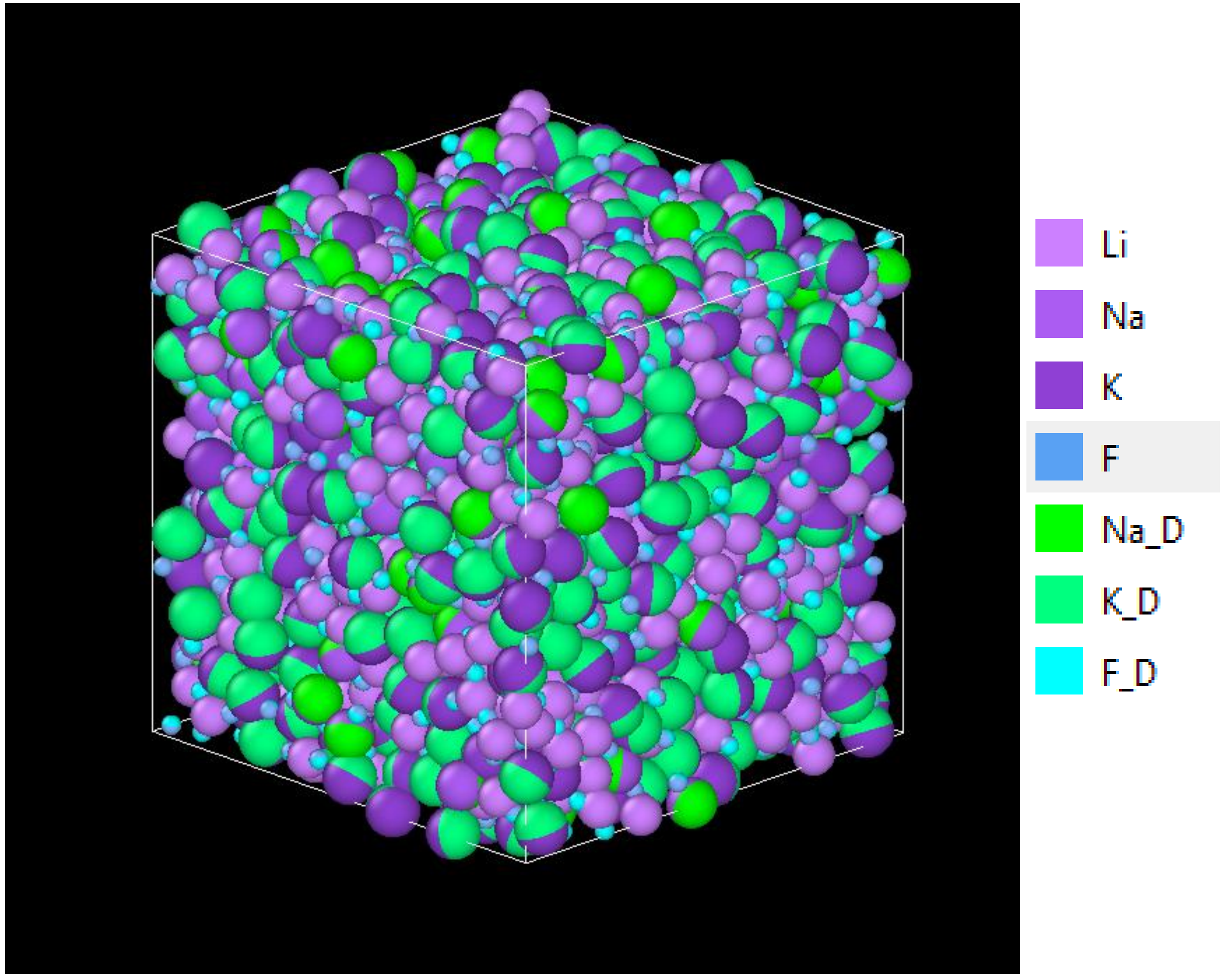
- Sample container, heater, power supply and temperature controller were all tested
- Standpipe and aluminum encapsulation which contains the heater pressure tested

Testing Using FLiNaK Salt

- FLiNaK was examined with Inductively Coupled Plasma Mass Spectrometry (ICP-MS)
- Various impurities exist in the FLiNaK, including Cr, Zn, Rb, and W with concentrations of about 9ppm, 12ppm, 37ppm, and 34.49ppm



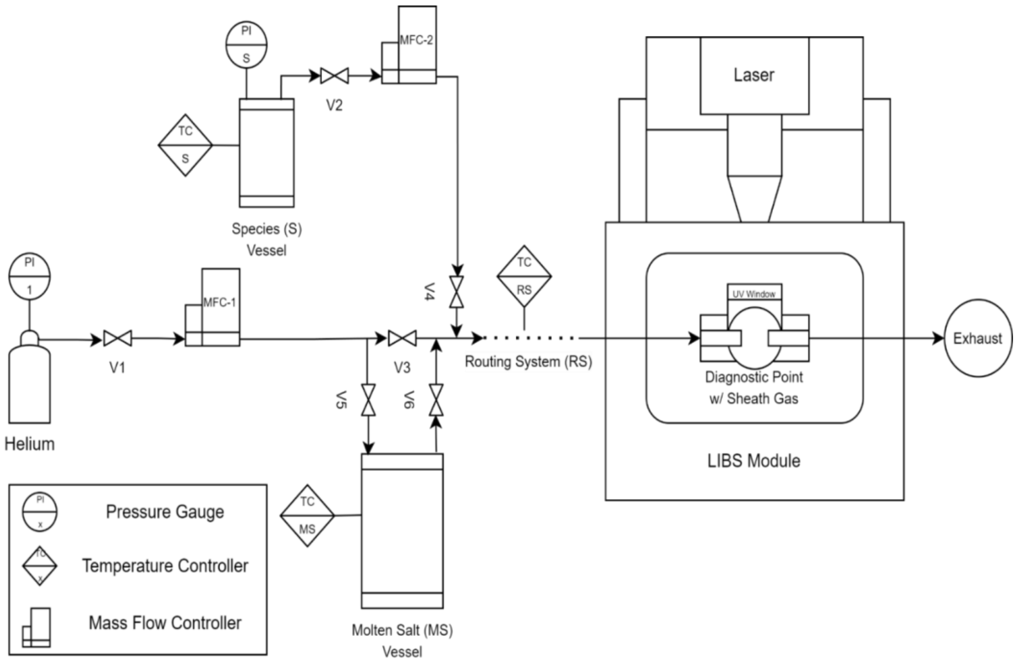
Understanding FLiNaK using Molecular Simulations

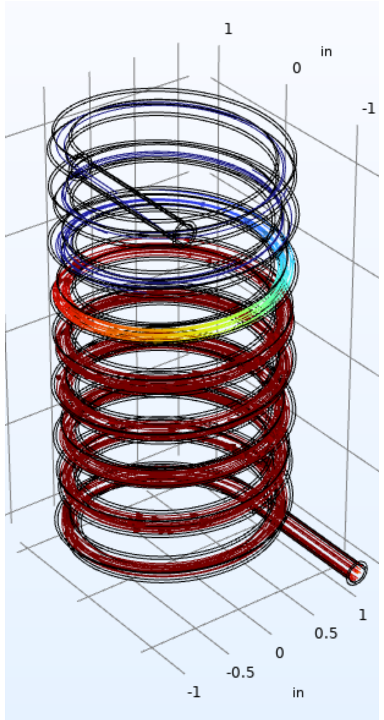


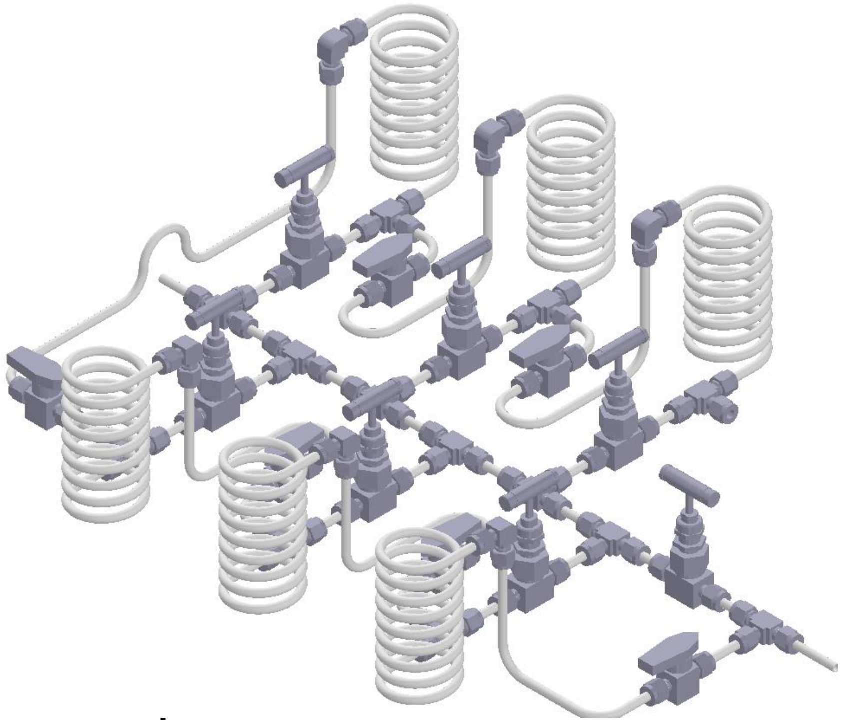
- MD Simulation to study the diffusion behavior and other properties of the molten salt
- Polarizable Ion Model (PIM):
  - Implemented through LAMMPS via the Drude Oscillator Model
  - Born-Mayer-Huggins base potential

$$E = A\exp\left(\frac{\sigma - r}{\rho}\right) - \frac{C}{r^6} + \frac{D}{r^8}$$

LIBS System Implementation

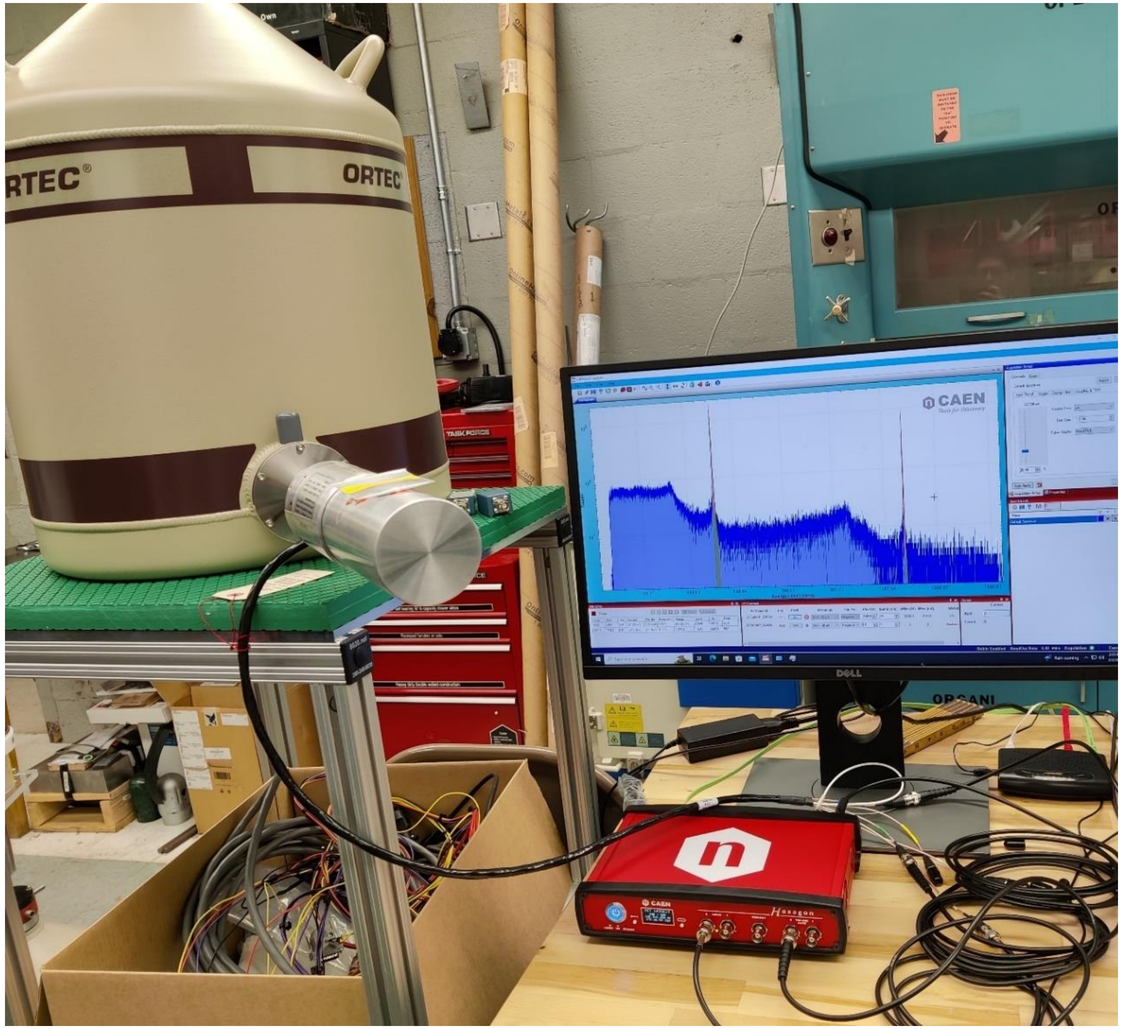




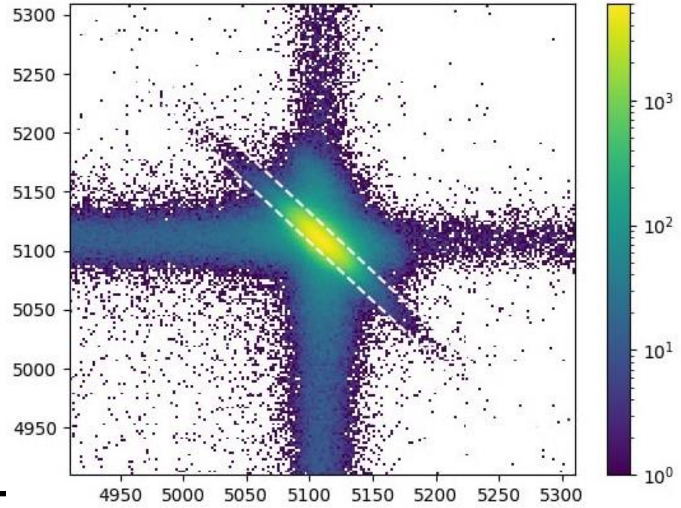


- LIBS system to measure transport properties of fission product
  - Mechanical design of the LIBS chamber, modular routing system
  - COMSOL Multiphysics simulation of heat loss & transport properties
  - **LIBS system to be delivered before end of 2023**

The Gamma Spectroscopy System



- Gamma spectroscopy systems for fission gas and e+PAS
  - Digital MCA tested
  - Coincidence counting – 2D map
  - Investigation of neutral network methods



  - E vs E plot created in CAEN MC2 and plotted in Python

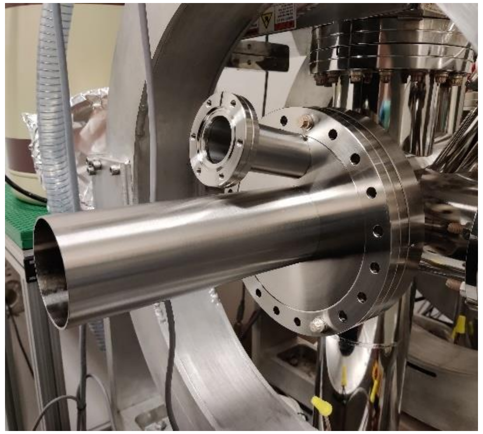
Massachusetts Institute of Technology

Pre and Post Irradiation Examination

- Major Capabilities
  - Neutron powder diffractometer
  - Neutron imaging
  - Intense positron beam
  - Ultracold neutron source (under testing)
  - Fission gas release and measurement loop
  - Neutron activation analysis
  - In-pool irradiation testing facilities
  - Molten Salt Irradiation Experiments

Upgrade of the e+PAS Spectrometer



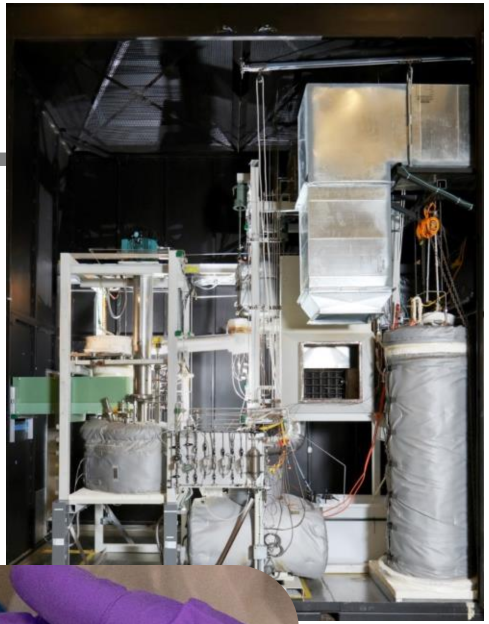
- New sample manipulator
  - Multi-sample changer
  - Heating/cooling capability
- New Magnetic shield
  - B-field simulation of the shielding of PMT
  - Combination of mild steel & Mu-metal layers
- New Target Chamber
  - Better implantation depth
  - Coincidence DBS

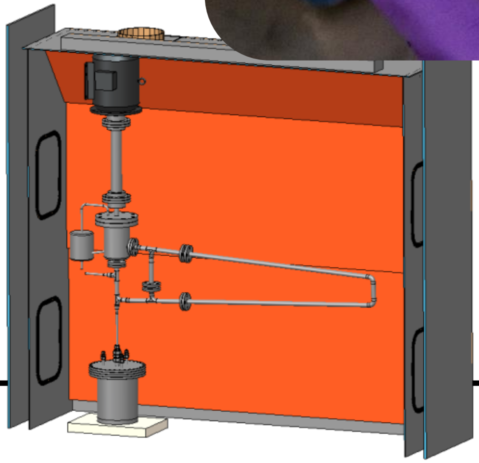
Summary

- Molten salt irradiation experiment (MSIE) facility implementation is underway
  - Testing of the vertical port completed
  - Major systems are under testing and/or fabrication
  - Gamma spectrometry system is established
  - LIBS system is procured and will be delivered before end of 2023
- Pre and post irradiation capability upgrades are progressing
  - PAS measurements upgrades completed
- Infrastructure to handle salt experiments is progressing
  - Lab space, glove box (operational), hotcell in reactor bay
- MSIE implementation at PULSTAR reactor is guided by
  - PULSTAR capabilities and past experience
  - Multi-physics design simulations
    - Safety and performance metrics
  - Regulatory requirements
    - **License amendment granted by NRC to irradiate fueled salts**

ORNL Synergy

- A consulting role to leverage experience in:
  - Large salt loop design and operation
  - Instrumentation experience
  - Component supply chain
  - FLiBe purification and handling
  - FLiBe corrosion testing
  - Past FLiBe-tritium loop plans





U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Molten Salt Reactor PROGRAM

Overview of the Molten Salt Reactor Program

Dr. Patricia Paviet

National Technical Director of the MSR Program

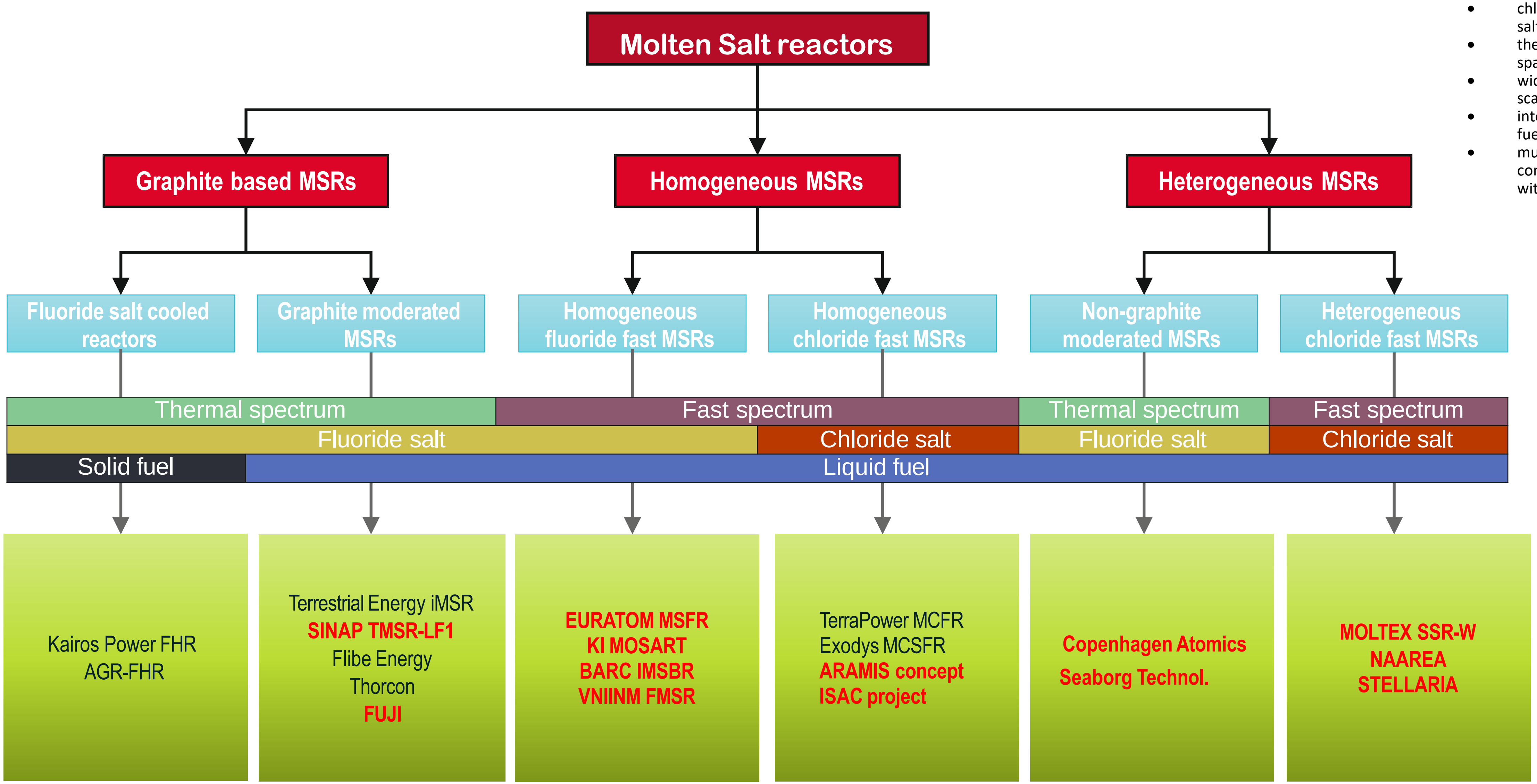
PNNL-XXXXXXX

Annual MSR Workshop - 25/26 October 2023

Molten Salt Reactor Concepts

A molten salt reactor (MSR) is any nuclear reactor that employs liquid halide salt to perform a significant function in-core. MSRs include a broad spectrum of design options including:

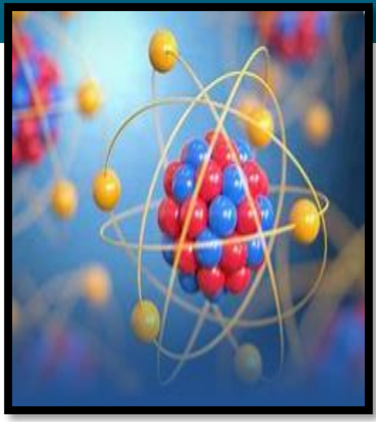
- liquid- and solid-fueled variants,
- chloride- and fluoride-based fuel salts,
- thermal, fast, time variant, and spatially varying neutron spectra,
- wide range of reactor power scales,
- intensive, minimal, or inherent fuel processing,
- multiple different primary system configurations, and compatibility with nearly all fuel cycles

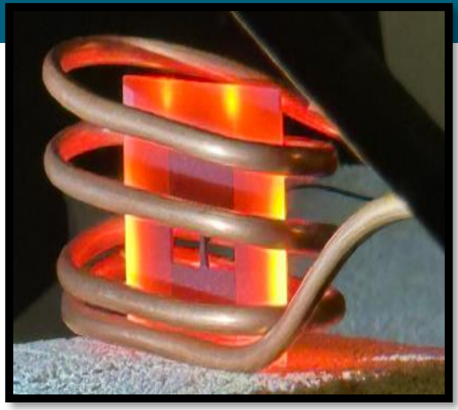
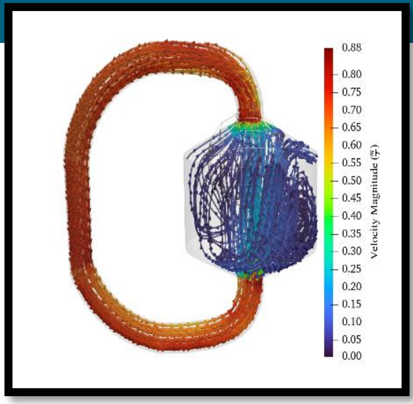


Adaptation of MSR taxonomy from IAEA TRS-489 in 2022

Mission

Vision: The DOE-NE MSR campaign serves as the hub for efficiently and effectively addressing, in partnership with other stakeholders, the technology challenges for MSRs to enter the commercial market.

Salt Chemistry

Determination of the Thermophysical and Thermochemical Properties of Molten Salts – Experimentally and Computationally

MSR Radioisotopes

Developing new technologies to separate radioisotopes of interest to the MSR community

Technology Development and Demonstration – Radionuclide Release

Radionuclide Release Monitoring, Sensors & Instrumentation, Liquid Salt Test Loop

Advanced Materials

Development of materials surveillance technology
Graphite/Salt Interaction
De-risk the transition from 316H to higher performance alloy 709

Mod & Sim

Resolve technical gaps related to mechanistic source term (MST) modeling and simulation tools.
Modeling radionuclide transport from a molten salt to different regions of an operating MSR plant

International Activities

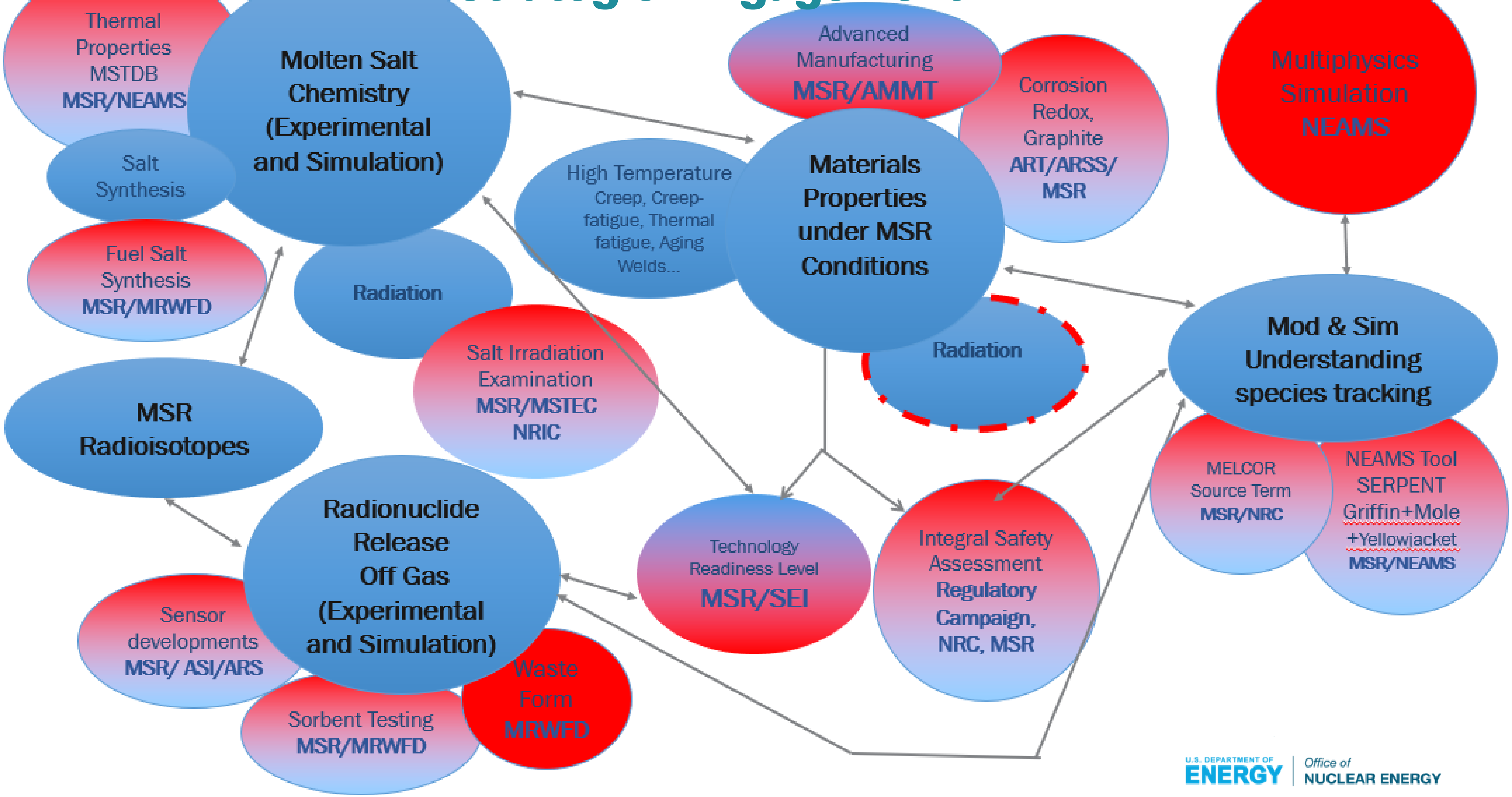
GEN IV International Forum — Expertise | Collaboration | Excellence

IAEA International Atomic Energy Agency

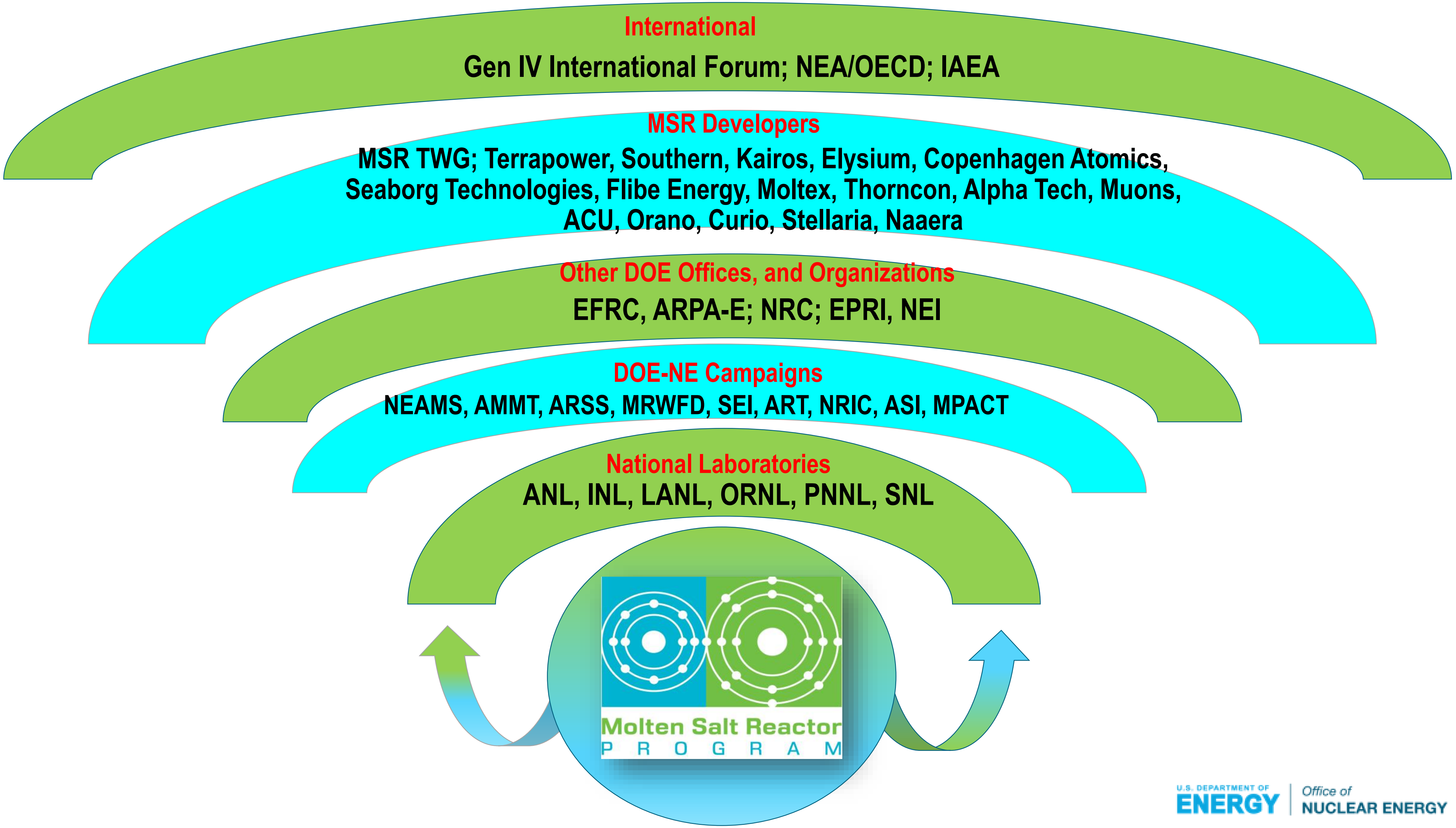
NEA NUCLEAR ENERGY AGENCY

Mission: Develop the technological foundations to enable MSRs for safe and economical operations while maintaining a high level of proliferation resistance.

Strategic Engagement

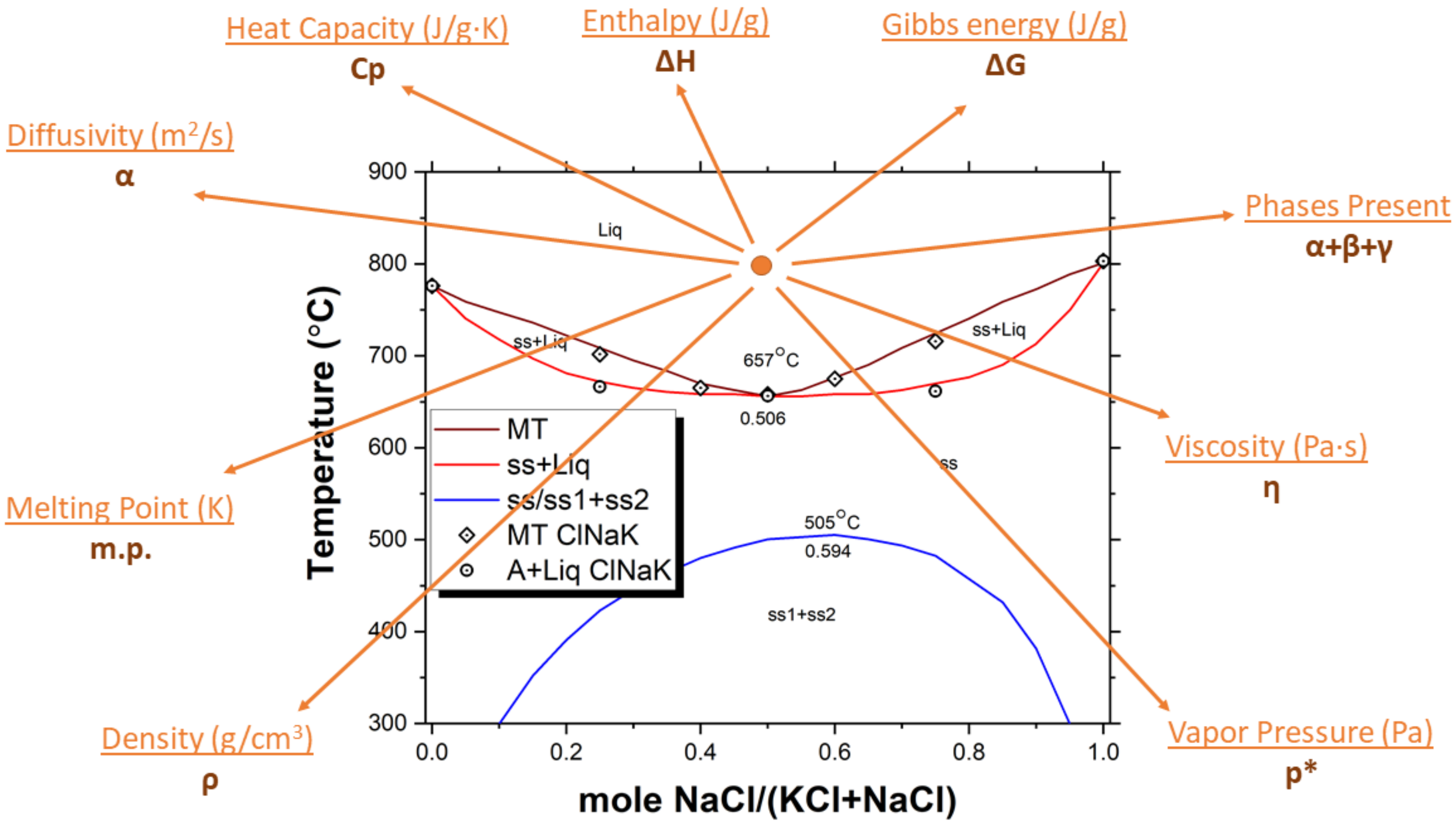


Stakeholders Engagement



Molten Salt Chemistry

Six US National Laboratories engaged in the determination of the thermophysical properties of molten salts in support of the Molten salt Thermal Properties Databases (MSTDB)



Courtesy Jason Lonergan, PNNL

MSTDB-TP Expansion Efforts

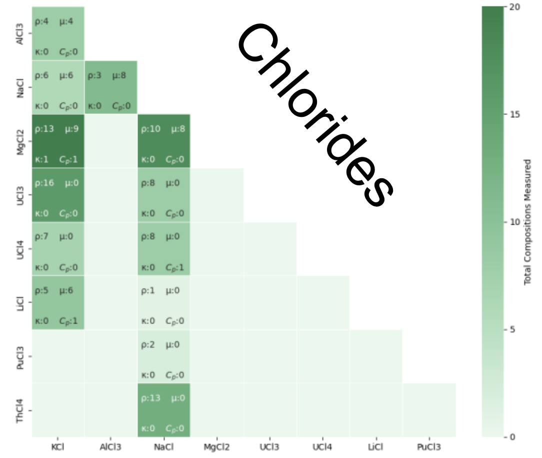
Available @ mstdb.ornl.gov

- **MSTDB-TP has undergone 2 major expansion efforts:**
  - 1.0 to 2.0 (68 entries to 273 entries)
  - 2.0 to 2.1 (273 entries to 448 entries)
- **These expansions incorporate replacements of old datasets as well**
  - E.g. recent literature has suggested UCl3 and relevant mixtures has a lower thermal expansion coefficient than previously understood
- **MSTDB-TP is being expanded for later releases**
  - This includes new pseudo-binary and higher order system data that exist in literature and need evaluated
  - MSTDB-TP will also include new data of new systems as it is published
- **MSTDB-TP is intending on including surface tension data in the future**
  - There is a significant body of literature already evaluated and tabulated

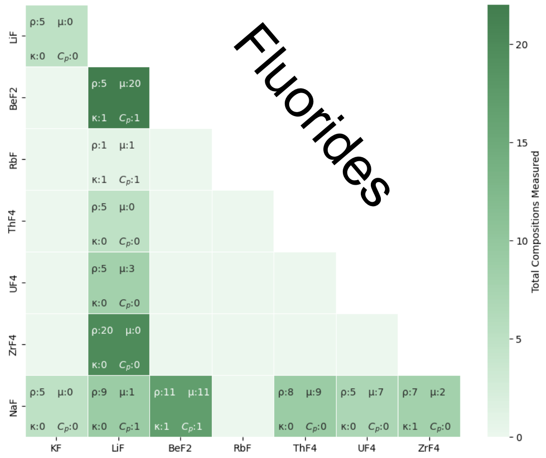
Pure:

Salt	Measurements			
	ρ	μ	κ	c_p
AlCl3	1	1	0	1
BeCl2	1	0	0	0
BeF2	1	1	1	1
CaCl2	1	1	1	1
CaF2	1	1	1	1
GdCl3	1	1	0	0
GdF3	0	0	0	0
KCl	1	1	1	1
KF	1	1	1	1
LaCl3	1	1	0	0
LaF3	1	0	0	1
LiCl	1	1	1	1
LiF	1	1	1	1
MgCl2	1	1	1	1
MgF2	1	1	1	0
NaCl	1	1	1	1
NaF	1	1	1	1
NdCl3	1	1	0	0
NdF3	0	0	0	1
NpCl3	0	0	0	0
NpF3	0	0	0	0
PuCl3	0	0	0	1
PuF3	0	0	0	1
SrCl2	1	1	1	0
SrF2	1	1	1	0
ThCl4	1	0	0	0
ThF4	1	0	0	0
UCl3	1	0	0	1
UCl4	1	0	0	0
UF3	0	0	0	1
UF4	1	1	0	1
ZrCl4	1	1	0	0
ZrF4	1	0	0	0

Binary:



Living database



Ternary:

Salt	Measurements			
	ρ	μ	κ	c_p
KCl-LiCl-NaCl	4	0	0	0
LiCl-NaCl-AlCl3	10	10	0	0
LiF-BeF2-ThF4	3	2	0	0
LiF-BeF2-ZrF4	1	0	0	0
LiF-NaF-BeF2	1	1	0	0
LiF-NaF-KF	1	1	1	1
LiF-BeF2-UF4	36	36	0	0
NaF-BeF2-UF4	79	71	0	0
NaF-KF-BeF2	1	1	0	0
NaF-KF-MgCl2	1	0	0	0
NaF-KF-UF4	1	1	1	1
NaF-KF-ZrF4	1	1	0	0
NaF-LiF-BeF2	4	4	0	0
NaF-LiF-ZrF4	10	1	0	1
NaF-ZrF4-UF4	5	3	2	3
RbF-ZrF4-UF4	2	2	1	1

Quaternary:

Salt	Measurements			
	ρ	μ	κ	c_p
LiF-BeF2-UF4-ThF4	1	1	0	0
LiF-BeF2-ZrF4-UF4	1	0	0	0
NaF-LiF-BeF2-UF4	1	1	0	0
NaF-LiF-KF-UF4	2	2	1	1
NaF-LiF-ZrF4-UF4	1	1	0	1

Courtesy Dianne Ezell and Tony Birri

MSTDB-TC Ver. 3 Released in May 2023

- **Significant increase in content plus a number of systems revised/updated**
- **New values/models generated from our measurements together with reported properties**

New additions for Ver. 3 over Ver. 2 in **bold**

	Fluorides	Chloride	Iodides
Alkali metals	LiF, NaF, KF, RbF, CsF	LiCl, NaCl, KCl, RbCl, CsCl	LiI, NaI, KI, CsI
Alkaline earth metal	BeF_2, CaF_2, **SrF_2, BaF_2**	$MgCl_2$, $CaCl_2$	BeI_2, MgI_2
Transition metals	NiF_2, **CrF_3**	$CrCl_2$, $CrCl_3$, $FeCl_2$, $FeCl_3$, $NiCl_2$	-
Other metals	**YF_3, ZrF_4**	$AlCl_3$	-
Lanthanides	LaF_3, CeF_3, NdF_3, **PrF_3**	$CeCl_3$, **$LaCl_3$**	-
Actinides	ThF_4,UF_3, UF_4	UCl_3, UCl_4, **$PuCl_3$**	UI_3, UI_4
Pseudo-binary	53 systems (v.2) **70 systems (v.3)**	60 systems (v.2) **70 systems (v.3)**	10 systems (v.2) **30 systems (v.3)**
Pseudo-ternary	25 systems (v.2) **30 systems (v.3)**	22 systems (v.2) **27 systems (v.3)**	None (v.2) **15 systems (v.3)**

New Content

BeF_2 and ZrF_4

- $LiF-BeF_2$
- $NaF-BeF_2$
- $KF-BeF_2$
- $CsF-BeF_2$
- BeF_2-UF_4
- BeF_2-ThF_4
- BeF_2-ZrF_4
- $LiF-ZrF_4$
- $CsF-ZrF_4$

Reciprocal

- LiF-CsI
- LiF-KI
- LiF-NaI
- KI-CsF
- KF-CsI
- NaF-KI
- KF-NaI
- NaF-CsI

Iodides

- KI-CsI
- NaI-LiI
- LiI-KI
- NaI-KI
- NaI-CsI
- LiI-CsI

Higher Order

- LiF-LiI-CsI
- LiF-LiI-NaI
- LiF-LiI-KI
- LiF-CsF-CsI
- LiF-KF-KI
- LiF-NaF-NaI
- LiF-NaF-NaI
- NaI-NaF-KF
- KF-KI-NaF
- NaF-NaI-KF
- LiF-NaF-CsI
- LiF-KF-CsI
- LiF-KF-CsI
- NaF-KF-CsI
- LiF-KF-CsF-CsI
- CsI-LiF-NaF-KF
- $MgCl_2-NaCl-UCl_{3,4}$
- $MgCl_2-KCl-UCl_{3,4}$

Courtesy Prof. Ted Besmann

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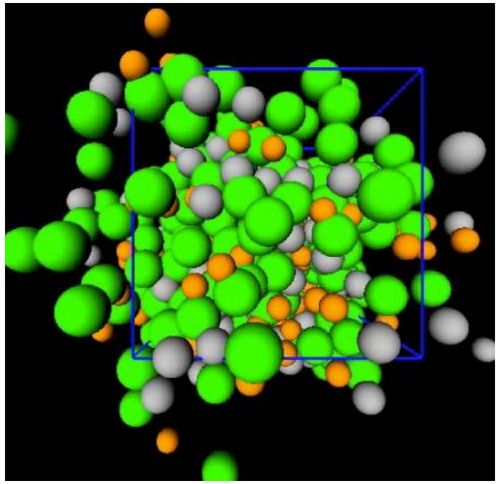
MSTDB-TC Thermochemical (Experimental) Data Needs for the MSR Program

- **Selective data needs for current system assessments**
  - **LiF-NiF_2** system: Need enthalpy of mixing, Cp for intermediate compound
  - **NaF-NiF_2** system: Need enthalpy of mixing, Cp for intermediate compounds
  - **KF--NiF_2** system: Need enthalpy of mixing, Cp for intermediate compounds
  - **$PuCl_3$** systems with **LiCl, NaCl, KCl, $MgCl_2$**: MSTDB-TC improved with phase equilibria, enthalpies of mixing, Cp for the intermediate compounds
- **System information and/or assessments needed for new reciprocal salt models**
  - **UI-$UF_{3,4}$**
  - **UI-$UCl_{3,4}$**
  - **BeI-BeF_2**
- **Phase Equilibria for Be-containing Systems Requiring Experimental Determination**
  - **BeF_2-CrF_2, BeF_2-FeF_2**, and **BeF_2-NiF_2**
  - **LiF-BeF_2-CrF_2, LiF-BeF_2-FeF_2**, and **LiF-BeF_2-NiF_2**

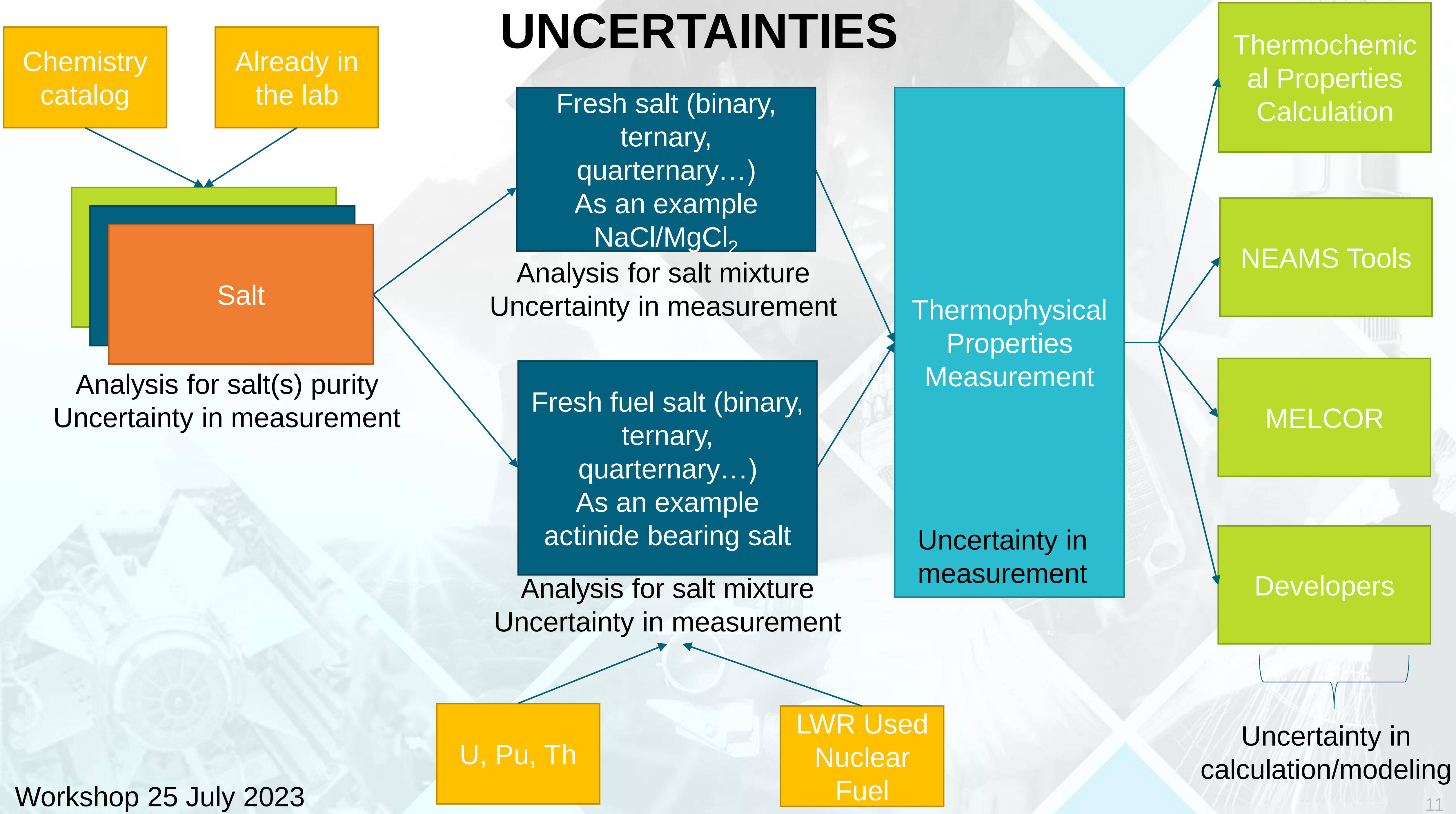
- **Atomistic modeling complementary to experiments**
  - Methods: We employ ab initio molecular dynamics (AIMD) as the primary tool. Data science approaches are also applied to accelerate discoveries.
  - Properties: We investigate a broad range of properties of molten salts, including liquid density, specific heat, mass and heat transport, and structure.

Computing facility at PNNL



Courtesy Toni Karlsson, INL Manh Thuong Nguyen, PNNL

UNCERTAINTIES



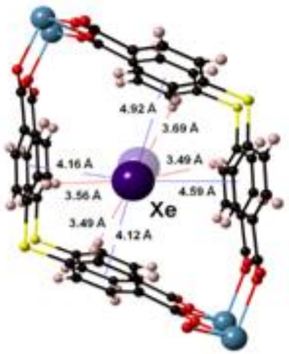
Technology Development and Demonstration

Multi-faceted approach to investigation of technologies for MSR off-gas systems

Component testing

- Large Scale Test Loop

- Xe/Kr separation in MOF

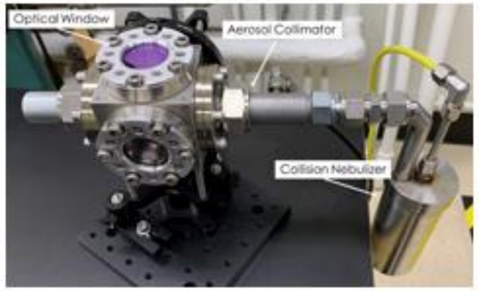


Radionuclide identification/speciation

Raman

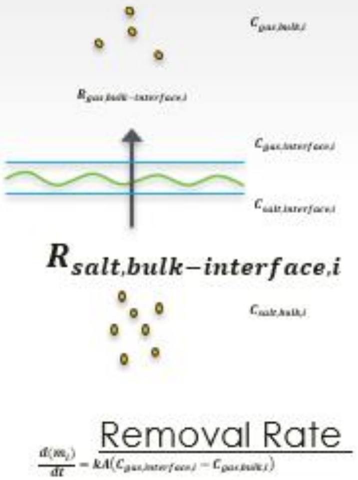
405 nm 532 nm 671

LIBS



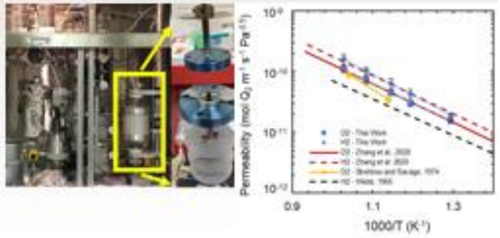
Source term modeling

- Gas-liquid interface
- Provides source term to off-gas

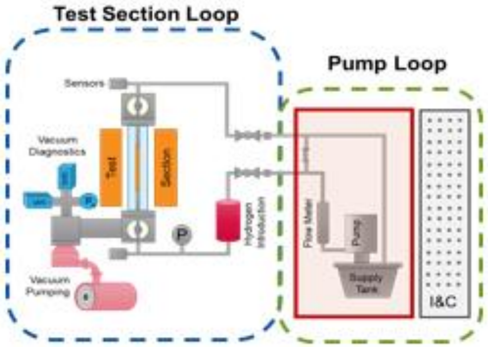


Tritium permeation

- Hydrogen isotope permeability in Hastelloy N



- Tritium transport salt loop



Sensors/ salt chemistry

- Salt composition
- Redox state
- Salt level

Particulate Monitoring

Automated Salt Sampling

Molten Salt Spill Accident

Processes for which experimental data are being generated to develop, parameterize, and validate models:

Spreading and flowing

- On containment floor and through tubing into drain tank

Heat transfer

- By convection, conduction, and radiation

Interactions with structural materials

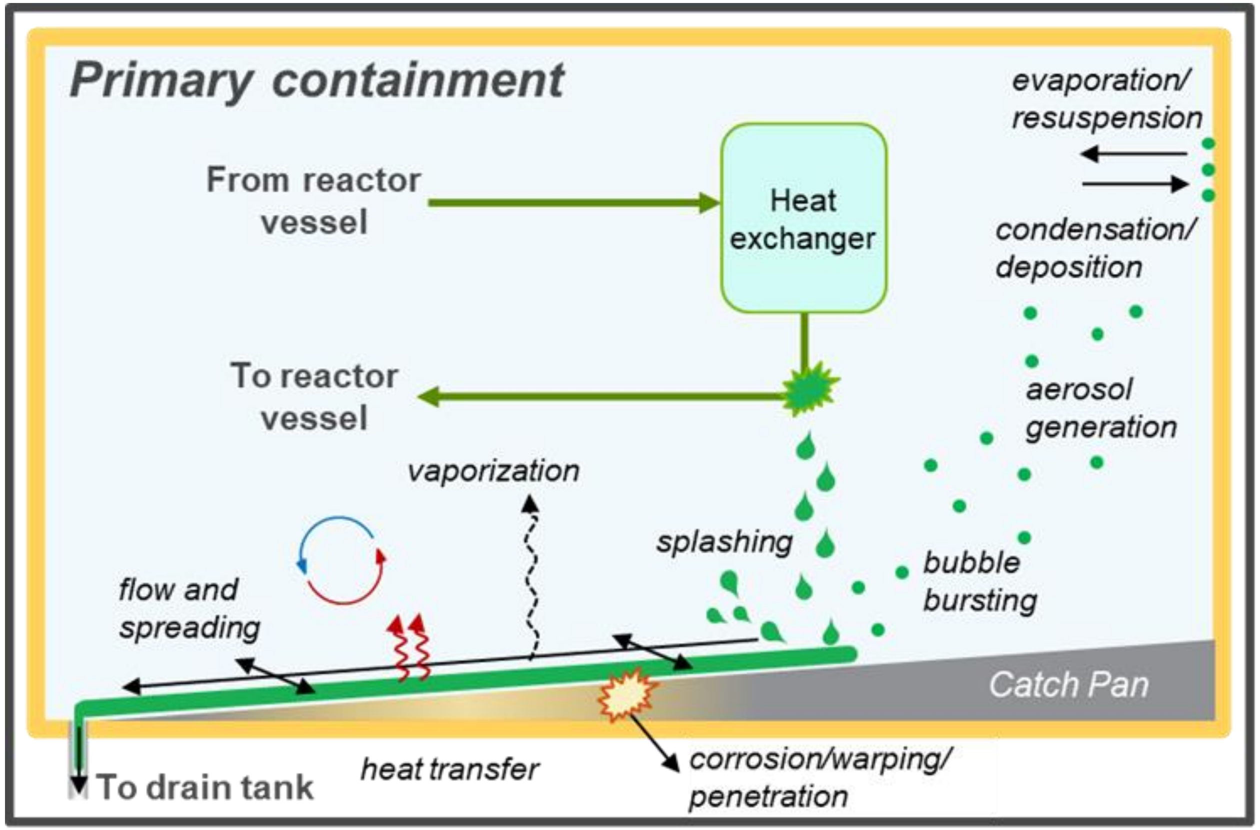
- Warping and corrosion

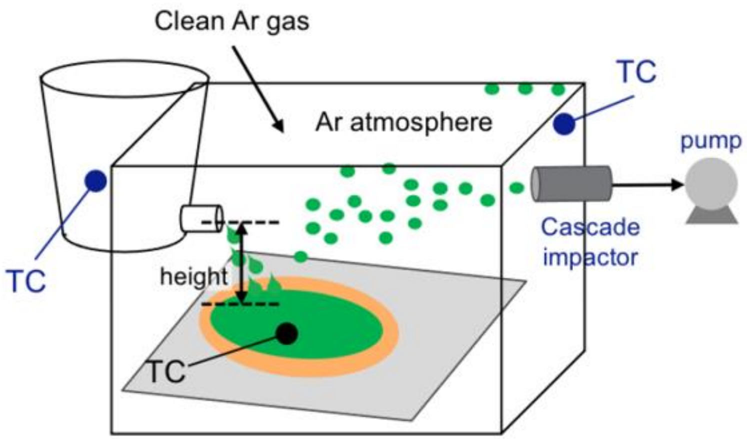
Vaporization and condensation

Aerosol and splatter formation

- Due to splashing, spraying, bubble bursting, and vapor nucleation

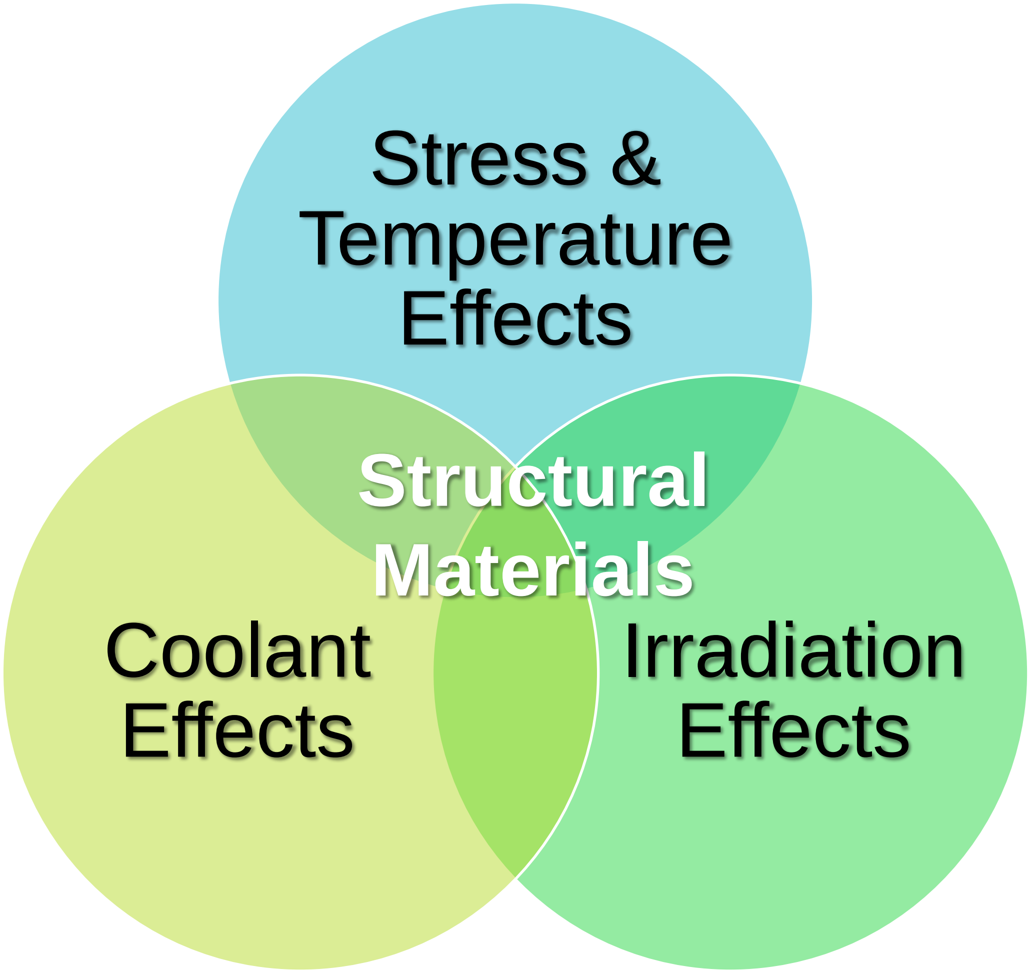
For MSR: salt spilling onto primary containment floor





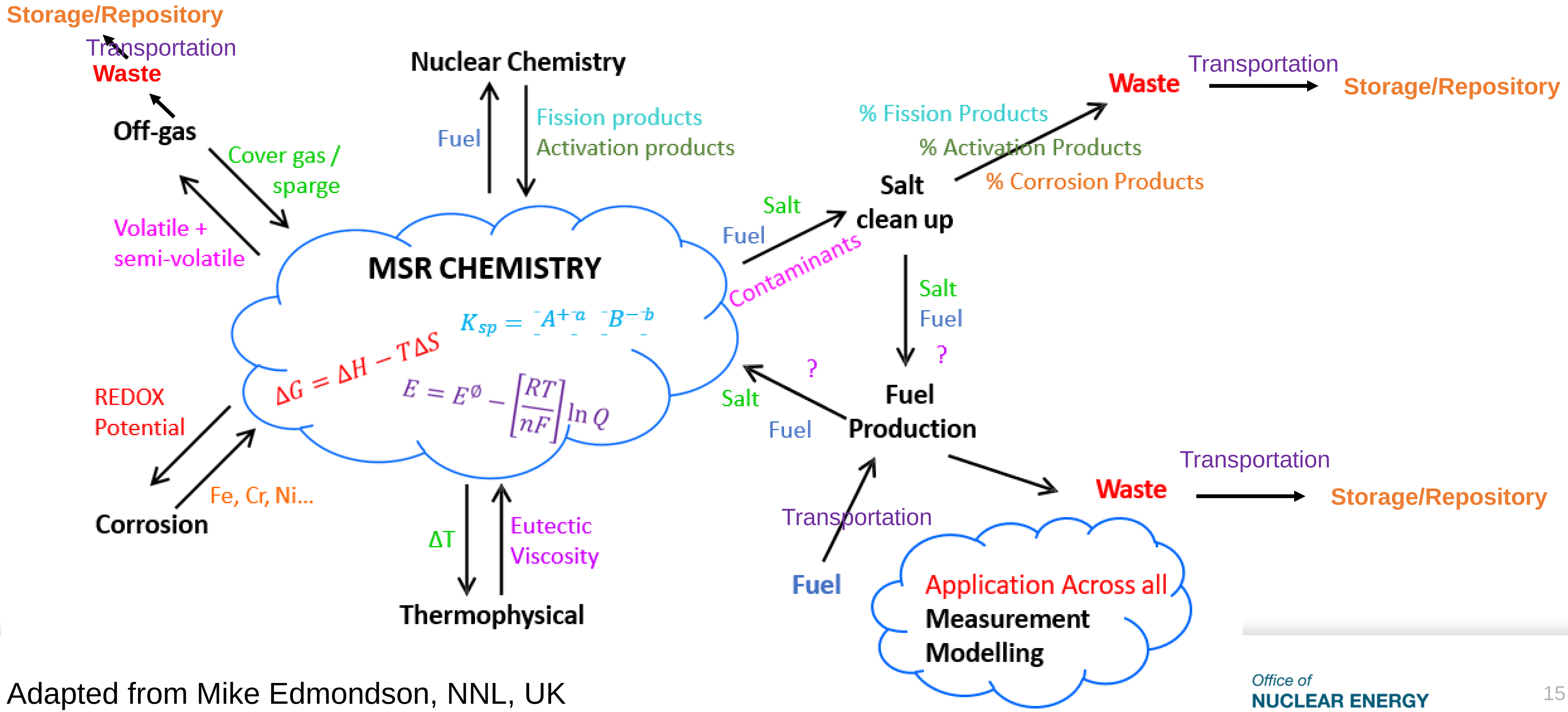
Materials Surveillance Technology

- Synergistic material degradation effects in operating reactors
- A technology gap is the availability of surveillance test articles that can induce mechanical damage passively during reactor operation and interact synergistically with materials degradation due to corrosion and irradiation
- This work bridges this gap by developing and maturing such materials surveillance technology



Courtesy Sam Sham, INL

WHERE IS THE CHEMISTRY IN AN MSR ?



Adapted from Mike Edmondson, NNL, UK
IAEA consultancy meeting 6-7 June 2023

New MSR Program Website

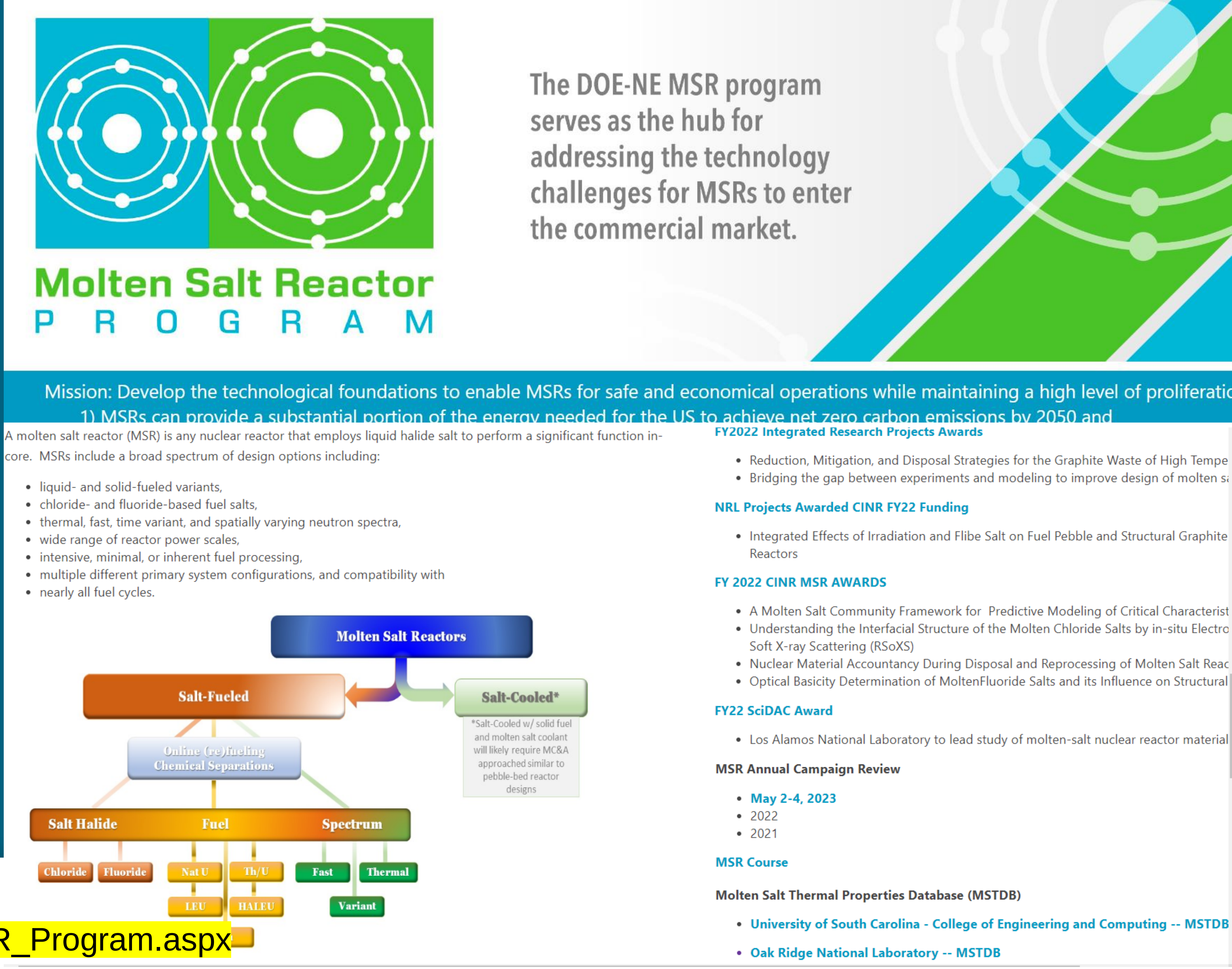
Information on:

MSTDB

MSR Campaign Review Meeting

Publications/Reports

GIF webinars



https://gain.inl.gov/SitePages/MSR_Program.aspx

MSR Campaign Reports

- Melissa Rose et al., “Effect of Cs and I on Thermophysical Properties of Molten Salts “, M3AT-23AN0705011M3AT, SEP 2023
- Melissa Rose et al. “Workshop-Uncertainty in MS Property Measurements and Predictions: Sent milestone report ANL/CFCT-23/32 t”, M3AT-23AN0705013, SEP 2023
- Trou Askin et al “Progress Report on Identification and Resolution of Gaps in Mechanistic Source Term Modeling for Molten Salt Reactors”, SAND-2023-10090, SEP 2023
- Bruce McNamara, “Chlorine isotopes separations, mid-year report, *M4AT-23PN1101043, PNNL -34297, May 2023*
- *Bruce Pint, et al. “The Dissolution of Cr and Fe at 850C in FLiNaK and FLiBe,* M3RD-23OR0603032, ORNL/SPR-2023/3170, SEP 2023
- Bruce Pint et al., “Measuring the Dissolution of Cr and Fe at 550°C-750°C in FLiNaK and FLiBe, ORNL/SPR-2023/3169, SEP 2023
- Ting-Leung Sam et al, “ Development of Surveillance Test Articles with Reduced Dimensions and Material Volumes to Support MSR Materials Degradation Management , INL /RPT-23-74540 , SEP 2023
- Mark Messner, “Modeling support for the development of material surveillance specimens and procedures”, NL-ART-268, SEP 2023
- Thomas Hartmann, , “Modeling of Austenitic MSR Alloys with Supporting Experimental Data-Part 2: Diffusion controlled corrosion in austenitic MSR containment alloys ,PNNL-34802, SEP 2023
- Sara Thomas “ Integrated Process Testing of MSR Salt Spill Accidents , ANL/CFCT-23/25 SEP 2023
- Hunter Andrews, “Establishing Isotopic Measurement Capabilities using Laser-Induced Breakdown Spectroscopy for the Molten Salt Reactor Campaign” (ORNL/TM-2023/3067. SEP 2023
- Kevin Robb et al. “*Molten Salt Loop testing of Sensors and Off-Gas Components: FY23 Progress”,* ORNL/LTR-2023/3087 *, SEP 2023*
- Nathaniel Hoyt, Assessment of salt sensor Performance, , M3RD-23AN0602061 , SEP 2023
- Danny Bottenus et al, “Molten Salt Reactor Radioisotopes Separation by Isotachophoresis”, PNNL-34997, SEP 2023
- Anne Campbell, “ Be2C synthesis, properties, and ion-beam irradiation damage characterization “, ORNL/TM-2023/3011 , AUG 2023
- Joanna McFarlane et al., Design of Instrumentation for Noble Gas Transport in LSTL Needed for Model Development “, ORNL/TM-2023/3138, SEP 2023
- S. Walker et al., “Application of NEAMS Multiphysics Framework for Species Tracking in Molten Salt Reactors”, INL/RPT-23-74376, (2023).

Strong Momentum for MSR

6-8 SEP 2023

Workshop on MSR chemistry and the Fuel Cycle
19-21 September 2023
Argonne National Laboratory

2-6 October 2023, Vienna Austria

16-20 OCT 2023

Gen IV International Forum - Webinars

https://www.gen-4.org/gif/jcms/c_84279/webinars

Series 8: Fluoride-Cooled High-Temperature Reactors (FHR)

- 27 April 2017
  Presenter: Prof. Per Peterson, UC Berkeley, USA
  Watch WEBCAST | DOWNLOAD PRESENTATION | VIDEO

Series 9: Molten Salt Reactors (MSR)

- 23 May 2017
  Presenter: Dr. Elsa Merle, CNRS, France
  Watch WEBCAST | DOWNLOAD PRESENTATION | VIDEO

Series 44: Molten Salt Reactor Safety Evaluation - A US Perspective

- 26 August 2020
  Presenter: Dr. David Holcomb, ORNL, USA
  Watch WEBCAST | DOWNLOAD PRESENTATION

Series 79: Off-gas Xenon Detection and Management in Support of Molten Salt Reactors

26 July 2023
Presenters: Hunter Andrews, ORNL, USA and Praveen Thallapally PNNL, USA
Watch WEBCAST | DOWNLOAD PRESENTATION

Series 21: Molten Salt Actinide Recycler and Transforming System with and Without Th-U support: MOSART

- 07 June 2018
  Presenter: Dr. Victor Ignatiev, Kurchatov Institute, Russia
  Watch WEBCAST | DOWNLOAD PRESENTATION | VIDEO

Series 73: Molten Salt Reactors taxonomy and fuel cycle performance

25 January 2023
Presenter: Dr. Jiri Krepel, Paul Scherrer Institute, Switzerland
Watch WEBCAST | DOWNLOAD PRESENTATION

Series 66: Nuclear Waste Management Strategy for Molten Salt Reactor Systems

15 June 2022
Presenter: Dr. John Vienna and Dr. Brian Riley, PNNL, USA
Watch WEBCAST | DOWNLOAD PRESENTATION

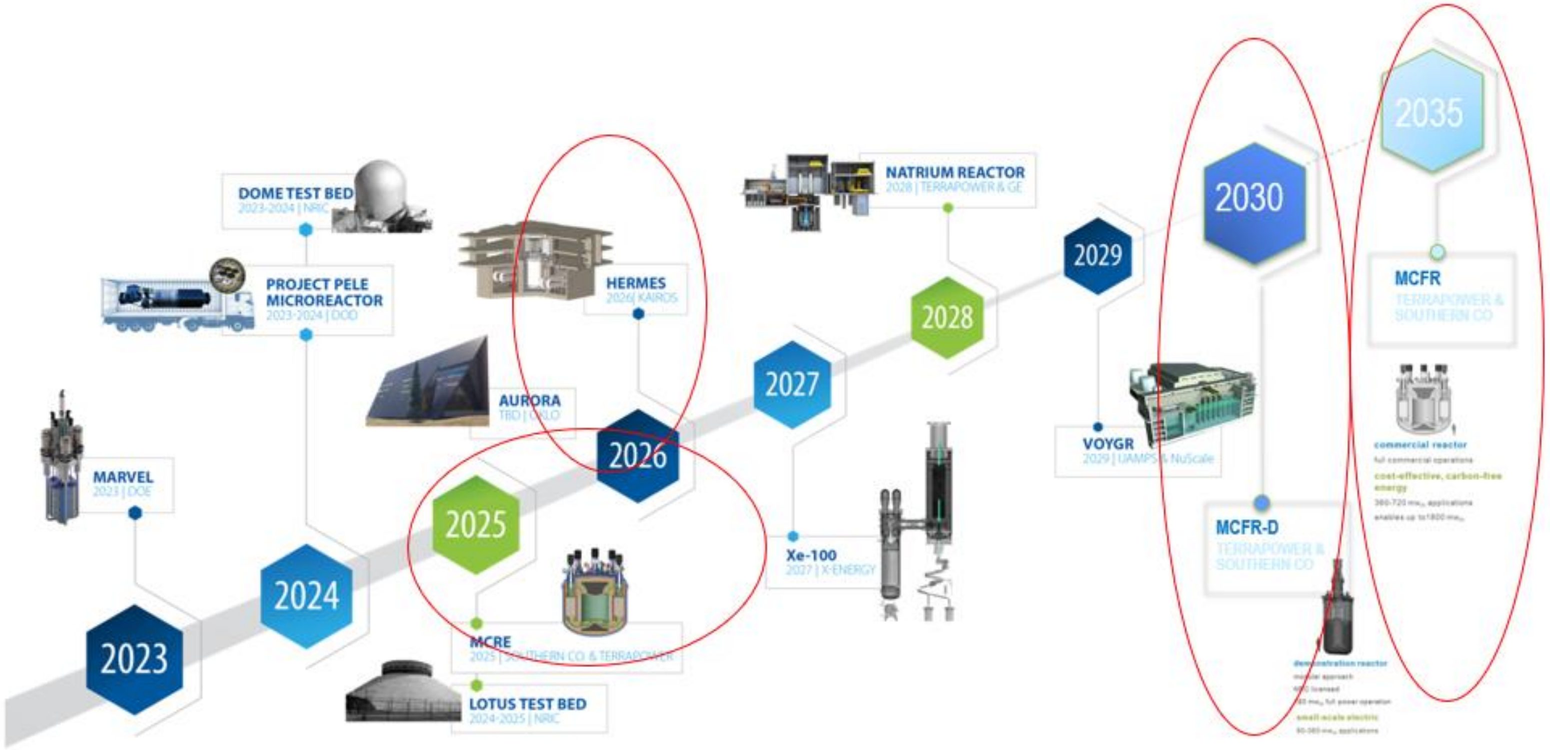
Conclusion

US government science and technology development programs support MSRs and other applications for molten salt technology. Opportunities exist to strengthen coordination among all programs supporting molten salt technology.

MSRs have **less data on the performance of safety features** than other advanced reactors.

Increased resources are needed to **overcome the remaining MSR technology hurdles** and improve economic viability

Increased coordination within the MSR community is needed



Adapted From Dr. Shannon Bragg-Sitton, INL – GIF webinar presented on 19 April 2022
“ Role of Nuclear Energy in decreasing CO_2 Emission”


Clean. Reliable. Nuclear.
ENERGY
NUCLEAR ENERGY

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Thank you

Patricia.Paviet@pnnl.gov

509-372-5983

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Molten Salt Reactor PROGRAM

Argonne NATIONAL LABORATORY

Molten Salt Research at Argonne National Laboratory

Melissa A. Rose

MSR Developer Workshop, ORNL October 25-26, 2023

Support a FOAK MSR by 2035

Activities At Argonne:

- Make high-quality measurements of molten salt properties
- Develop standardized measurement methods
- Perform salt spill tests generate data for accident scenario analysis
- Develop sensors for chemistry control and MC&A
- Develop molten salt test bed

Generate data and develop technologies needed to design, license and operate MSRs

- Thermal properties of molten salts with and without fission products
- Data to support accident scenario analysis
- Technologies for monitoring chemistry for operation control and MCA and safeguards

Actively engaging with industry to address needs for MSR development

- Coordinating GAIN, NEUP, and direct-funded activities with MSR developers
- Hosting regular discussions to enhance collaboration between national labs and stakeholders.
- Coordinating with ORNL to incorporate new data and quality assessments into the Molten Salt Thermal Database to facilitate use by MSR developers

Argonne Expertise and capabilities for advancing MSRs

- Thermophysical property measurements
- Materials compatibility and corrosion studies
- Electrochemical monitoring and control of salt chemistry and materials accountability
- Linking understanding of fuel cycle chemistry and engineering

Radiological facility housing purpose-built inert atmosphere gloveboxes used for measurements with salts containing actinides, beryllium and simulated fission products

- **Glovebox furnace wells from six to thirty-six inches with furnace capability to 800°C**
- **Induction and resistance furnaces for high temperature applications**

Thermophysics laboratory with equipment located in argon-atmosphere radiological gloveboxes

Molten Salt Property Measurements at Argonne

- Phase transition temperatures
- Heat Capacity
- Thermal Diffusivity and Conductivity
- Viscosity
- Density
- Vapor Pressure
- Mass Diffusion Coefficients
- Activity Measurements

Compositional analyses for major and minor elements, trace contaminants including dissolved oxygen

Rotational Viscometer Installed in a Glovebox for Measuring Molten Salt Viscosity

Development of standard measurement methods

- Proceduralized measurement methods to generate records suitable for NQA-1 qualification of results
- Leading task group for standardizing rotational viscometer measurement method formed at June 2023 ASTM meeting.
- Hosting tri-weekly MSR Chemistry discussions to coordinate collaborations between national labs on measurements of molten salt properties.

Laser Flash Analyzer for Measuring Thermal Diffusivity of Molten Salts

Measuring Effects of Fission Products on Molten Salt Thermal Properties

Measured thermal behaviour, heat capacity and thermal diffusivity of salts doped with fission products for comparison with measurements of the same salts without dopants.

Eutectic NaCl-UCl_3 with CsCl and CsI dopants

Two doped FLiNaK salts representing high and low burn up

- Inspired by depletion calculation results for MSRE
- Same salts as used in salt spill testing to provide fundamental data

Doped NaCl-UCl_3 Composition

Compound	Concentration, mol %
NaCl	65
UCl_3	34
CsCl	0.9
CsI	0.01

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
Te	0.005	0.025

Pure FLiNaK

Doped FLiNaK (low burnup)

Doped FLiNaK (high burnup)

M.A. Rose, L. Gardener, T.T. Lichtenstein. *Property Measurements of NaCl-UCl3 and LiF-NaF-KF Molten Salts Doped with Surrogate Fission Products*. ANL/CFCT-23/23. Sept. 2023.

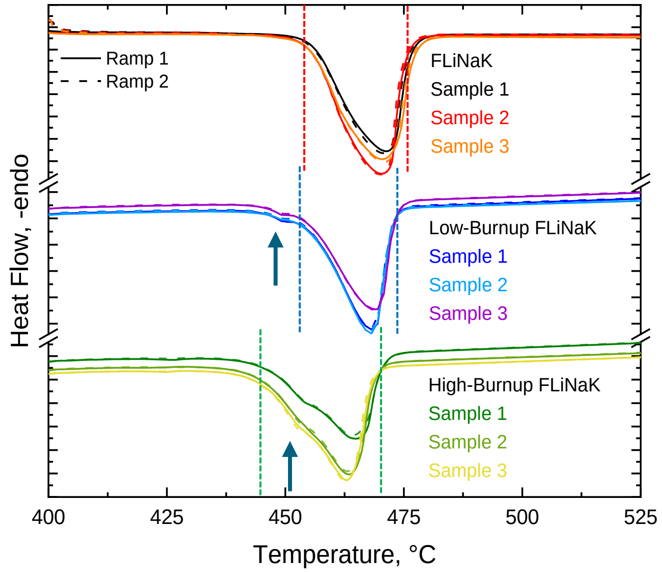
Fission Products Have Only Minor Effect on Thermal Properties

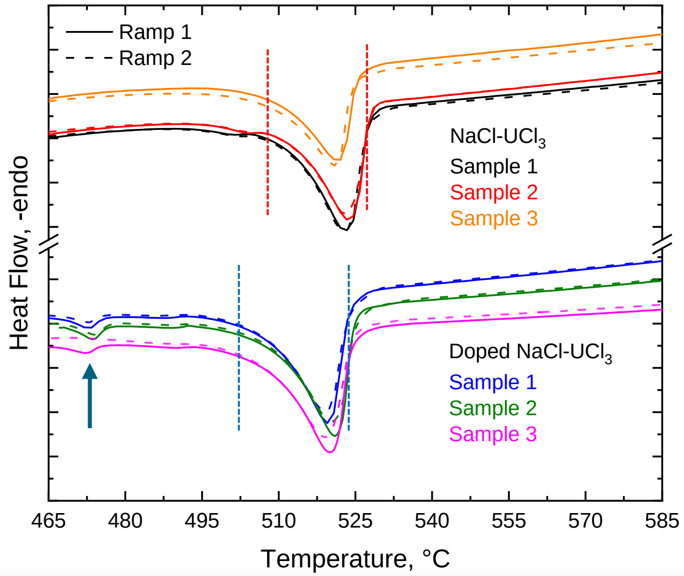
Fission products depress onset of melting and liquidus temperatures

Fission products introduce additional low temperature features.

Fission products at these concentrations do not produce a measurable change in heat capacity and thermal diffusivity

- **Measured thermal behavior of salt samples encapsulated in sealed gold cells by differential scanning calorimetry (DSC) :**
  - ➢ Replicate analyses are shown by solid and dashed colored curves
- **Dopants shift the eutectic transition to slightly lower temperatures**
  - ➢ Onset of melting and liquidus shown as vertical dashed lines
- **Additional transitions are observed in doped salt**
  - ➢ Indicated by arrows





M.A. Rose, L. Gardener, T.T. Lichtenstein. *Property Measurements of NaCl-UCl3 and LiF-NaF-KF Molten Salts Doped with Surrogate Fission Products*. ANL/CFCT-23/23. Sept. 2023.

Workshop Addressing Uncertainty in Molten Salt Thermal Property Values and Predictions

July 25, 2023

Four sessions with presentations and discussions:

1. Quality Assessment of Measured Property Values
2. Quantifying Uncertainty in Property Models
3. Quantifying Consistency of Property Predictions with Measured Values
4. Quantifying Uncertainty in System Models

Recommendations from the workshop report:

- Continue to apply transparent, thorough, and documented quality assessment processes to data in both MSTDB-TC and -TP.
- Quantify the uncertainty in model predictions where data gaps must be bridged by modeling; use of Bayesian statistics was recommended.
- Standardize methods for measuring the thermal properties of molten salts to enable the generation of high-quality property data.
- Identify and produce a standard reference material to enable researchers to quantify the accuracy of property measurement methods and cross-compare work from different labs and using different methods.
- Promote regular interaction between modelers and those measuring properties of molten salts to communicate identified needs for specific data.

Salt Spill Tests

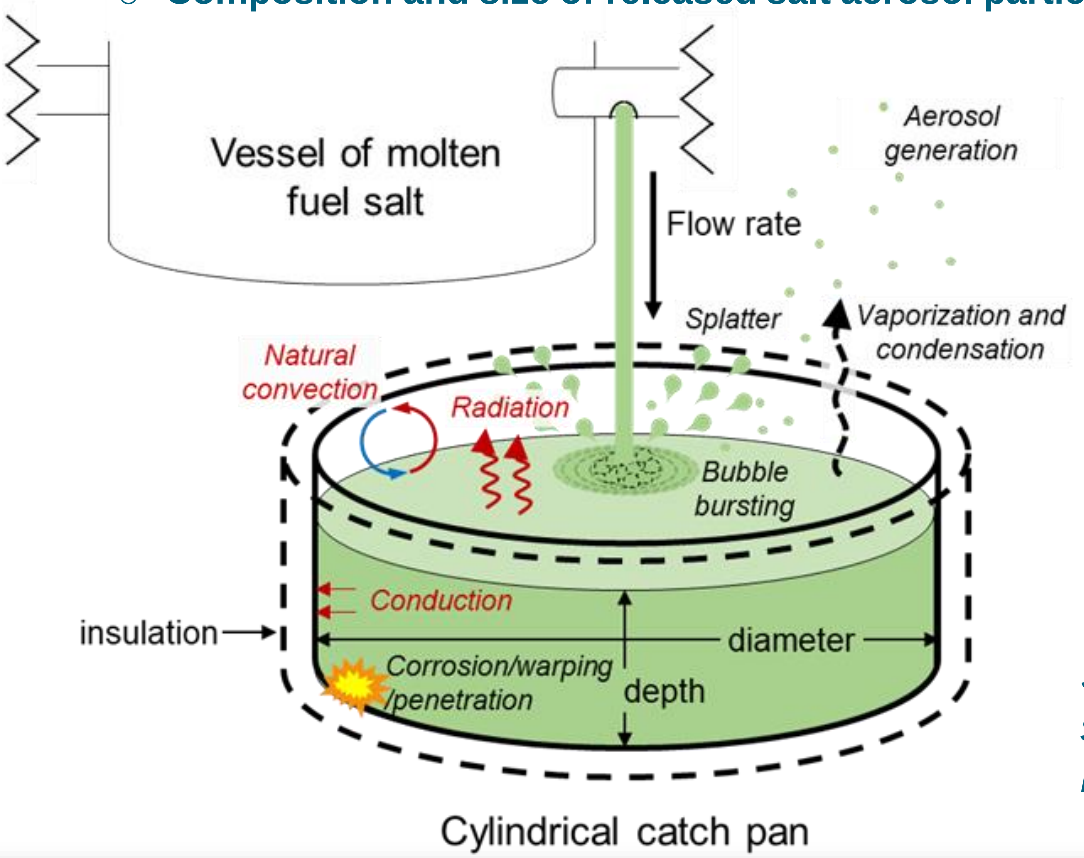
Objective: To provide the experimental data that are needed to close identified gaps in mechanistic source term and accident progression models to support MSR licensing

FY23 test results will be presented at poster session by Sara Thomas

Integrated process tests are being conducted that simulate molten fuel salt spill accidents at a laboratory scale to generate essential experimental data.

Quantified processes include:

- **Heat transfer from spilled molten salt pool to surroundings**
- **Compositional changes to bulk salt after spilling**
- **Composition and size of released salt aerosol particles**



Schematic of molten salt spill scenario being simulated in laboratory-scale tests

Thomas, S., and Jackson, J. (2023). *Integrated process testing of MSR salt spill accidents*. Argonne National Laboratory report ANL/CFCT-23/25.

Molten Salt Technology Testbeds

Argonne has several flow systems, purification systems, and large-scale vessels that act as testbeds for molten salt technology development

These highly modular systems enable engineering-scale testing of a wide variety of new molten salt technologies for process monitoring, control, corrosion studies, material accountancy, etc.

Some of Argonne's flow systems are installed within large-scale gloveboxes. This approach enables:

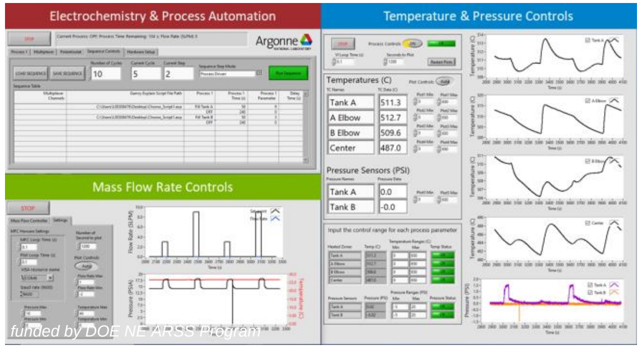
- Straightforward operations with a variety of actinide fuel salts
- Rapid reconfiguration of the flow systems (changing pipe diameters, test sections, etc.)
- Easy removal and installation of new modular components and instrumentation

funded by DOE NE ARSS Program

funded by DOE NE ARSS Program

Many of these flow systems are fully automated. This has allowed us to readily achieve:

- Long-duration salt operations extending into multiple years
- Component testing under thousands of different test conditions



funded by DOE NE ARSS Program

Molten Salt Sensors

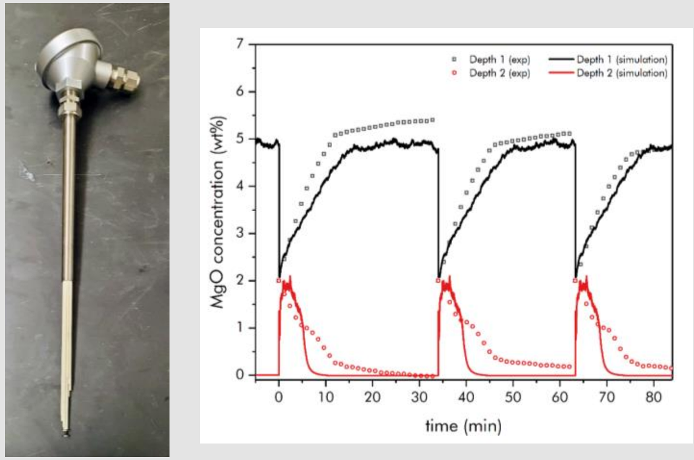
Argonne has developed monitoring technologies for a variety of molten salt equipment including flow loops, salt purification systems, and process vessels.

Deployable sensors for composition, redox state, particle concentrations, etc. have been demonstrated.

Electrochemical Monitoring of Salt Composition

Windowless Optical Monitoring of Composition

Automated Salt Sampling



Particulate Monitoring

Molten Salt Reactor Fuel Cycle Chemistry Workshop

Held at Argonne National Laboratory

September 19-21, 2023

Invited experts in MSR Fuel Cycle Chemistry from National Labs, Universities, Industry, DOE, NRC and other R&D organizations

- 46 attendees from 19 institutions
- 10 industry participants
- 28 national lab participants
- 5 university participants
- Department of Energy and Nuclear Regulatory Commission

Workshop held to assist the office of material and chemical technologies (NE43) to develop fuel cycle technologies for molten salt advanced reactors in advance of their deployment

Identify technological gaps in the molten salt fuel cycle and future research directions to close these gaps

Front End Topics:

- Synthesizing
- Purifying
- Scale-up of fuel synthesis
- Fuel Qualification

Back End Topics:

- Recovering and recycling actinides
- Purifying used salts
- Insoluble fission product removal
- Safeguards for molten salt fuel cycle facilities

Argonne NATIONAL LABORATORY

Report to be issued in December 2023

U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Summary

Argonne supports the development of Molten Salt Reactors by:

- Making high-quality measurements of molten salt properties
- Standardizing molten salt property measurement methods
- Generating data for accident scenario analysis through salt spill tests
- Developing molten salt sensors for chemistry control and MC&A
- Developing a molten salt test bed for validation of molten salt sensors

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.

Molten Salt Reactor PROGRAM

Argonne NATIONAL LABORATORY

Thank you

Melissa A. Rose
marose@anl.gov

U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Pacific Northwest NATIONAL LABORATORY

Overview of PNNL Capabilities in Support of MSR Development

Praveen K. Thallapally

PNNL-SA-191673

Pacific Northwest National Laboratory
Richland, Washington 99352

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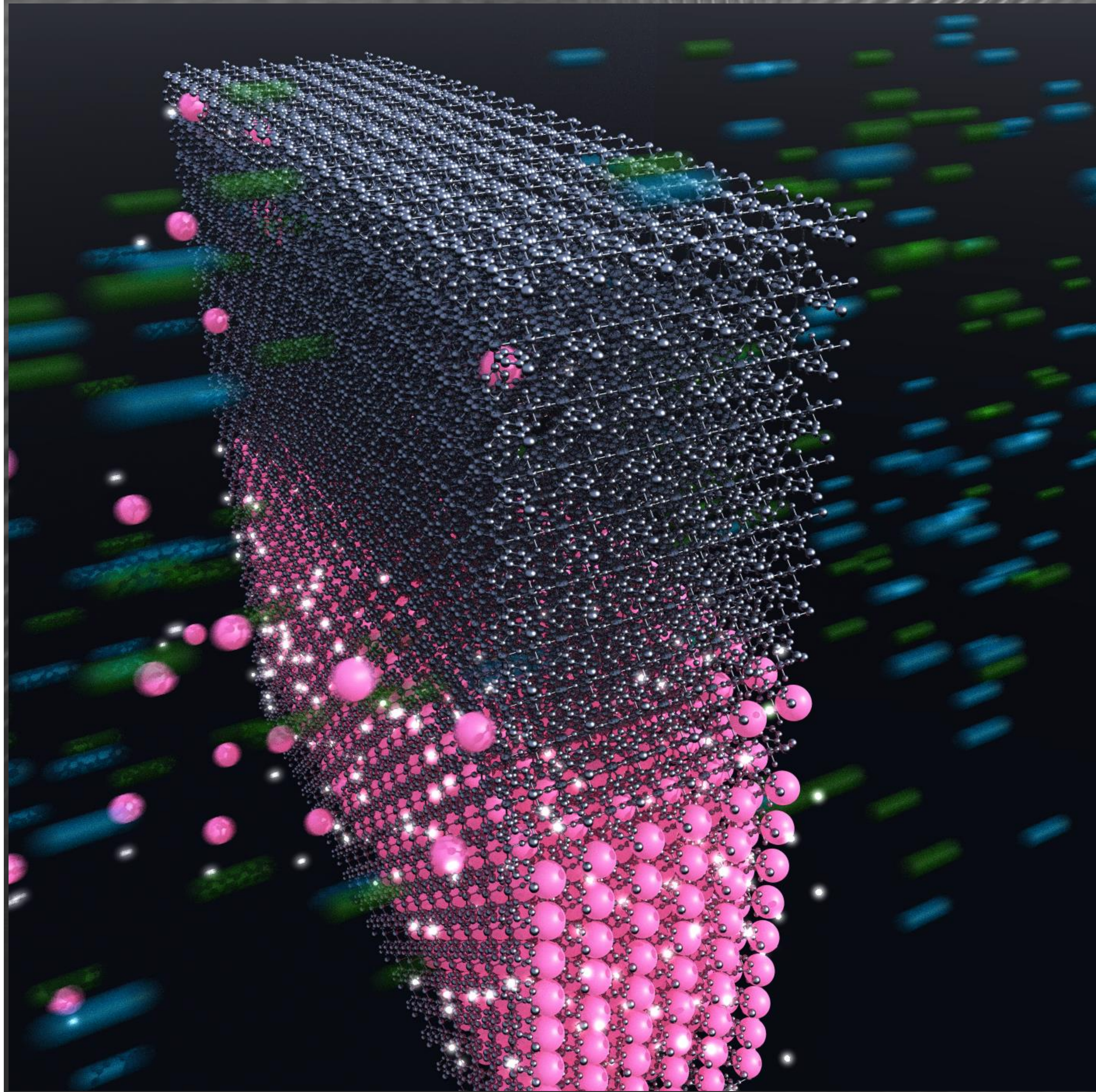
PNNL is operated by Battelle for the U.S. Department of Energy



Acknowledgements

DOE, NE-5, NE-4 and NNSA Offices

Dr. Patricia Paviet and Dr. Ken Marsden, NTDs

Dr. Manh-Thuong Nguyen –Ab initio calculations
Dr. Kyle Makovsky – Thermophysical properties
Dr. Tatiana Lewinsky – Easy-XAFS
Dr. Thomas Hartmann - Corrosion
Dr. Bruce McNamara, Dr. Zach Huber, Dr. Connor Hilton – Chloride and fluoride salt
Dr. Bruce McNamara, Dr. Zach Huber, Dr. Mike Powell, Dr. Tyler Schlieder – Chlorine isotope separation
Dr. Danny Bothenus – Electrophoresis (chlorine isotope separation)
Dr. Amanda Lines and Dr. Samuel Bryan - OLM
Dr. Praveen K. Thallapally – Off-gas management
Dr. Brian Riley – Waste form development
Dr. Mark Murphy – Radiation testing

Ali Zbib – Industry POC at PNNL

Pacific Northwest
NATIONAL LABORATORY

DOE's 17 national laboratories tackle critical scientific challenges

Radiochemical Processing Laboratory (RPL)

Vital asset for nuclear research

- Nuclear energy, waste treatment, materials characterization, nonproliferation, weapons stockpile, and isotope production
- Hazard Category II; Safeguard Category II/III Nuclear Facility
- Only radionuclide monitoring lab in the U.S. certified by the Comprehensive Nuclear-Test-Ban Treaty Organization to process air particulate samples
- Microgram-to-kilogram quantities of fissionable materials; megacuries of other radionuclides

PNNL Capabilities

- Predict fundamental properties of molten salts using computational tools
- Validate models by synthesis and characterization of molten salts
- On-line monitoring, off-gas management, and isotope separation
- Waste-form development
- Materials Corrosion
- Prototype development and testing in collaboration with industrial partners
- Commercialization and technology transfer

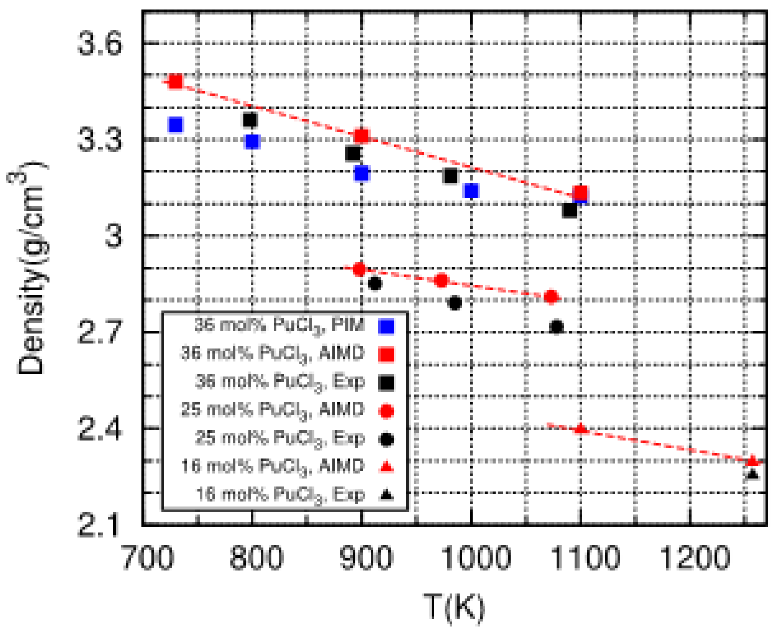
Ab Initio Molecular Dynamics (AIMD) and Data Science Capabilities

Pacific Northwest
NATIONAL LABORATORY

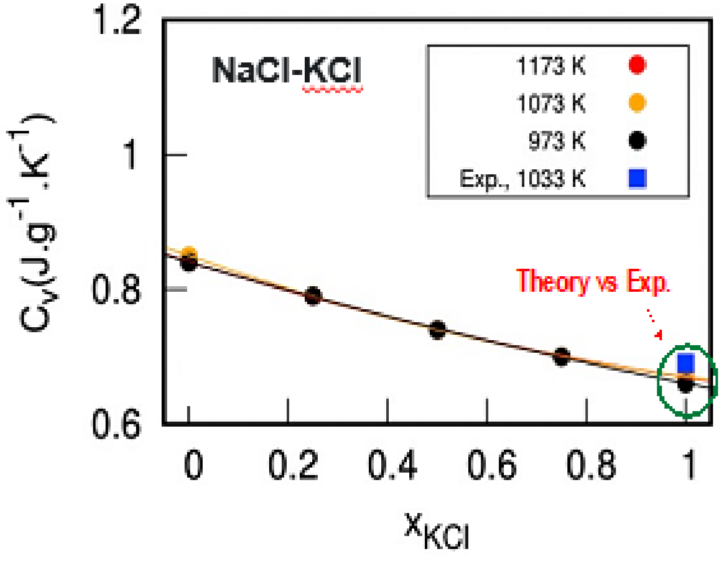
Complementary to experiment.

- Predict fundamental properties.
- AIMD simulations, especially, of actinide-containing systems for liquid density, thermodynamics, a structure.
- Molecular dynamics based on machine learning interatomic potentials of large systems for structure and transport.
- Machine learning for structure analyses.

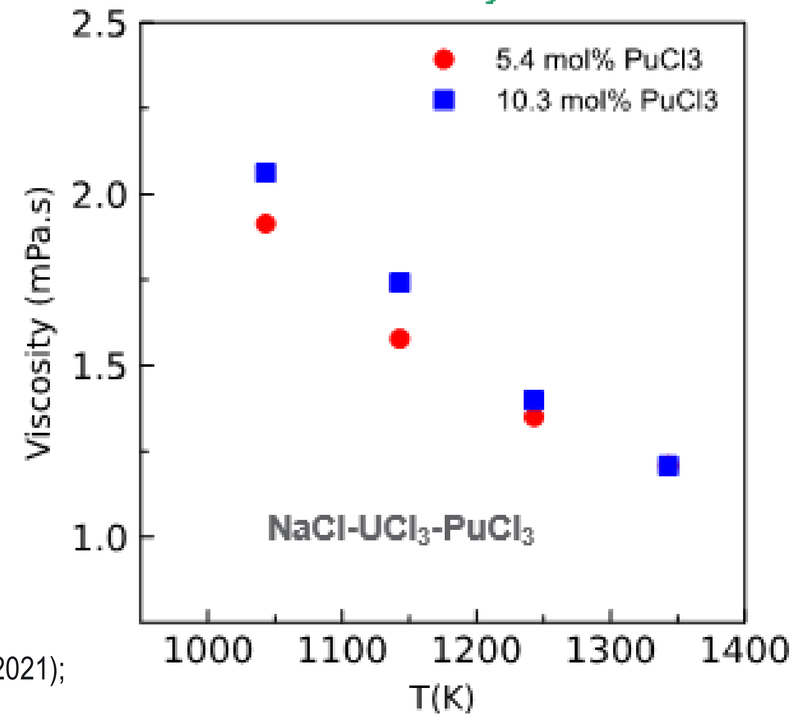
Density



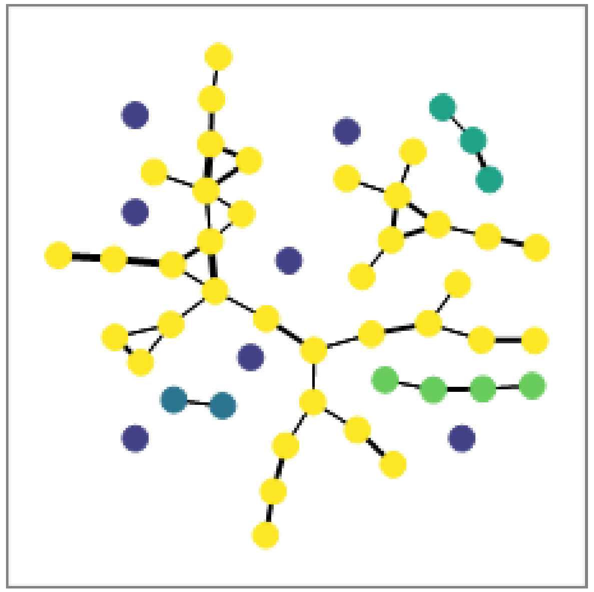
Heat capacity



Viscosity



Clustering of actinide chloride



$PuCl_3$-NaCl

Nguyen et al., J. Mol. Liq., 326, 115262 (2021); Nguyen et al., *ACS Applied Materials & Interfaces* 13, 53398 (2021); Nguyen et al., J. Mo. Liq., 365, 120115 (2022); Nguyen et al., *Applied Materials Today* 35, 101951 (2023)

Thermophysical Property Measurement

- Previous FY's focused on developing new thermophysical property measurement capabilities at PNNL to support MSTDB
  - Heat Capacity (DSC, Drop Cal): Online
  - Enthalpy of Fusion (Drop Cal): Online
  - Melting Point (TMA, DSC): Online
  - Vapor Pressure (TGA-DTA): Online/Dev
  - Emissivity (pyrometer): Online/Dev
  - Viscosity (TMA): In development
- FY24 goal is to determine impurities and their effect on thermophysical properties utilizing modeling and experimental techniques
  - Coupled high-temp furnace with Karl Fischer Titrator for water content
  - Ab Initio Molecular Dynamic Modeling

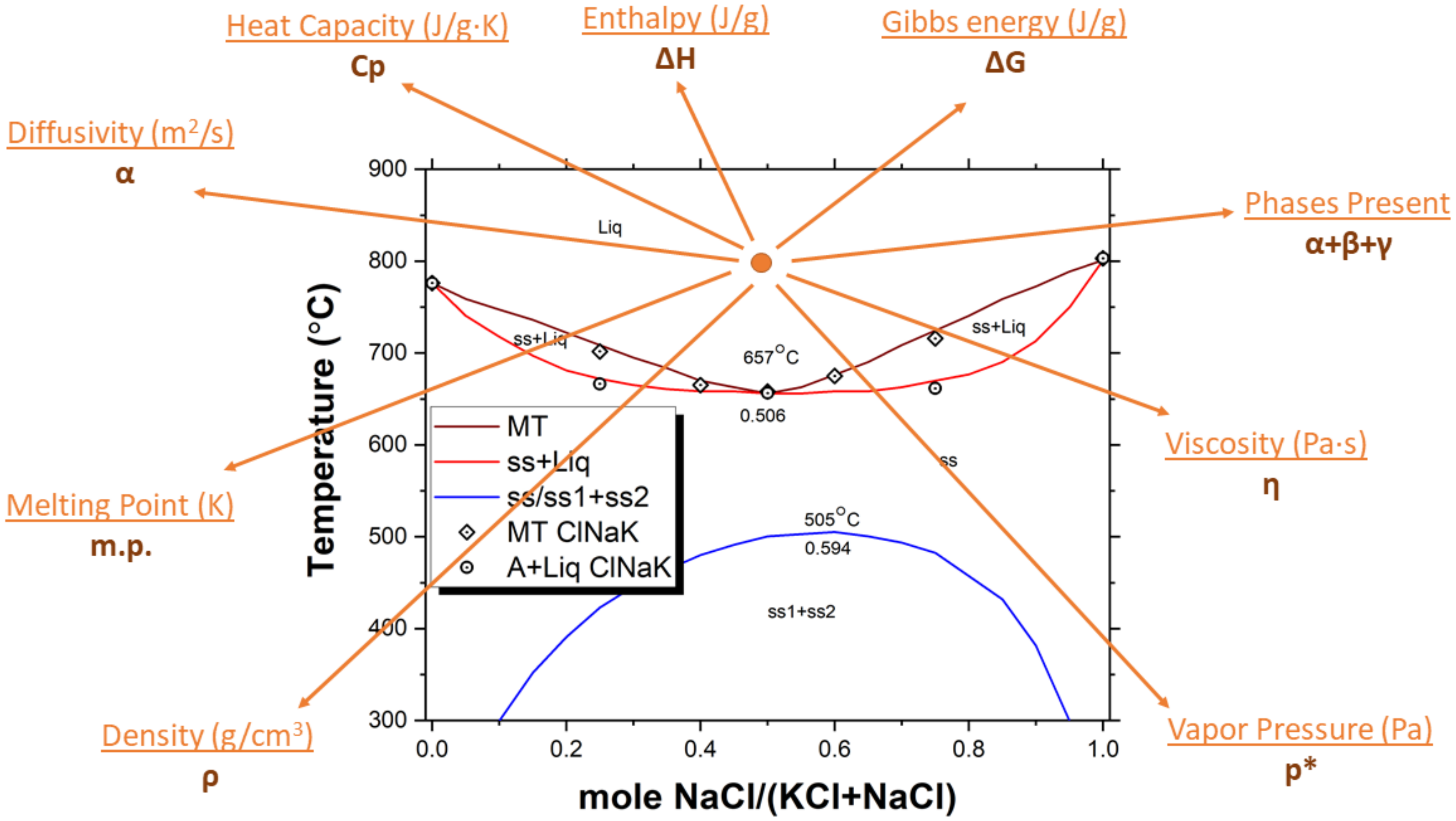
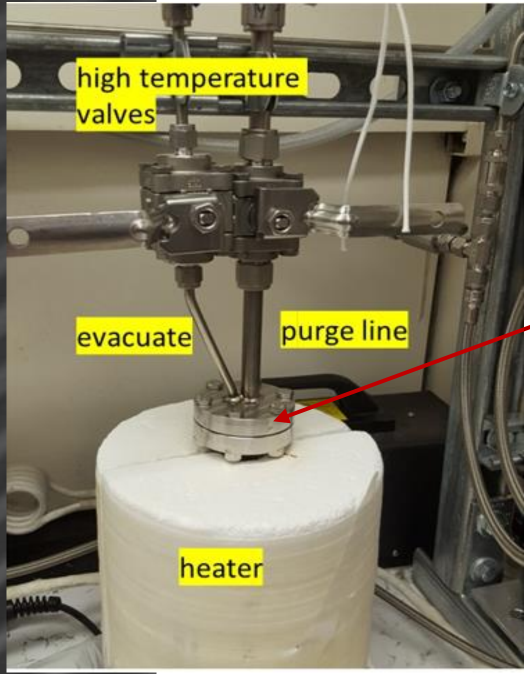


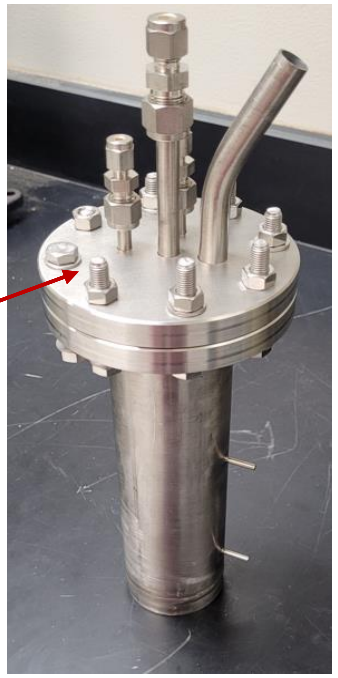
Figure credit: J. Lonergan

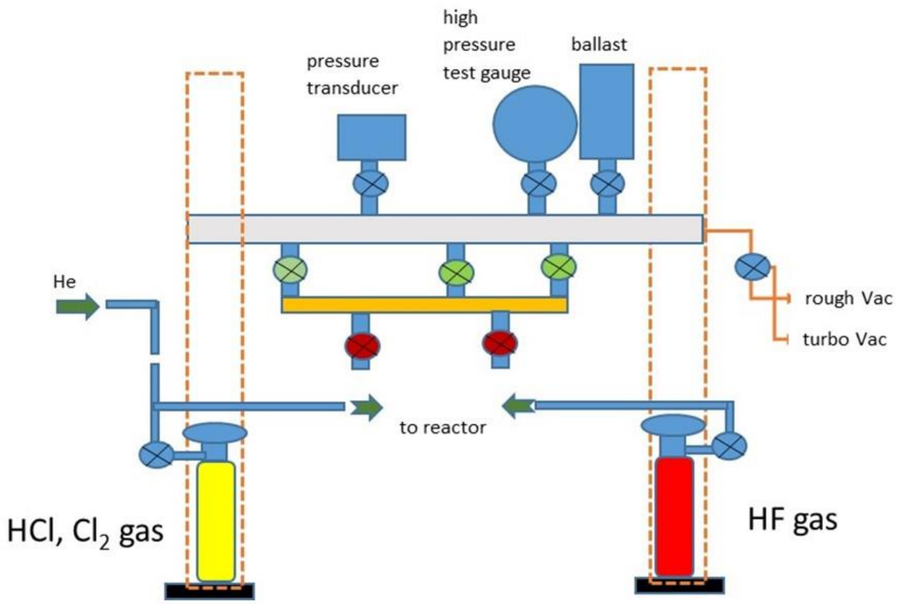
Goal is to provide data to support MSTDB

Actinide Salt Synthesis

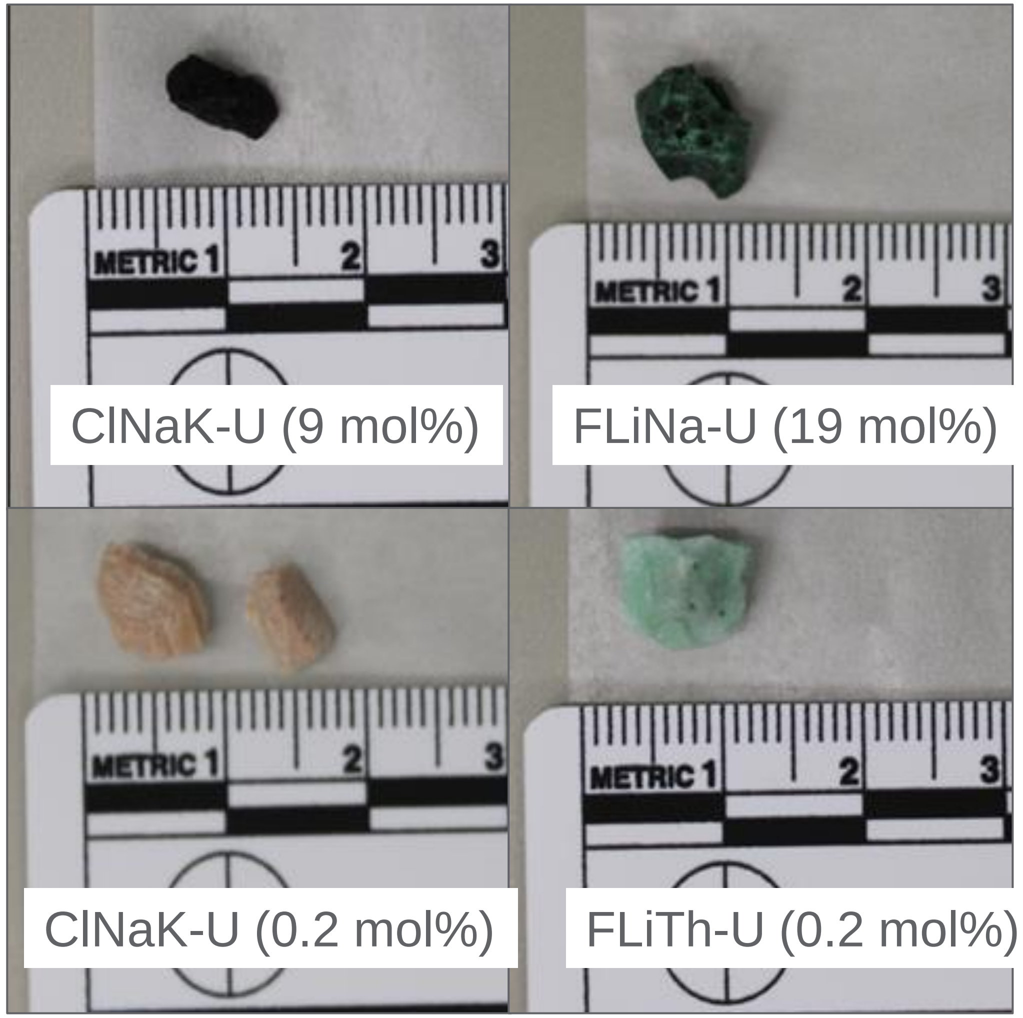
- Fabrication of chloride and fluoride U/Th salts in inert atmospheres
  - 1-50g scale
- Measurement of isotopics (TIMS) and concentrations in salts (ICP-MS)
- Measurement of melting point (DSC) and phase of salts (XRD)
- In FY24, making Pu salts for safeguards project







The vacuum line for preparation of fluoride and chloride salts



Mass spec samples of U salts produced for safeguards project

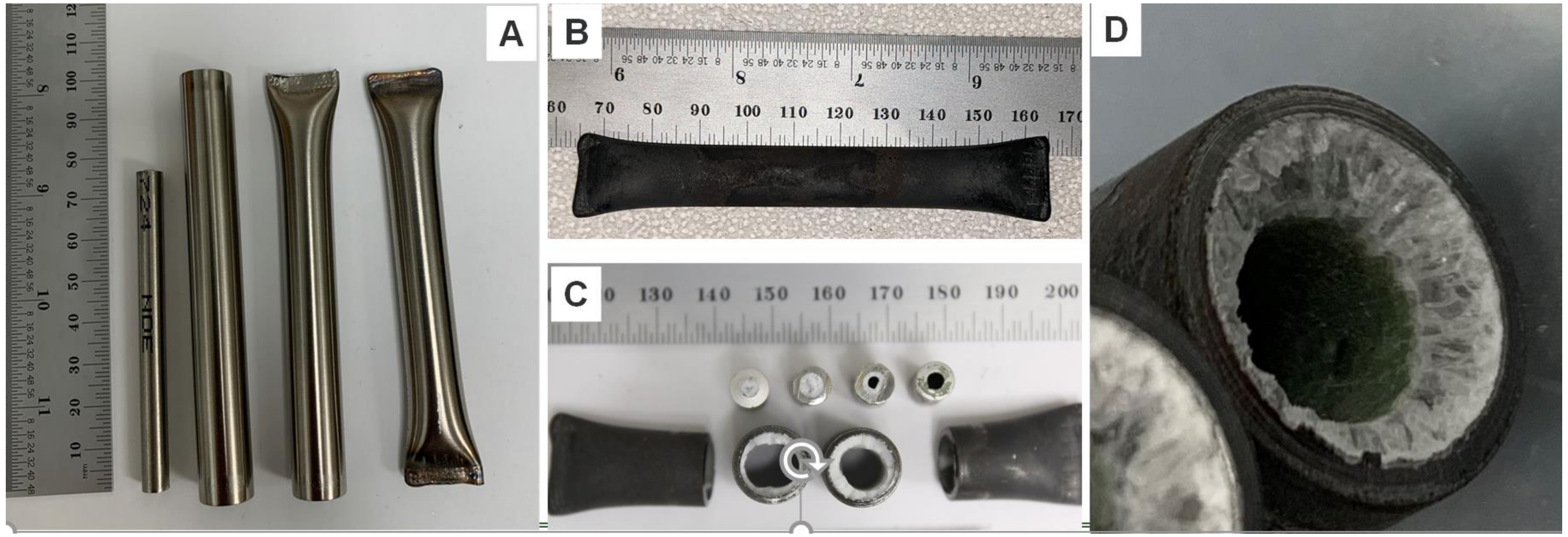
Corrosion of Austenitic Alloys under Molten Salt Condition

- Corrosion Tests of SS316 in eutectic NaCl-KCl salt at 700 °C and 800 °C.

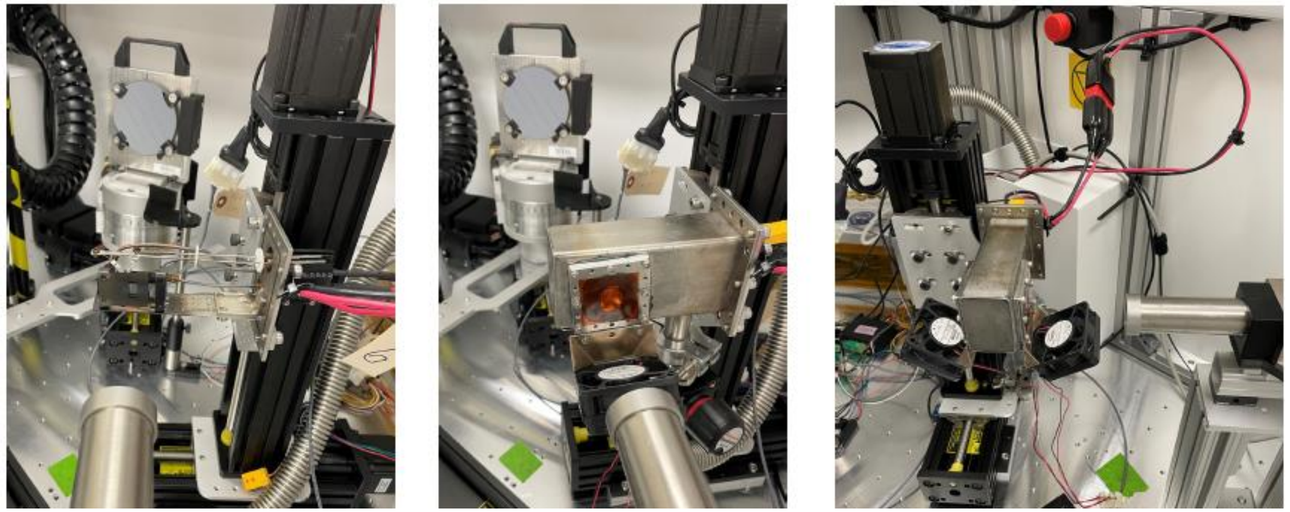
- Upcoming tests of SS316H and Alloy 716 in eutectic NaCl-$MgCl_2$ at 500 °C and 650 °C:

  - Corrosion kinetics of wrought & AM SS 316 and Inconel 617 will be explored.

  - Speciation of Cr, Ni, and Co in molten salt matrix will be characterized using various spectroscopy and microscopy.

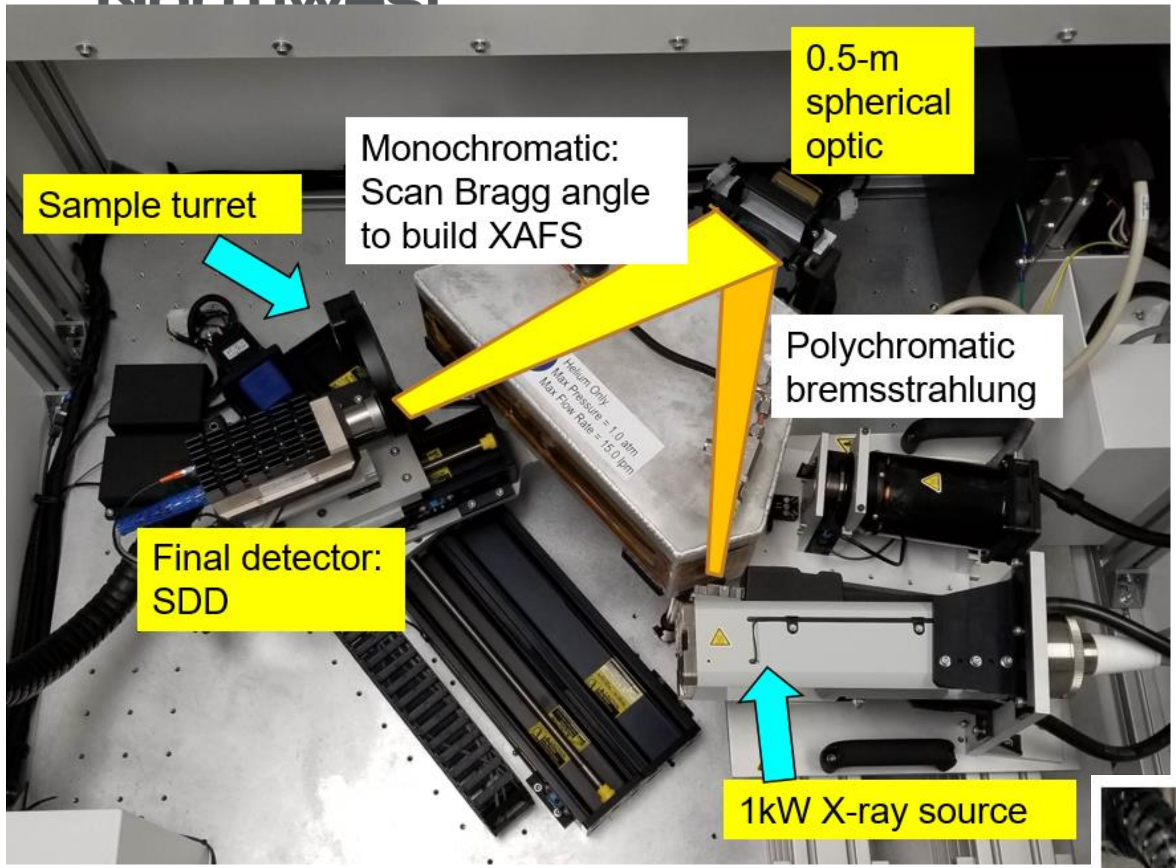


SS316 test ampoules to determine chromium diffusivity.



Vacuum furnace for EasyXAFS 300 to allow for in-situ metal halide speciation under molten salt conditions.

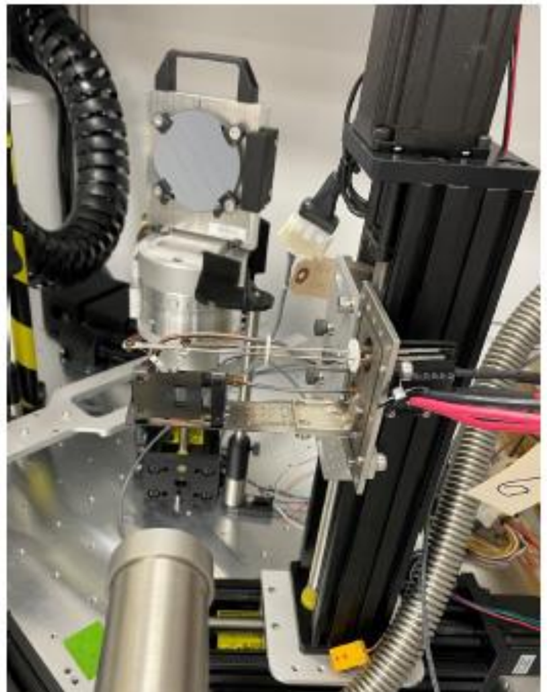
PNNL's EasyXAFS 300 for *in-situ* XANES/EXAFS measurements

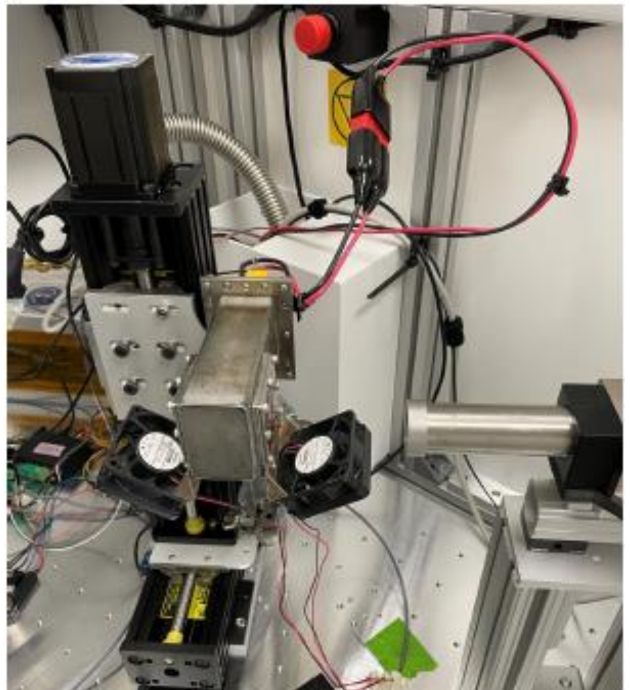


XAFS ⟷ Modeling

Changes in **local structure** (inter-atomic distances and coordination numbers) with high temperatures (air-free)

Changes in physical properties, solubility and chemical reactivity





Vacuum furnace to allow for measurements at 20 - 1000 °C

EasyXAFS 300 instrument for *in-situ* XAFS measurements to determine the speciation of actinide-, lanthanide- and transition metal halides in molten salts at PNNL

Chlorine Isotope Separation System for Chloride MSR

- Thermal diffusion isotope separation system for enrichment of ^{37}Cl. FY24 will upgrade to produce >99% ^{37}Cl enrichment

- Multi-physics model exists to optimize and inform facility designs at multiple scales

- Precise Cl isotope ICP-MS method with $HCl_{(L)}$ – no chemistry needed and >1% accuracy on $^{37}Cl/^{35}Cl$ ratio

WHY is Cl enrichment needed?

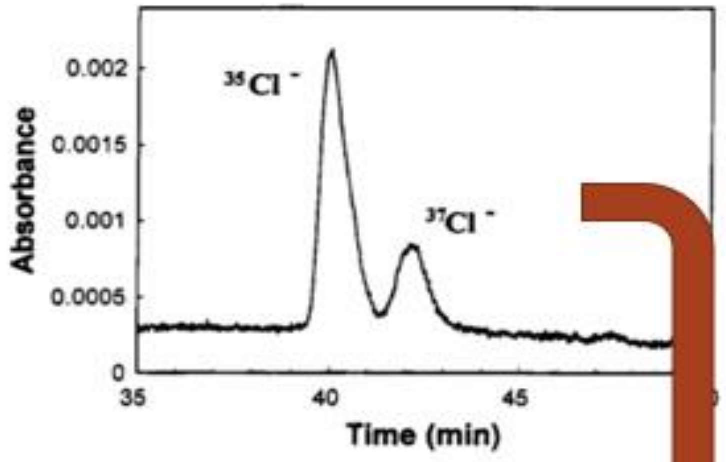
- ^{35}Cl (76% of natural chlorine) has large neutron capture cross section
- ^{36}Cl activation product is long-lived (301,000 years) and energetic (709 keV) beta emitter
- Highly soluble in water

Separation of Chlorine Isotopes by Electrophoresis

Pacific Northwest

Capillary Electrophoresis from Literature – ng's of material

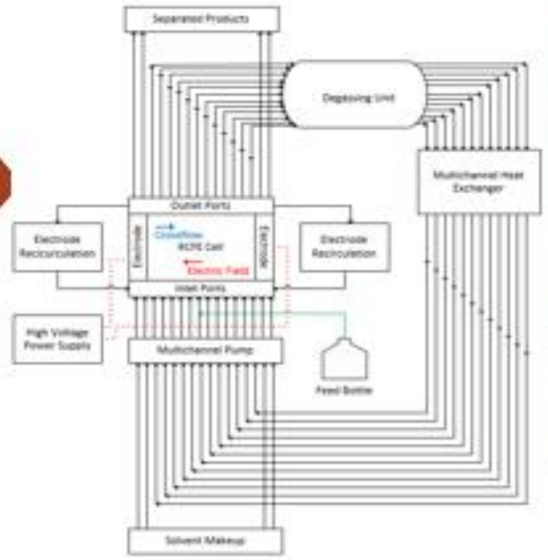
Experimental Results



Analytical Chemistry 2018, 90 (15) , 9410-9417.

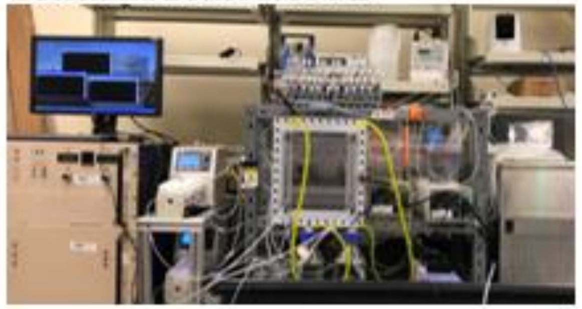
Flat-Bed Recycle Continuous Flow Electrophoresis (RCFE) – g's of material

Experimental Setup

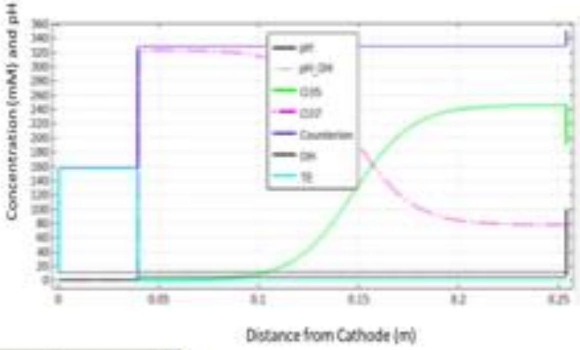


Optimized Separation in Previous Device at WSU

Fabricated Device at PNNL

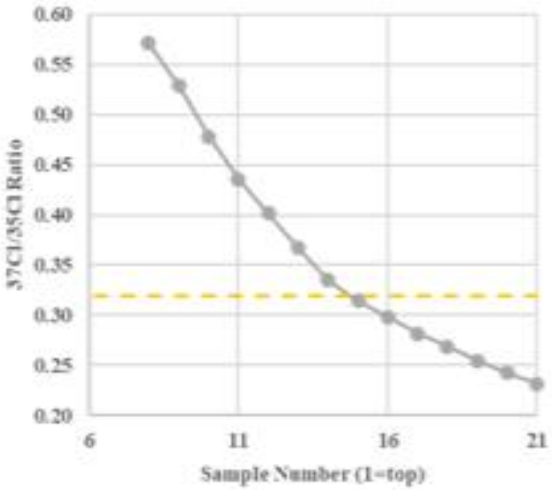


Numerical Simulation Optimized Flat-Bed RCFE

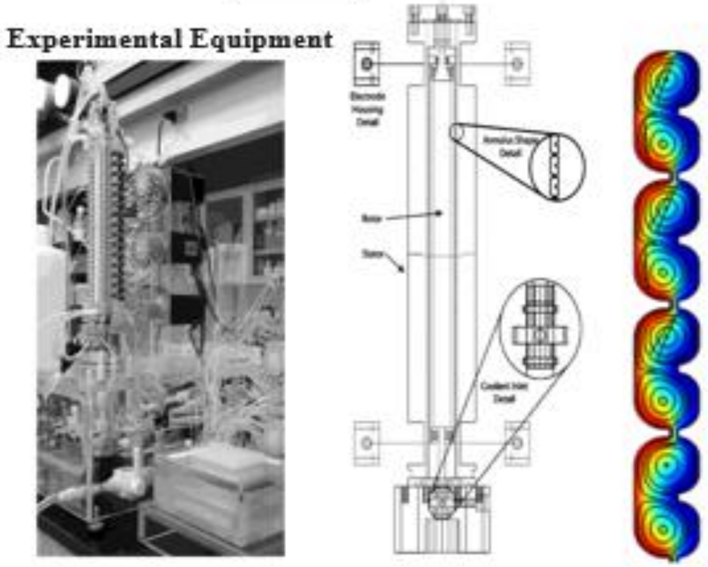


Proof of Principle in Unoptimized Preparative Free-Flow Electro focusing in a Vortex Stabilized Annulus – mg's of material

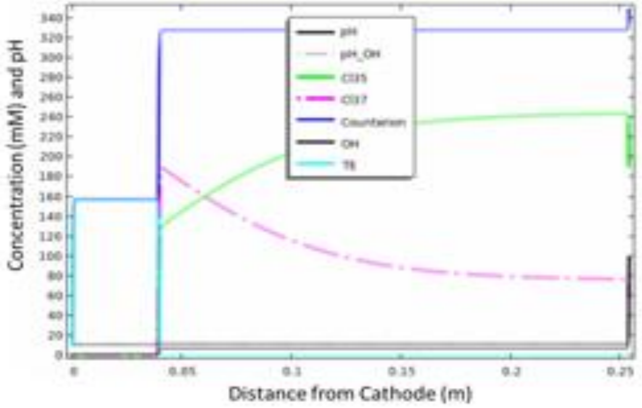
Experimental Results



Experimental Equipment



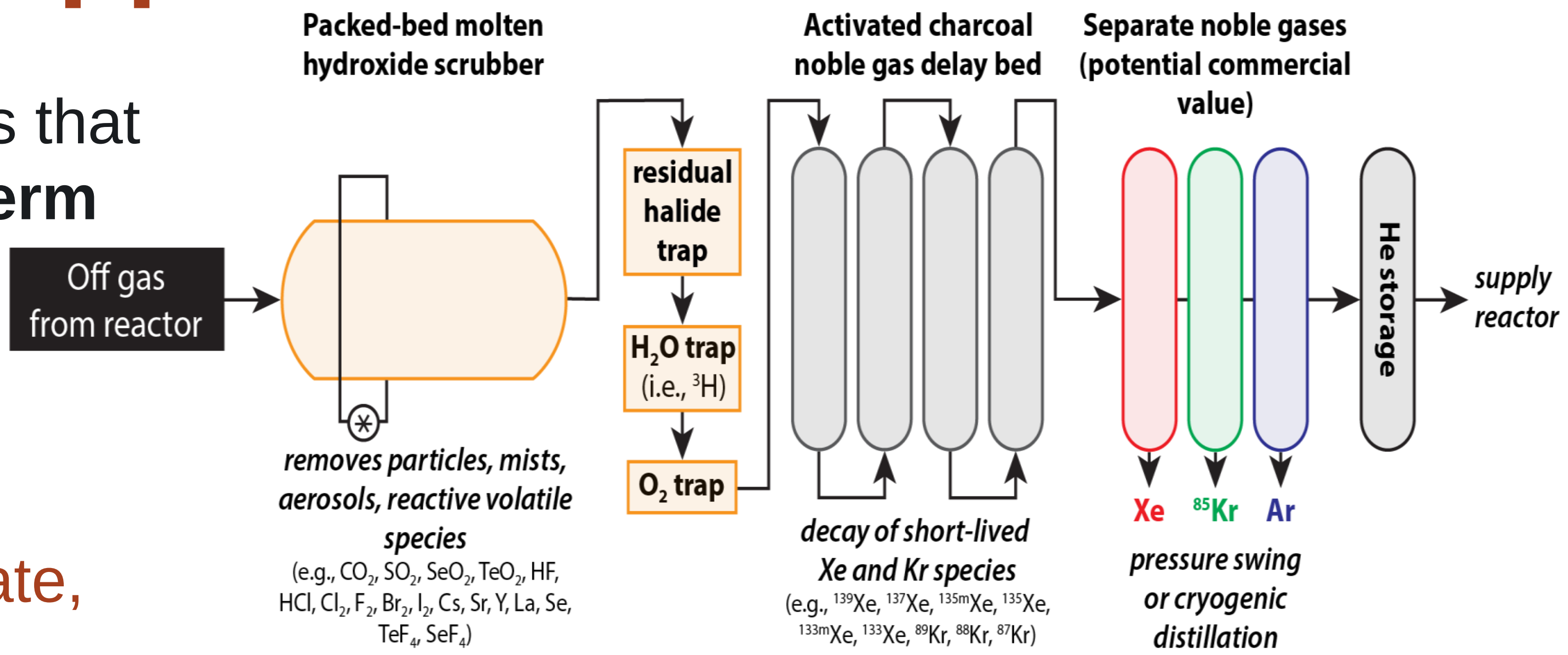
Numerical Simulation



Collaboration with Neil Ivory at Washington State University

On-line Monitoring and Off-gas Management in Support of MSRs

- Building tools, materials and membranes that enable **safe**, **cost effective**, and **near-term deployment** of MSRs
- OLM to support:
  - In Situ and Real-time accounting of nuclear material (conc, oxidation state, speciation etc), off-gas composition (iodine, hydrogen isotopes etc)
  - Enabling vendors to find workable solutions to accountancy challenges in liquid fueled reactors



Mcfarlane, J.; Ezell, N.; Del Cul, G.; Holcomb, D. E.; Myhre, K.; Chapel, A.; Lines, A.; Bryan, S.; Felmy, H. M.; Riley, B. *Fission Product Volatility and Off-Gas Systems for Molten Salt Reactors*; Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States): 2019.

Current Technologies:

1) Too complex, 2) Large footprint, 3) Costly, 4) Hazardous and safety issues

- **Advanced materials and membranes for Off-gas management**
  - Develop a modular and compact integrated off-gas system coupled with sensors
  - Demonstrate off-gas treatment technologies to meet vendor needs, support licensing and deployment activities

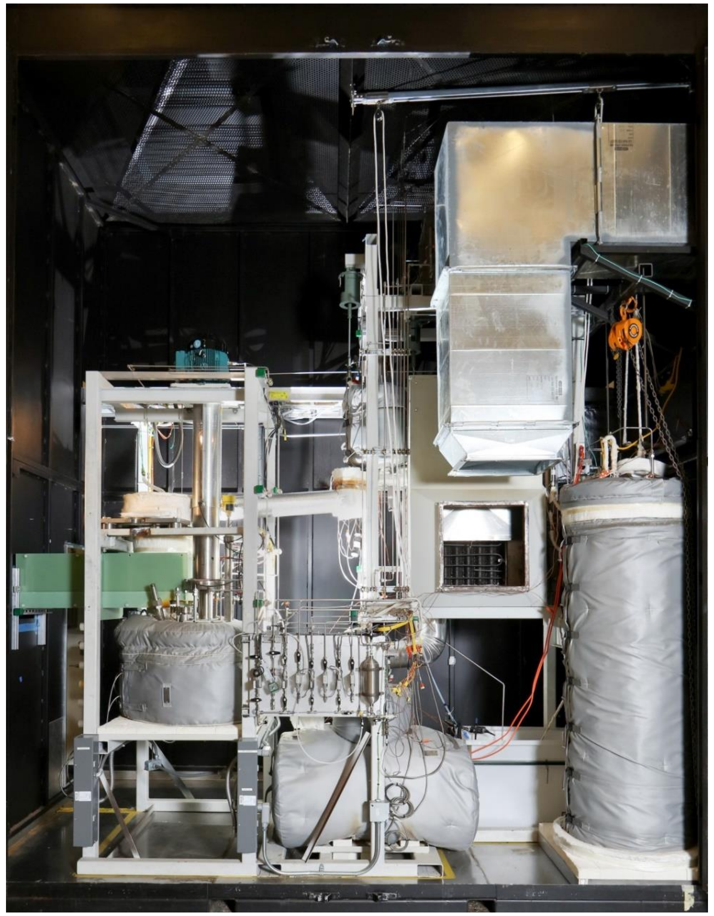
Optical Spectroscopy Tools

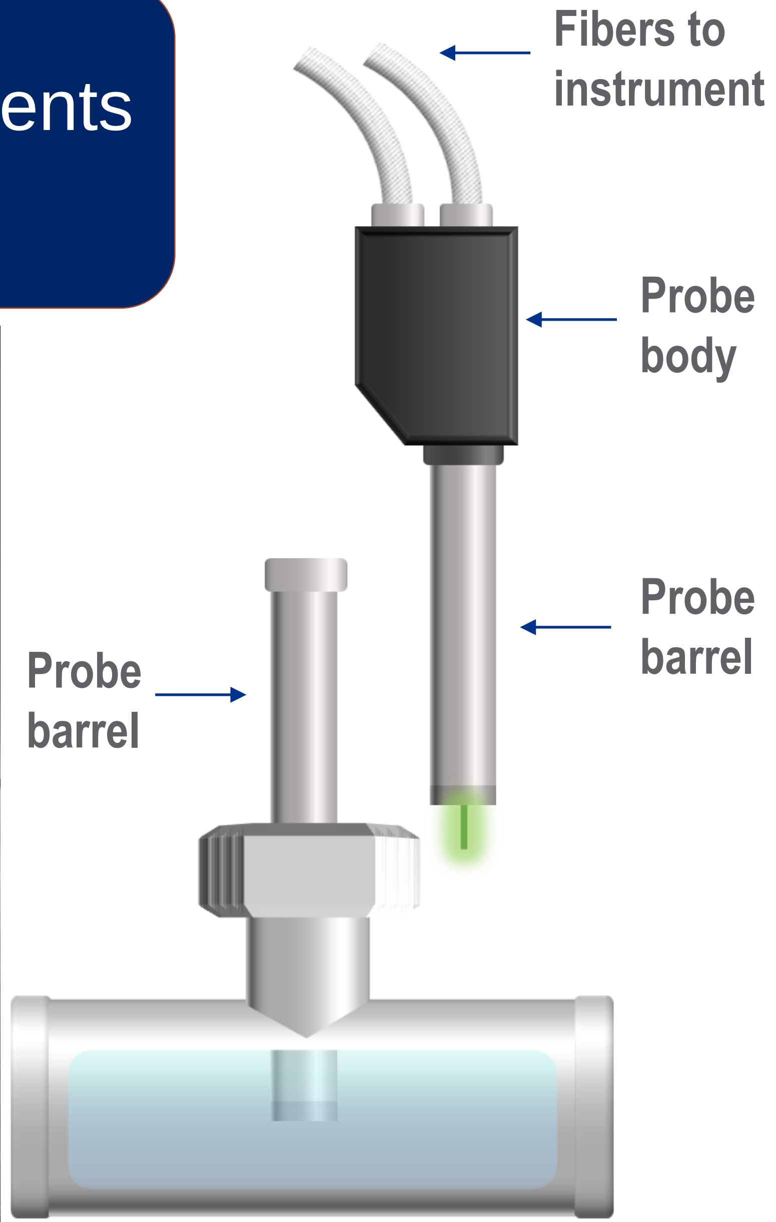
- Can provide detailed chemical composition information
- Highly flexible, Fast, Robust and
  - Chemical targets (Iodine in the gas and salt phase)

- **Collaboration between ORNL and PNNL**
  - Supporting system development and demonstrations
  - Laying foundation for tools that enable cost effective and near-term deployment of technology

- **Opportunities for Collaboration between PNNL and INL** on tritium monitoring
- Additional industry collaborations

Testing probe components in ORNL LSTL





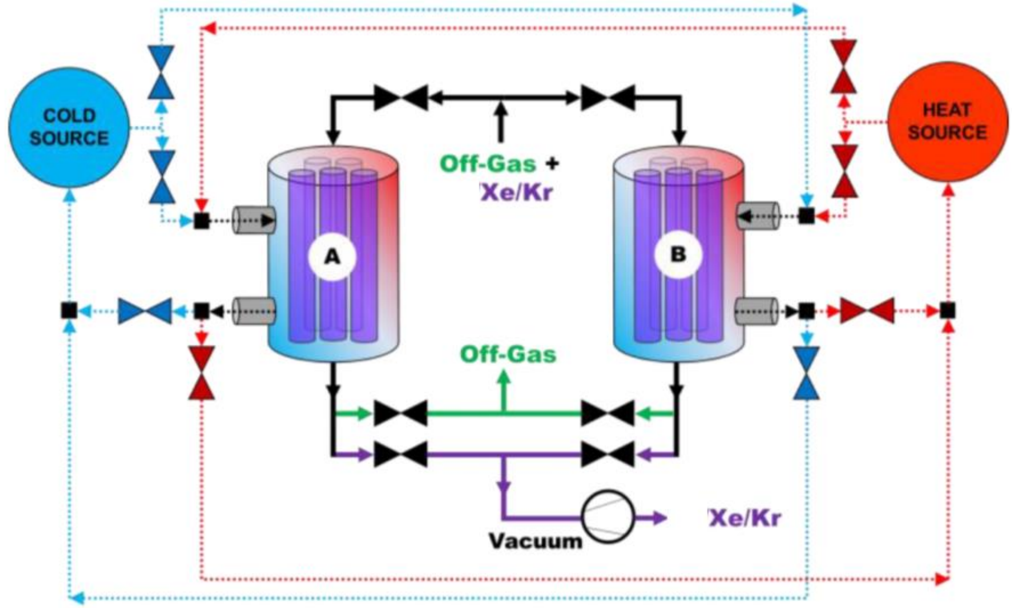
Branch, Shirmir; Felmy, Heather; Schafer Medina, Adan; Bryan, Samuel; Lines, Amanda Exploring the complex chemistry of Uranium within molten chloride salts" *Industrial & Engineering Chemistry Research*, 2023, 62, 37, 14901–14909.

Adan Schafer Medina, Heather M. Felmy, Molly E. Vitale-Sullivan, Hope E. Lackey, Shirmir D. Branch, Samuel A. Bryan, and Amanda M. Lines *ACS Omega* 2022 *7* (44), 40456-40465. DOI: 10.1021/acsomega.2c05522

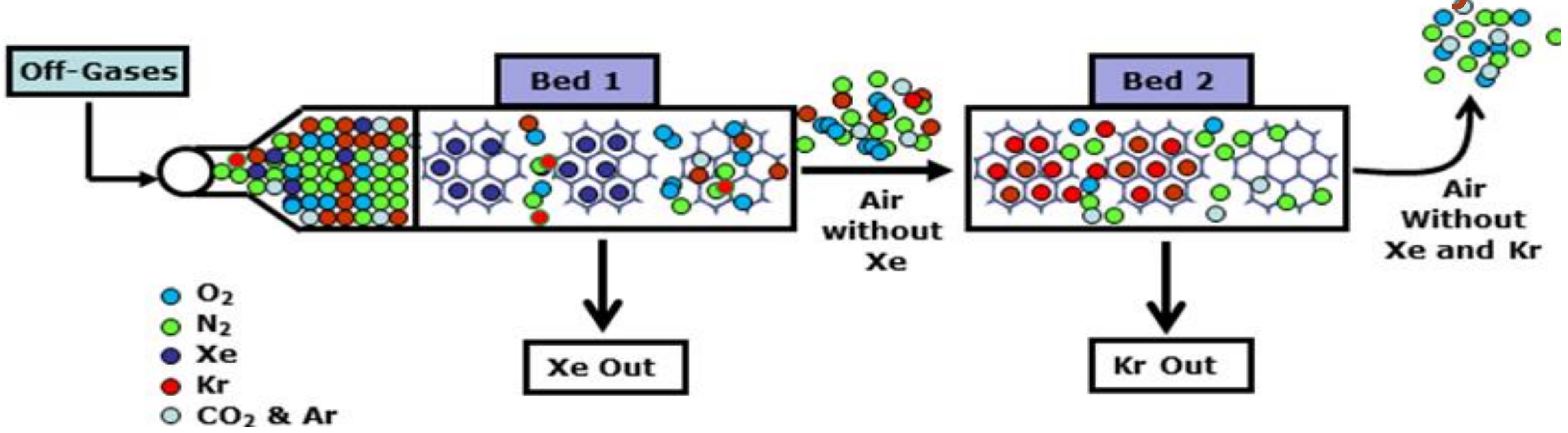
Pacific Northwest
NATIONAL LABORATORY

Metal Organic Framework Materials and Membranes for Off-gas Management

- Design and development of radiation tolerant functional materials (MOFs) for off-gas management (noble gases, iodine, tritium)
- Single and dual column breakthrough studies to demonstrate the Xe/Kr removal at RT
- Build, test and integrated off-gas system
- Process modelling and economic analysis



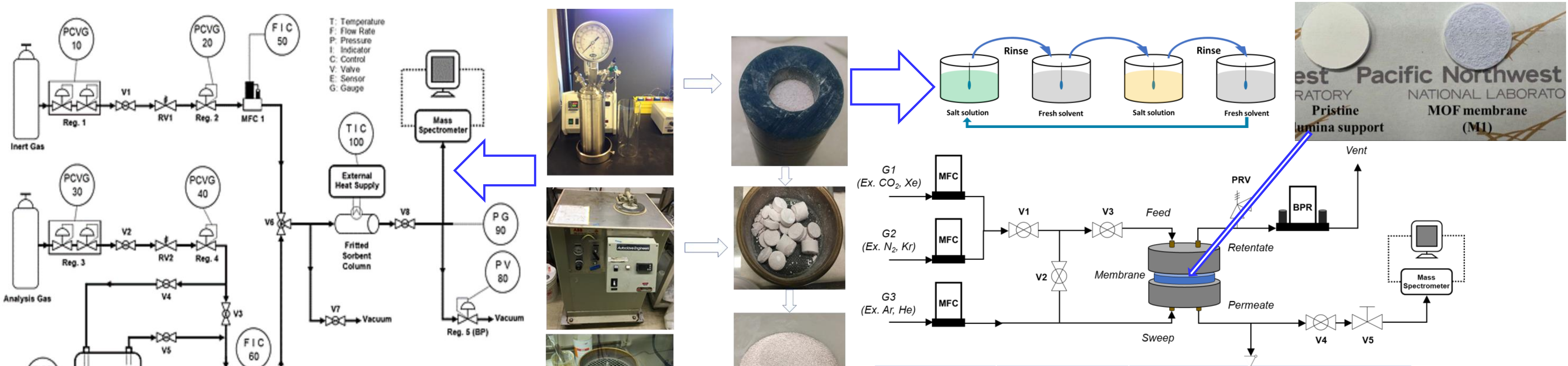
Noble Gas System



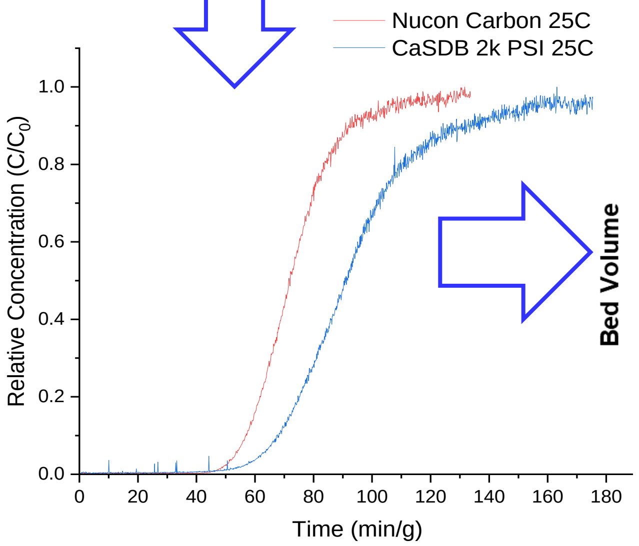
- The economic assessment indicate improvements in annual operating costs and improved environmental release profiles with potentially high decontamination factors.

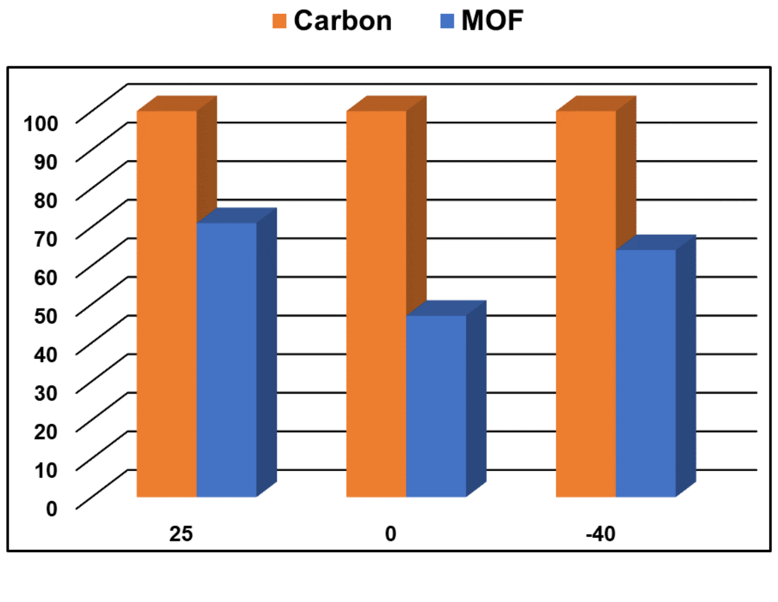
Thallapally and co-workers *ACS Appl. Mater. Interfaces* 2020, 12, 40, 45342–45350
Thallapally and co-workers *Nature Communications*, 2020; *Nature Communications*, 2016; *Nature Materials*, 2018

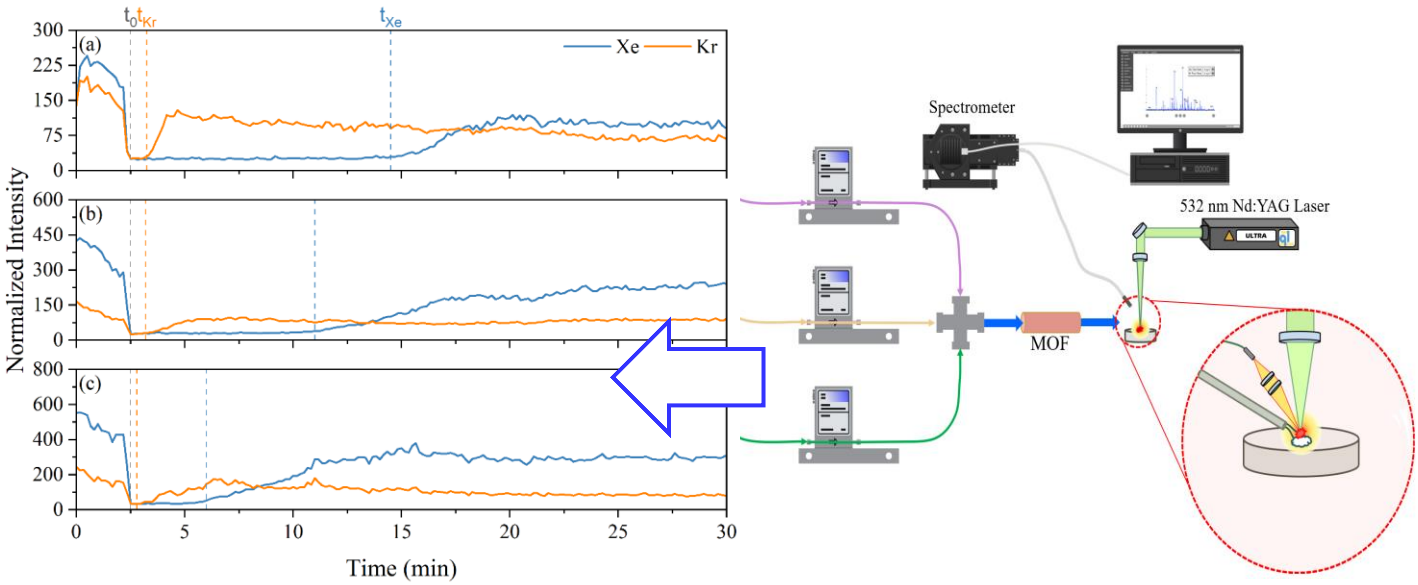
Capabilities in Off-gas Management



	Xe GPU	Kr GPU	Kr/Xe Selectivity
Membrane 1	1.818×10^5	2.262×10^5	1.24
Membrane 2	2.202×10^5	2.580×10^5	1.17







Thallapally, PK., Vienna et. al., USPTO WO/2017/218346A1

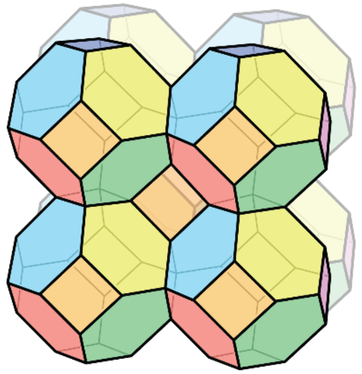
Banerjee, D, Thallapally, PK, Kunapuli R., Mcgrail, BP, Liu J et al., Surface acoustic wave sensors for refrigerant leak detection., *USPTO WO2021/041359 A1*

Collaboration with ORNL

Hunter et. al., *Micromachines*, 2022, 14, 82

Salt Treatment and Immobilization

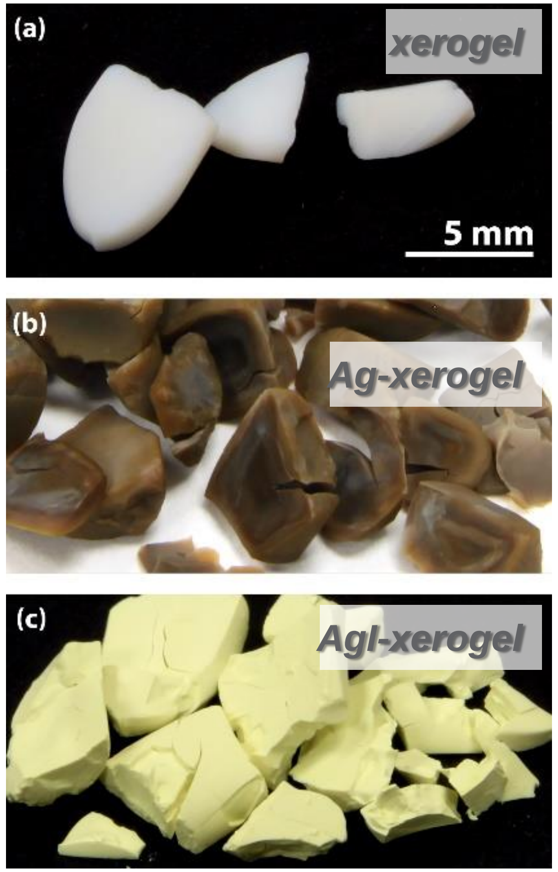
Sodalite
(Cl/I salts)

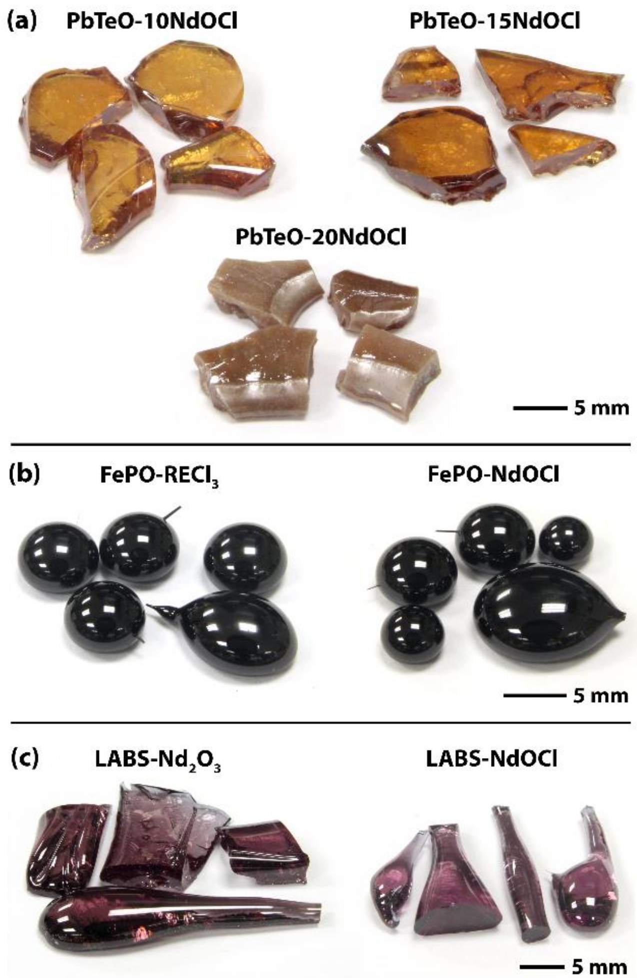


- MSR wastes will likely require stabilization prior to disposal
  - Remove halogens through treatment (*dehalogenation*)
  - Partitioned waste streams into different waste forms

- Options for Cl treatment and waste forms including glasses and glass-bonded mineral waste forms

- Halide gas capture of high interest using *zeolites*, *aerogels*, and *xerogels*





Glassy waste forms
(high-rare earth streams)

Riley et al. (2017a, 2017b, 2020a, 2020b), Chong et al. (2021, 2022)

Radiation Stability Testing

- PNNL's Radiological Exposures and Metrology Lab (REM Lab) contains highly characterized beta, gamma-ray, neutron, and X-ray fields

- Supported a wide range of applications, including radiation effects on materials and electronics

- PNNL can simulate a wide variety of temperature (from -60 to 200 °C), humidity (20 – 90%), and vacuum environments within these radiation fields.

Radiation experiments are planned during FY'24

Acknowledgements

DOE, NE-5, NE-4, NNSA Offices

Dr. Patricia Paviet and Dr. Ken Marsden, NTDs

Ali Zbib – Industry POC at PNNL

Dr. Manh-Thuong Nguyen –Ab initio calculations
Dr. Kyle Makovsky – Thermophysical properties
Dr. Tatiana Lewinsky – Easy-XAFS
Dr. Thomas Hartmann - Corrosion
Dr. Bruce McNamara, Dr. Zach Huber, Dr. Connor Hilton – Chloride and fluoride salt
Dr. Bruce McNamara, Dr. Zach Huber, Dr. Mike Powell, Dr. Tyler Schlieder – Chlorine isotope separation
Dr. Danny Bothenus – Electrophoresis (chlorine isotope separation)
Dr. Amanda Lines and Dr. Samuel Bryan - OLM
Dr. Praveen K. Thallapally – Off-gas management
Dr. Brian Riley – Waste form development
Dr. Mark Murphy – Radiation testing

U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Clean. Reliable. Nuclear.

Oak Ridge National Laboratory, Foundational Studies to Support Molten Salt Reactor Development

Oak Ridge National Laboratory

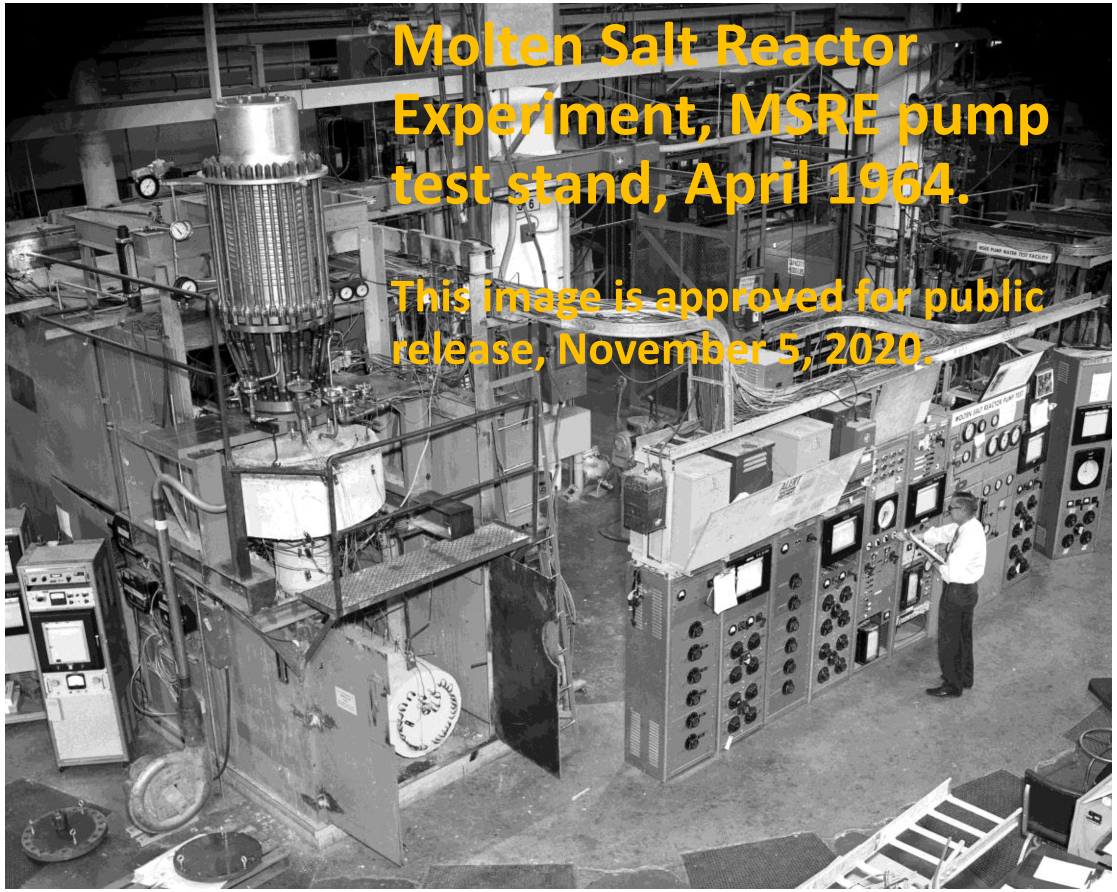
Molten Salt Reactor Workshop

October 25-26, 2023

Joanna McFarlane, ORNL, Oak Ridge, TN, USA

Patricia Paviet, National Technical Director of the Molten Salt Program

ORNL has been investigating molten salt systems since the 1950's to the present



- Fundamental studies at bench-top scale (poster)
  - Thermophysical property measurements (Birri, Termini)
  - Salt interfacial properties (Moon, Orea)
- Preparation, purification, and mixing of fuel salts
  - Carrier salts including FLiBe (Sulejmanovic)
  - Uranium salts (Mayes, Richards)
- Interactions with materials
  - Intrusion into graphite (Gallego)
  - Alloy qualification (Pint)
- Off-gas
  - Chemical speciation (McFarlane)
  - Sensors (Andrews)
  - Links to Materials Recovery and Waste Forms (McFarlane, Mayes, Ngelale)
- Pumped test loops (LSTL, FSTR)
  - Component testing and loop operation (Robb, Orea, Nguyen)
  - Sensor development (Robb, Andrews, PNNL and ANL collaborators)
- Modeling and simulation
  - Gas transport (Lee, Westphal)
  - System modeling (Salko)
  - MSTDB (Ezell, Besmann, Birri)

Fluoride salts are being prepared with HF or NF_3

(Dino Sulejmanovic, sulejmanovid@ornl.gov, Jason Richards, richardsjm@ornl.gov)

- Carrier Salt and Actinide Fluorides
  - Hydrogen fluoride (HF)
  - Ammonium Bifluoride ($NH_4F \cdot HF$)
- Preparation for thermochemical and corrosion testing.
- Other anions, corrosion products, available for fundamental science

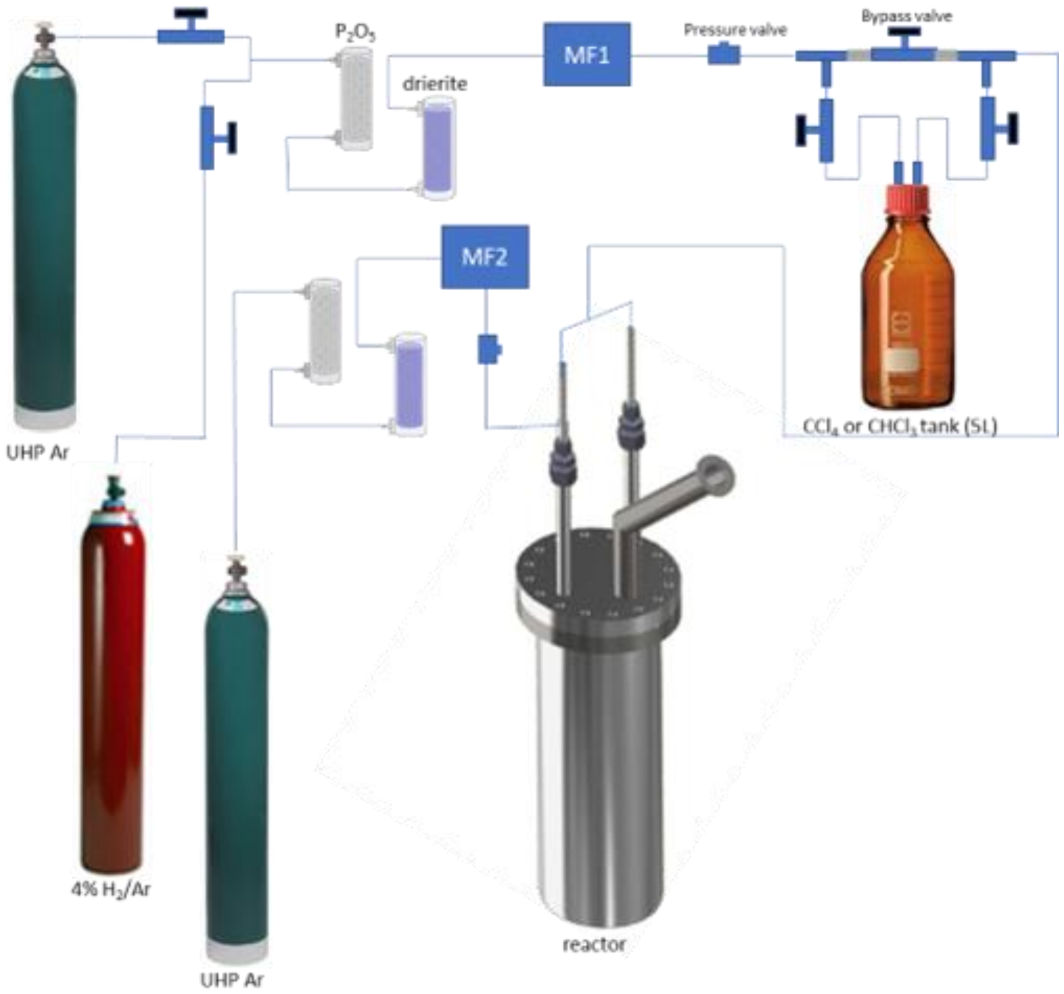
New fluoride salt purification system for exploring new purification processes (e.g. replacing HF with NF_3)

Salt chemistry and corrosion testing

Chloride salt production being tested with several reagents

(Richard Mayes mayesrt@ornl.gov, Breanna Vestal vestalbk@ornl.gov, Dino Sulejmanovic)

Chlorination using CCl_4



- Actinide Chlorides
  - Carbochlorination
    - Carbon tetrachloride (CCl_4)

$$CCl_4 + 2MgO \rightarrow 2MgCl_2 + CO_2$$

    - Hexachloropropene
  - Sulfur chlorides ($SOCl_2$, SCl_2, S_2Cl_2)
- Multiple oxidation states of uranium are possible

Handling and processing of purified salts

Molten Salt Thermal Properties Database-Thermochemical (*MSTDB-TC*): Computing Chemical States (Ted Besmann, besmann@sc.edu)

- Library of Gibbs energy functions and models compatible with equilibrium solver FactSage™ and open-source codes
- Development at Univ. South Carolina: Access via **mstdb.ornl.gov**

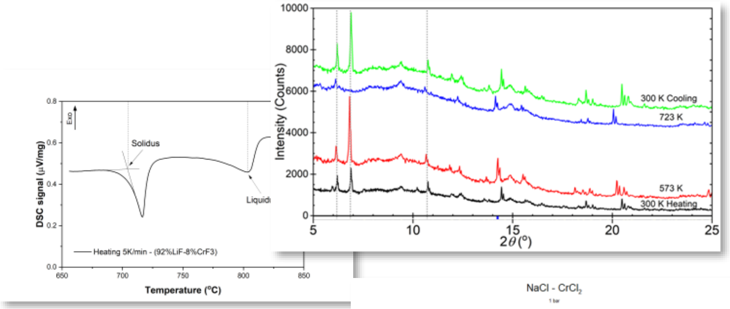
MSTDB-TC Ver. 3.0 Content

	Fluorides	Chlorides	Iodides
Alkali metals	LiF, NaF, KF, RbF, CsF	LiCl, NaCl, KCl, RbCl, CsCl	LiI, NaI, KI, CsI
Alkaline earth metal	BeF_2, CaF_2, SrF_2, BaF_2	$MgCl_2$, $CaCl_2$	BeI_2, MgI_2
Transition metals	NiF_2, CrF_3	$CrCl_2$, $CrCl_3$, $FeCl_2$, $FeCl_3$, $NiCl_2$	-
Other cations	YF_3, ZrF_4	$AlCl_3$	-
Lanthanides	LaF_3, CeF_3, NdF_3, PrF_3	$CeCl_3$, $LaCl_3$	-
Actinides	ThF_4, UF_3, UF_4	UCl_3, UCl_4, $PuCl_3$	UI_3, UI_4
Pseudo-binary	70 systems	70 systems	30 systems
Pseudo-ternary	30 systems	27 systems	15 systems
Higher order	16 systems	2 systems	All 18 include iodides

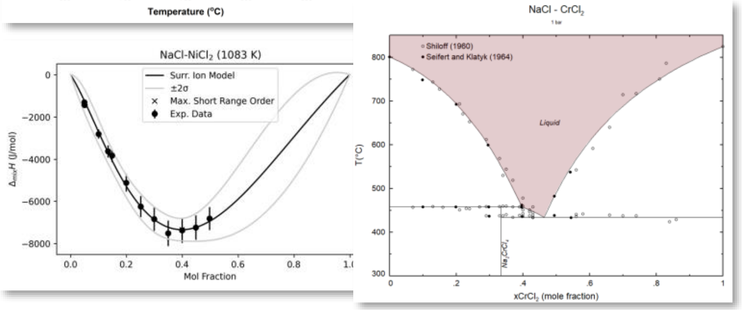
Component Data

Compound	$\Delta_f H^o(298)$ J/mol	$S^o(298)$ J/mol K	C_p J/mol K	Temp. Range K
CsF (l)	-535,041	108.1938	70.56	298-1400
LiF (l)	-598,653.75	42.956	64.45	298-2000
NaF (l)	-557,859.5	52.583	73.036	298-2000
KF (l)	-551,944	71.144	70.485	298-2000

Measurements



Modeling



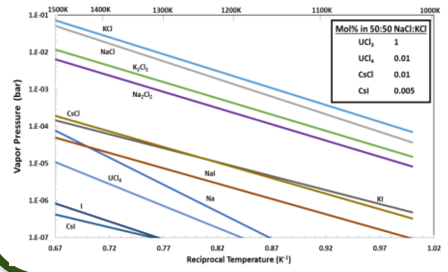
Database

Gibbs Energy Functions

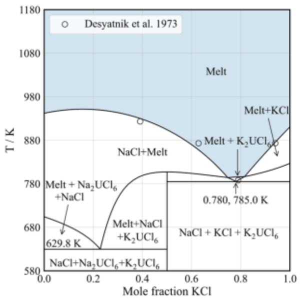
- Compounds
- Vapor Species
- Salt Melt
- Solid Solutions


```
System U-F-Li
    3    2    2    3   12
 U                    F                    Li
  238.02891000        18.99840320          6.94100
   6    1    2    3    4    5    6
   6    1    2    3    4    5    6
 gas_ideal
 IDMX
 LiF
   1  1     0.0     1.0     1.0
  6000.0000     -351581.57      37.443358     -35.397917
 0.27571767E-07 0.00000000
 UF4
   1  1     1.0     4.0     0.0
  6000.0000     -1639992.8      343.21185     -103.82600
 0.24183333E-06  510660.00
 LIQUsoln
```

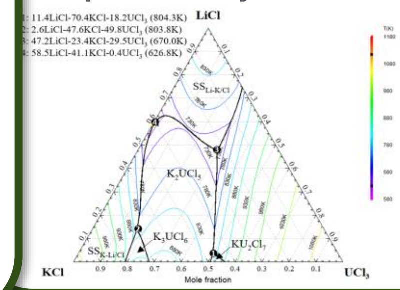

Computed Vapor Pressures



Phase Equilibria



Liquidus Projections



General Atomics Center
College of Engineering and Computing
UNIVERSITY OF SOUTH CAROLINA

MSTDB-TP (Tony Birri, birriah@ornl.gov)

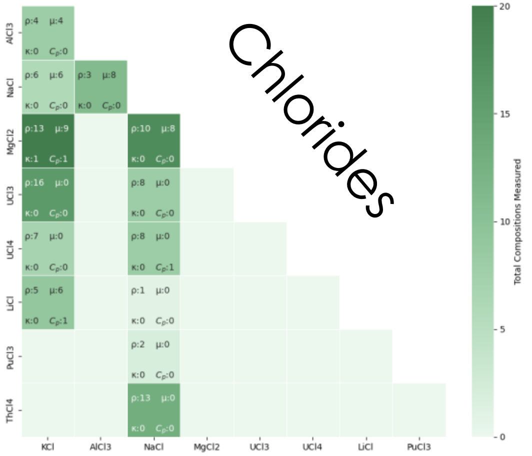
Oak Ridge National Laboratory · NEAMS · University of South Carolina · Molten Salt Reactor Program

- The Molten Salt Thermal Properties Database–Thermophysical (MSTDB-TP) contains empirical relations for the following properties:
  - Melting and boiling points
  - Density
  - Viscosity
  - Heat Capacity
  - Thermal Conductivity
- As per the current version release (**v2.1**) There are **448 entries**, including:
  - 33 pure compounds
  - 243 pseudo-binaries
  - 166 pseudo-ternaries
  - 6 pseudo-quaternaries
- Each property entry in the database includes a margin of experimental error
  - Determined on a case-by-case basis
  - This list is constantly expanding. The data is based on the outputs of 140+ independent experimental studies in literature
- This is one of two arms of MSTDB; MSTDB-TC contains thermochemical properties

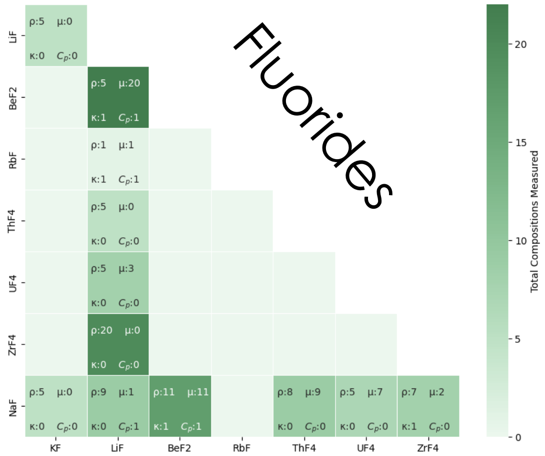
Pure:

Salt	Measurements			
	ρ	μ	κ	c_p
AlCl3	1	1	0	1
BeCl2	1	0	0	0
BeF2	1	1	1	1
CaCl2	1	1	1	1
CaF2	1	1	1	1
GdCl3	1	1	0	0
GdF3	0	0	0	0
KCl	1	1	1	1
KF	1	1	1	1
LaCl3	1	1	0	0
LaF3	1	0	0	1
LiCl	1	1	1	1
LiF	1	1	1	1
MgCl2	1	1	1	1
MgF2	1	1	1	0
NaCl	1	1	1	1
NaF	1	1	1	1
NdCl3	1	1	0	0
NdF3	0	0	0	1
NpCl3	0	0	0	0
NpF3	0	0	0	0
PuCl3	0	0	0	1
PuF3	0	0	0	1
SrCl2	1	1	1	0
SrF2	1	1	1	0
ThCl4	1	0	0	0
ThF4	1	0	0	0
UCl3	1	0	0	1
UCl4	1	0	0	0
UF3	0	0	0	1
UF4	1	1	0	1
ZrCl4	1	1	0	0
ZrF4	1	0	0	0

Binary:



Living database



Ternary:

Salt	Measurements			
	ρ	μ	κ	c_p
KCl-LiCl-NaCl	4	0	0	0
LiCl-NaCl-AlCl3	10	10	0	0
LiF-BeF2-ThF4	3	2	0	0
LiF-BeF2-ZrF4	1	0	0	0
LiF-NaF-BeF2	1	1	0	0
LiF-NaF-KF	1	1	1	1
LiF-BeF2-UF4	36	36	0	0
NaF-BeF2-UF4	79	71	0	0
NaF-KF-BeF2	1	1	0	0
NaF-KF-MgCl2	1	0	0	0
NaF-KF-UF4	1	1	1	1
NaF-KF-ZrF4	1	1	0	0
NaF-LiF-BeF2	4	4	0	0
NaF-LiF-ZrF4	10	1	0	1
NaF-ZrF4-UF4	5	3	2	3
RbF-ZrF4-UF4	2	2	1	1

Quaternary:

Salt	Measurements			
	ρ	μ	κ	c_p
LiF-BeF2-UF4-ThF4	1	1	0	0
LiF-BeF2-ZrF4-UF4	1	0	0	0
NaF-LiF-BeF2-UF4	1	1	0	0
NaF-LiF-KF-UF4	2	2	1	1
NaF-LiF-ZrF4-UF4	1	1	0	1

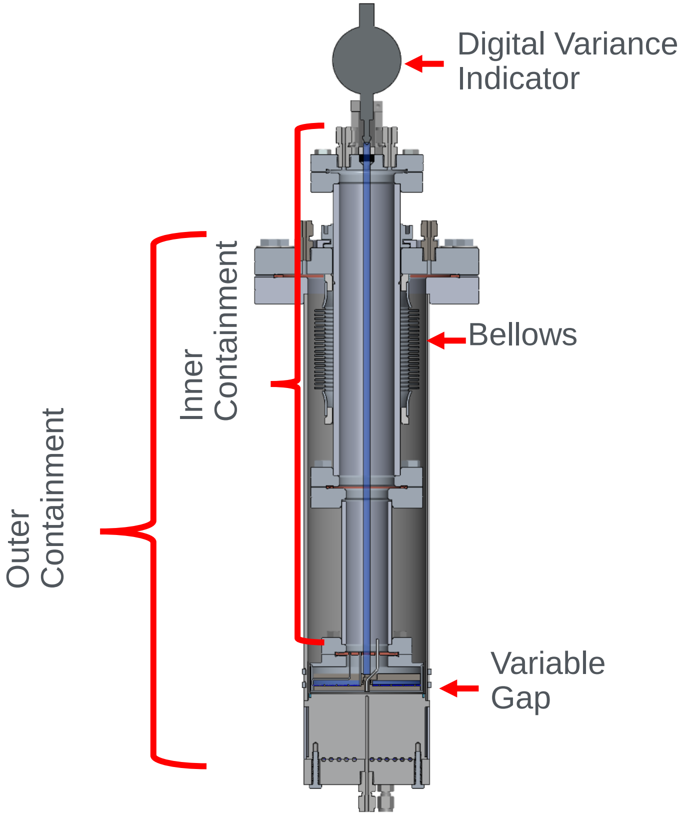
Measurement of Molten Salt Thermal Conductivity and Viscosity

Contributors: Anthony Birri, Nick Termini, N. Dianne Bull Ezell

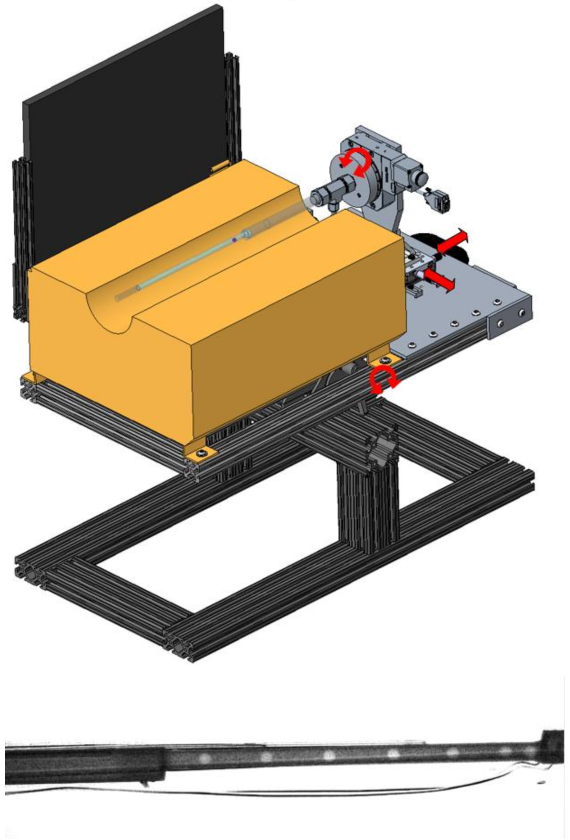
A precise understanding of thermophysical properties of molten salts in MSRs is necessary for developing an accurate understanding of nuclear reactor thermal hydraulics. MSR developers will rely on precise, low-uncertainty data which is experimentally validated

- A thermal conductivity and viscosity measurement system have been developed and tested at ORNL for application with MSR relevant salts
- The thermal conductivity system is a variable gap technique, measuring temperature difference across a gap with driven heat flow
- The viscosity system is a rolling ball viscometer, based on terminal velocity of a ball rolling through the salt
- Both chloride and fluoride salt systems have been tested with these systems

Thermal Conductivity System



Viscosity System



These systems have been used to measure systems such as LiF-NaF-KF and NaCl-KCl which are systems or subsystems that are being considered for MSR coolant or fuel by multiple developers. Data has been supplied to the Molten Salt Thermal Properties Database from this work; tens of individuals from industry are subscribed

Point-of-contact: Anthony Birri, birriah@ornl.gov

Interfacial property measurements –

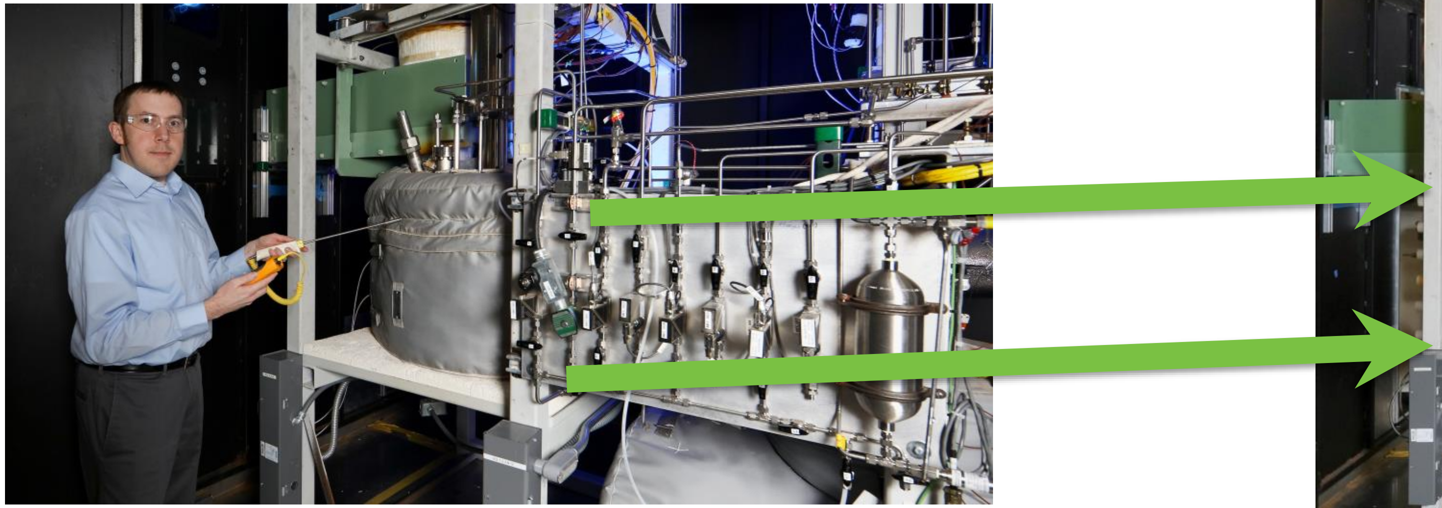
(Daniel Orea oread@ornl.gov, Thien Nguyen nguyend@ornl.gov)

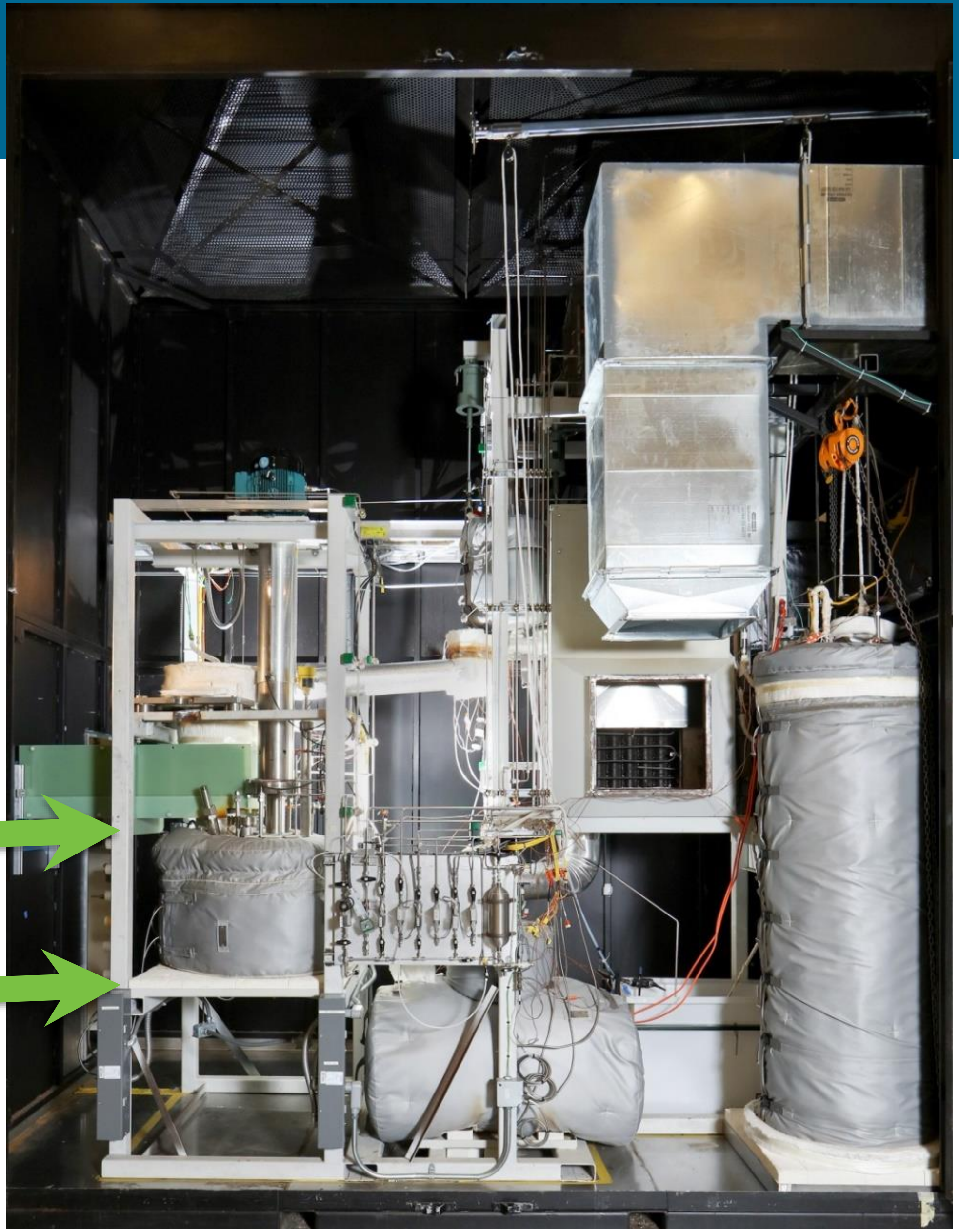
- Bubble transport was studied in LiCl-KCl eutectic
  - He, Ar, Kr, N_2
  - Multiple flow rates, two orifice diameters
- Shadowgraph method tracked changes in geometry and movement in a column of salt.
- Particle Image Velocimetry (PIV) was used to observe vortices in the salt caused by bubble movement.

The Liquid Salt Test Loops are used for component, materials, and sensor testing - Kevin Robb (robbkr@ornl.gov)

- Sensors placed in loop headspaces
  - Optics for Raman probe
  - Cascade impactor for aerosol loading
- Redox sensor in salt
- Residual gas analyzer to track gas introduction and movement through the system
- FASTR → pumped NaCl-KCl-$MgCl_2$ heated to > 600°C

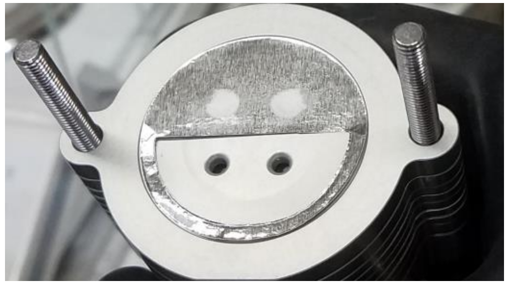
LSTL → pumped FLiNaK heated > 600°C

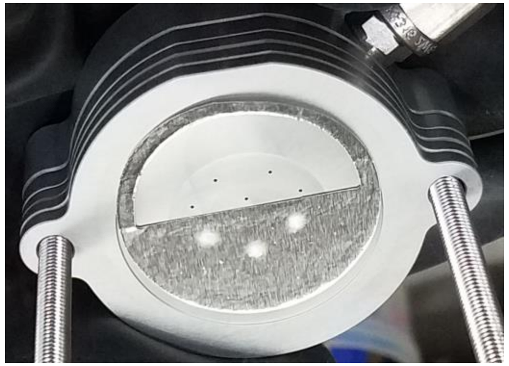




Probe/sensor testing

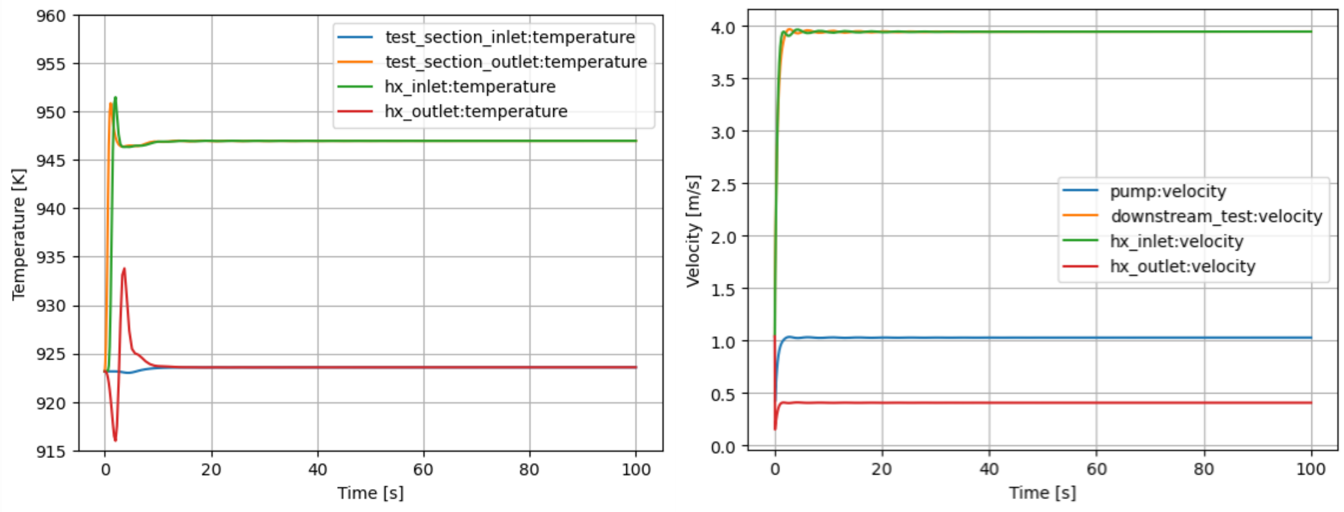
- Sensors retrieved and stored under inert conditions
- Optical sensors to be returned to PNNL for characterization (Amanda Lines Amanda.lines@pnnl.gov)
- Cascade impactor stages to be analyzed by gravimetry and ICP-MS (Hunter Andrews andrewshb@ornl.gov)



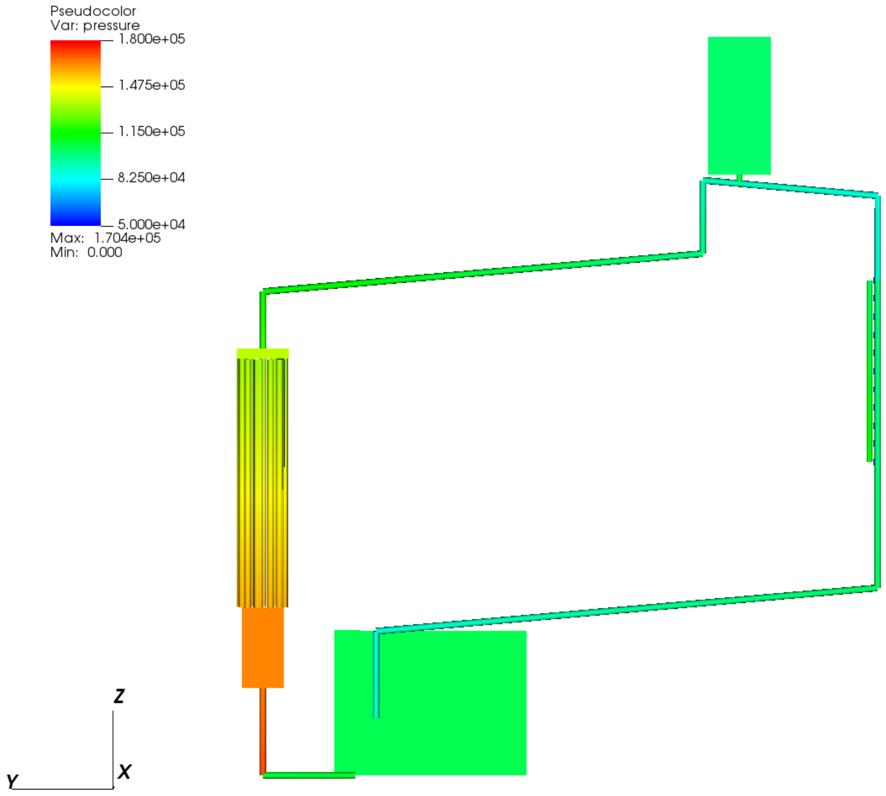


Loop model developed for the LSTL (Bob Salko, salkork@ornl.gov)

- A model was created in the NEAMS system T/H code, SAM
- Modeling options tuned to obtain steady-state heat balance with reasonable mass flow rate and system temperature



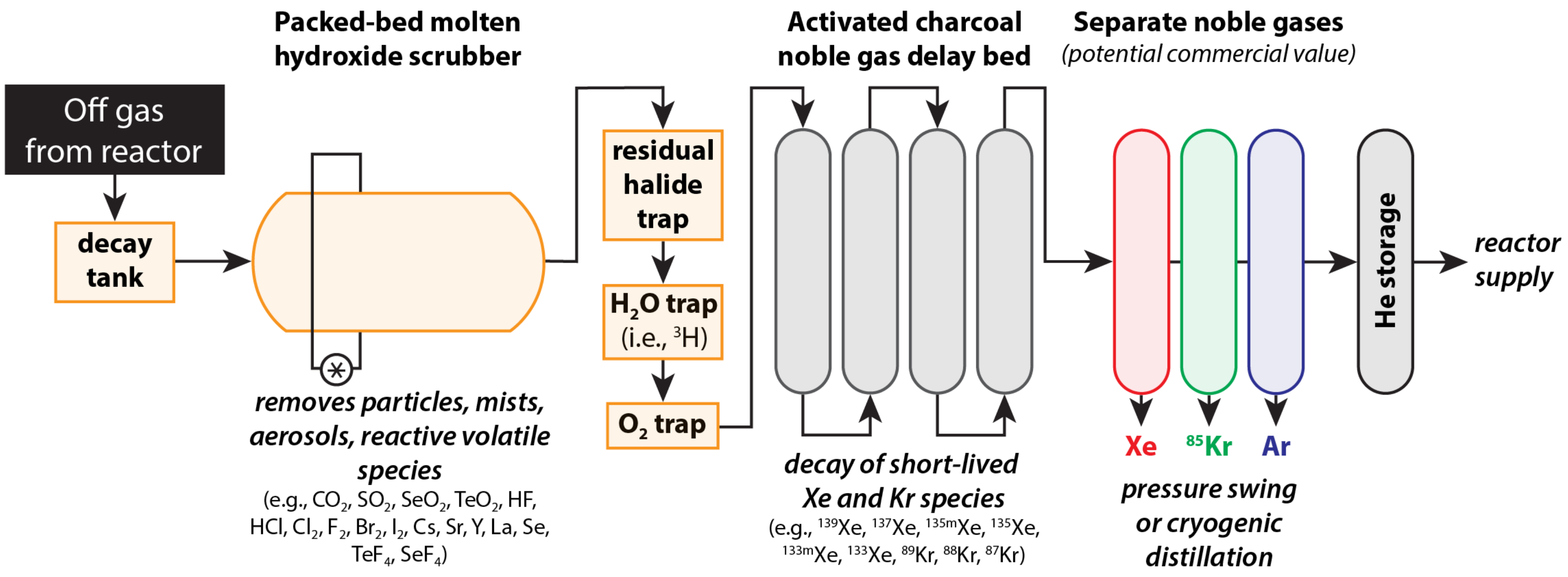
SAM temperature and velocity distribution prediction in LSTL



SAM pressure distribution visualization

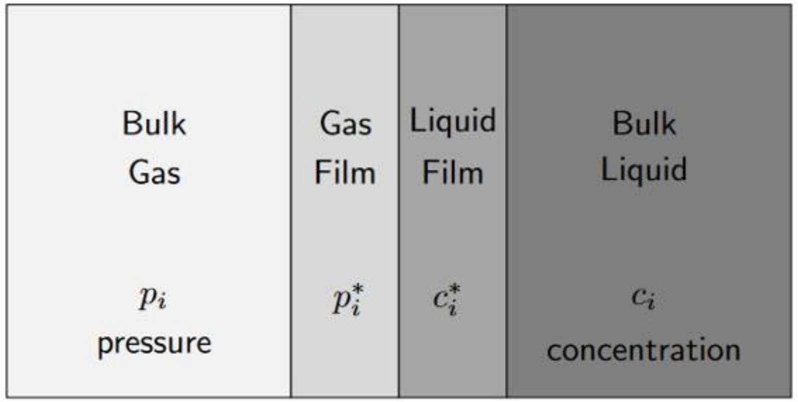
The MSR off-gas system part of the safety envelope of MSRs

(Joanna McFarlane, mcfarlanej@ornl.gov)



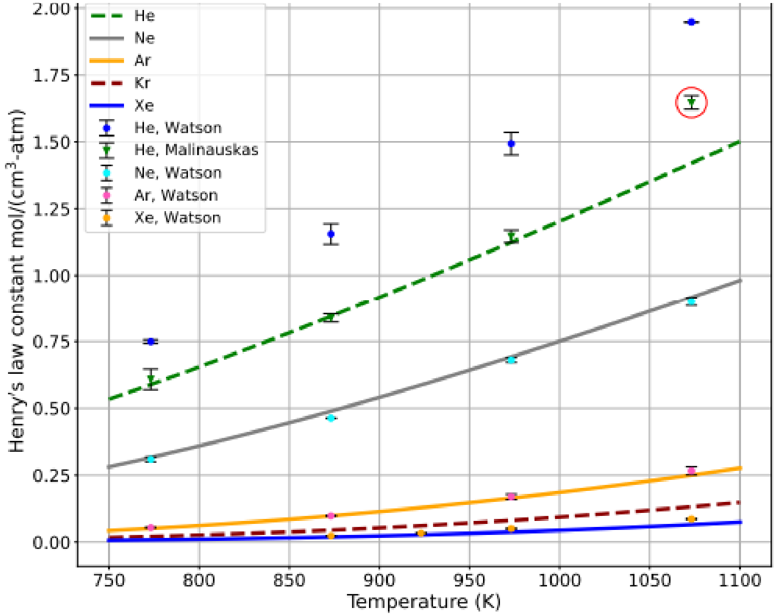
- Off-gas provides the pressure boundary for MSRs.
- Volatilities dependent on FP speciation & salt conditions (chemical and physical).
- Requires online monitoring for radionuclide transport, waste heat removal.

B. J. Riley, J. McFarlane, G. D. DelCul, J. D. Vienna, C. I. Contescu, C. W. Forsberg, "Molten salt reactor waste and effluent management strategies: A review," Nuclear Engineering and Design, Volume 345, 2019, Pages 94-109



$$c_i^* = p_i H$$

$$p_i^* = c_i / H$$



The entropy change for an equilibrium process can be explained by the Gibbs free energy.

$$\Delta G = \Delta \mathcal{H} - T \Delta S$$

where $\Delta \mathcal{H}$ is Enthalpy change, and ΔS is Entropy change, and T is temperature in K. When the temperature of a system changes, the Henry's constant changes and is related to the Van 't Hoff equation. The least squares regression can find the arbitrary number, α and β.

$$\Delta G(r, T; \gamma(T), \alpha, \beta) = RT \ln (K_H) = 4\pi r^2 \alpha \gamma(T) + \frac{4}{3} \pi r^3 \beta RT,$$

where R is the ideal gas constant, r is Van der Waals radius, and γ is the surface tension.

We have considered the mechanism of mass transfer between phases without convection. The overall mass-transfer coefficients were defined by $c_l = p_g H = c_g HRT$ and $K_G = K_L H$ where $p_g = c_g RT$ and $R = 82.05746[\mathrm{cm}^3 \cdot \mathrm{atm}/(\mathrm{K} \cdot \mathrm{mole})]$

$$\text{Liquid transport:}$$

$$\frac{\partial c_l}{\partial t} = K_L a \left(c_g HRT - c_l \right)$$

$$\text{Gas transport:}$$

$$\frac{\partial c_g}{\partial t} = K_G a \left(c_g RT - c_l / H \right)$$

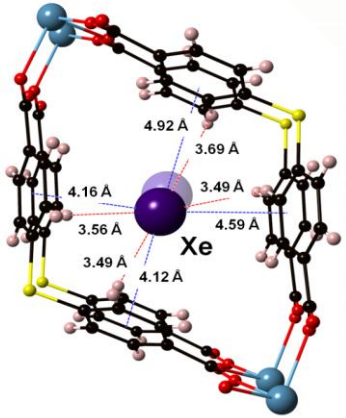
where c is the concentration of species in liquid, p is partial pressure of species in gas phase, and H is Henry's gas constant. a is gas-liquid interfacial area per unit volume.

Cross-cutting collaborative evaluation of the MSR off-gas system

Component testing

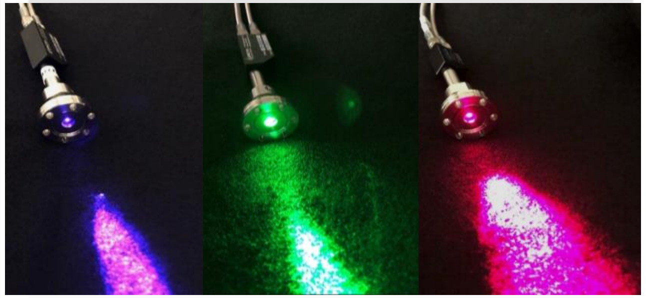
- Large Scale Test Loop

- Xe/Kr separation in MOF



Radionuclide identification

Raman

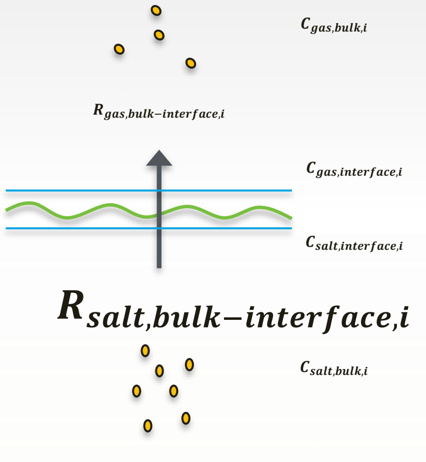


405 nm 532 nm 671

LIBS

Source term modeling

- Gas-liquid interface
- Provides source term to off-gas

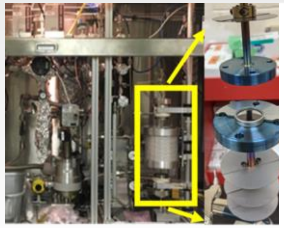


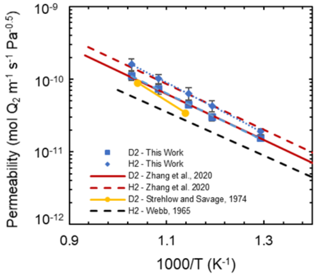
Removal Rate

$$\frac{d(m_i)}{dt} = kA(C_{gas,interface,i} - C_{gas,bulk,i})$$

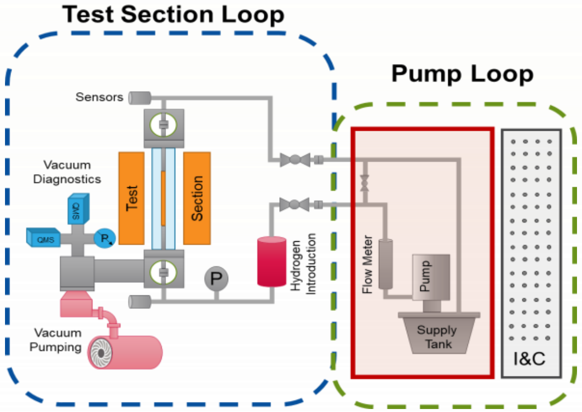
Tritium permeation

- Hydrogen isotope permeability in Hastelloy N



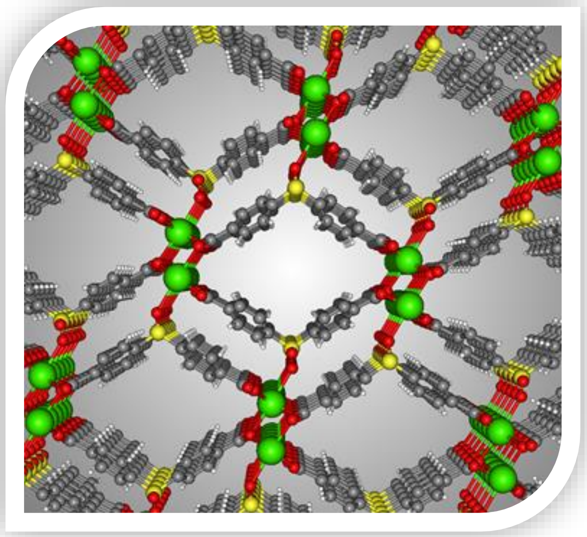


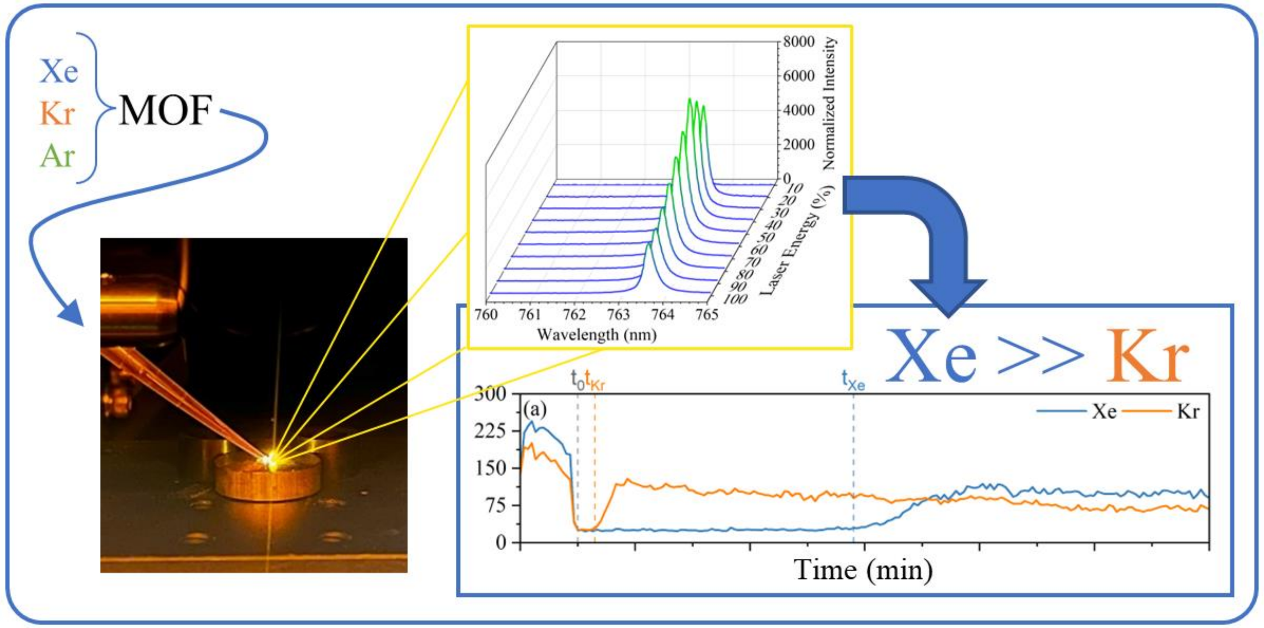
- Tritium transport salt loop



Xenon and Krypton are monitored using Laser Induced Breakdown Spectroscopy (LIBS) – (Andrews (ORNL)/Thallapally (PNNL))

- The Xe and Kr breakthrough was monitored via laser-induced breakdown spectroscopy
- Cut out plot shows the LIBS signal breakthrough profiles used to calculate MOF Xe selectivity
  - Kr always breaks through the MOF far faster than Xe despite changes in gas composition
  - This illustrates the MOFs superior Xe selectivity
- This was the first demonstration of LIBS being used to monitor and evaluate radionuclide capture systems for a molten salt reactor off-gas





H. Andrews and T. Thallapally – GIF Webinar "Off-gas Xenon Detection and management in support of Molten Salt Reactors" – July 2023
https://register.gotowebinar.com/recording/5194755268349550594

Molten salt compatibility: what is our motivation?
(Bruce Pint pintba@ornl.gov)

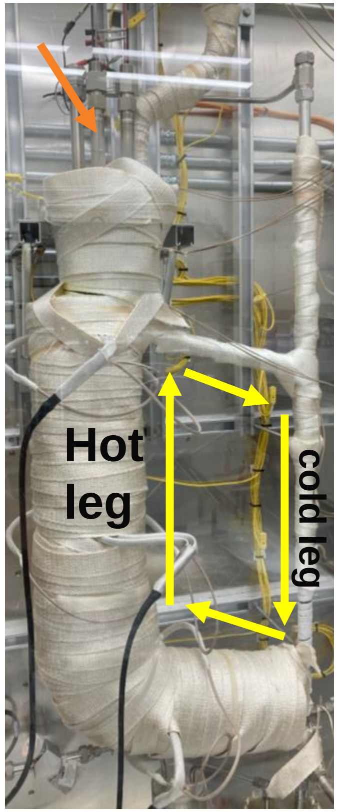
What are we afraid of?

- Inconsequential: Cr surface depletion
- **Mass transfer**
  - Block flow in channel!

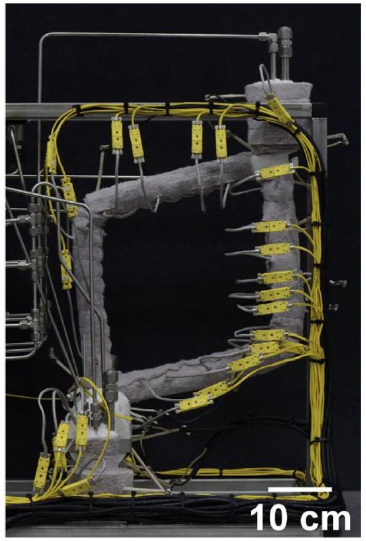
Kelleher 2022 Materials Today
- Ni 200 loop, 14 h at 620° C, unpurified NaCl-$MgCl_2$ salt

How do we study it?

- Flowing salt experiments
  - Forced convection loop
  - Thermal convection loop



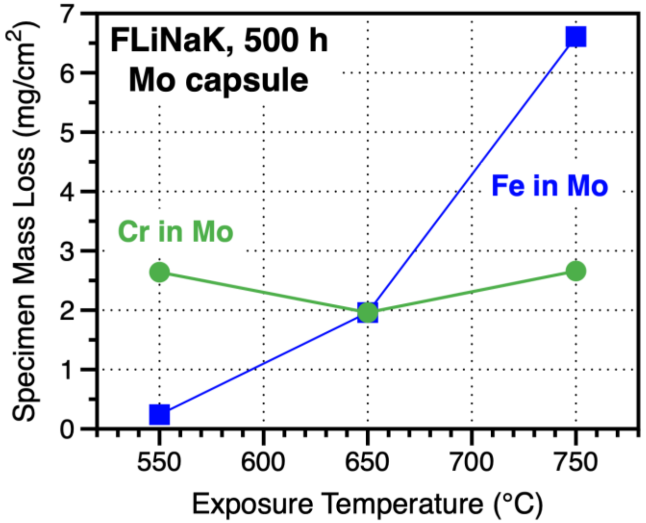
2021 ORNL FLiBe TCL
1 m tall



TerraPower "microloop"

How do we understand it?

- Dissolution experiments
  - Compare Cr and Fe in isothermal salt
  - Experiments in FLiNaK and FLiBe in progress
    - 550°-850°C

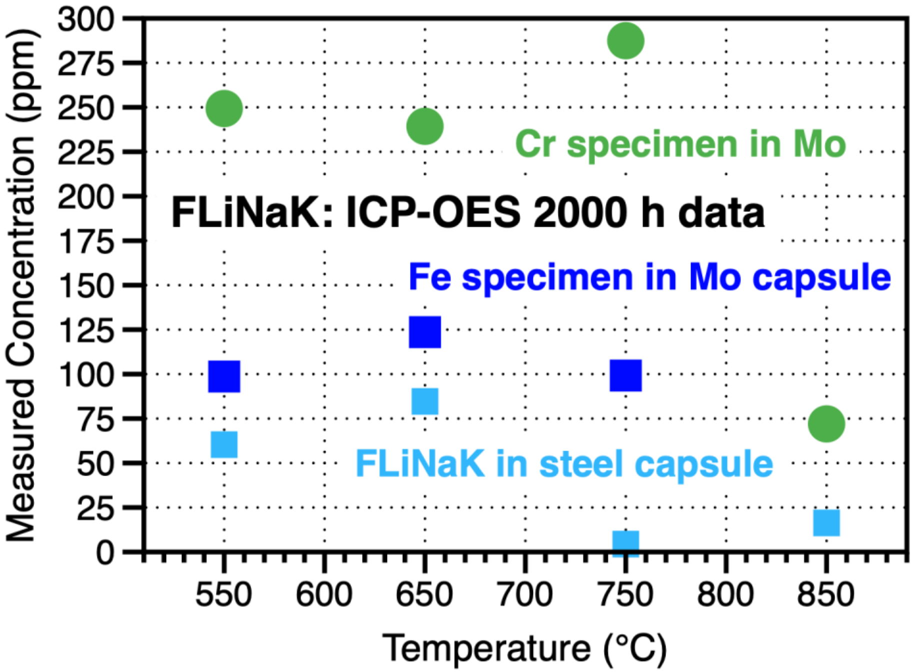


Corrosion modeling –

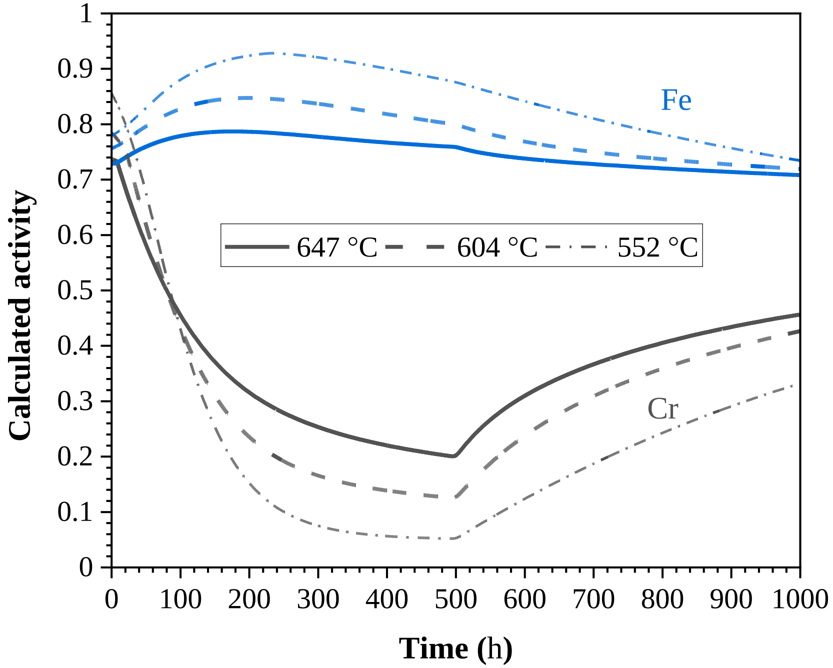
(Bruce Pint, Rishi Palli pallirr@ornl.gov)

- Goal to model dissolution based on salt-alloy chemical potential equilibrium
  - Stainless steels need to consider both Fe and Cr dissolution
  - Collecting data in NaCl-$MgCl_2$, FLiNaK and FLiBe
  - Moving from modeling static behavior to flowing salt loop results
    - Increased validation needed for different salts and flowing conditions

ORNL capsule test



Cr & Fe dissolution after 2000 h

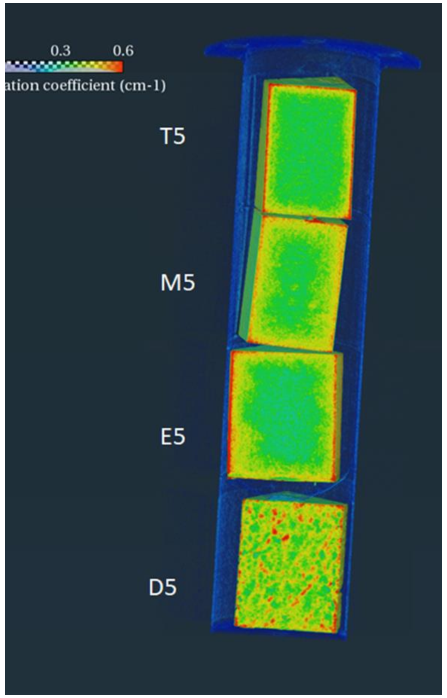


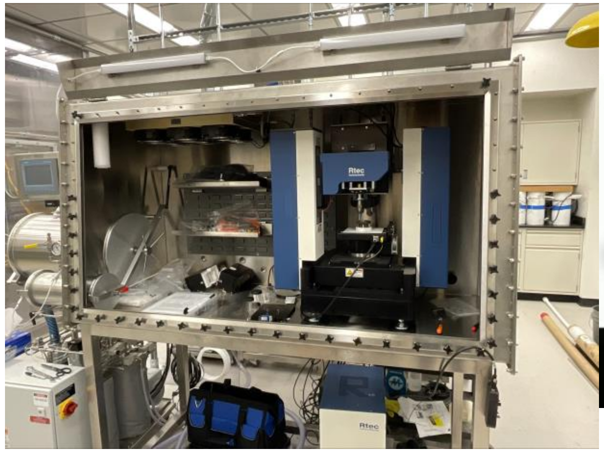
Calculated activities based on observed saturation

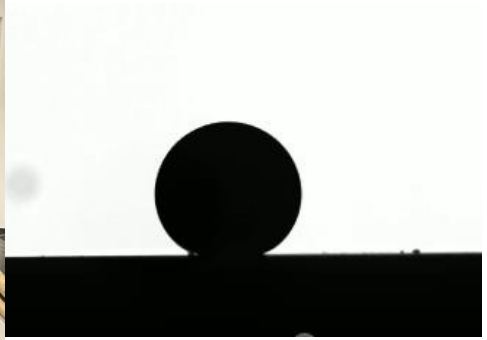
Materials – Graphite - Salt studies: Highlights

(Nidia Gallego gallegonc@ornl.gov)

- Continued to utilize the intrusion system (FLiNaK, < 10 bar, < 750ºC) to conduct measurements on a wide range of graphite grades and intrusion conditions
- Demonstrated and implemented the use of neutron imaging to study intrusion and determine **salt penetration and distribution**: currently studying the effect of time and temperature
- Commissioned contact angle measurement system and initiated data collection to support development of predicting models.
- Completed initial scoping studies of the wear behavior of graphite in molten salts.
- Commissioned new wear facilities to have better environmental control.
- Participation in ASTM and ASME, GIF seminar and PMB.
- Publications: 3 TMs; 4 Journal Pub.; 1 book chapter (ASTM STP), and many presentations.



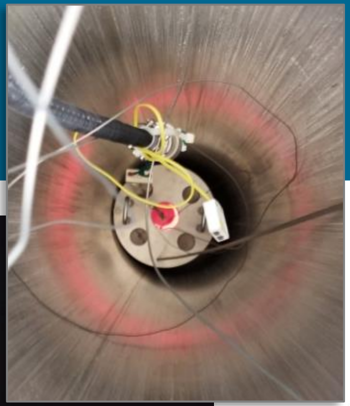




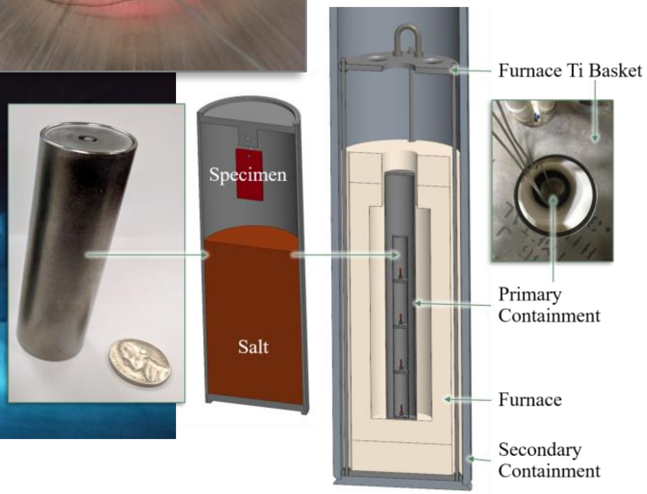
Materials Testing of Be_2C – (Anne Campbell campbellaa@ornl.gov)

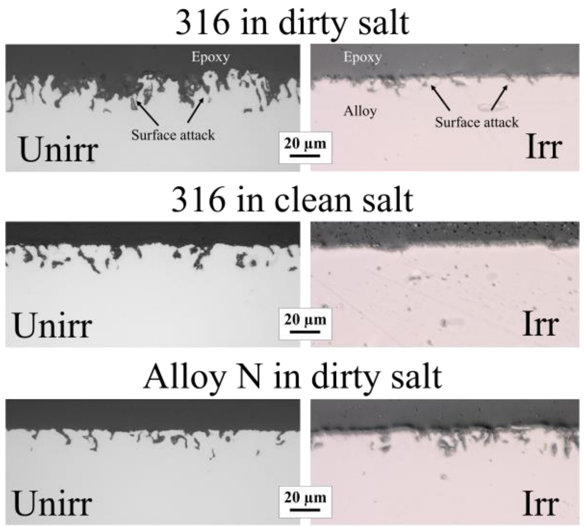
- Evaluation of the concept of using Be_2C as an alternative moderator to graphite. Need to test for irradiation damage.
- Materion – provided Be_2C
- ORNL – high temperature stability testing, degradation in H_2, irradiation damage modeling
- U of Michigan – ion irradiation of Be_2C, HIP pressing of Be_2C powder to pellets

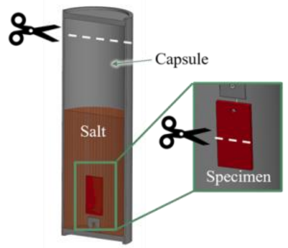
Corrosion Irradiation Study – (Dianne Ezell bullnd@ornl.gov)

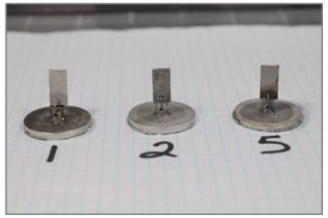


- ORNL completed a 21-Hour (800˚C) irradiation in the OSU research reactor in August 2018
  - Corrosion specimens: Alloy N & SS316
  - Salt composition: 30 g of KCL-MgCl2 in a 58/42 molar ratio
  - Clean salt < 30 ppm oxide
  - Aggressive salt containing as much as 1% oxide
  - Neutron fluence = 5.38 × 1016 n/cm2
- Results: (Compare irradiated specimens to unirradiated specimens)
  - Irradiated samples corroded less than unirradiated samples
  - Consistent with experiments at MIT in which samples irradiated with a proton beam
  - This is attributed to the inverse-kirkendall effect counteracting the selective Cr attack usually observed in engineering alloys









Ezell, N. D. B., Raiman, S. S., Kurley, J. M., & McDuffee, J. "Neutron irradiation of alloy N and 316L stainless steel in contact with a molten chloride salt." Nuclear Engineering and Technology 53.3 (2021): 920-926.

Recent ORNL publications in MSR related investigations.

The program has contributed by developing knowledge and experts who have supplied input to commercial entities, universities, NRC, and other government agencies

- Materials
  - K. M. Moorthi S, J.R. Keiser, D. Sulejmanovic, T.M. Lowe, P.M. Singh, Evaluation of corrosion behavior of various Fe- and Ni-based alloys in molten Li_2BeF_4 (FLiBe), Nuclear Technol. (2023), https://doi.org/10.1080/00295450.2023.2229176
  - J.R. Keiser, P.M. Singh, M.J. Lance, H.M. Meyer III, K.G. Myhre, T.M. Lowe, D. Sulejmanovic, E. Cakmak, V.A. Cox, C.S. Hawkins, A.W. Willoughby, Interaction of beryllium with 316H stainless steel in molten Li_2BeF_4 (FLiBe), J. Nucl. Mater. 565153698 (2022), https://doi.org/10.1016/j.jnucmat.2022.153698
- LIBS
  - H. Andrews, J. McFarlane, Characterization of surrogate molten salt reactor aerosol streams, ORNL/TM-2021/2205
  - H. Andrews, J. McFarlane, D. Holcomb, D.B. Ezell, K. Myhre. Sensor technology for molten salt reactor off-gas systems, Advances in Instrumentation and Control Systems, NPIC&HMIT, June 14-17 2021, 723-733, https://dx.doi.org/10.13182/T124-34454
- Off-gas design
  - H.B. Andrews, J. McFarlane, A.S. Chapel, N.D.B. Ezell, D.E. Holcomb, D. De Wet, M.S. Greenwood, K.G. Myhre, S.A. Bryan, A. Lines, R.J. Riley, H.M. Felmy, P.W. Humrickhouse, Review of molten salt reactor off-gas management considerations, Nucl. Eng. & Design 385, 11529 (2021). https://doi.org/10.1016/j.nucengdes.2021.111529
  - Lee, Kyoung, Wesley Williams, Joanna McFarlane, Dave Kropaczek, and Dane de Wet. "Semi-Empirical Model for Henry's Law Constant of Noble Gases in Molten Salts." (2023), https://www.researchsquare.com/article/rs-3352622/v1.

Acknowledgments

- **Funding from the United States Department of Energy, Office of Nuclear Energy, Advanced Reactor Technologies Program (Patricia Paviet - NTD)**

Clean. Reliable. Nuclear.

Actinide-Molten Salt Chemistry and Properties Research at Los Alamos National Laboratory

Marisa Monreal
Research Scientist
Chemistry Division: Inorganic, Isotope, and Actinide Chemistry Group (C-IIAC)
Los Alamos National Laboratory
mmonreal@lanl.gov

Molten Salt Reactor Workshop
Oak Ridge National Laboratory
October 25-26 , 2023

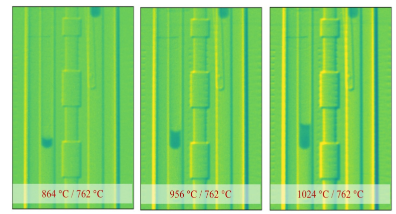
LA-UR-23-32040

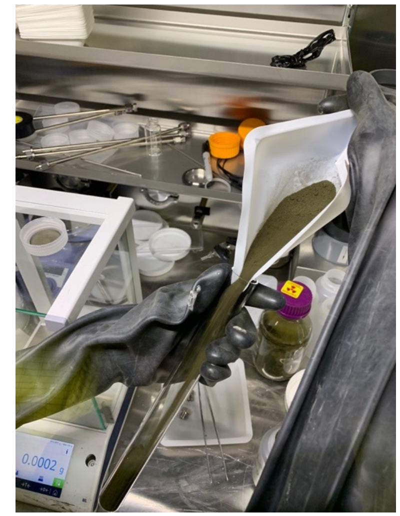
LANL Actinide-Molten Salt Chemistry and Properties Research

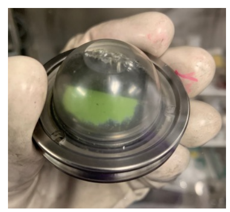
Systems of focus: actinide (uranium, thorium, plutonium) halides dissolved in alkali or alkaline earth metal halides

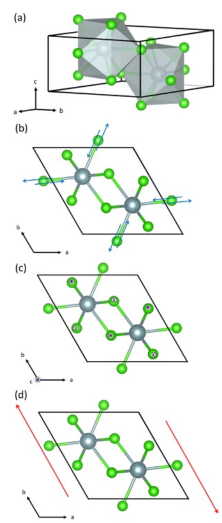
Research activities:

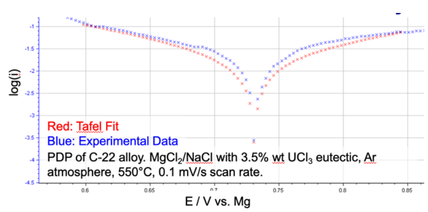
- Preparation and characterization of pure/dry solvent salts
- Synthesis of actinide halides (e.g., $PuCl_3$, UCl_3)
- Study of chemical & thermophysical properties
- Evaluating materials of construction in extreme environments
- Development of in-situ diagnostics
- Identifying signatures and diversionary tactics











Science, technology, and engineering that informs and impacts:

- ✓ Nuclear energy
- ✓ Nuclear security
- ✓ Fundamental actinide science
- ✓ Nonproliferation, global security

FY21-23* LDRD Directed Research Project (#20210113DR):
“Advanced Characterization to Enable Prediction of Actinide-Molten Salt Behavior”

PI: Marisa Monreal (C-IIAC); Co-PIs: David Andersson (MST-8), Matt Jackson (MST-DO)

Main objectives:

1. To integrate advanced characterization techniques in both experiment and modeling
2. To generate an experimentally validated predictive capability with quantified uncertainty for actinide-molten chloride salts (**uranium, thorium, and plutonium**)

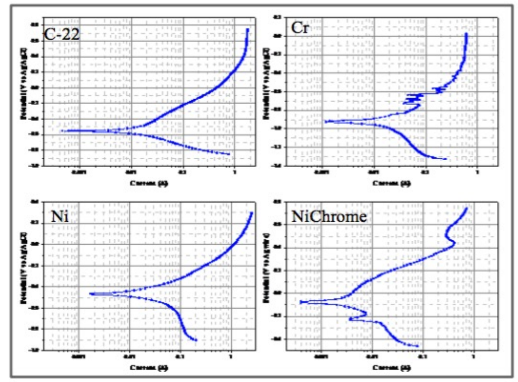
Technical goals:

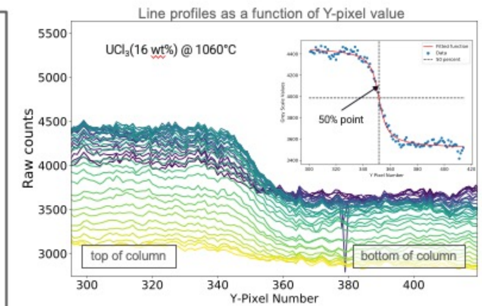
1. Develop atomic scale simulations of macroscale properties, then parametrized physics-based models with quantified uncertainty ***(Modeling and Simulation Thrust)***
2. Synthesize and prepare pure materials: actinide chlorides and solvent salts ***(Chemistry Thrust)***
3. Experimentally determine macroscale properties and examine local structure ***(Thermophysical Properties Thrust, Chemistry Thrust)***

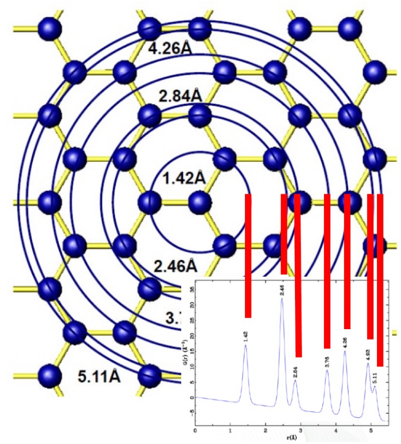
**Extension to May 2024: Density, Viscosity, & Pair-distribution-function (”PDF”)*

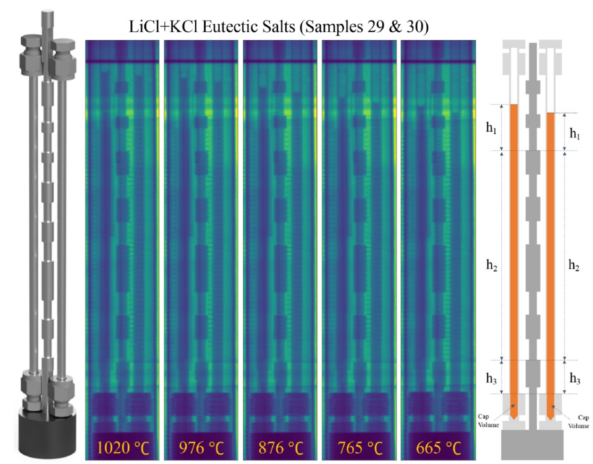
Actinide-Molten Salt Experimental Capabilities at LANL

Properties	Experimental Techniques
Density	Neutron Radiography, Conventional (Push-rod) Dilatometry
Viscosity	Dynamic Neutron Radiography, Rotational Viscometry
Melting Point/Phase Diagram, Heat Capacity	Differential Scanning Calorimetry (DSC)
Corrosion	Electrochemistry, Exposure Tests
Heat of Dissolution, Enthalpy of Mixing, Heat Capacity	Drop Calorimetry
Thermal Diffusivity	Laser Flash Analysis (LFA)
Local Structure	Pair Distribution Function (PDF) Analysis, Raman Spectroscopy, Electrochemistry
Synthesis & Characterization	Inorganic halide synthesis, SEM, Melting Point (DSC), pXRD, SS-NMR Spectroscopy

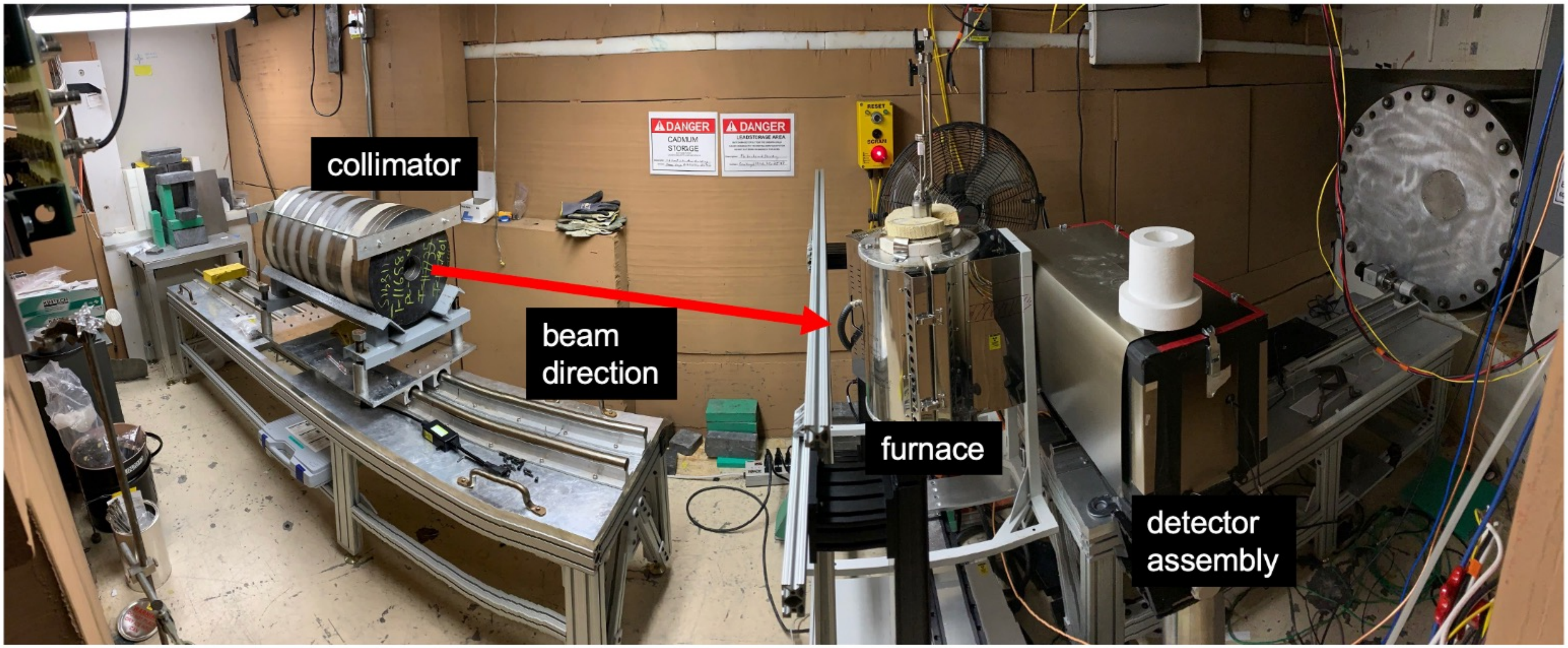






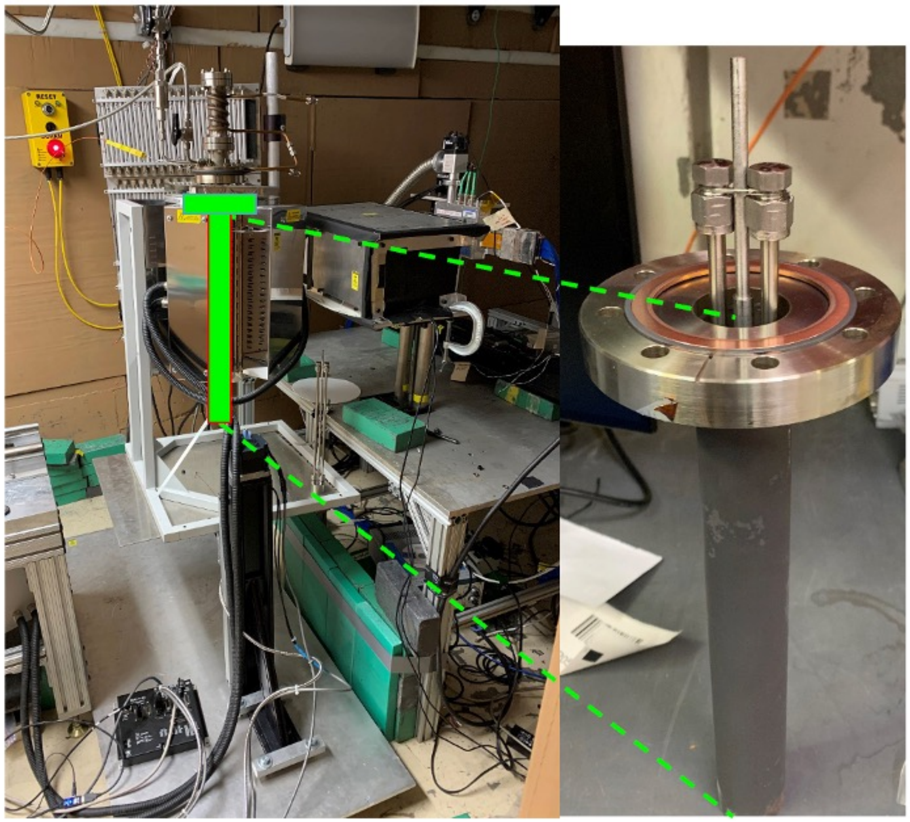


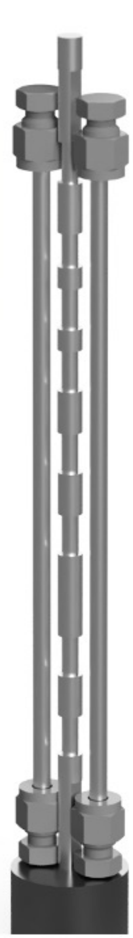
Actinide-Molten Salt Density using Neutron Radiography at LANSCE: Experimental Setup

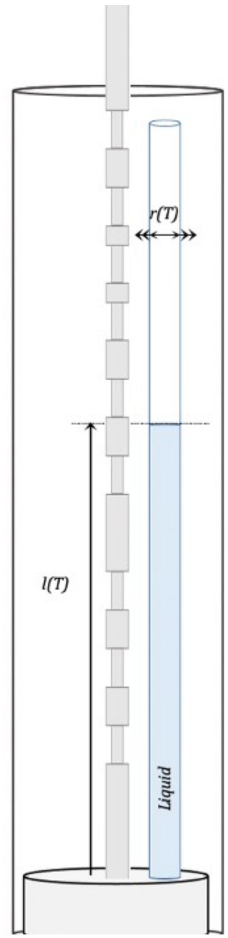


Flight Path 5 at Los Alamos Neutron Science Center (LANSCE)

Actinide-Molten Salt Density using Neutron Radiography

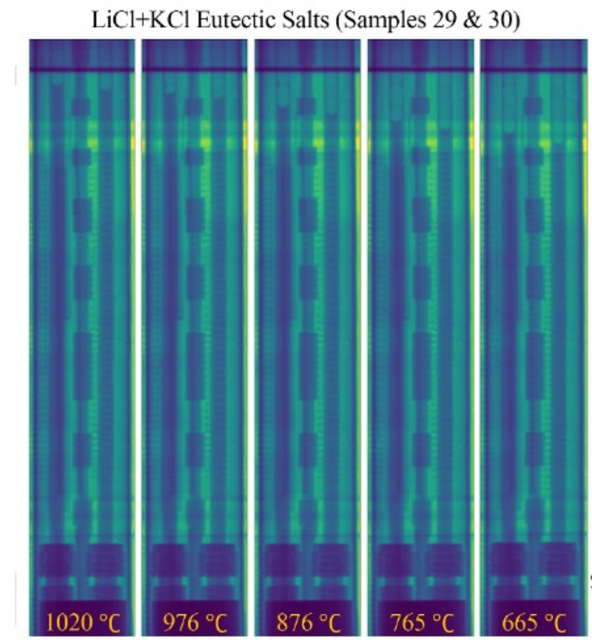




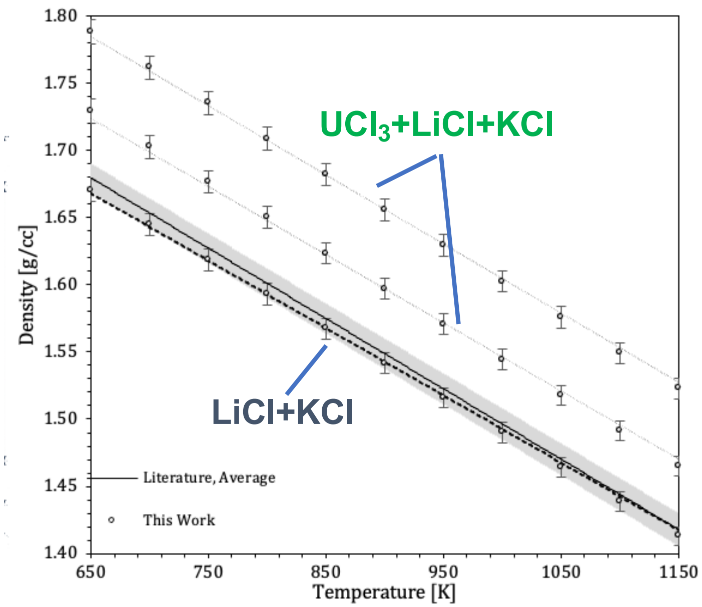


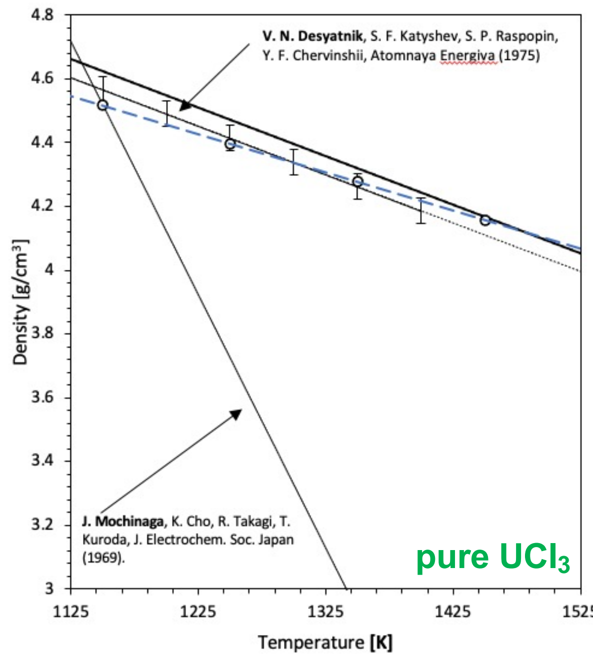
Fluid height is determined using the known height of a feature on our reference

- Images stitched together
- Heights determined at different temperatures

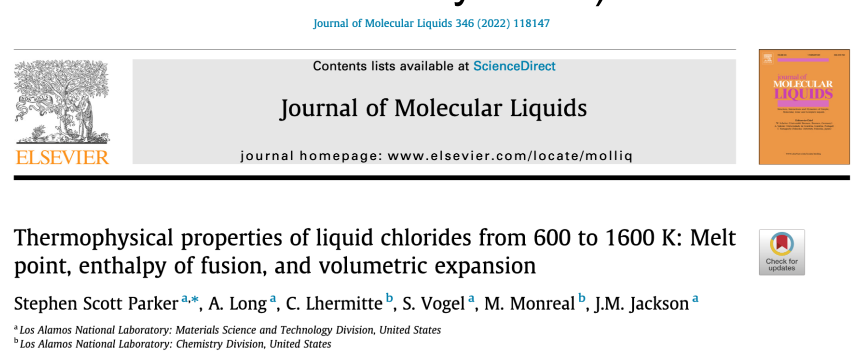


Density using Neutron Radiography: UCl_3-bearing Molten Salt Results





- ✓ Successful demonstration of novel, unique-to-LANL capability for **accurate measurement of liquid density of salts**, including uranium-bearing samples
- ✓ Two journal publications (imaging technique[1], and density data[2])


Journal of Molecular Liquids 346 (2022) 118147

Contents lists available at ScienceDirect

Journal of Molecular Liquids

journal homepage: www.elsevier.com/locate/molliq

ELSEVIER

Thermophysical properties of liquid chlorides from 600 to 1600 K: Melt point, enthalpy of fusion, and volumetric expansion

Stephen Scott Parker [a,*], A. Long [a], C. Lhermitte [b], S. Vogel [a], M. Monreal [b], J.M. Jackson [a]

[a] Los Alamos National Laboratory: Materials Science and Technology Division, United States
[b] Los Alamos National Laboratory: Chemistry Division, United States

(1) Long, A., Parker, S., Carver, T. Jackson, J. M., Monreal, M., Newmark, D., Vogel, S., *J. Imaging,* **2021,** *7,* 88
(2) Parker, S., Long, A., Lhermitte, C., Vogel, S., Monreal, M., Jackson, J. M., *J. Mol. Liq.,* **2022,** *346,* 118147

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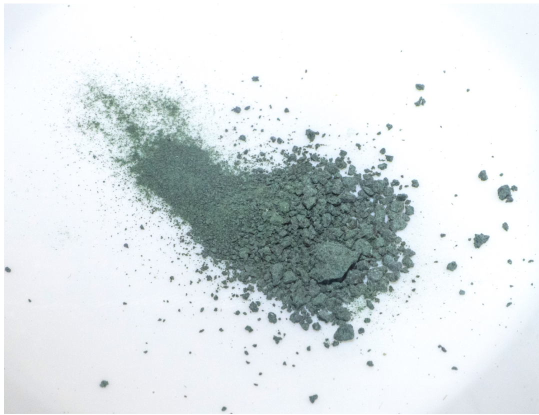
Plutonium-Molten Salt Characterization: Differential Scanning Calorimetry



$PuCl_3$ + NaCl eutectic salt

Thank you!: Toni Karlsson, INL

Sample Stage

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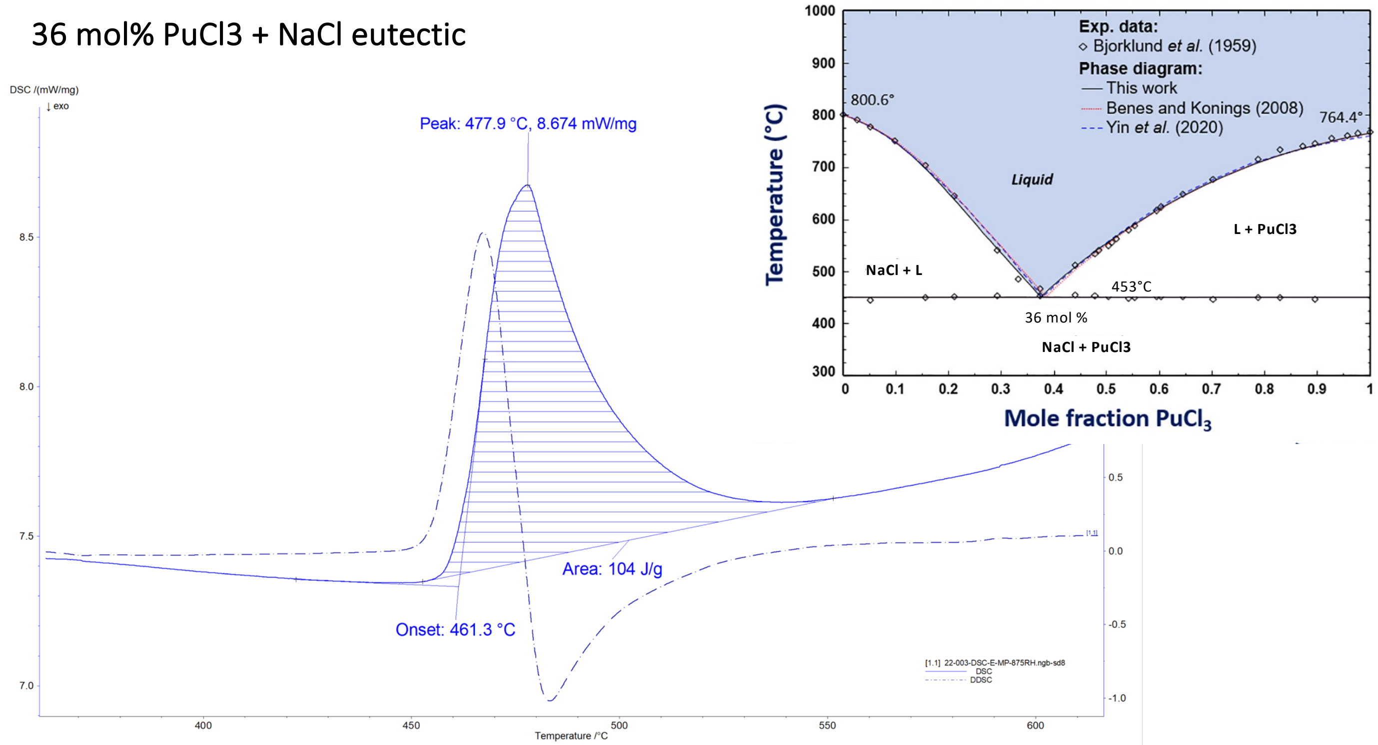
36 mol% PuCl3 + NaCl eutectic



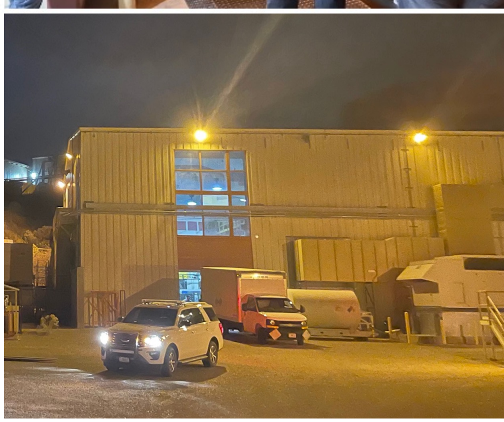
Melt Point Data: cooling onset 453 +/- 8 °C [1], heating onset 456 +/- 5 °C peak 480 +/- 3 °C [3]

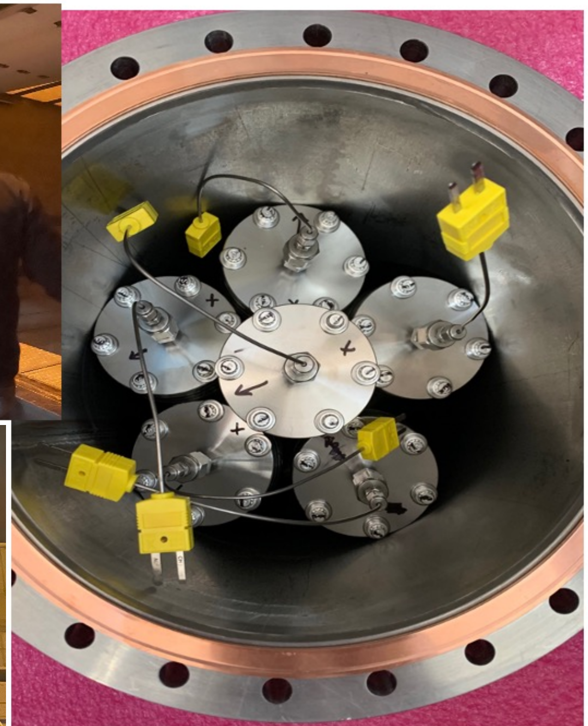
This work: $T_{melt,\ onset}$ = 461 +/- 2 °C, $T_{melt,\ peak}$ = 478 +/- 2 °C ΔH_{fusion} = 104 J/g

Molten Salt Reactor PROGRAM

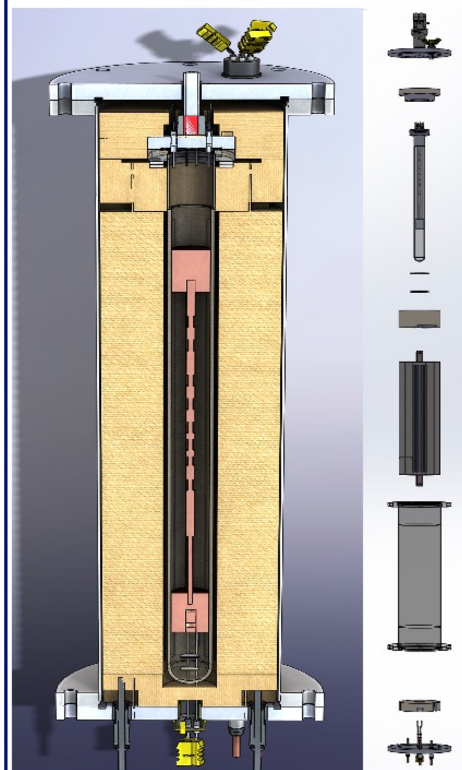
$PuCl_3$-NaCl Density Experiments at LANSCE, December 2022

Sample move: PF-4 to LANSCE: December 9th, 2022





Required a New State-of-the-art Furnace

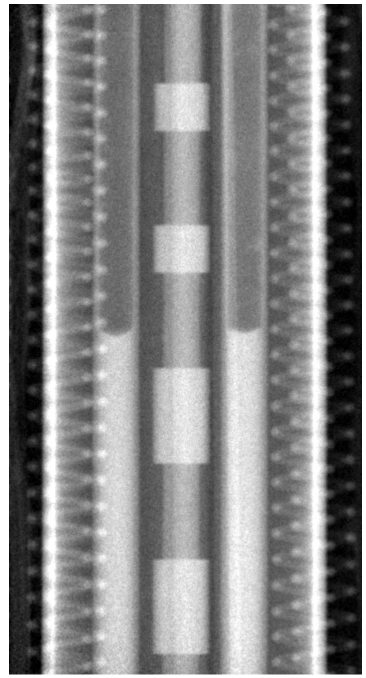


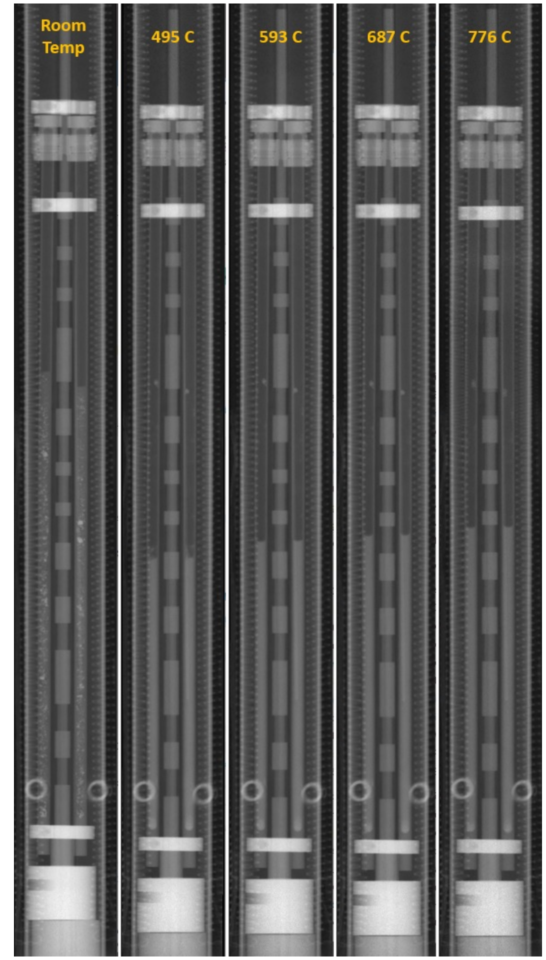
Furnace Design by Travis Carver

$PuCl_3$-NaCl Density Experiments at LANSCE, December 2022

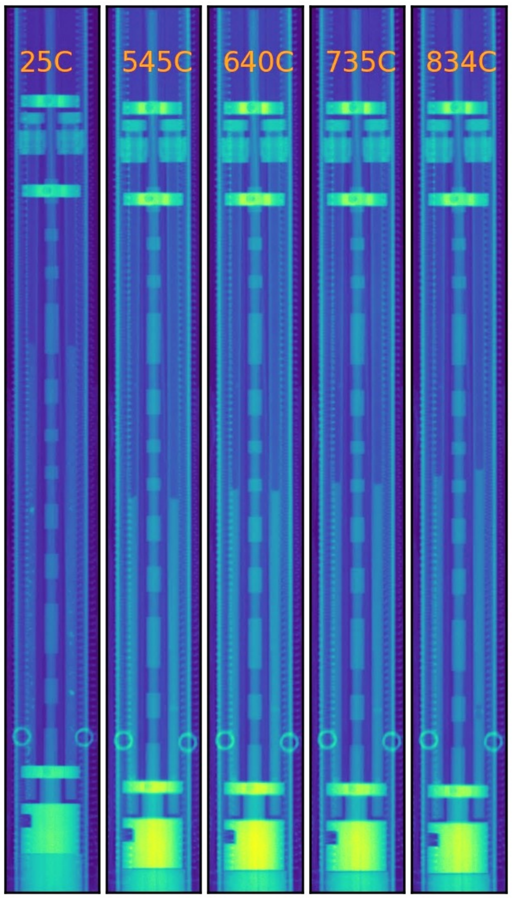
Experimental Details:

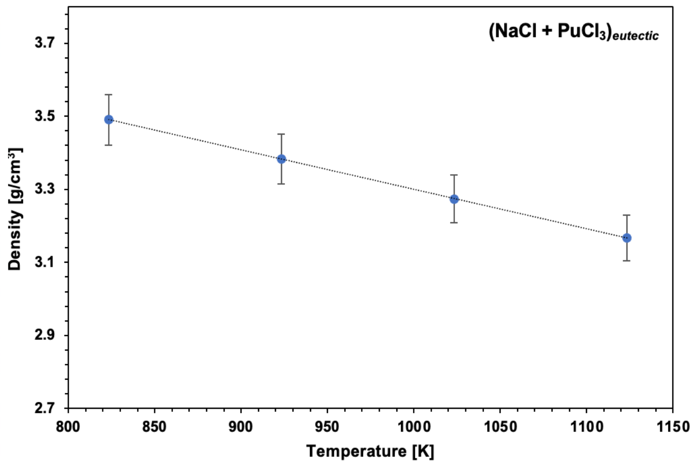
- Beam Time on FP5: Dec 10th – 20th, 2022
- Maximum Temperatures: ~950 ^{o}C
- Exposure Times: 1 min
- ~12- to 15-hour measurements per sample pair
- Each pair was measured once
- Used gantry to move sample through FOV
- 4-5 full sample scans were performed at elevated temperatures for each sample-pair; images of meniscus every ~5 ^{o}C

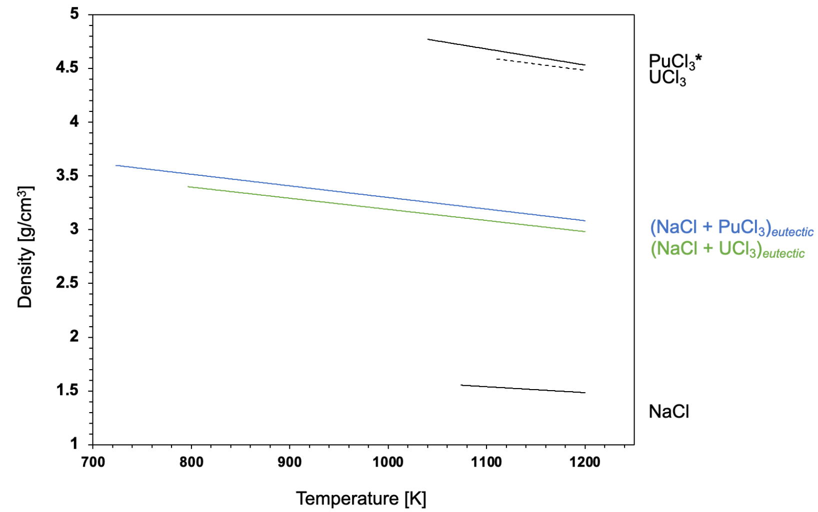




Density using Neutron Radiography: $PuCl_3$-NaCl preliminary results







Temperature [°C]	Density [g/cm³]
550	3.49
650	3.38
750	3.27
850	3.17

- Plotted results are from preliminary image analysis, error analysis (2% error bars shown)
- Pu > U density
- Next steps: complete analysis, comparison with INL (experimental), PNNL/ORNL (modeling); publish; 2023 beam cycle!

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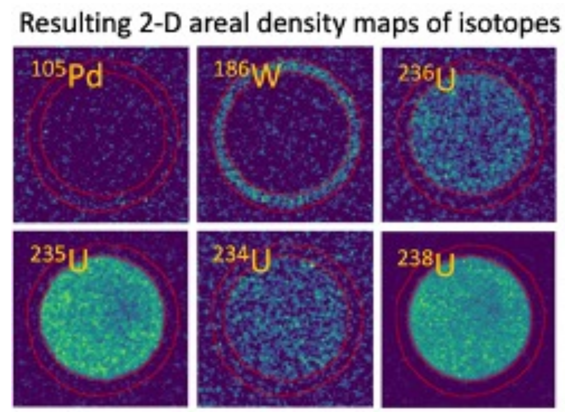
**Pure $PuCl_3$ liquid density derived from measurements of salt mixtures of $PuCl_3$ with NaCl, $MgCl_2$, and UCl_3*

Actinide-Molten Salt using Neutron Radiography: Features

- Eyes on sample the whole time (watch out for bubbles!)
- Modular setup: multiple samples can be measured simultaneously, and samples can be swapped quickly (measurement times depend on furnace)
- Can measure same samples multiple times
- Suitable for Pu materials
- Potential to extract **additional information** with other advanced neutron imaging techniques
  - For example: Temps and actinide density can be measured in-situ with neutron resonances (i.e., ERNI)
- Neutron radiography methods (density, viscosity) complement higher-throughput methods



Energy-Resolved Neutron Imaging (ERNI) isotope mapping

Next up: 2023 LANSCE Experiments

LANSCE 2023 beam cycle:

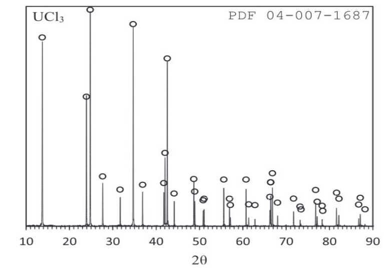
1. **Pair distribution function (PDF)** measurements on molten mixtures of UCl_3, UCl_4, NaCl, $MgCl_2$
    - Including **room temp-to-melting point diffraction measurements**
2. **New** $PuCl_3$ compositions for **density** measurements by neutron radiography
    - Lower $PuCl_3$ concentrations; additional binary, ternary compositions (containing UCl_3, $MgCl_2$)
3. **Viscosity** measurements by dynamic neutron radiography; UCl_3-NaCl system
    - Improved apparatus, including new spheres made in-house

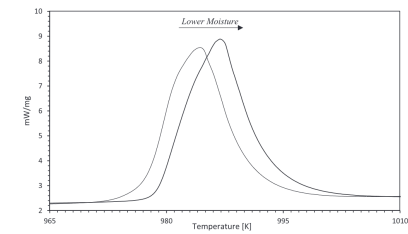
- Supported by/coordinated with:
    - **Solid state nuclear magnetic resonance (SS-NMR) spectroscopy (actinide; ^{35}Cl)**
    - **Raman spectroscopy**
    - **Electroanalytical studies**

Capability Highlight: Actinide Halide Synthesis and Characterization

Synthesis of *pure, isolable* actinide chlorides and fluorides to enable property research

- Both conventional & novel synthetic routes (e.g., for UCl_3, UCl_4, $ThCl_4$, UF_4)
- Characterization techniques to confirm purity (e.g., SS-NMR; pXRD; DSC)
  - Impurities: other actinide species; water; products of rxn with water

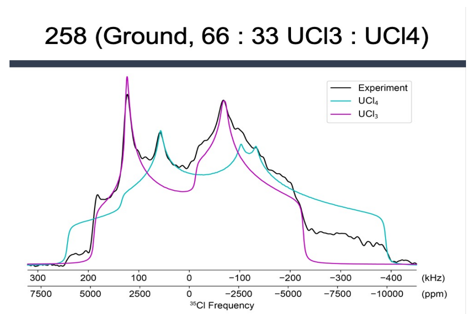




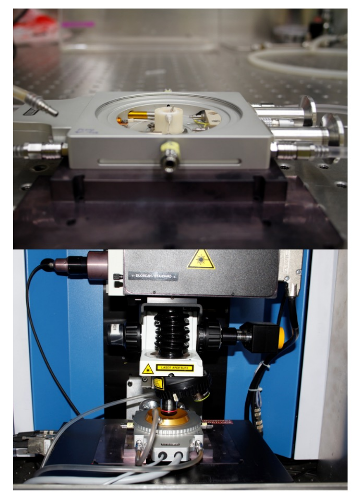
$UCl_3(py)_2$ —thermal elimination→ UCl_3

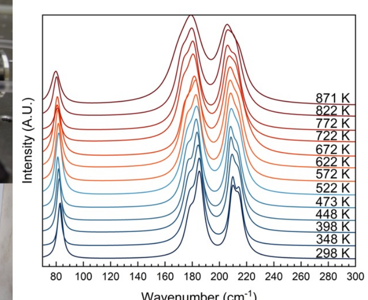
$UI_4(diox)_2$ —fluorination in organic solvent→ UF_4

Synthesis: *Nicholas Capra, Karla Erickson*



SS-NMR: Adam Altenhof, Harris Mason





High-T Raman: Andrew Strzelecki

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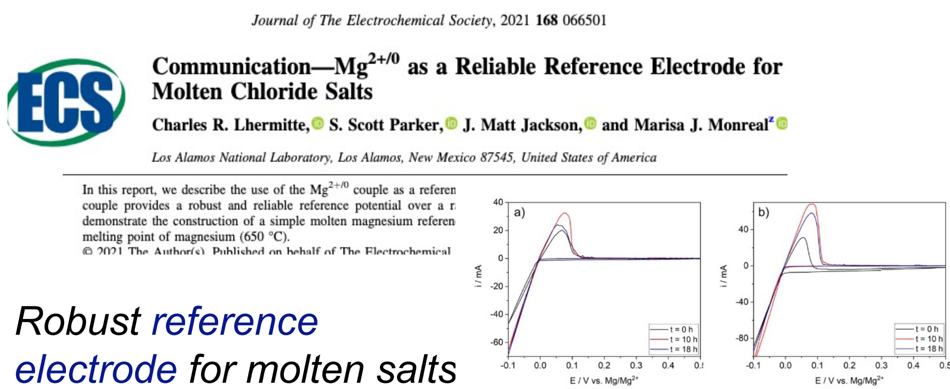
Capability Highlight: Molten Salt Electrochemistry

Electrochemical studies of actinide-molten salts: speciation & redox behavior; corrosion



Journal of The Electrochemical Society, 2021 **168** 066501

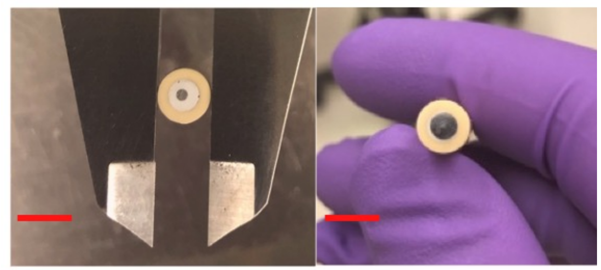
Communication—$Mg^{2+/0}$ as a Reliable Reference Electrode for Molten Chloride Salts

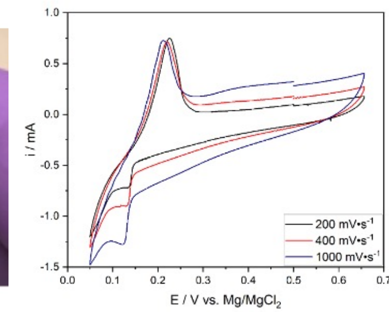
Charles R. Lhermitte, S. Scott Parker, J. Matt Jackson, and Marisa J. Monreal[z]

Los Alamos National Laboratory, Los Alamos, New Mexico 87545, United States of America

In this report, we describe the use of the $Mg^{2+/0}$ couple as a referen
couple provides a robust and reliable reference potential over a r
demonstrate the construction of a simple molten magnesium referen
melting point of magnesium (650 °C).
© 2021 The Author(s). Published on behalf of The Electrochemical

Robust reference electrode for molten salts

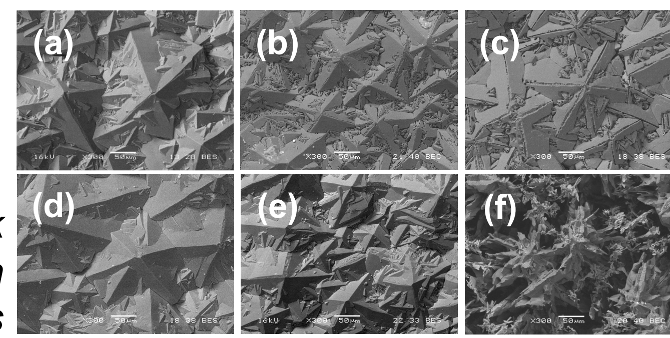




Electromotive force measurements of UCl_3-$MgCl_2$-NaCl using small area working electrodes

Hannah Patenaude *(Graduate Student)*
*****Poster**:*** *"Electrode Materials for f-Block Electroanalytical Chemistry in Molten Chloride Salts"*

Boron-doped diamond for f-block electroanalytical chemistry in molten chloride and fluoride salts



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Publications

Density via neutron radiography

Variable temp crystal structure... with neutrons

Technique: density via neutron radiography

Electrochemistry (reference electrode)

Mod-sim

Technique: conventional (push-rod) dilatometry

Raman

Drop Cal

Synthesis

Electrochemistry (EMF)

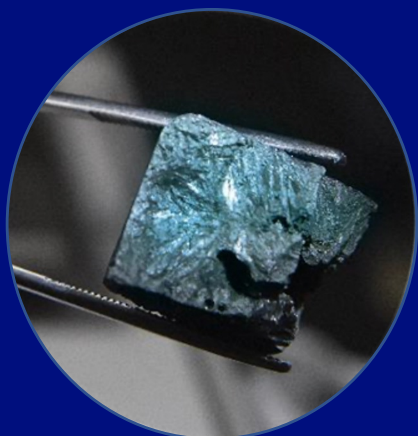
1. Parker, S., Long, A., Lhermitte, C., Vogel, S., Monreal, M., Jackson, J. M. *"Thermophysical properties of liquid chlorides from 600 to 1600 K: Melt point, enthalpy of fusion, and volumetric expansion", J. Mol. Liq.* **2022,** *346*, 118147.
2. Vogel, S., Andersson, D., Monreal, M., Jackson, M., Parker, S., Wang, G., Yang, P., and Zhang, J. *"Crystal Structure Evolution of UCl_3 from Room Temperature to Melting." JOM*, **2021,** *73,* 3555-3563.
3. Vogel, S., Monreal, M., Shivprasad, A. *"Materials for Small Nuclear Reactors and Micro Reactors, including Space Reactors." JOM*, **2021**, *73,* 3497-3498.
4. Long, A., Parker, S., Carver, T. Jackson, J. M., Monreal, M., Newmark, D., Vogel, S. *"Remote Density Measurements of Molten Salts via Neutron Radiography", J. Imaging*, **2021**, *7,* 88.
5. Lhermitte, C., Parker, S., Jackson, J. M., Monreal, M. *"$Mg^{2+/0}$ as a reliable reference electrode for molten chloride salts", J. Electrochem. Soc.*, **2021**, *168,* 066501.
6. Andersson, D. and Beeler, B. *"Ab initio molecular dynamics (AIMD) simulations of NaCl, UCl_3 and NaCl-UCl_3 molten salts", J. Nuc. Mat.,* **2022**, *568,* 153836.
7. S. S. Parker, N. M. Abdul-Jabbar, M. Jackson, M. Monreal. *"Feasibility of Volumetric Expansion of Molten Chlorides by Conventional Pushrod Dilatometry" J. RadioAnal. Nucl. Chem.,* **2022,** *331,* 5259.
8. Strzelecki, A., Wang, G., Hickam, S., Parker, S., Batrice, R., Jackson, J. M., Conroy, N., Mitchell, J., Andersson, D., Monreal, M., Boukhalfa, H., Xu, H. "In situ High Temperature Raman Spectroscopy of UCl_3: A Combined Experimental and Theoretical Study", *accepted—Inorganic Chemistry, **2023***

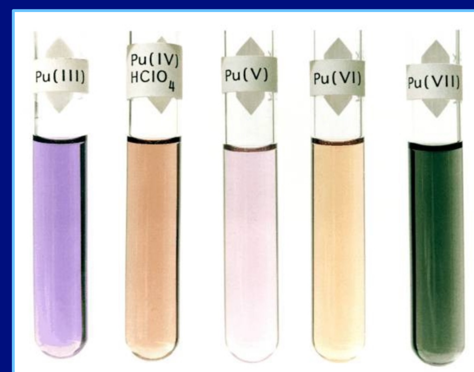
- Strzelecki, A., Xu, H., et. al. *"New Methodology for Measuring the Enthalpies of Mixing of Molten Salts Using High Temperature Drop Calorimetry", submitted*
- Erickson, K., Parker, S., Monreal, M. *"Thermal Elimination of Pyridine from a Uranium Trichloride Precursor", in preparation*
- Lhermitte, C., Patenaude, H., Parker, S., Erickson, K., Jackson, J. M., Monreal, M. *"Electrochemical behavior and electromotive force measurements of U^{3+}/U $MgCl_2$-NaCl melts", in preparation*

New Plutonium R&D Capability:

Plutonium Science Laboratory (“PluS Lab”)

-- Gram-scale, non-irradiated materials --





PLUTONIUM CAPABILITY 1:
Molecular chemistry & materials science

ENVIRONMENT 1:
O_2- and H_2O-free

PLUTONIUM CAPABILITY 2:
Aqueous chemistry

ENVIRONMENT 2:
Water solutions

PLUTONIUM CAPABILITY 3:
Molten salt science

ENVIRONMENT 3:
High-temperature (400 °C-900°C), O_2- and H_2O-free

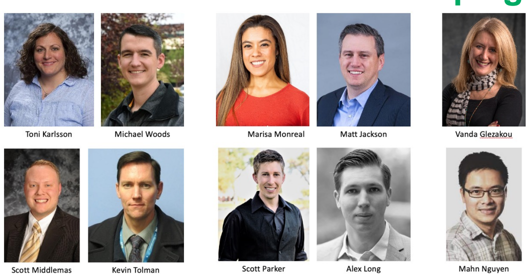
Currently open position IRC125275 – Visit lanl.jobs

Sponsor: Nonproliferation Stewardship Program (NSP)

Acknowledgements

Scott Parker
Alex Long
Matt Jackson
David Andersson
Sven Vogel
Travis Carver
Shane Mann
Ping Yang
Gaoxue Wang
Doug Ware
Karla Erickson
Nicolas Capra
Adam Altenhof
Harris Mason
Hannah Patenaude
Jarom Chamberlain
Hongwu Xu
Hakim Boulkhalfa
Andrew Strzelecki
Sarah Hickam

INL-LANL-PNNL-ORNL MSR Campaign Team



Funding:

LANL Laboratory Directed Research and Development (LDRD) Directed Research Project #20210113DR

Molten Salt Reactor Campaign

Gateway for Accelerated Innovation in Nuclear (GAIN) #NE-21-25117

University Collaborators, visiting students:
University of Utah, MIT, UC Berkeley, OSU, UNLV

*This work was performed, in part, at the Los Alamos Neutron Science Center (**LANSCE**), a NNSA User Facility operated for the U.S. Department of Energy (DOE) by Los Alamos National Laboratory (Contract 89233218CNA000001).*

Molten Salt Reactor Analysis with SCALE 6.3.1

Donny Hartanto

Research and Test Reactor Physics Group

2023 Molten Salt Reactor Workshop

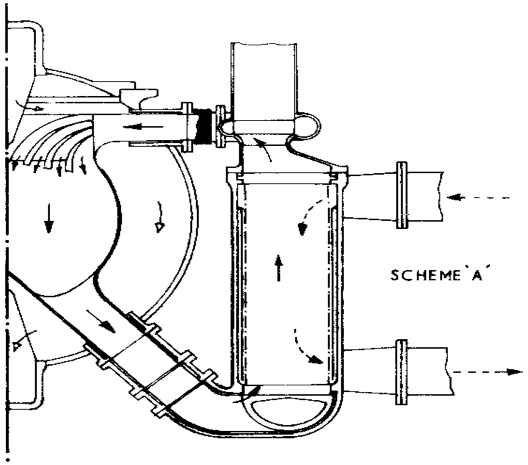
October 25, 2023

Contents

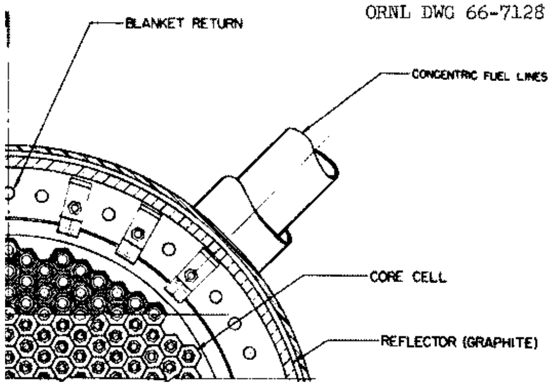
- **Introduction**
- **Applications**:
  - Time-dependent system-average inventory
  - Location-dependent inventory
  - Core neutronics parameters
  - Decay heat and activity
  - Few-group cross section generation using SCALE/Shift
  - Examples: Fluoride-salt MSR (MSRE) and Chloride-salt MSR (MCFR)
- **Conclusions**

Molten Salt Reactors

- **Liquid-fueled molten salt reactors (MSRs)** are any reactor technology that dissolves fuel within a carrier salt
  - Fast spectrum molten salt reactor (MSR) cores with large volumes of salt
  - Thermal spectrum MSR cores with fixed moderator material
- **Key differences of MSRs to LWRs for mod&sim:**
  - Continuous circulation of the fuel
  - Consideration of both core and loop
  - **Nuclide removal** from the fuel (fission product removal)
  - **Nuclide feed** to the fuel (refueling)
- **Results of interest:**
  - System-average fuel salt composition as a function of time
  - Location-dependent fuel salt inventory in the system
  - Neutronic characteristics at specific point in time



½-core fast spectrum design [1]



¼-core thermal spectrum design [2]

[1] "An Assessment of a 2500MWe Molten Chloride Salt Fast Reactor" (1974).
[2] "Design Studies of 1000-MW(e) Molten-Salt Breeder Reactors" (1966).

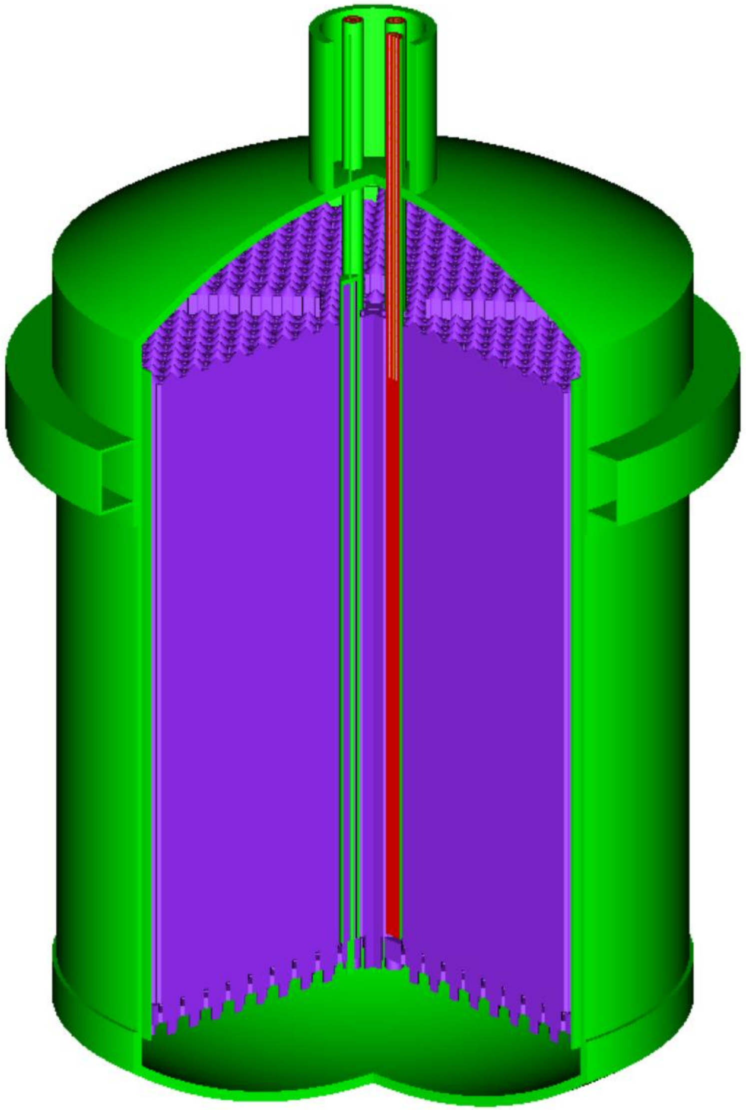
SCALE

ORNL code system for nuclear modeling and simulation

- Initiated by the U.S. Nuclear Regulatory Commission (NRC) in the 1980s to provide confirmatory analysis capabilities for light-water reactor (LWR) criticality, transportation, and spent fuel applications
  - Current sponsors include DOE Nuclear Criticality Safety, DOE NNSA, and U.S. NRC
  - Over 7,000 user licenses for the v6.2 series (2016)
    - Over 20 international regulatory bodies use SCALE
    - More than 100 trainees/year, including courses at OECD/NEA and IAEA
  - New v6.3 series (2023) recently available from RSICC
    - V&V-ed non-LWR capability for tristructural isotropic (TRISO)-based systems, graphite moderation, and molten salt fueled reactors (MSRs)
    - Additional HALEU/HBU/ATF enhancements
    - Inclusion of the Shift Monte Carlo code

- **Leading-edge capabilities**
  - Criticality safety
  - Radiation shielding
  - Spent fuel inventory
  - Reactor physics/operation
  - Activation/Isotope production

Emerging capabilities in v7.0 (~2025) for rapid non-LWR inventory generation, Mo99 production, and comprehensive uncertainty quantification.



MSRE SCALE Model

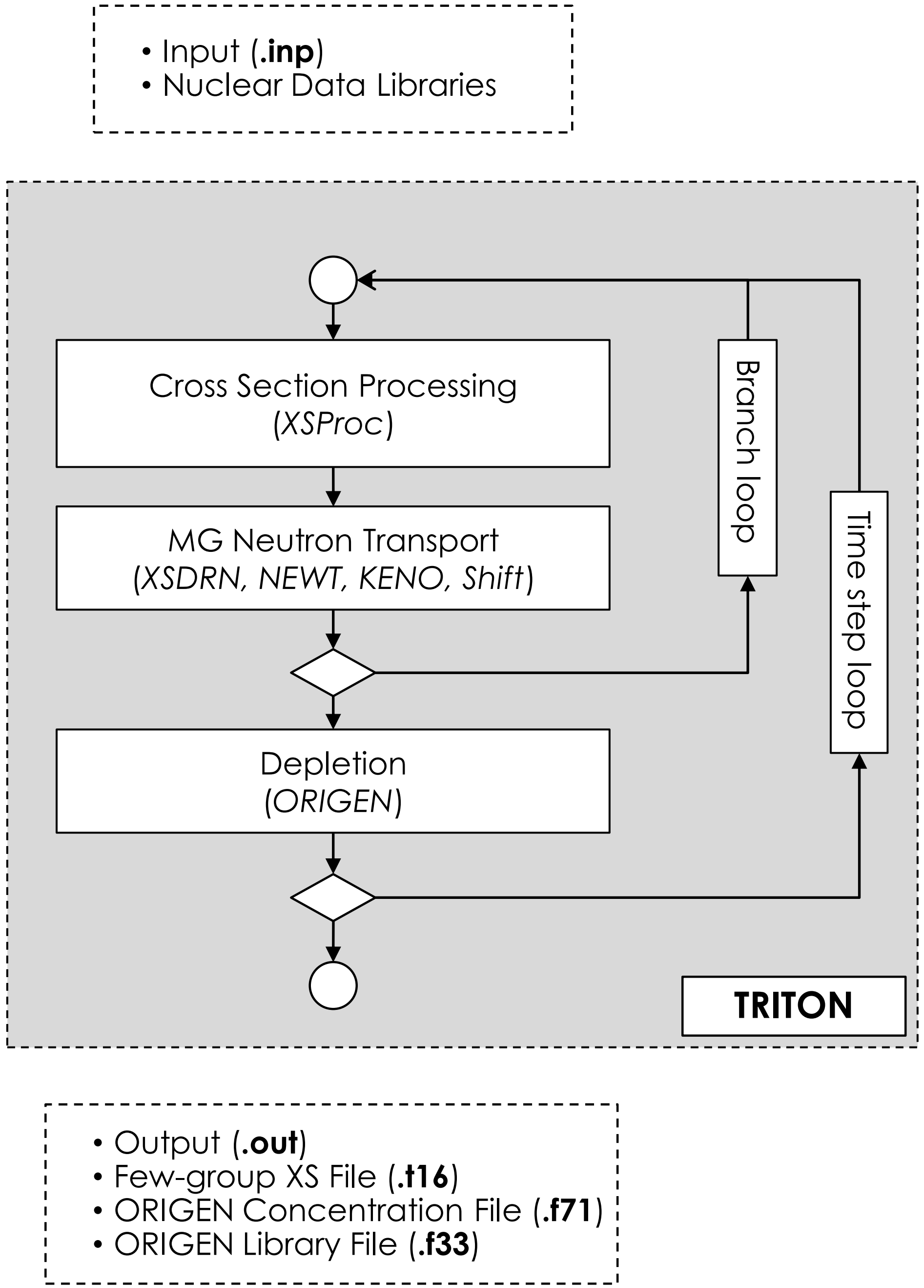
https://scale-manual.ornl.gov

SCALE/TRITON Sequence

TRITON sequence functions include:

- Cross section processing with XSProc
- Neutron transport:

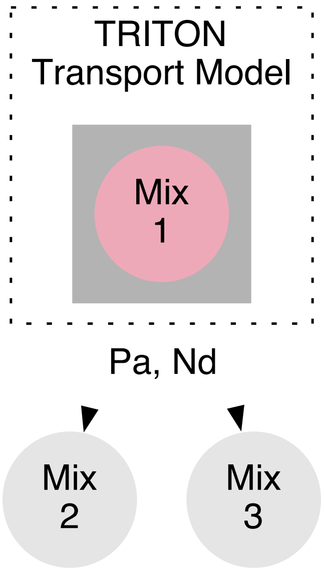
  1-D (XSDRN), 2-D (NEWT), or 3-D (KENO, Shift)
- Transport-to-depletion coupling
  - Normalizes power/flux levels
  - Prepares transition matrices for ORIGEN
  - Manages time-stepping (predictor-corrector)
- Branch calculations for 2-D lattice physics analysis
- Model updates
  - From depletion: concentration changes
  - From user input: Geometry, temperature, concentration changes



TRITON FLOW Block

- A FLOW block that allows users to specify fractional removal and continuous feed from/to mixture:

$$\frac{dN_i}{dt} = \sum_{j \neq i}^{M} (l_{ij}\lambda_j + f_{ij}\sigma_i\phi) N_j(t) - \left(\lambda_i + \sum_{k}^{W} \lambda_{rem,ik} + \sigma_i\phi \right) N_i(t) + S_i(t)$$

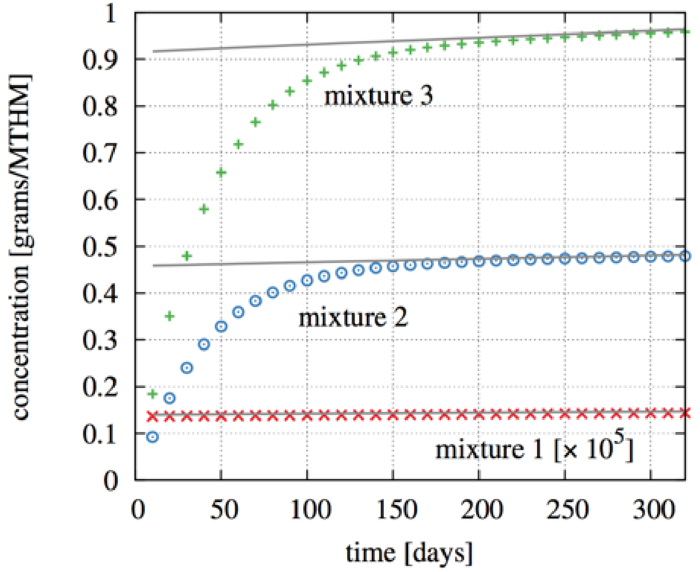


- Example: Th-based MSR unit cell model.
  - Removal of Pa and Nd from irradiated mixture into initially empty mixtures 2 and 3:

$$\lambda_{rem,mix1 \rightarrow mix2}$$

  - Pa and Nd concentrations in waste mixtures 2 and 3 reach equilibrium based on the removal rate from mixture 1 and their decay rates.
  - TRITON determines the equivalent source for mix 2:

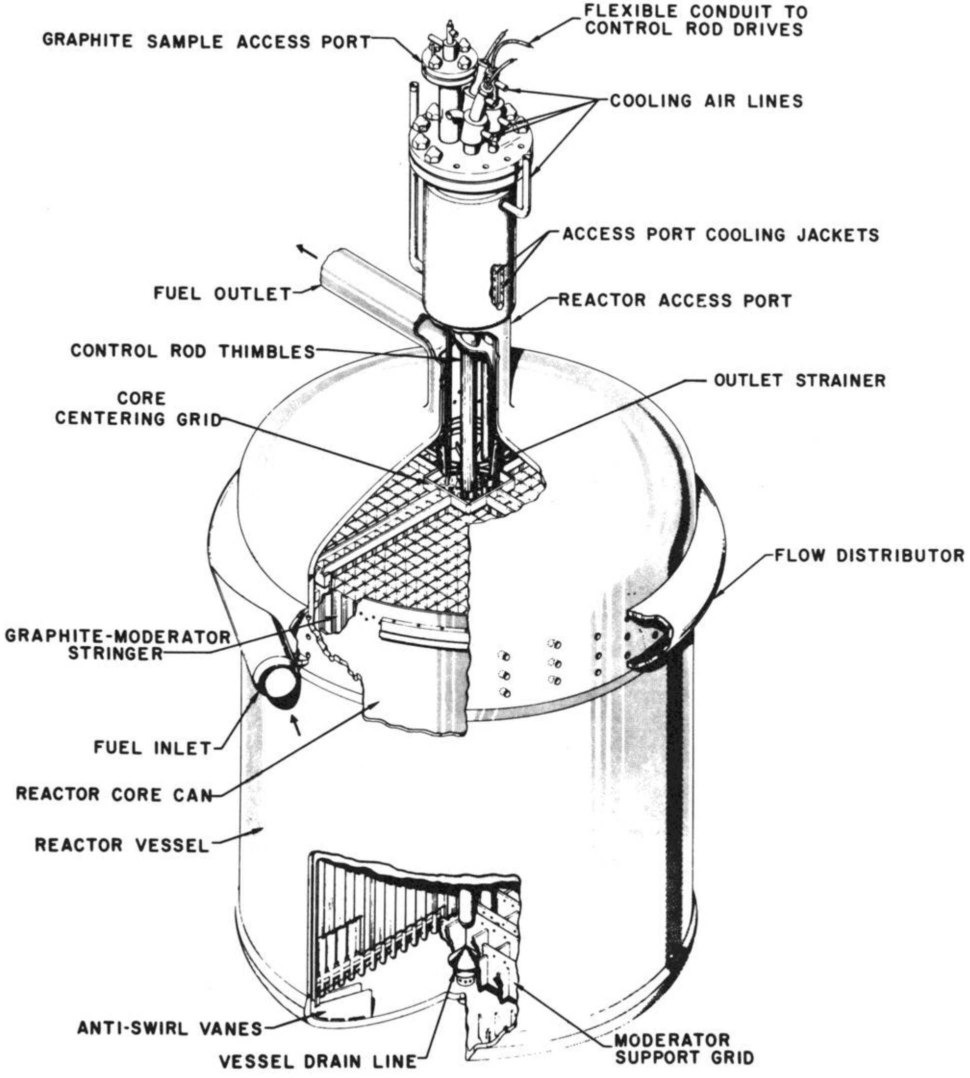
$$S(t) \approx \lambda_{rem,mix1 \rightarrow mix2} N(t)$$



Fluoride-salt MSR (MSRE)

MSRE – Model Description

Description	Value [3, 4]
Power	10 MWth (initial criticality) 8 MWth (during operation)
Fuel/coolant	$LiF\text{-}BeF_2\text{-}ZrF_2\text{-}UF_2$
Enrichment	34.5 wt.% ^{235}U
Moderator	Graphite
Structure	Nickel-based alloys
Nuclide removal	• Noble gases via Off-Gas System (OGS) • Noble metal plate-out at heat exchanger (HX)
Re-fueling	Irregular re-fueling by capsules with HEU fuel salt
Operating time	~375 equivalent full-power days with ^{235}U fuel

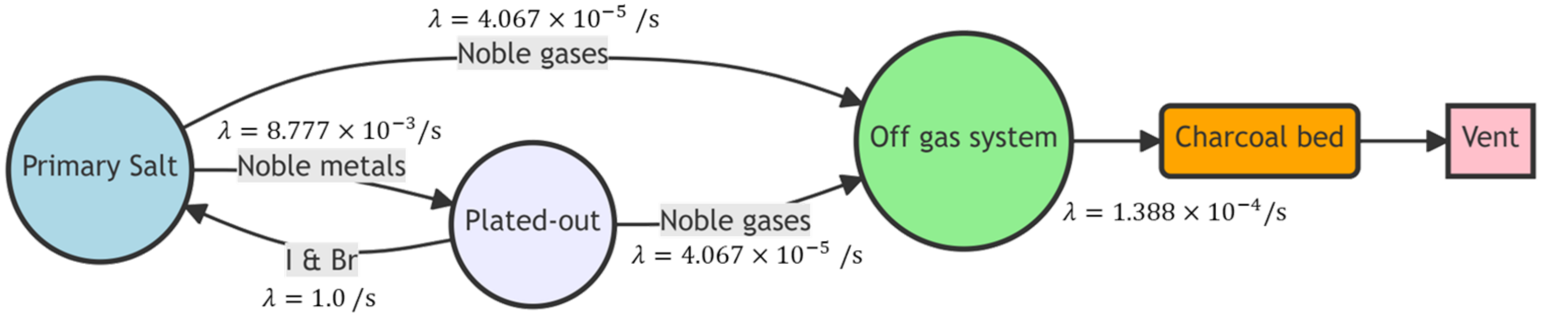


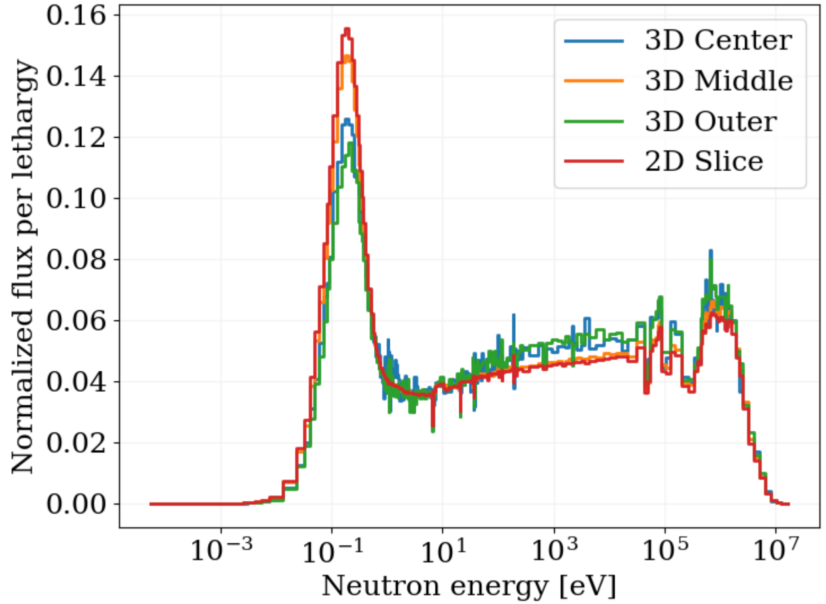
MSRE reactor vessel [3]

[3] R. C. Robertson (1965), "MSRE Design and Operations Report Part I: Description of Reactor Design," ORNL-TM-0728, ORNL.
[4] M. Fratoni, et al. (2020), "Molten Salt Reactor Experiment Benchmark Evaluation," DOE-UCB-8542, 16-10240, UC Berkeley, doi:10. 2172/1617123

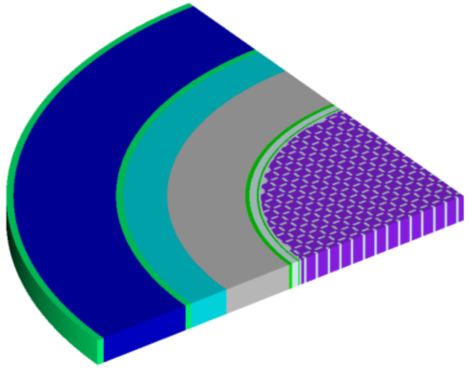
MSRE – System Average Inventory Generation

- **2D core slice model:**
  - Representative spectral conditions through radial leakage and representative moderator-to-fuel ratio, while allowing shorter runtimes compared to full core
  - Depletion up to 375 days, the total operation time of MSRE with ^{235}U fuel
  - Representation of system through adjusted power level
  - Nuclide removal from fuel salt in system is derived from MSRE operation:





Neutron flux comparison between 3D and 2D slice model

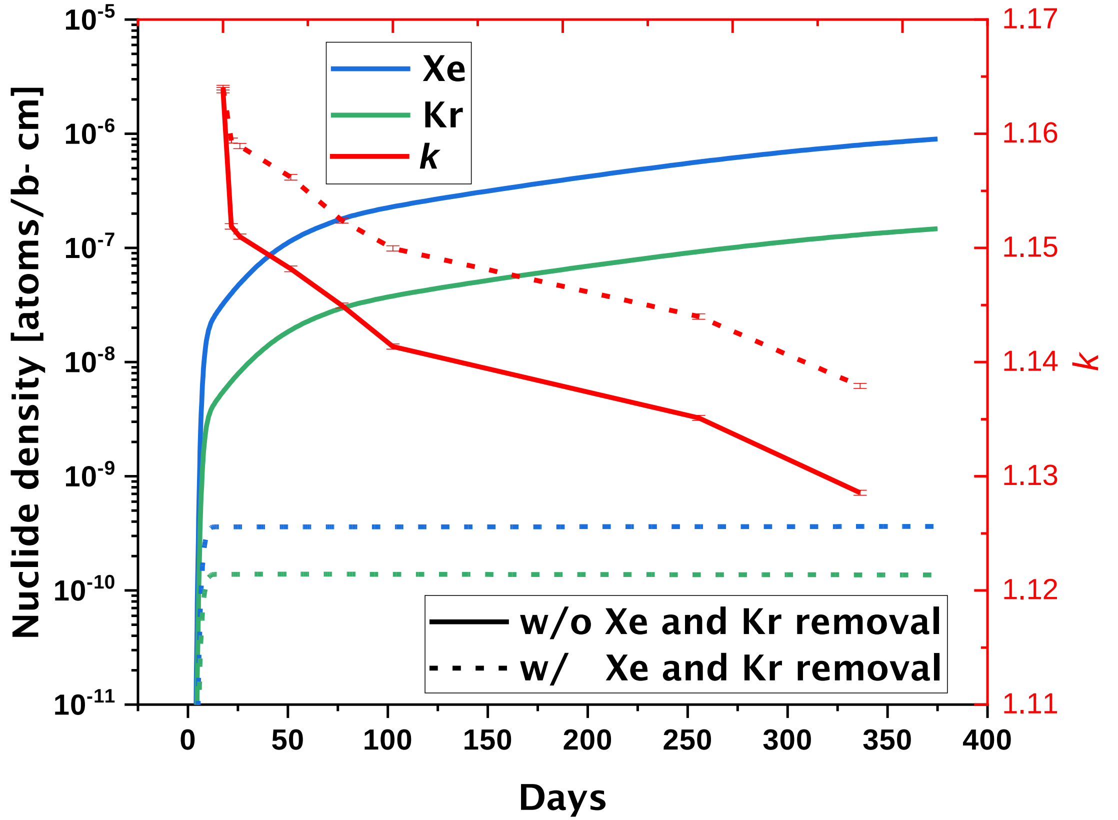


SCALE "2D" slice model

MSRE – System Average Inventory Generation

- Depletion at low power level of 8 MWth, with flux level 1.88 · 10^{13} n/cm^2-s
- No re-fueling in this depletion calculation
- At 375 days:
  - 5.627% ^{235}U consumed,
  - 0.455% ^{238}U consumed,
  - 13.76 GWd/tHM burnup achieved

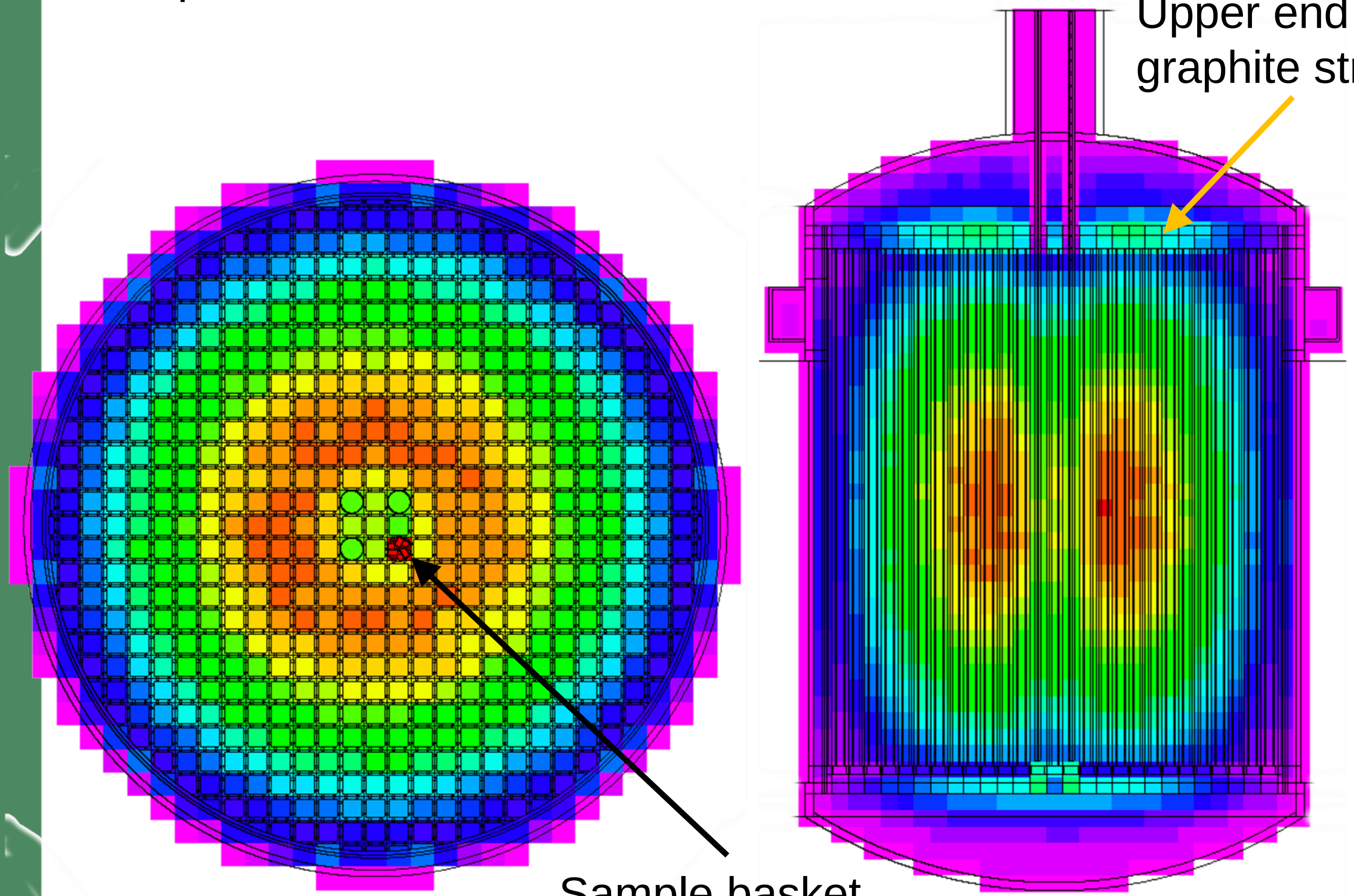
	Amount removed after 375 days
Noble gas	0.170 kg / 30.6 L
Insoluble metals	0.611 kg
Sometimes soluble metals	0.057 kg



Comparison of Xe and Kr nuclide densities with and without Xe/Kr removal

MSRE – Power Distribution & Reactivity Coefficients

- Used TRITON-KENO 3D full core model based on IRPhEP benchmark specifications as basis

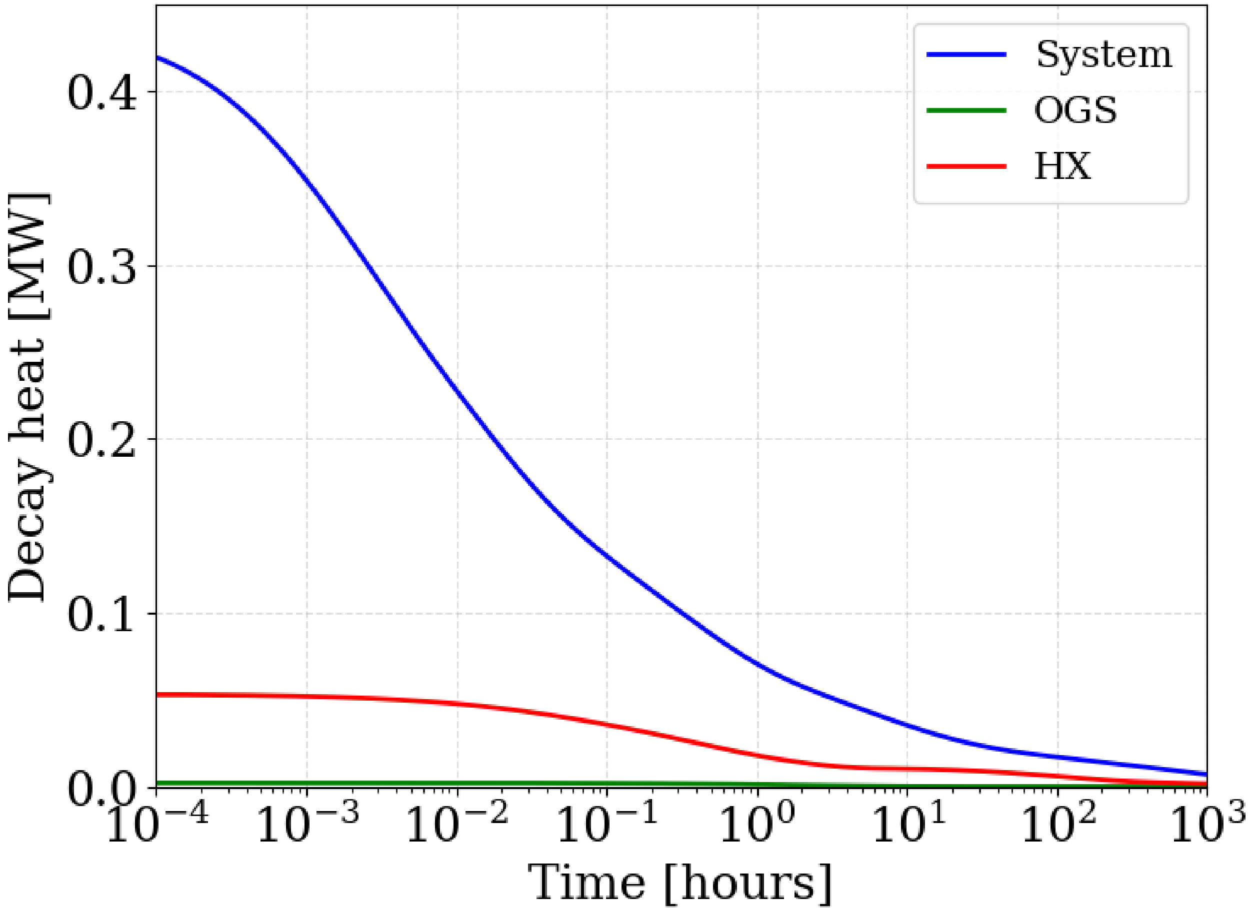


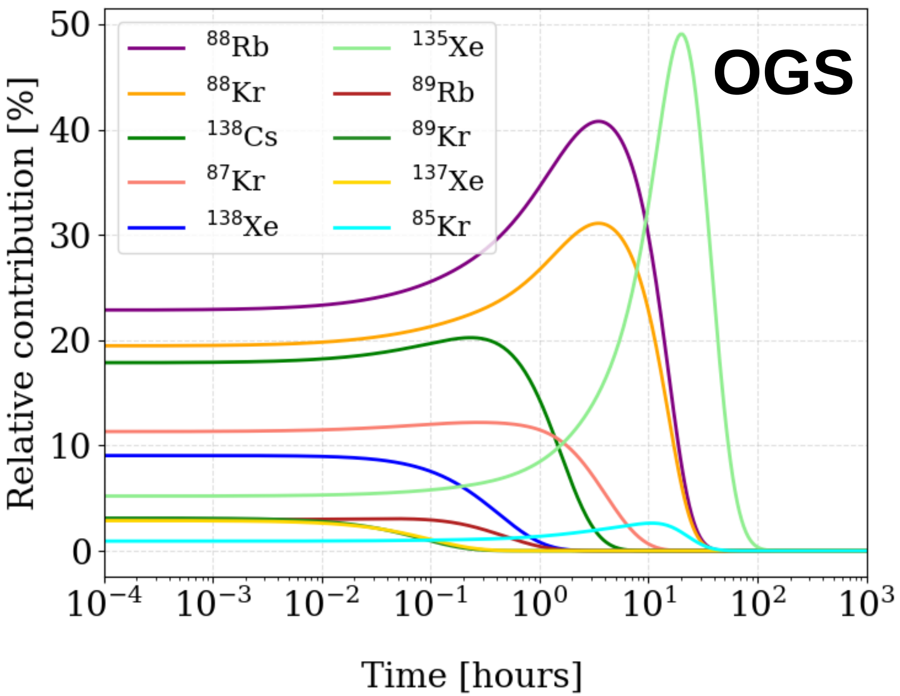
Fission rate distributions

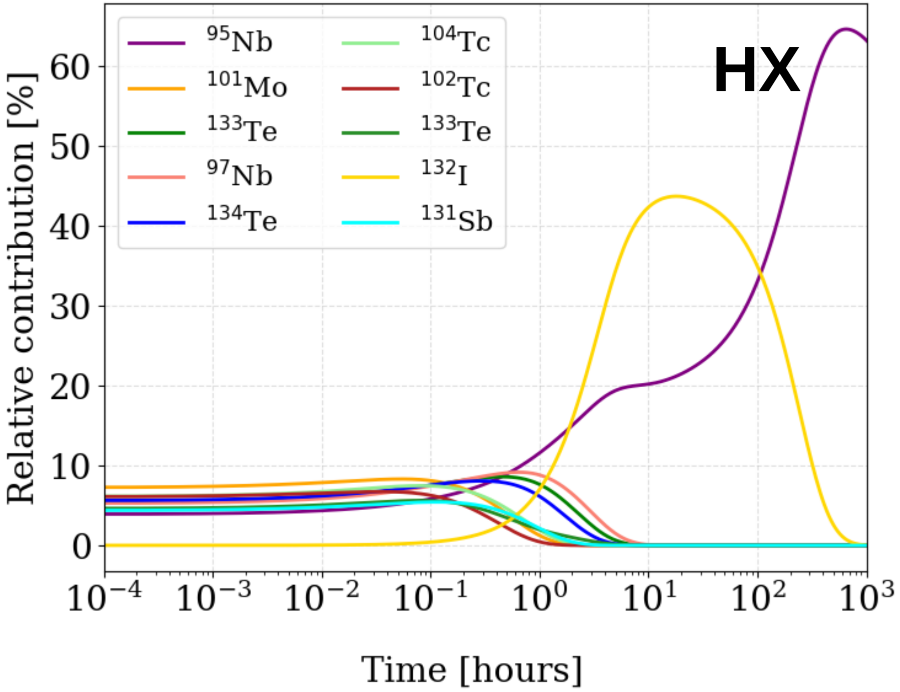
Component	Fresh core	375 days
β_{eff} [pcm]	704 ± 14	697 ± 22
$\alpha_{graphite}$[pcm/K]	-5.13 ± 0.05	-4.83 ± 0.07
α_{salt}[pcm/K]	-8.27 ± 0.12	-8.28 ± 0.12

Component	Reported by MSRE
β_{eff} [pcm]	666.1
$\alpha_{graphite}$[pcm/K]	-4.68
α_{salt}[pcm/K]	-8.46 ± 1.26

MSRE – Decay Heat at EOC







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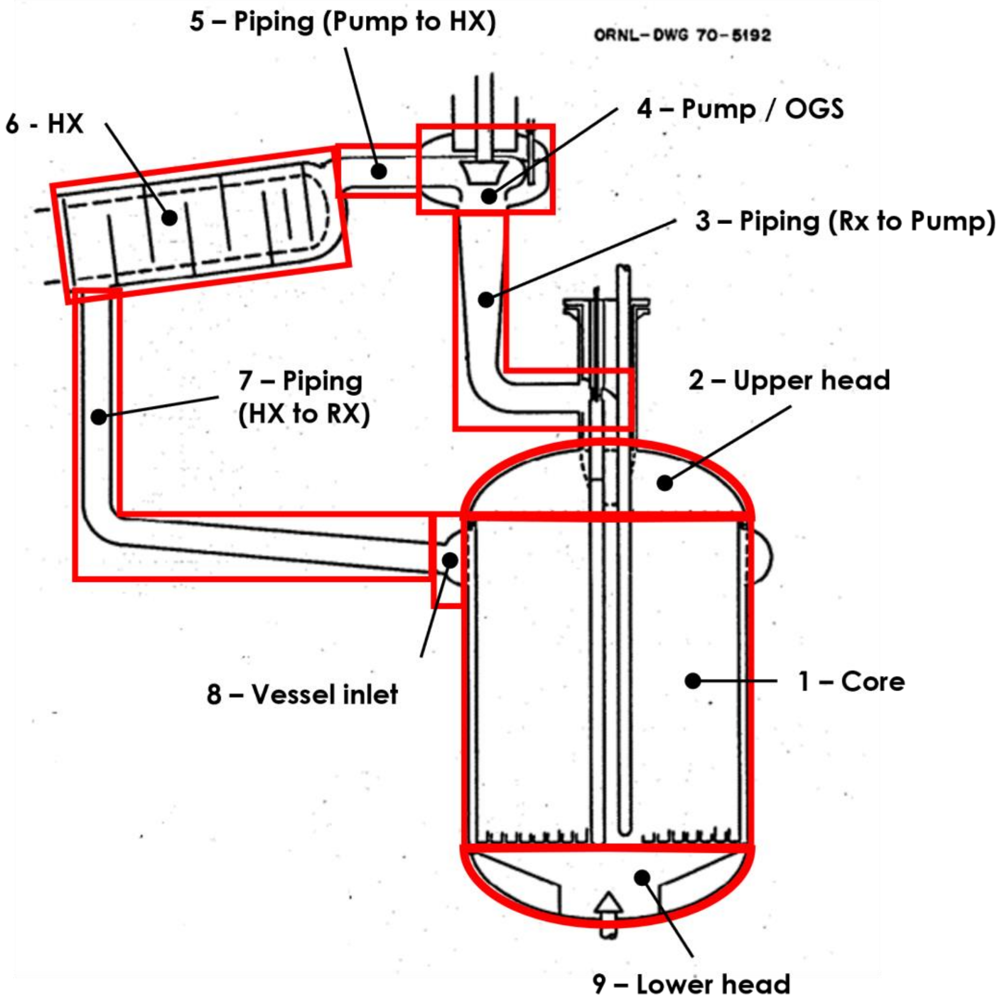
to edit

MSRE – Location-Dependent Inventory

- **Approach**:
  - Take system-average fuel salt composition from TRITON depletion at specific point in time
  - Divide system in several regions
  - Develop chain of ORIGEN inputs that calculates inventory of a *fuel slug* that travels through the different regions
  - Specify residence time and flux level of the fuel salt in the different regions
  - Consider nuclide removal in ORIGEN inputs only in specific regions
- Observe nuclide concentrations in a specific region over the number of loops → observe convergence

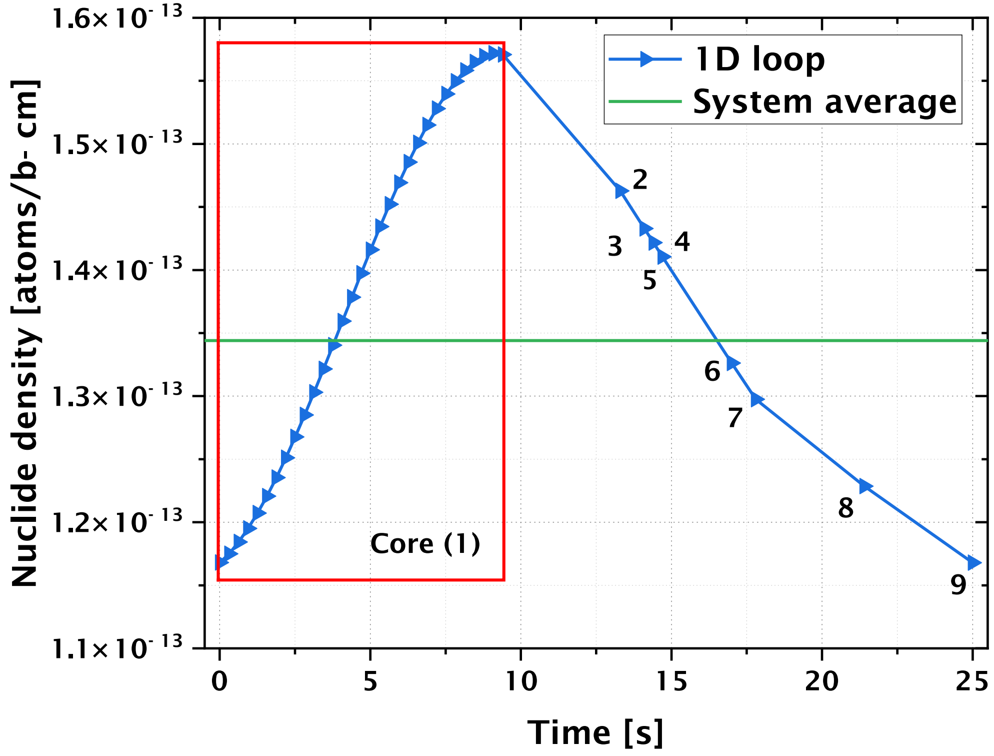


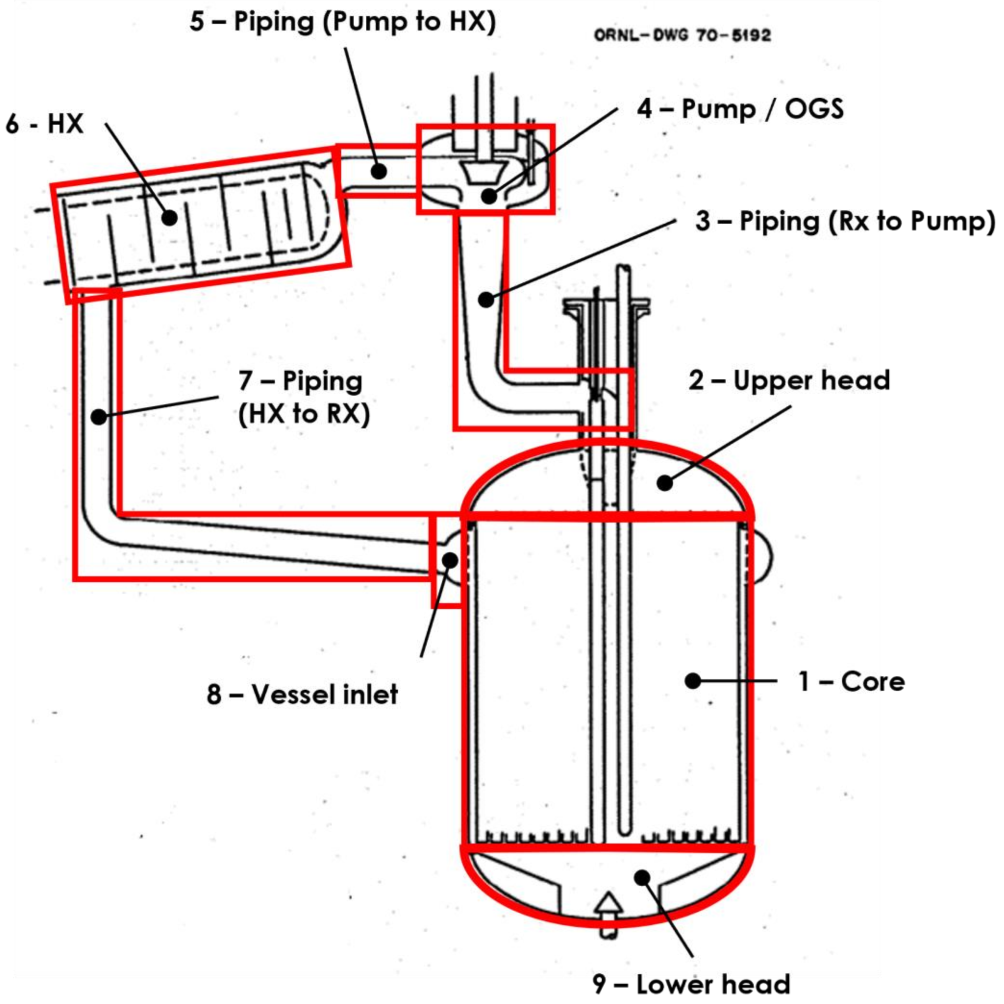
Regions in MSRE system for ORIGEN model

MSRE – Location-Dependent Inventory

- Short-lived nuclide (I-137, $t_{1/2}$=24.5s) as a **function of location** in the loop

(Converged) I-137 concentration in the different regions of the loop



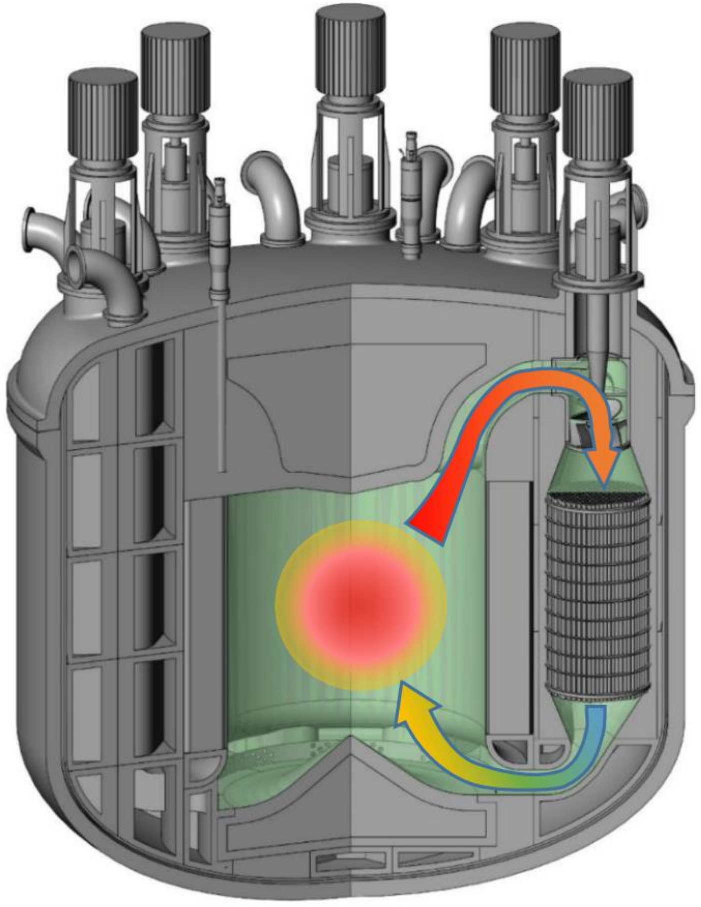


Regions in MSRE system for ORIGEN model

Chloride-salt MSR (MCFR)

MCFR – Model Description

Description	Value [3, 4]
Power	180 MWth
Fuel/coolant	$NaCl\text{-}UCl_3$
Enrichment	HALEU (<20 wt.% ^{235}U)
Reflector	Varied
Structure	Inconel alloys
Nuclide removal	• Noble gases via Off-Gas System • Noble metal via Filtering System
Re-fueling	Online
Operating time	~10 equivalent full-power years

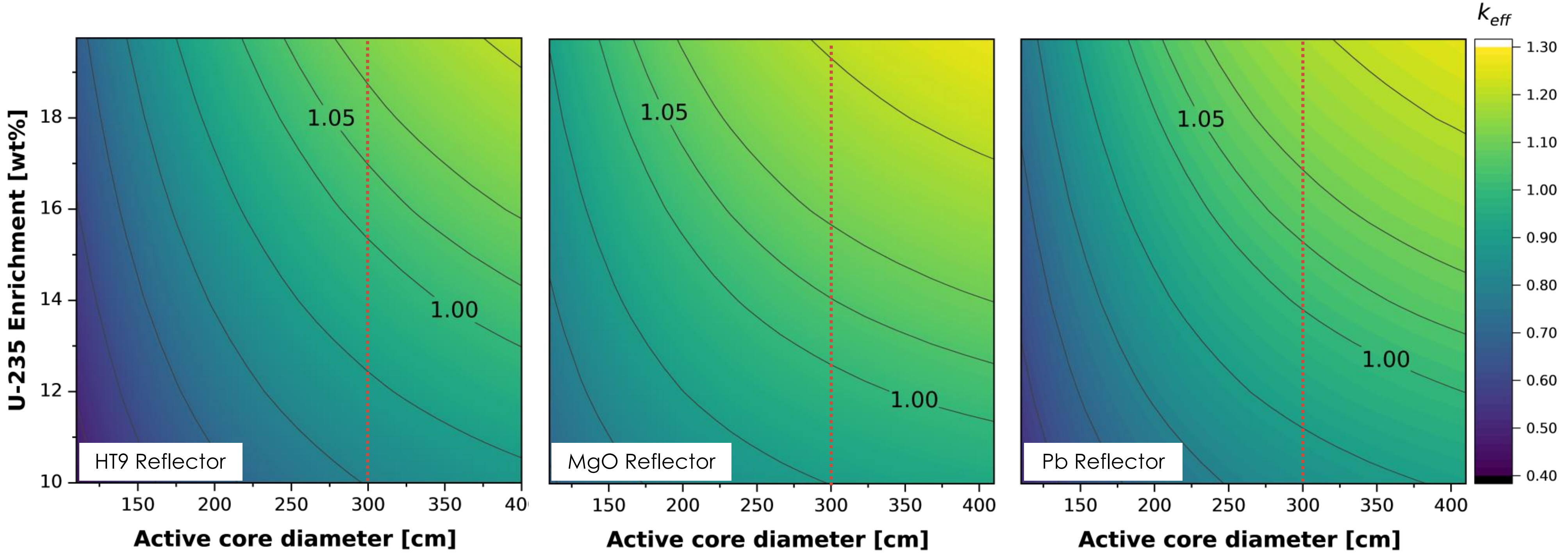


Molten Chloride Fast Reactor [5]

[5] J. Latkowski(2021), "TerraPower's Molten Chloride Fast Reactor," National Academies of Sciences, Engineering and Medicine.

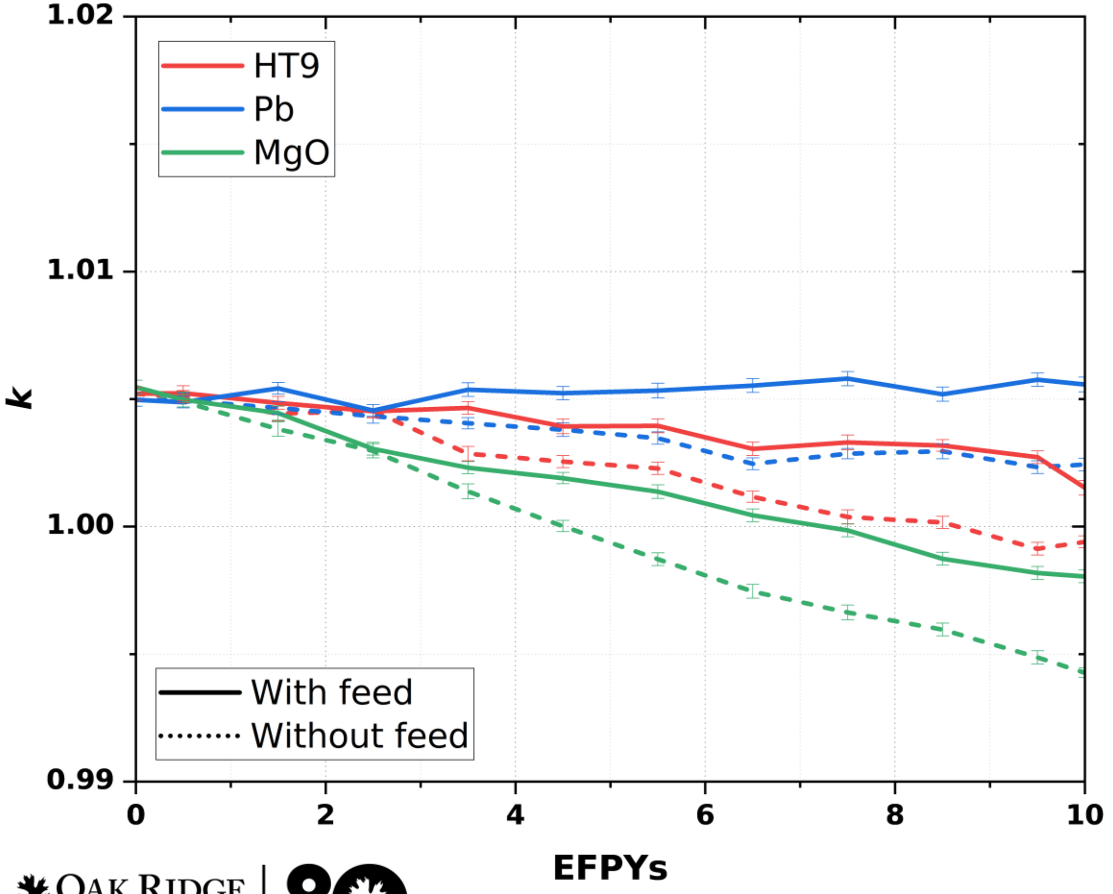
MCFR – Dimension vs. Enrichment

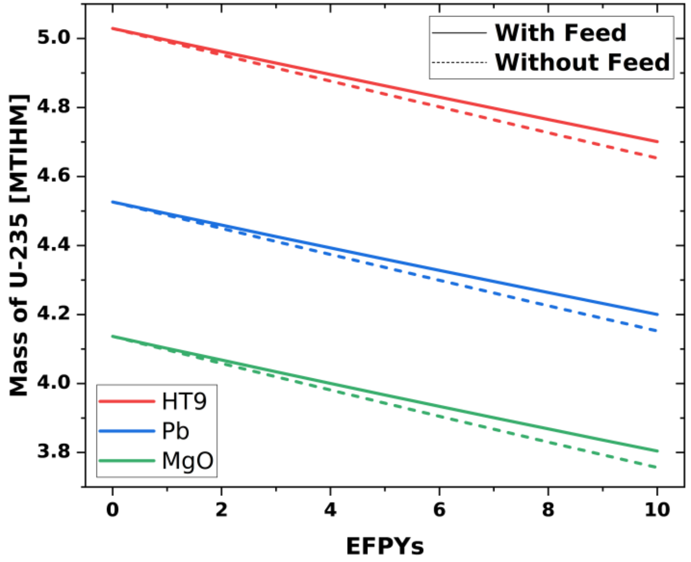
- MgO reflector gives softer spectrum than Pb and HT9.
  - Attributed to higher elastic scattering cross section and moderating ratio of MgO.
- The softer neutron spectrum increases the fission cross section of ^{235}U by about 20% and, consequently, reduces the required uranium enrichment.



MCFR – Reactivity vs. Lifetime

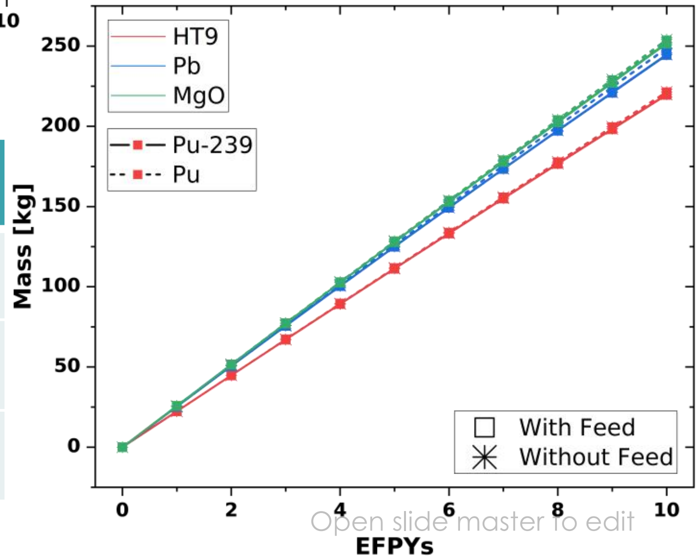
- The makeup fuel salt contains uranium with an enrichment of 19.75 wt.%, and it is continuously fed with the same rate to the primary fuel salt at 0.767 mg U/s for each core.





Reflector	^{235}U BOC [MTHM]	^{235}U EOC [MTHM]
HT9	5.029	4.701
Pb	4.526	4.200
MgO	4.137	3.804

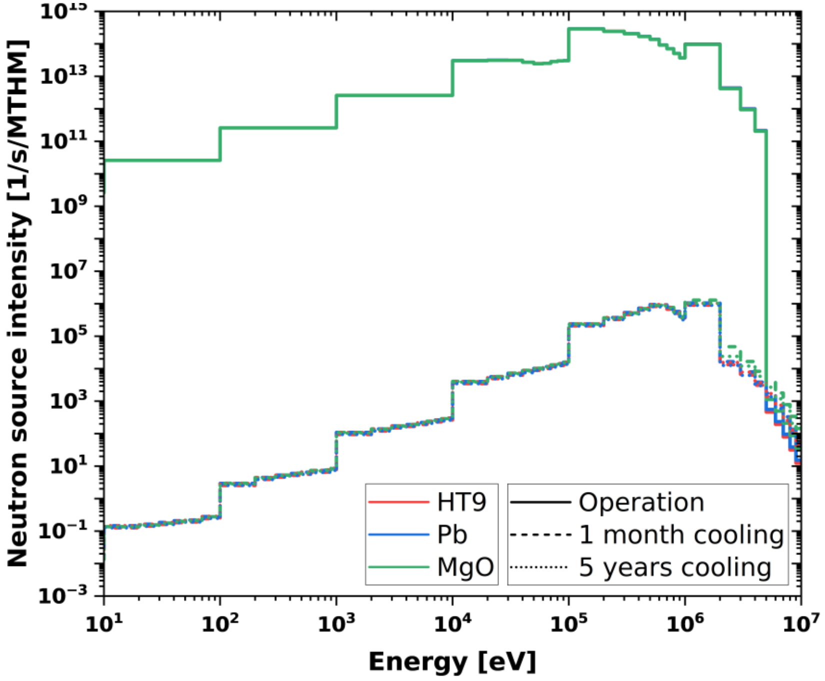
Reflector	^{239}Pu [kg]	Pu [kg]	^{239}Pu/ Tot. Pu
HT9	219.62	221.17	0.99
Pb	251.58	253.58	0.99
MgO	244.37	248.51	0.98

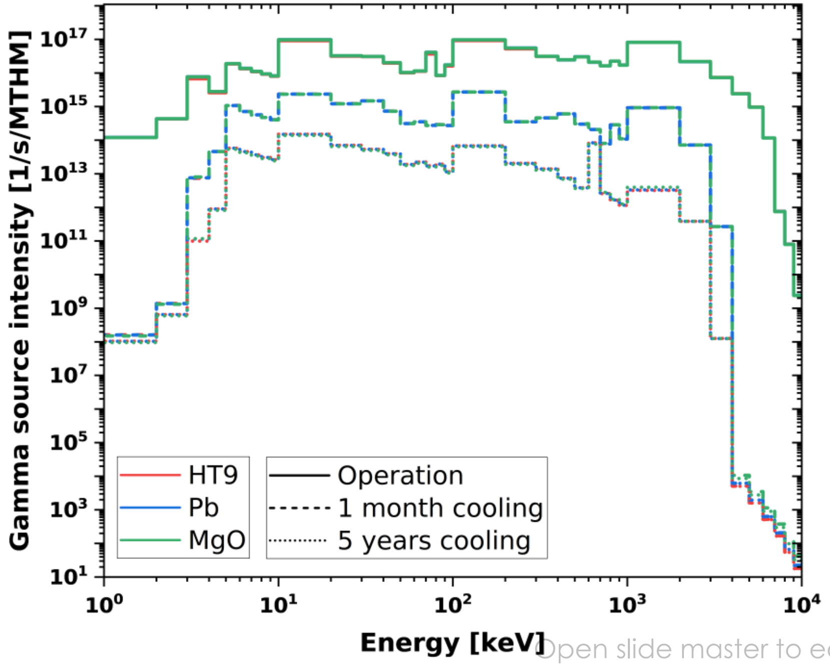


MCFR – Gamma & Neutron Intensity

- During operation:
  - Neutron sources are dominated by delayed neutrons
  - Major gamma sources are ^{239}U, ^{239}Np, ^{92}Rb, ^{94}Y.

- During cooldown:
  - Neutron sources are dominated by (a, n)
  - Major gamma contributors are
    - At 1 month: Sr-90, Y-90, Ba-137m, Pr-144, Pm-147
    - At 5 years: Y-91, La-140, Ce-141, Ce-144, Pr-144



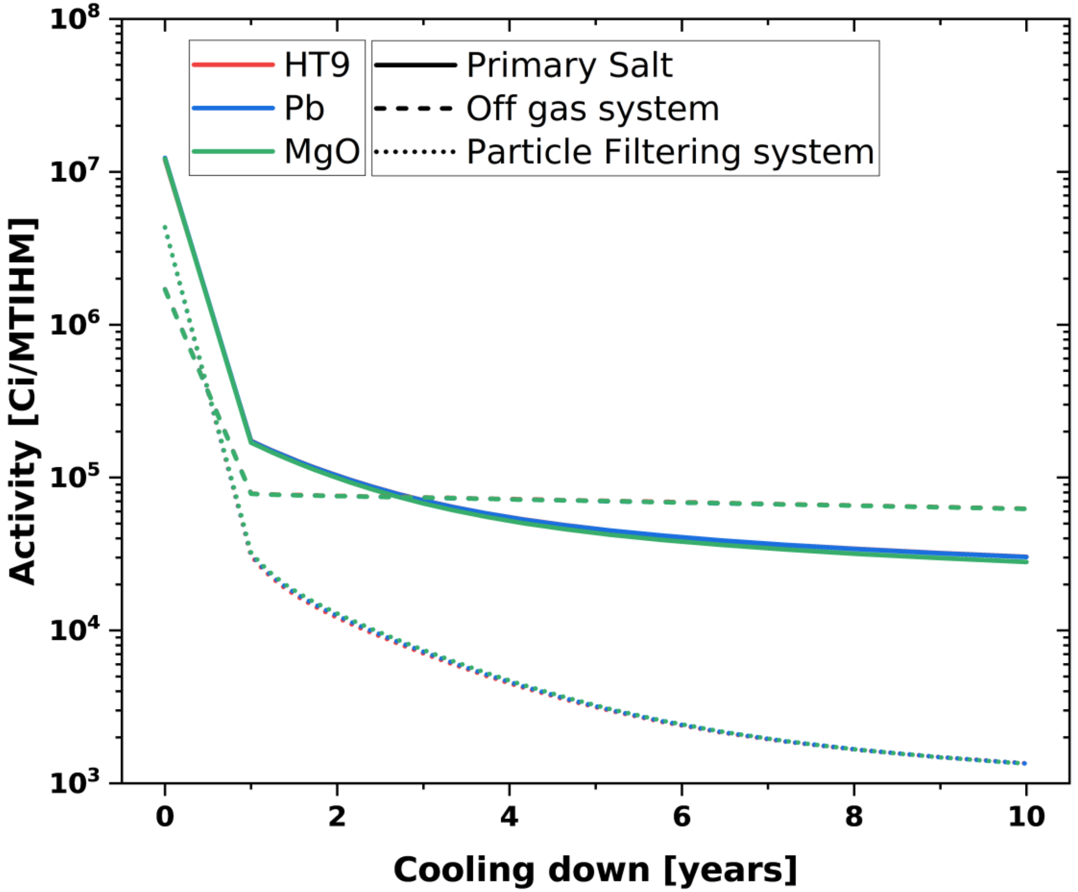


MCFR – Activity in Salt and Waste Streams

- The activities during the cooling time in the primary fuel salt, off-gas system, and particle filtering system after operating for ten years.

- The top contributors to the activity in the off-gas system are ^{137}Cs, ^{137m}Ba, ^{90}Y, ^{90}Sr, and ^{138}Cs.

- The major contributors in the particle filtering system are ^{134}Te, ^{134}I, ^{95}Nb, ^{95}Zr, and ^{133}Xe.

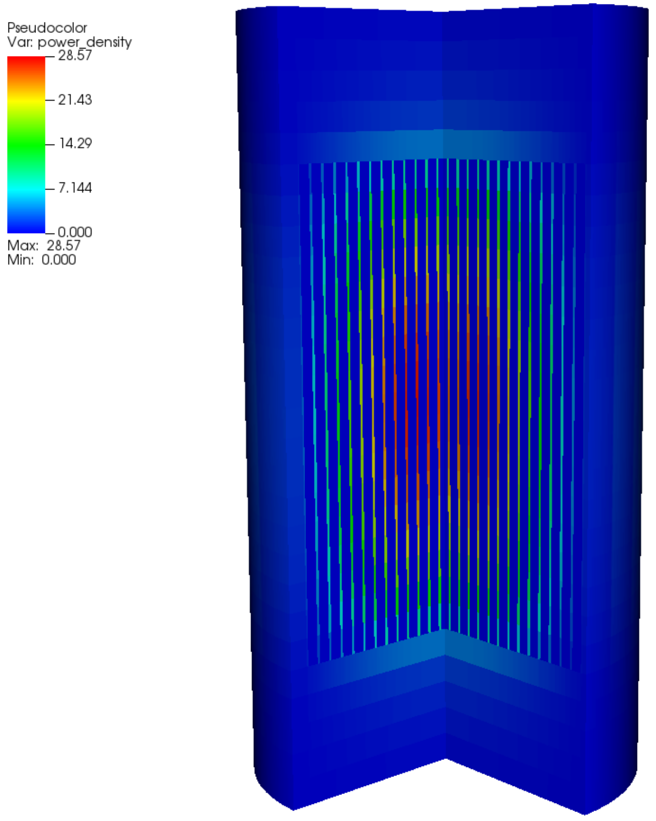


SCALE/Shift Application

Few-group cross section generation using SCALE/Shift

- SCALE/Shift Monte Carlo code can be used to generate few-group cross section for deterministic codes such as Griffin to analyze Molten Salt Reactor.

Code	Fine Group	Coarse Group	k	Diff [pcm]
Shift CE	-	-	1.01097 ± 0.00008	-
Shift/Griffin	258	8	1.00482	615
	258	20	1.00013	1084
	172	8	1.00432	665
	172	20	1.00393	704
	8	8	**1.01189**	**-92**
	20	20	1.00587	510

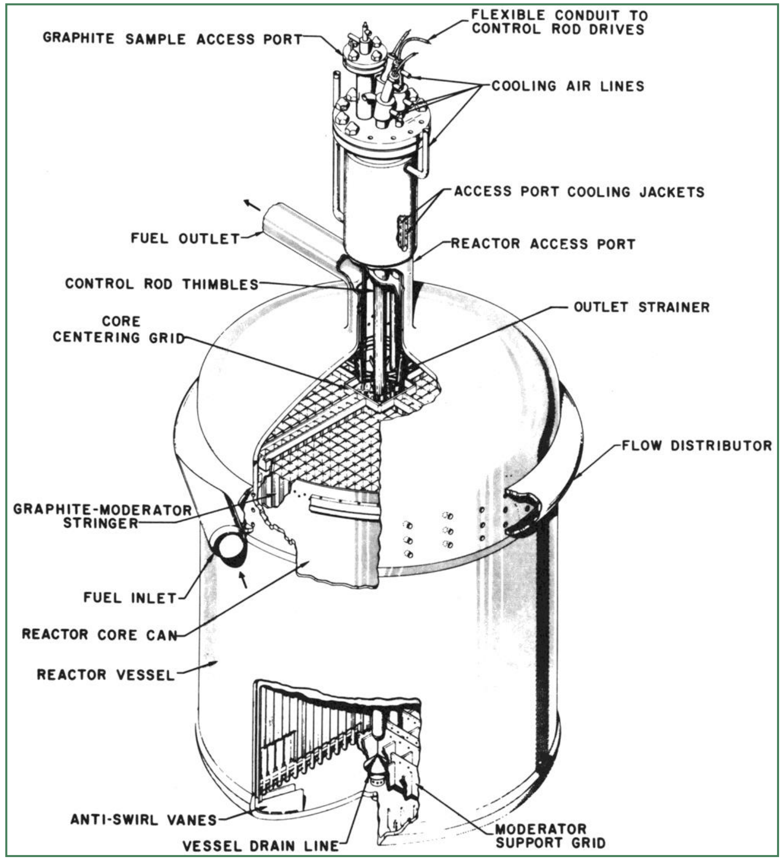


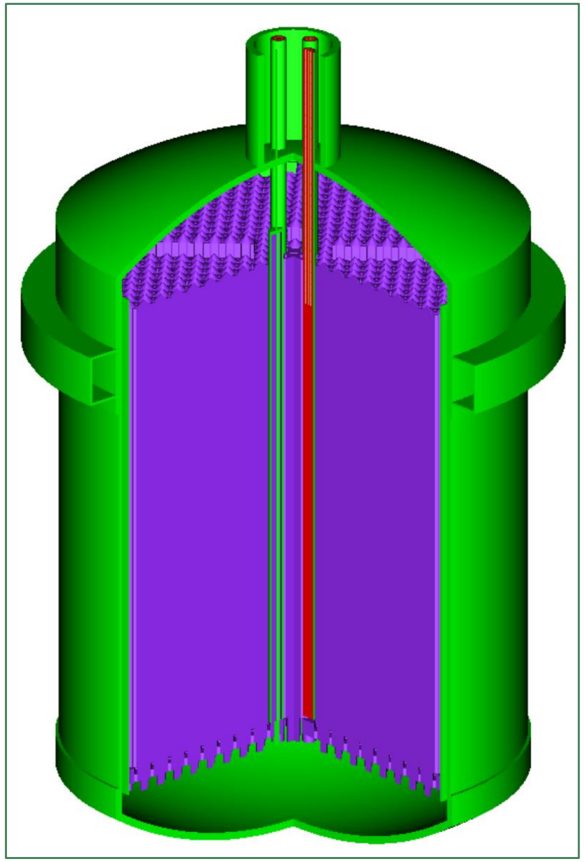
Conclusions

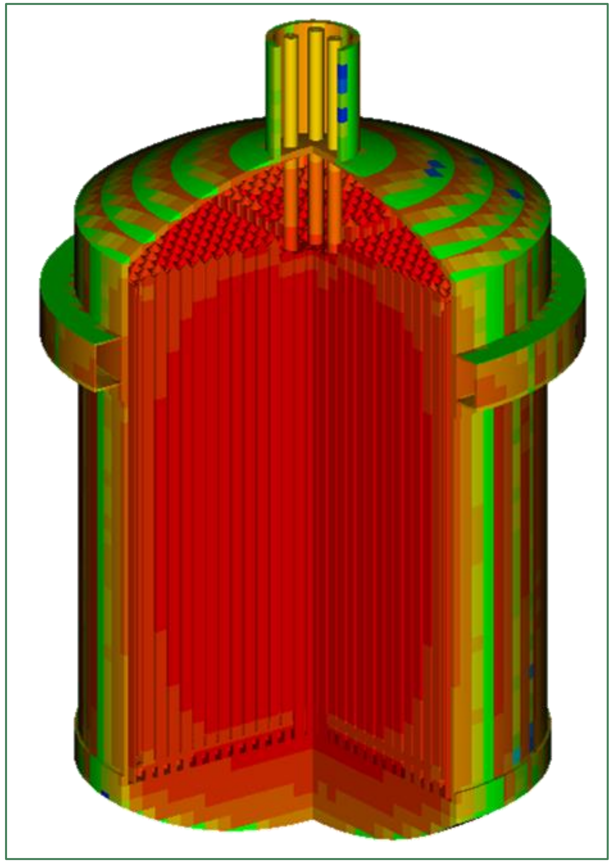
- The accurate predictions of time-dependent liquid fuel isotopic composition throughout months to years of reactor operation are critical for reactor and processing system design, safety analysis, source term characterization, and safeguards approach, etc.
- The capability to simulate irradiation with continuous material feeds and removals is available in the SCALE 6.3.1 code system for predicting the isotopic composition throughout months to years of operation in advanced liquid-fueled nuclear reactor systems, such as MSRs.
- The breadth of available modules within SCALE provides for the extension to other relevant capabilities, including sensitivity and uncertainty analyses, optimization approaches, and source terms assessments.

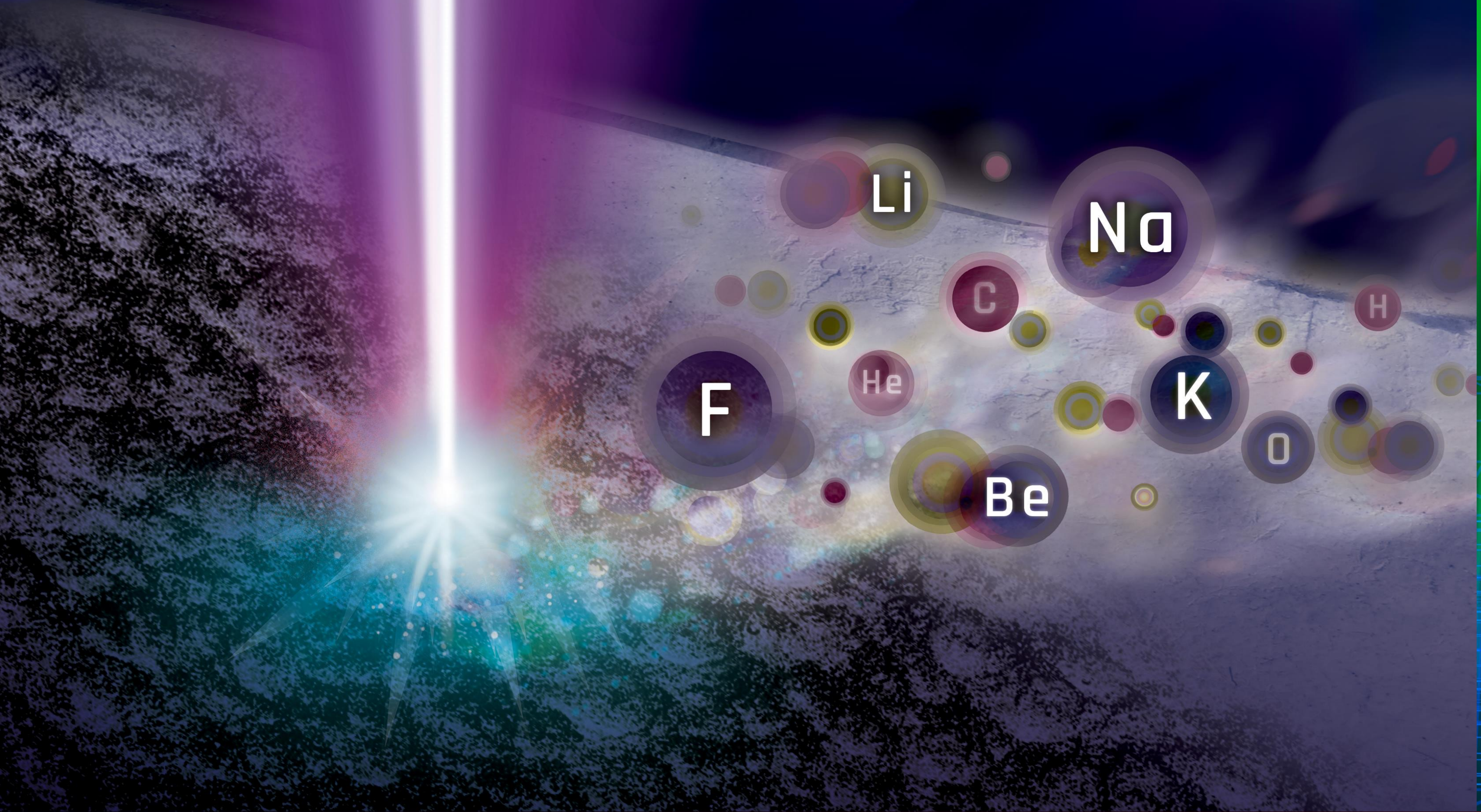
ACKNOWLEDGMENT
This presented work was supported by Nuclear Regulatory Commission, DOE Advanced Reactor Safeguards (ARS) program, and DOE Nuclear Energy Advanced Modeling and Simulation (NEAMS) program.

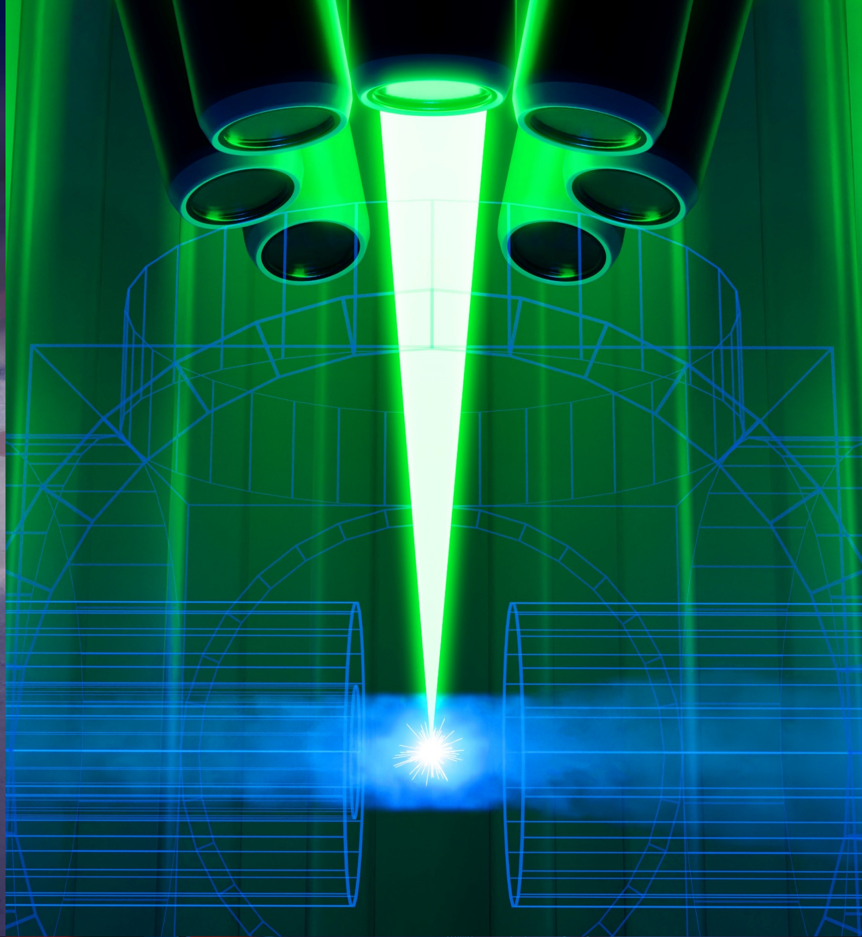
Thank you!


GRAPHITE SAMPLE ACCESS PORT
FLEXIBLE CONDUIT TO CONTROL ROD DRIVES
COOLING AIR LINES
ACCESS PORT COOLING JACKETS
FUEL OUTLET
REACTOR ACCESS PORT
CONTROL ROD THIMBLES
CORE CENTERING GRID
OUTLET STRAINER
FLOW DISTRIBUTOR
GRAPHITE-MODERATOR STRINGER
FUEL INLET
REACTOR CORE CAN
REACTOR VESSEL
ANTI-SWIRL VANES
VESSEL DRAIN LINE
MODERATOR SUPPORT GRID



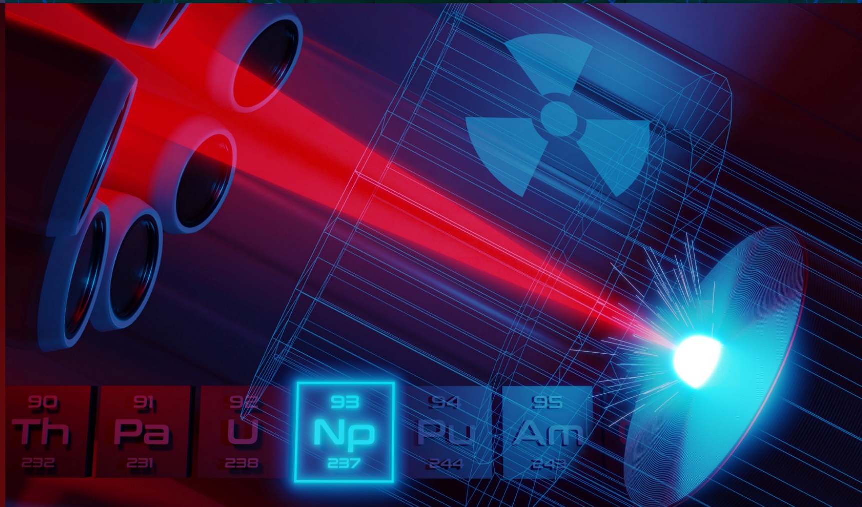






Laser-Induced Breakdown Spectroscopy

A Versatile Tool for MSR Applications



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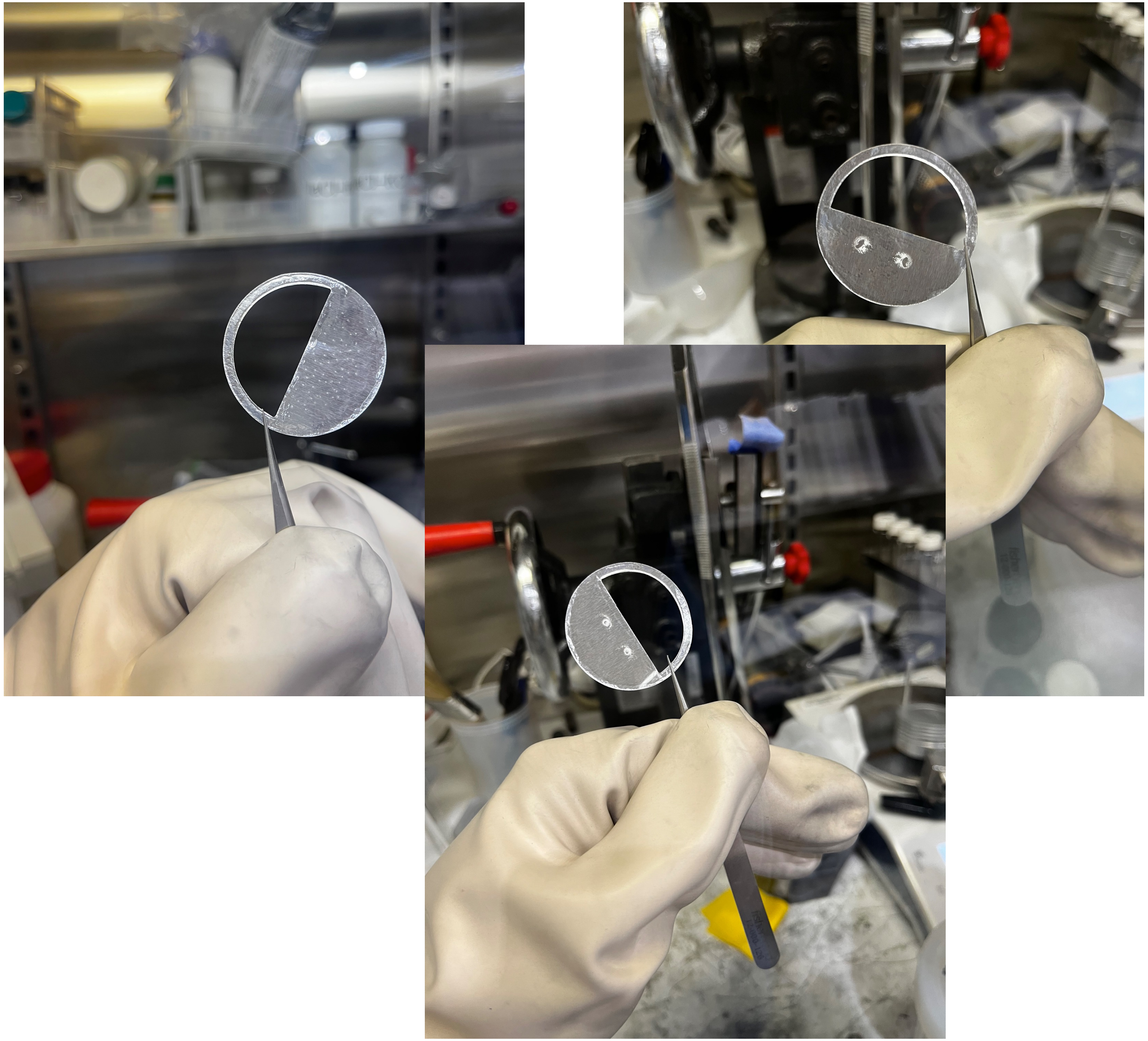
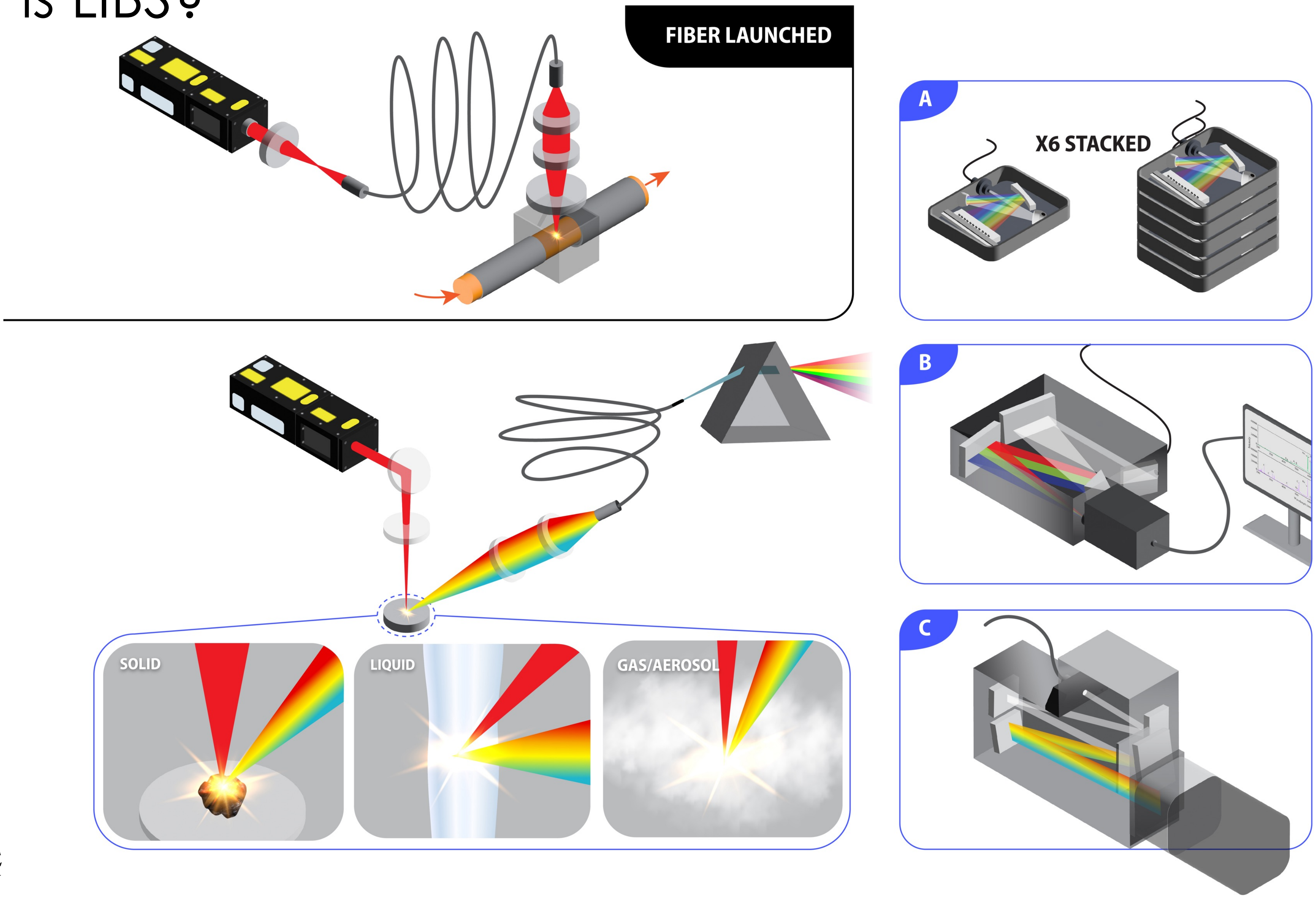
MSR Challenges

- Liquid fuel
- Inert environment
- Aerosol formation
- Radiation
- Changing chemistry



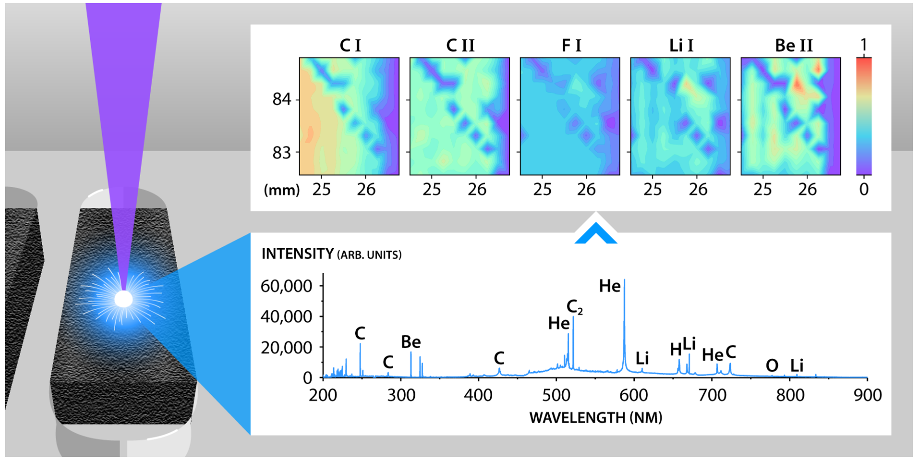
What is LIBS?



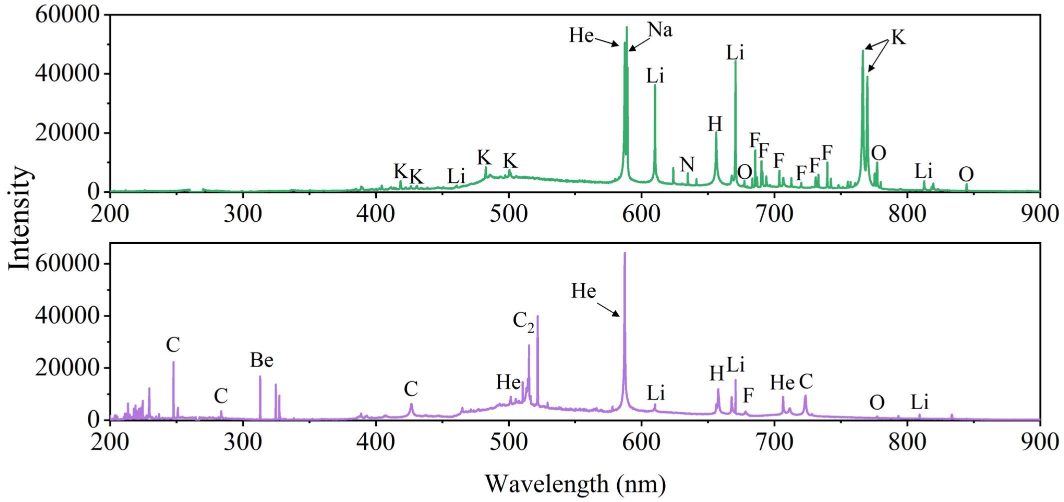
Why LIBS?

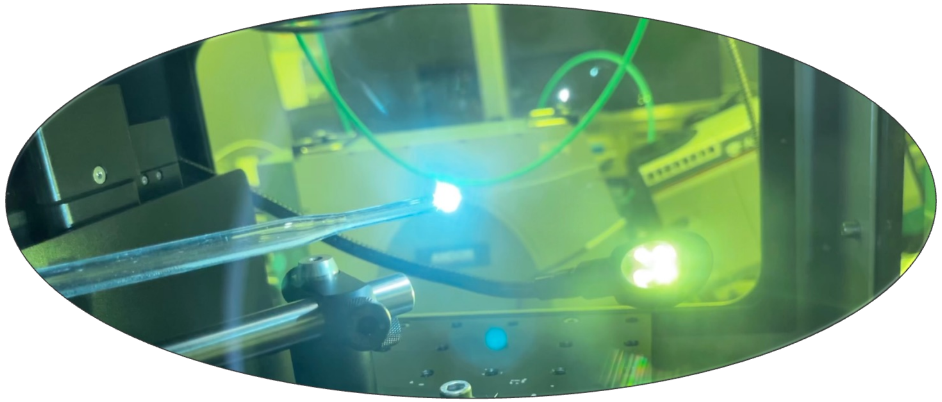
- Elemental (occasionally isotopic) technique
- Sensitivity across the periodic table
- Capable of remote measurements
- Rapid analysis
- Customizable to the application
- Can monitor solids, liquids, gases, and mixtures

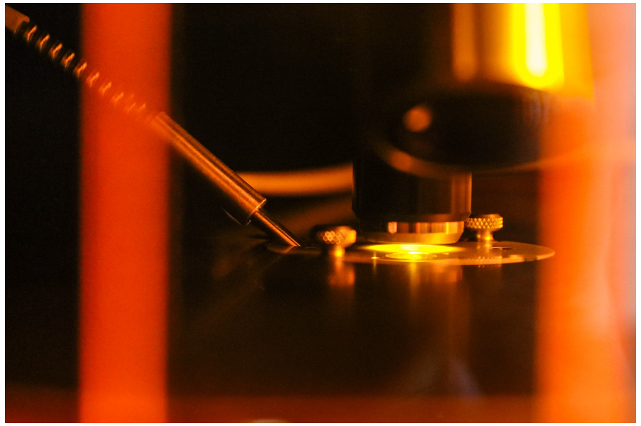
How can LIBS be used?



- Frozen salt analysis
  - As procured, purified, and post testing
- Investigating salt – material interactions
  - Graphite, structural materials
- Online monitoring
  - In-situ salt analysis, off-gas monitoring
- Real-time isotopic composition







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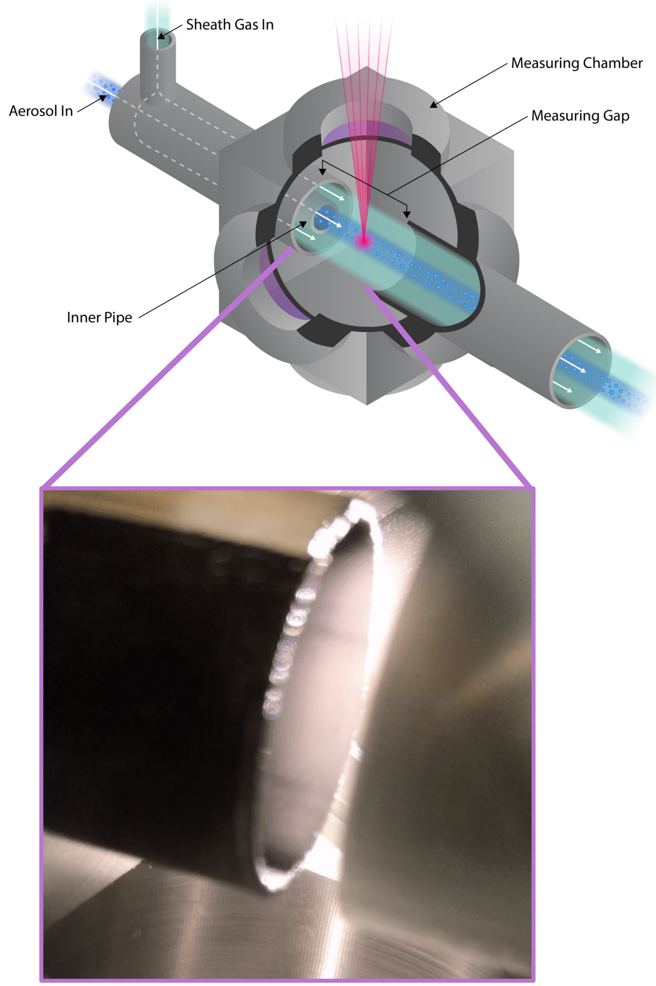
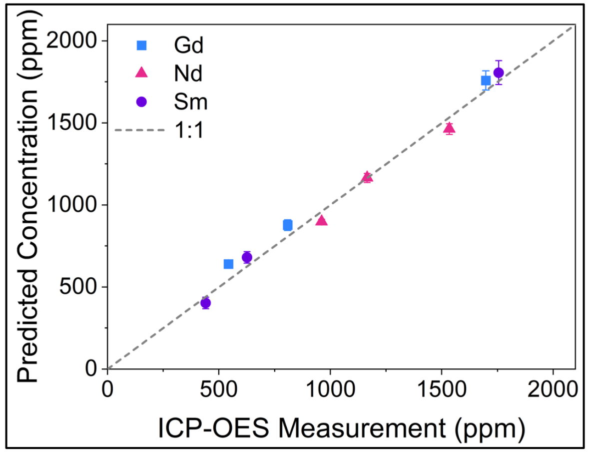
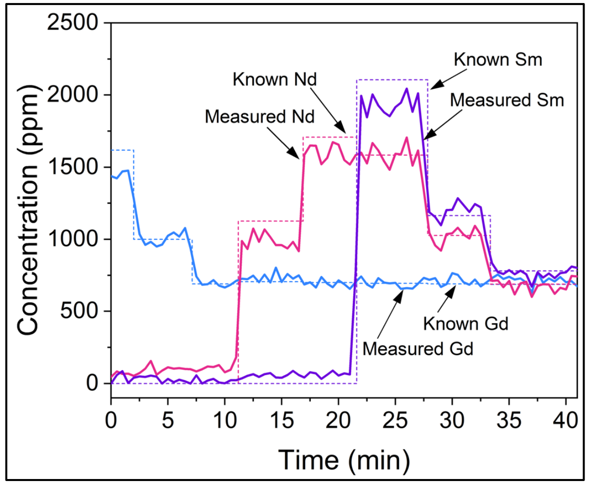
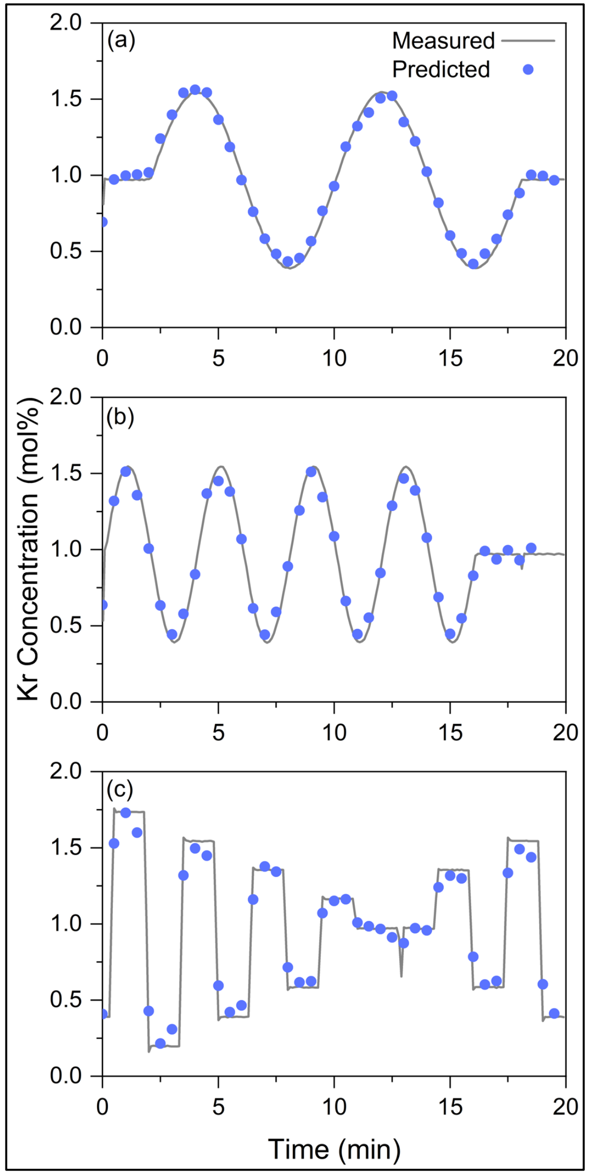
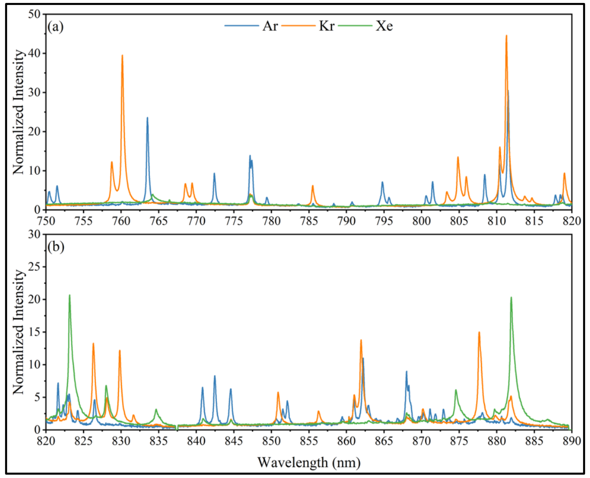
MSR Off-gas streams can be monitored using LIBS

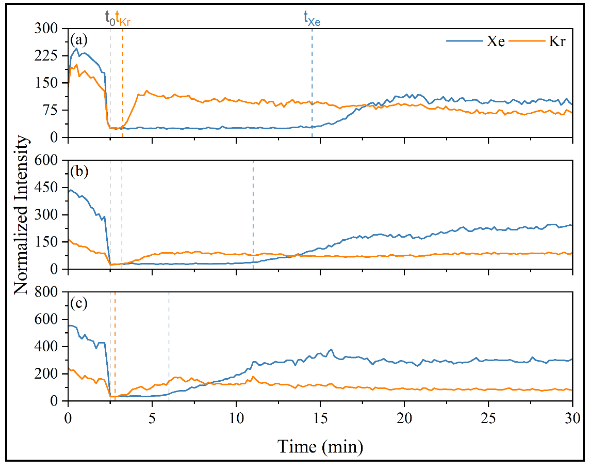




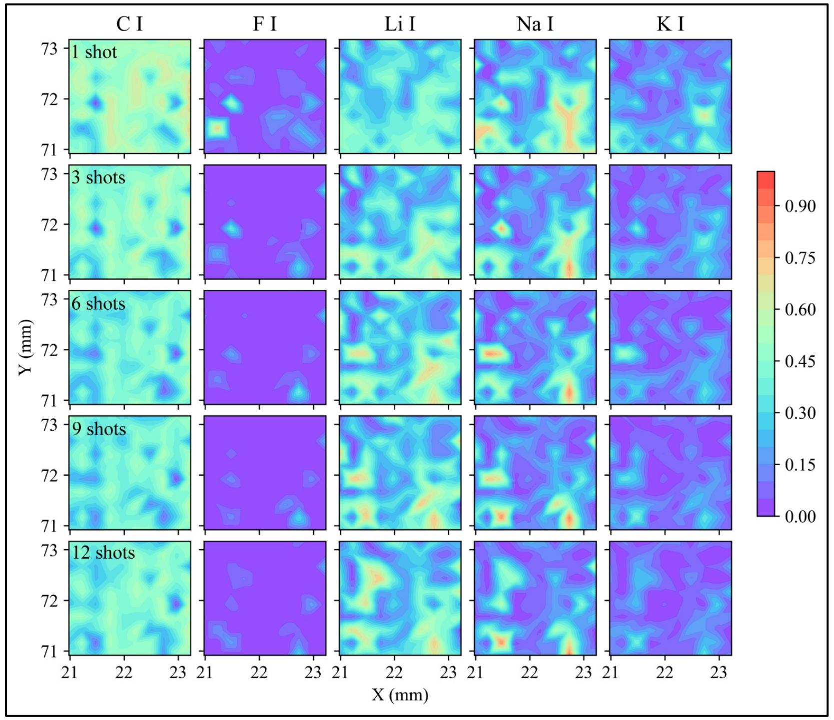


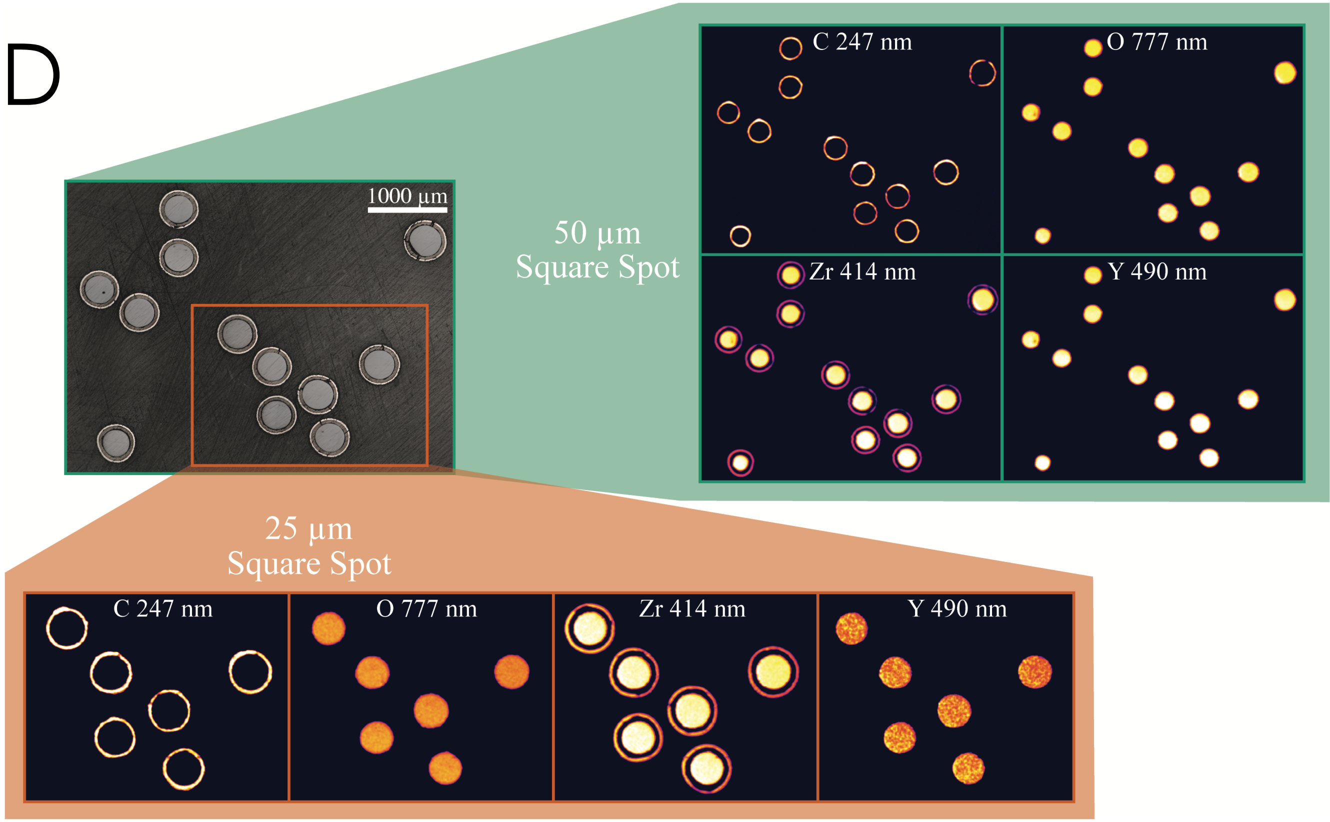


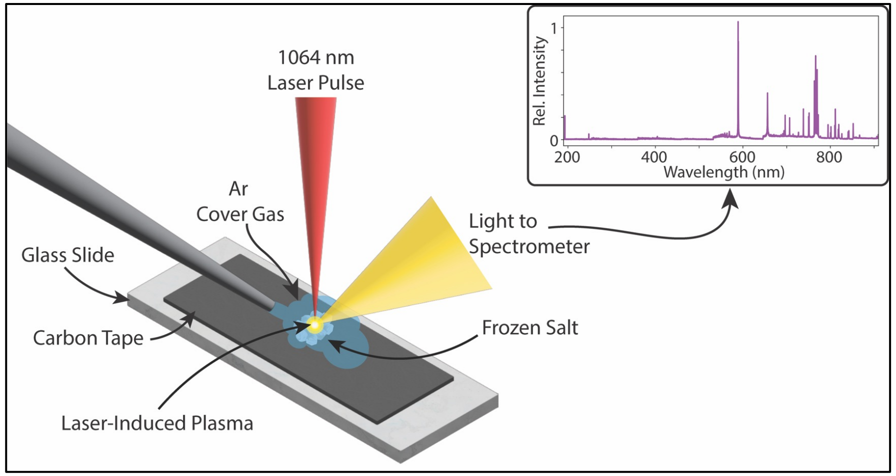


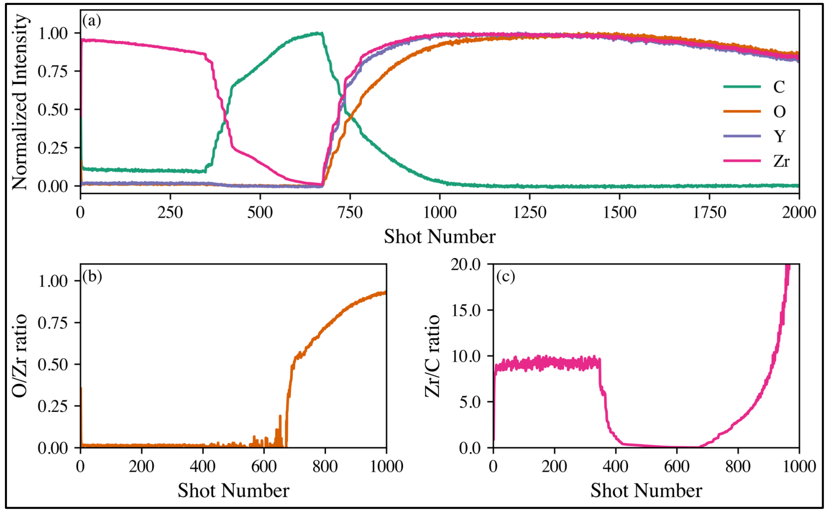


LIBS can map materials in 3D

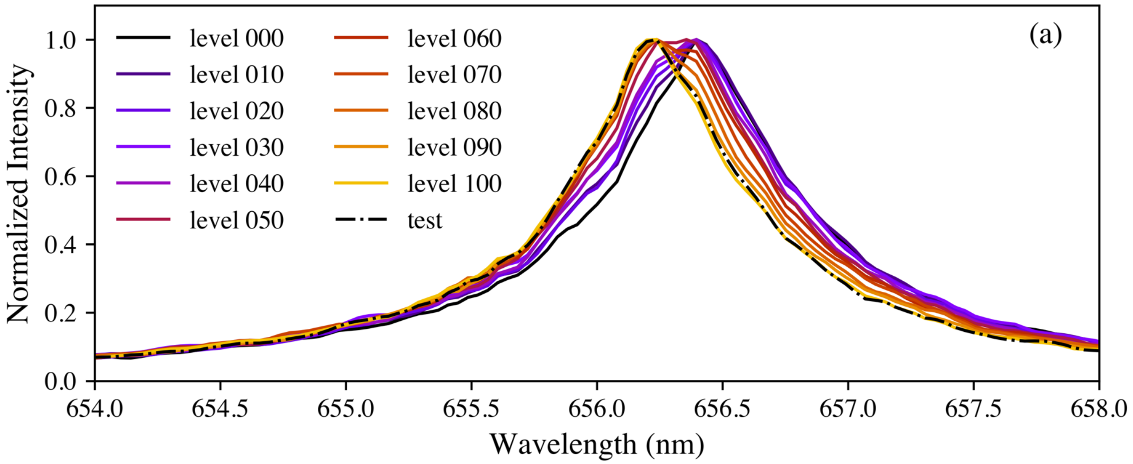


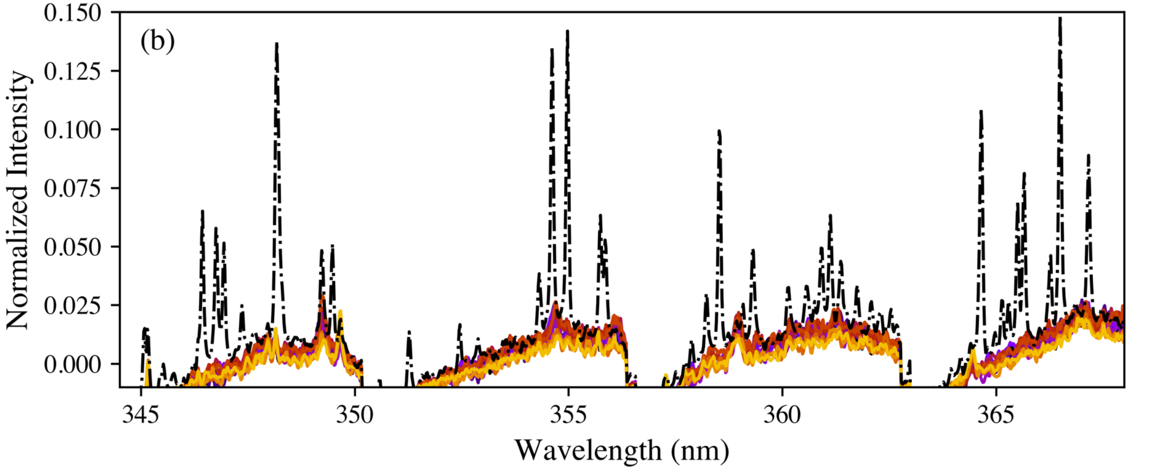


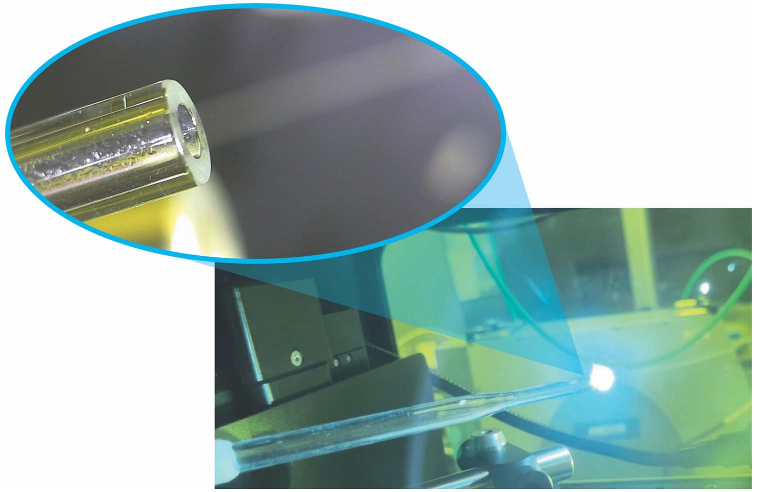


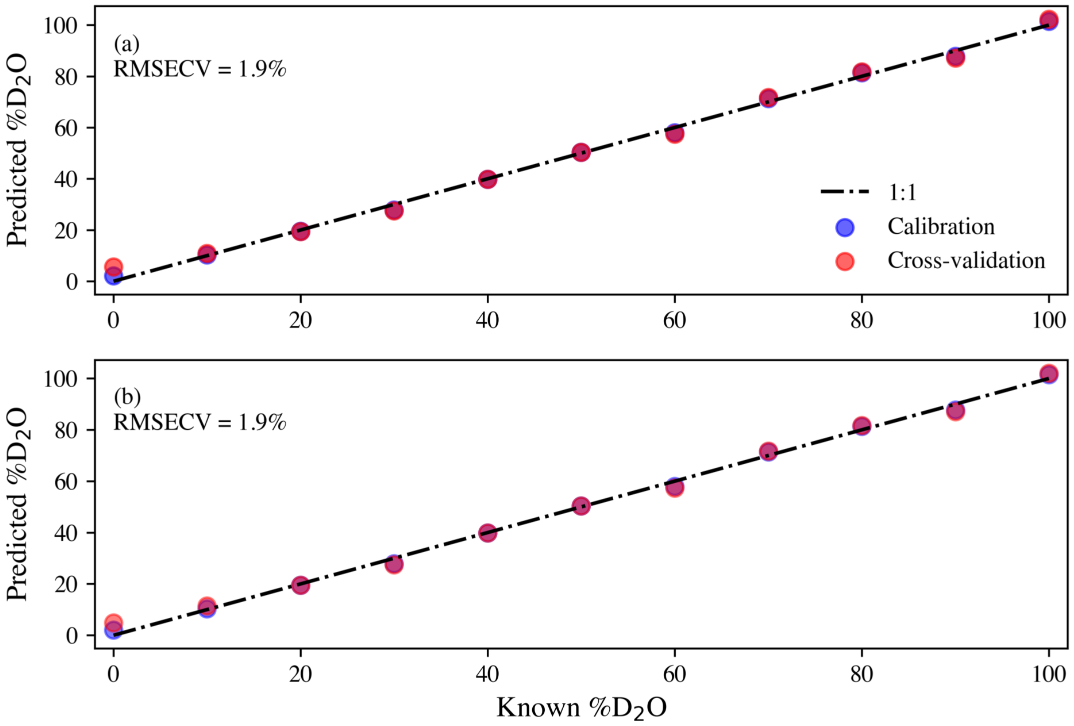


LIBS can monitor isotopes relevant to MSRs



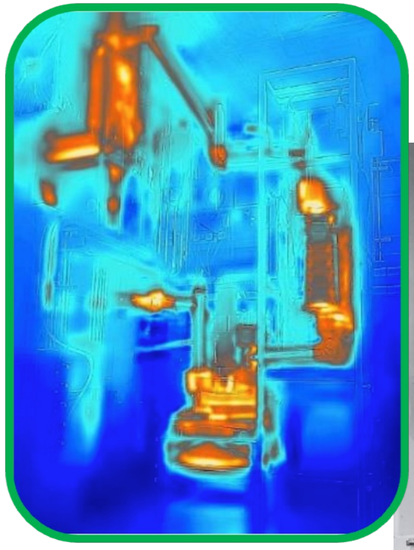






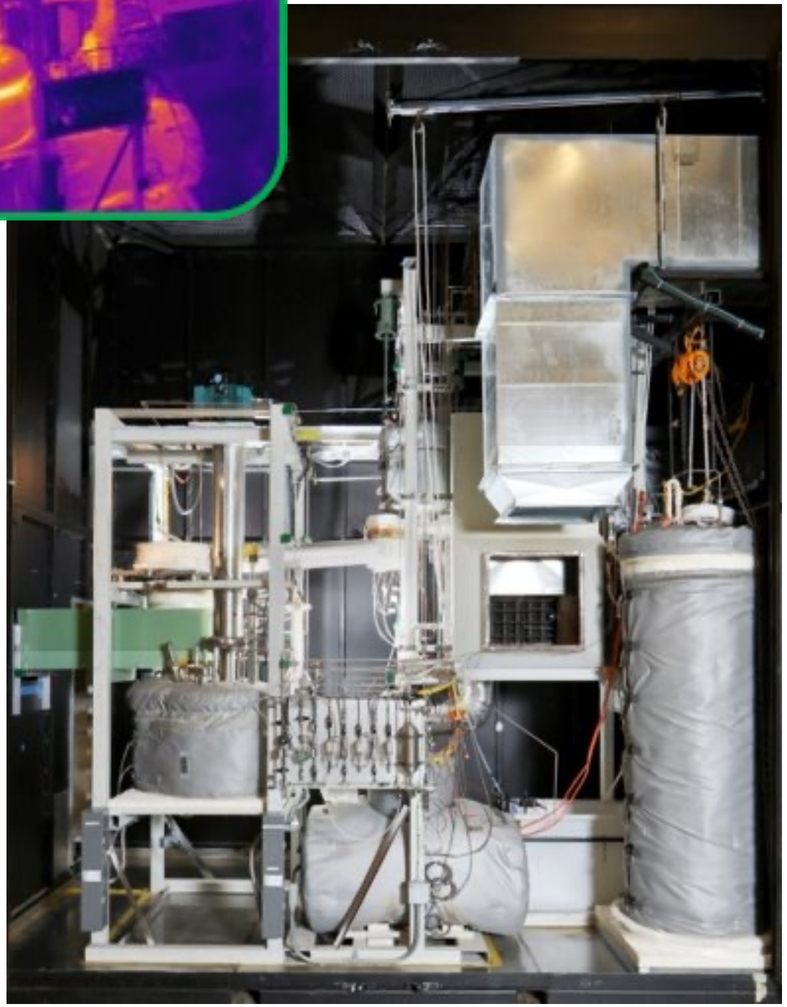
OAK RIDGE
National Laboratory

Next steps involve expanding the application of LIBS to engineering test scales



FASTR Loop (chloride salt)

LSTL Loop (fluoride salt)



Questions?

Reach out via e-mail: **andrewshb@ornl.gov**

We are hiring a postdoctoral researcher!
jobs.ornl.gov: Req ID#11892

Molten Salt Reactor
PROGRAM

Usage of Surrogate Fluids for Optimization of Component Level Design for Heat Transport Systems within Molten Salt Reactors

Lane B. Carasik, Ph.D. and the FAST Research Group

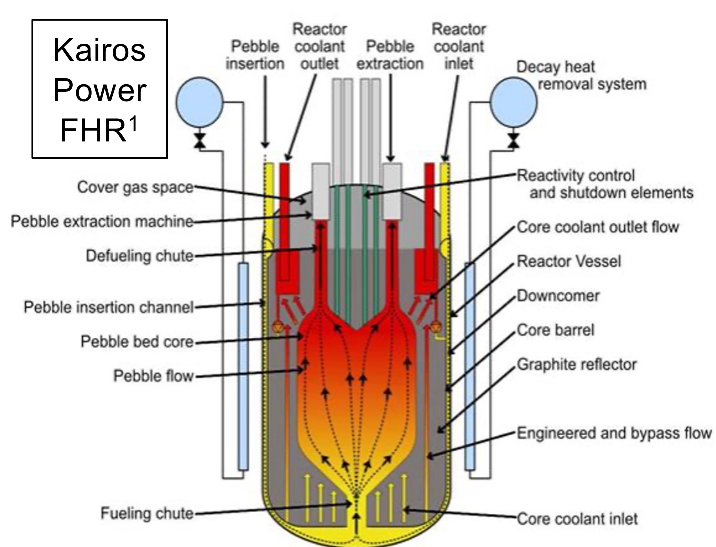
Fluids in Advanced Systems and Technology (FAST) Research Group, Virginia Commonwealth University

Email: lbcarasik@vcu.edu – Group Website: fastresearchgroup.weebly.com

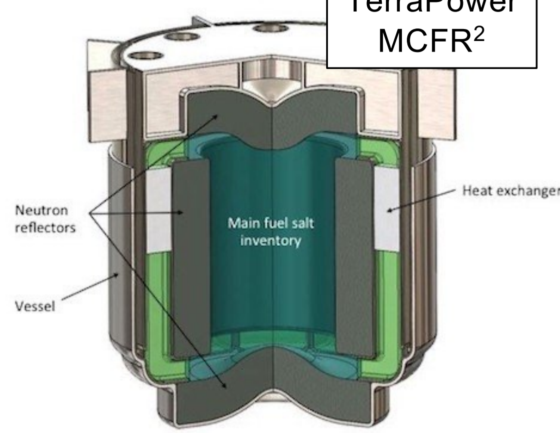
Motivation – Design and Licensing of MSRs

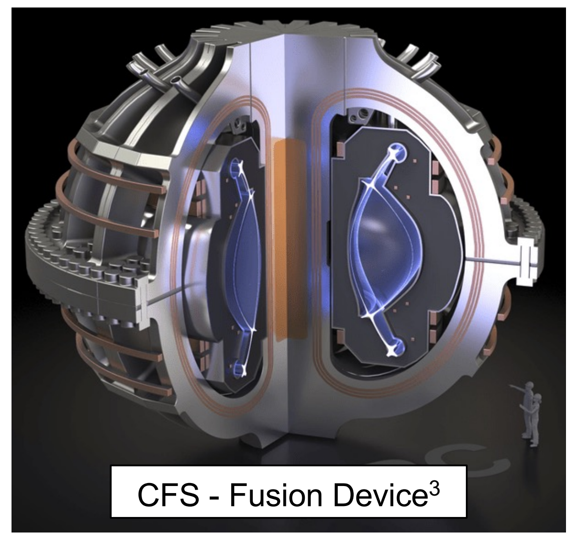
- Molten Salt Reactors/Systems (FHR, MCFR, and others) require high temperature salt loops that are needed for design, licensing, and modeling development (CFD & System codes).
- **Challenge:** Gathering experimental data in molten salt systems can be expensive and has associated hazards inherent to high temperature and corrosive salts.

Kairos Power FHR[1]



TerraPower MCFR[2]



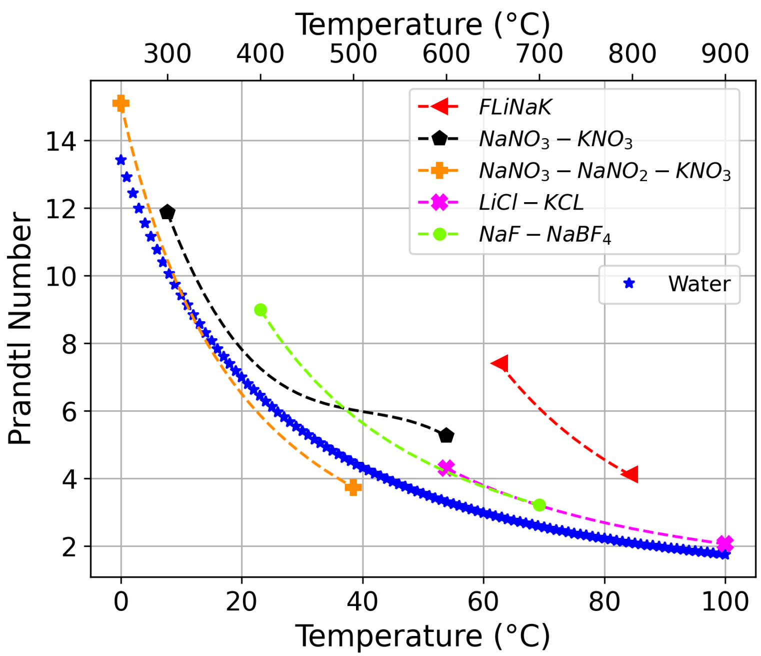


CFS - Fusion Device[3]

[1]NRC. Kairos. United States Nuclear Regulatory Commission, 2018. [2]TerraPower MCFR https://www.energy.gov/ne/articles/southern-company-and-terrapower-prep-testing-molten-salt-reactor [3]Commonwealth Fusion Systems, 2022, https://cfs.energy/technology

Scaling and Similitude for MSR Design

We take advantage of surrogate fluids for molten salts to do scaled heat transfer and fluid dynamics experiments.



Relevant scaling parameters/non-dimensional numbers:

$$\mathrm{Pr} = \frac{\mu c_p}{k} \qquad Gr = \frac{g\beta \vartriangle T\, {D_h}^3}{\nu^2} \qquad Re = \frac{\rho u D_h}{\mu}$$

Desired Heat Transfer/Fluid Dynamics Design Information:

$$HTC \sim Nu = functon\ (Re, Gr, Pr, Geom, BCs)$$

$$dP \sim f = function(Re, Geom)$$

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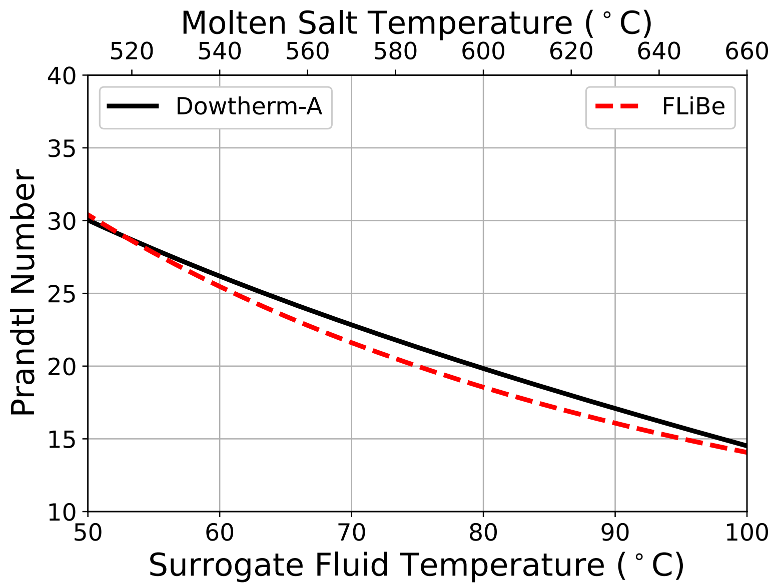
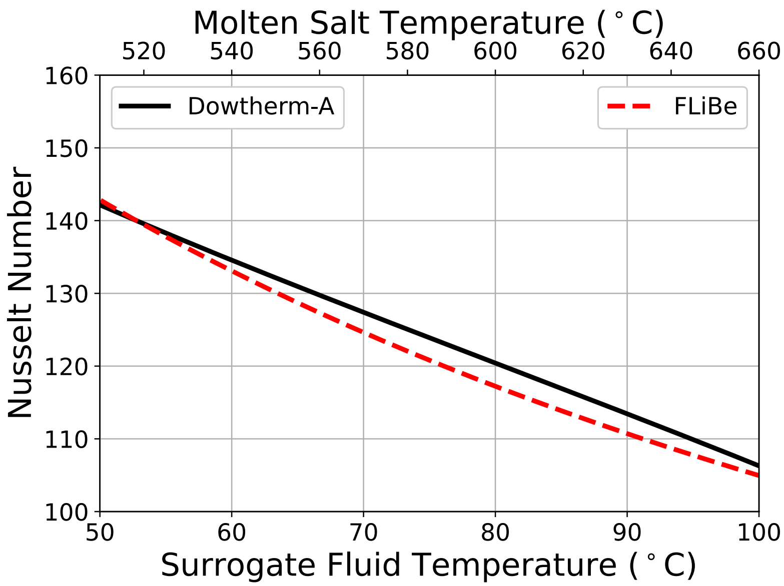
Cabral, A., et al., "Identification of Surrogate Fluids for Molten Salt Coolants used in Energy Systems Applications including Concentrated Solar and Nuclear Power Plants," Int. J. Energy Res., Vol. 46(3), pp. 3554-3571, 2022.

Similitude of Heat Transfer through Prandtl Scaling – Ex: Straight Pipe Surrogate Experiment



$$Re = \frac{\rho u D_h}{\mu}$$

$$Pr = \frac{\mu c_p}{k}$$



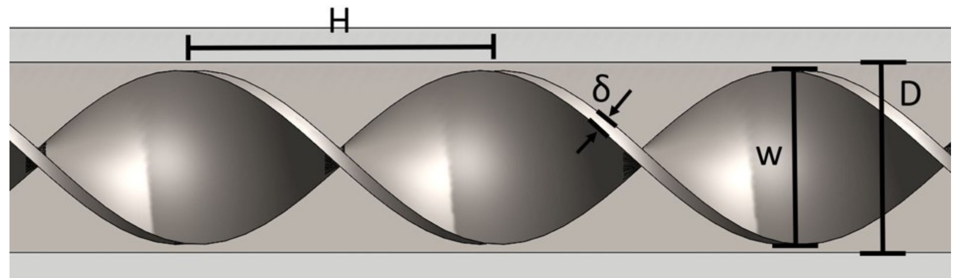
Example: Reynolds Number = 10k and over a representative Temperature Range

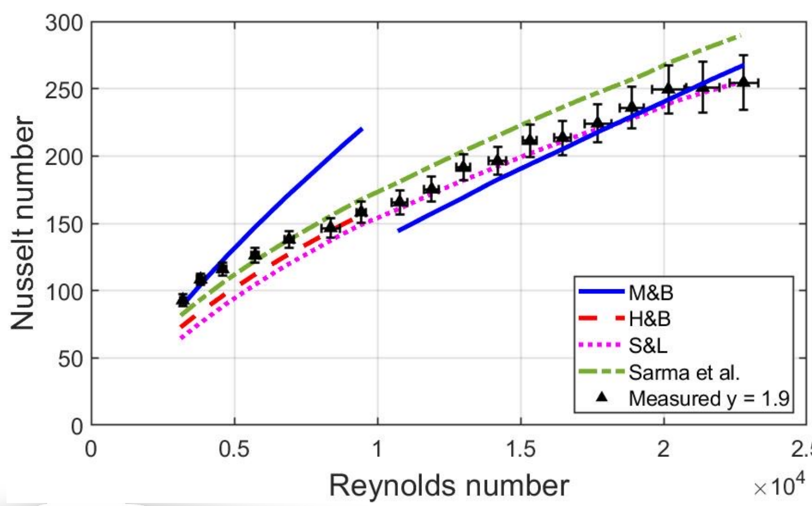
$$HTC \sim Nu = f\ (Re, Pr, Geom, BCs)$$

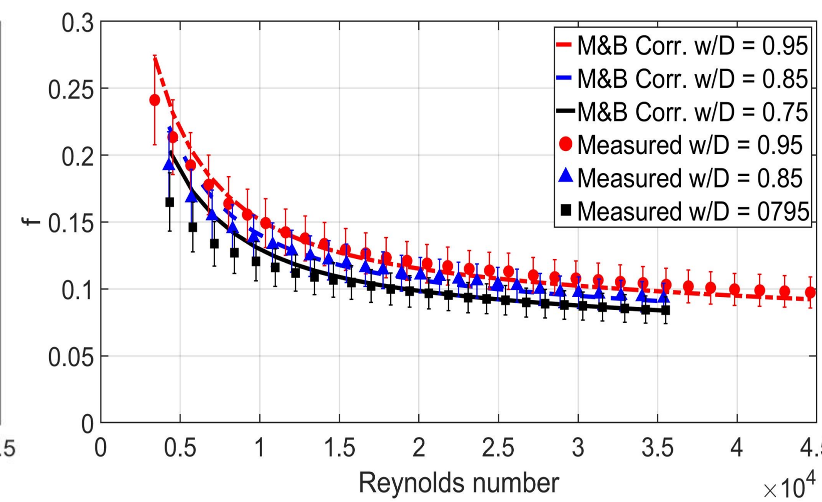
VCU

Cabral, A., et al., "Identification of Surrogate Fluids for Molten Salt Coolants used in Energy Systems Applications including Concentrated Solar and Nuclear Power Plants," Int. J. Energy Res., Vol. 46(3), pp. 3554-3571, 2022

Use Case: Heat Transfer Enhancements







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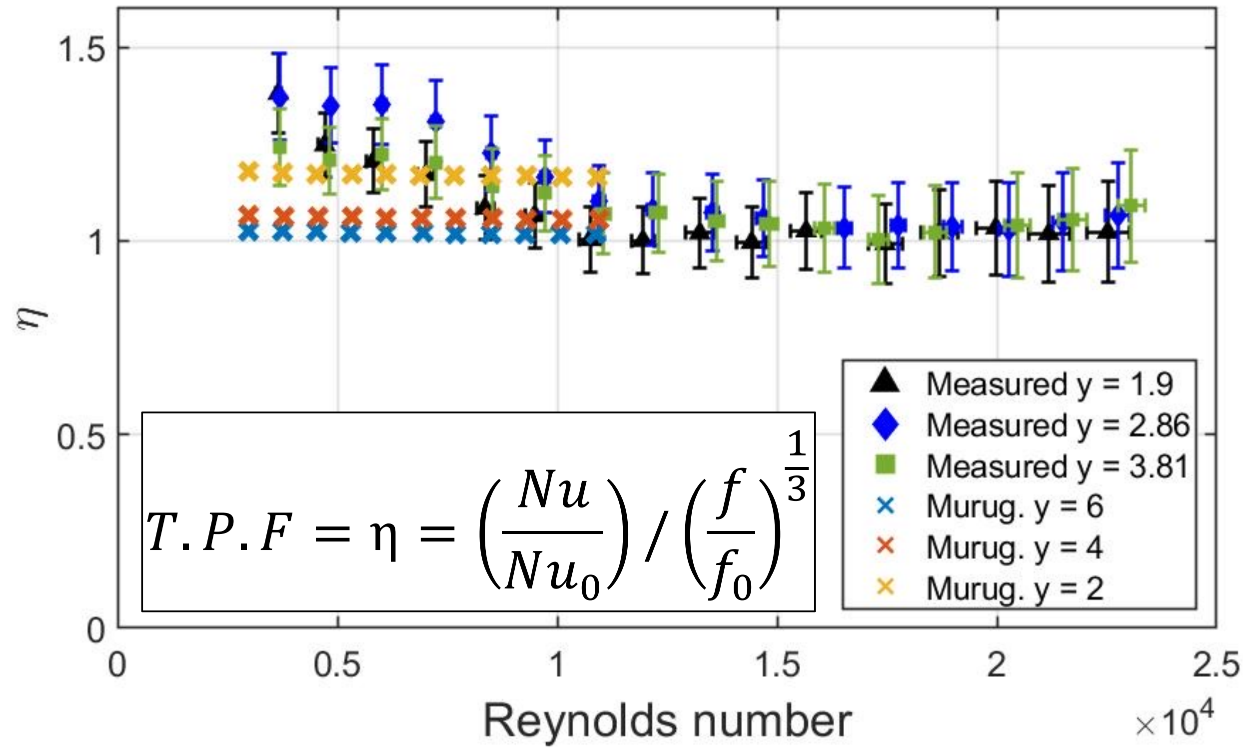
[1]Cabral, A., et al., "Assessing Heat Transfer Correlations through Experimental Studies of Twisted Tape Inserts in Heat Exchanger Tubes" – Under Review. [2]Manglik and Bergles, *ASME J Heat Transf*, **115** (1993). a Manglik and Bergles, *ASME J Heat Transf*, **115** (1993). [3]Smithberg and Landis, *ASME J. Heat Trans,* **86** (1964). [4] Sarma et al, *Int. Journal of Therm. Sciences,* **44** (2005). [5]Hong and Bergles, *J. Heat Transf,* **98** (1976).

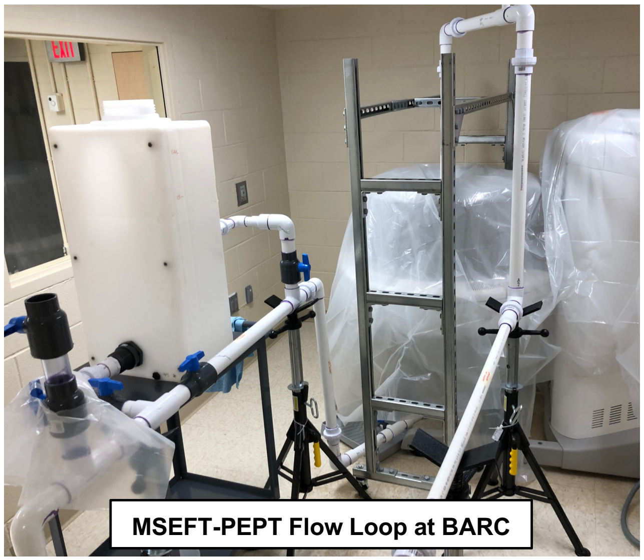
Use Case: Heat Transfer Enhancements



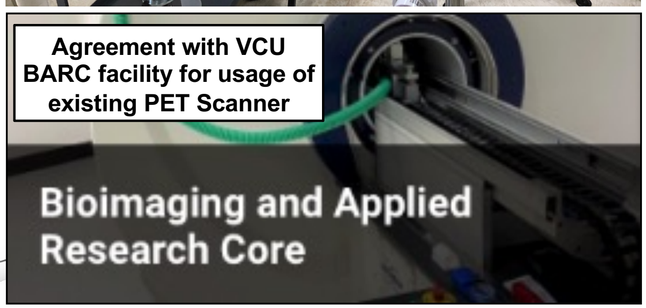
$$T.P.F = \eta = \left(\frac{Nu}{Nu_0}\right) / \left(\frac{f}{f_0}\right)^{\frac{1}{3}}$$

[1]Cabral, A., et al., "Assessing Heat Transfer Correlations through Experimental Studies of Twisted Tape Inserts in Heat Exchanger Tubes" – Under Review. [2]Manglik and Bergles, *ASME J Heat Transf*, **115** (1993).

FAST RG Flow Exp. in Heat Transfer Components

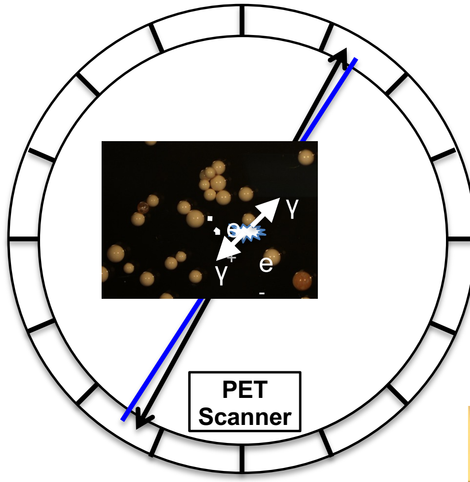


MSEFT-PEPT Flow Loop at BARC

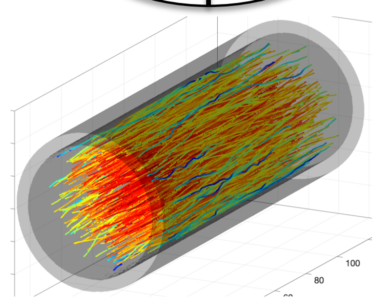


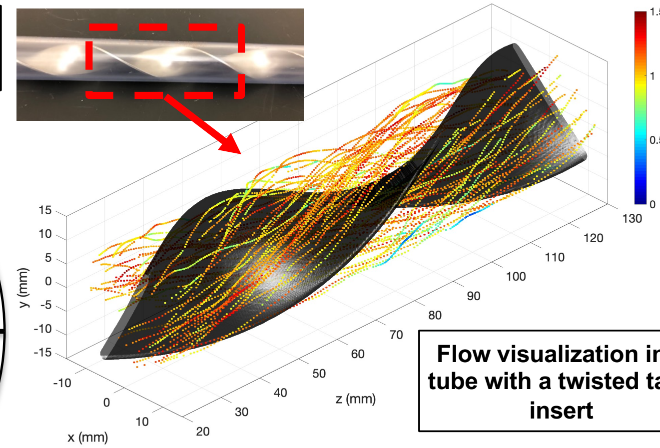
Agreement with VCU BARC facility for usage of existing PET Scanner

Positron Emission Particle Tracking (PEPT) & CT uses radiotracers to map flow fields

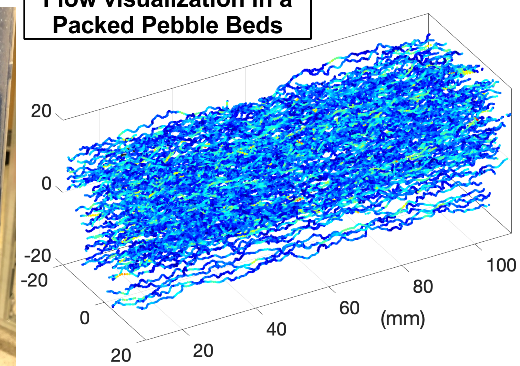


PET Scanner





Flow visualization in a tube with a twisted tape insert



Flow visualization in a Packed Pebble Beds

Wiggins, C., et al., "Noninvasive interrogation of local flow phenomena in twisted tape swirled flow via positron emission particle tracking (PEPT)," Nuc. Eng. Des., Vol. 387, pp. 1116012022, 2022.

Conclusion

We can use surrogate fluids (Water and Mineral Oils) in place of molten salts to do scaled heat transfer and fluid dynamics experiments.

This should be viewed to reduce research and development costs and limit the total number of tests in molten salts for component optimization.

Acknowledgements

This work was supported under awards, 31310018M0031, 31310021M0038, from the Nuclear Regulatory Commission. The statements, findings, conclusions, and recommendations are those of the author(s) and do not necessarily reflect the view of the U.S. Nuclear Regulatory Commission.

This research was supported by an award from the Jeffress Trust Awards Program in Interdisciplinary Research Program funded by the Thomas F. and Kate Miller Jeffress Memorial Trust, Bank of America, Trustee.

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UNIVERSITY OF MICHIGAN

Developing a Non-Destructive Method for Measuring Holdup in Liquid Fueled MSRs

Diego Macias, Stephen Raiman

Complications from Hold Up in MSRs

- Leads to unaccounted fissile material
- Increases dose to workers
- Fission product deposition may alter mechanical properties of salt facing materials
- Makes decommissioning more expensive

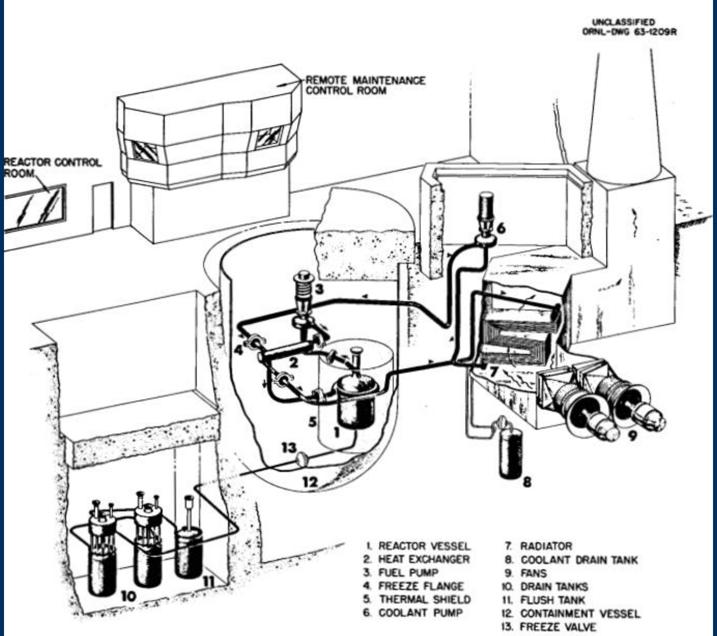
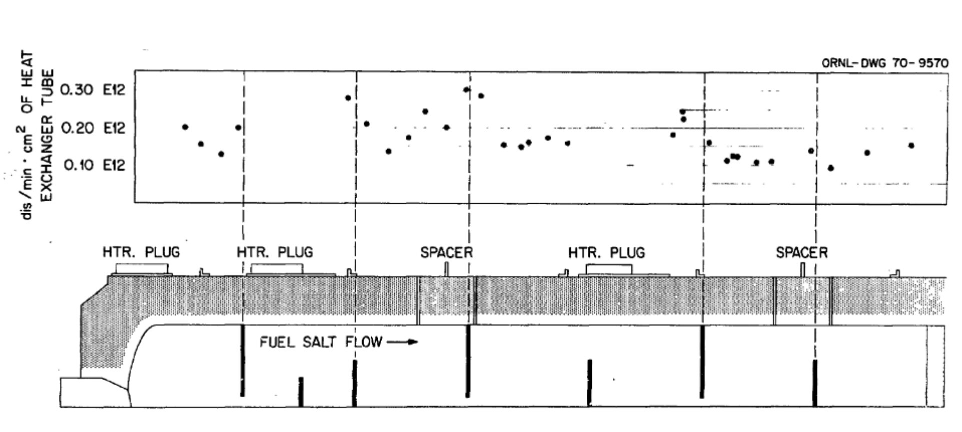


Diagram of the MSRE

R.C. Robertson ORNL-TM-728

Deposited Fission Products were Found Throughout the MSRE Circuit After Decommissioning

- Components of the MSRE were analyzed using Gamma Ray spectroscopy
  - Heat Exchanger
  - Off Gas lines
  - Drain Tank
  - Pump Bowl
- Non uniform hold up of fission products was detected
  - Baffle plates had up to 4X the activity of other salt facing material



Activity of 95Nb at reactor shut down in the MSRE heat exchanger

A. Houtzeel ORNL-TM-3151

Possible Causes of Hold Up

- Temperature and flow gradients
- Oxides and impurity reactions
- Localized flow and temperature transients
- Intergranular or bulk diffusion
- Crevices, cracks, and geometrical irregularities

Gathering Data to Improve Accountancy in MSRs

Detection of Deposits on Components Exposed to Static Salt

→ Isotope Signature →

Hold Up- Measurements in Pumped Loop

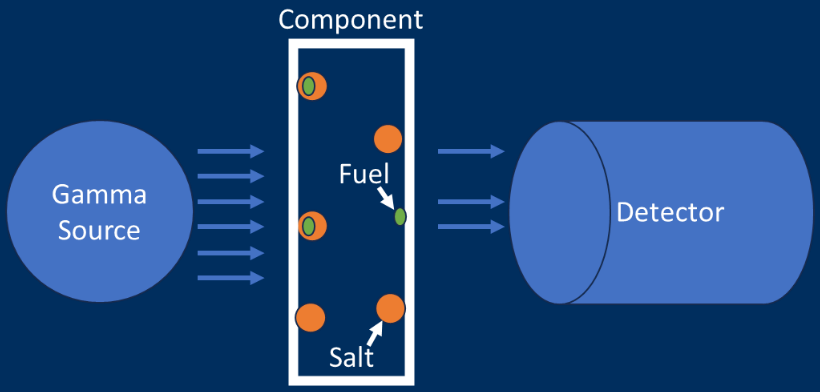
→ Hold Up Location and Inventory →

Build 1D Thermal Hydraulic Models in TRANSFORM

Non-Destructive Method of Measuring Hold Up

- Densitometry measurements are taken of components before and after salt exposure
  - Changes in density can be related to the presence of salt, fission products and fuel

- Measurements and detection in collaboration with Jesse Bruner and Shaheen Dewji at Georgia Tech



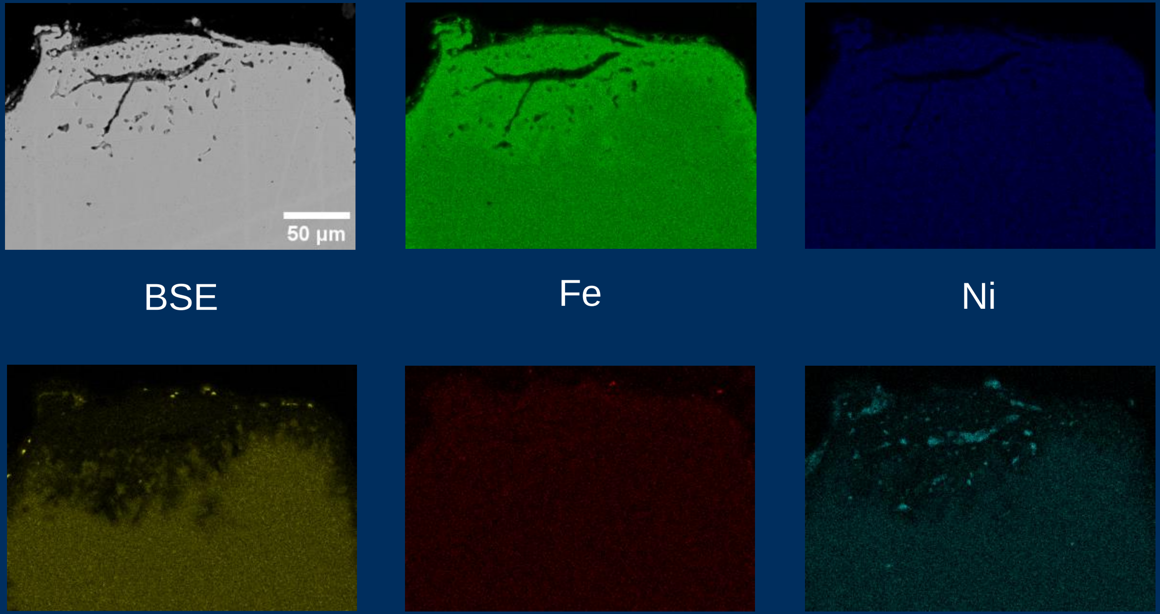
Testing Conditions to Recreate Hold Up and Deposition

- Fluoride Salt
  - FLiNaK with Te and Eu additions
  - Cycling between 600 and 700 ℃ every hour for 500h
- Starting with static tests
  - Tube geometry
  - Heat exchanger

Salt containment (left) and heating set up (right)

Post Exposure Examination Shows Eu (fuel surrogate) Deposition

- 316 SS
- 700 - 600ºC FLiNaK + EuF_3 + Te
- 500 Hours

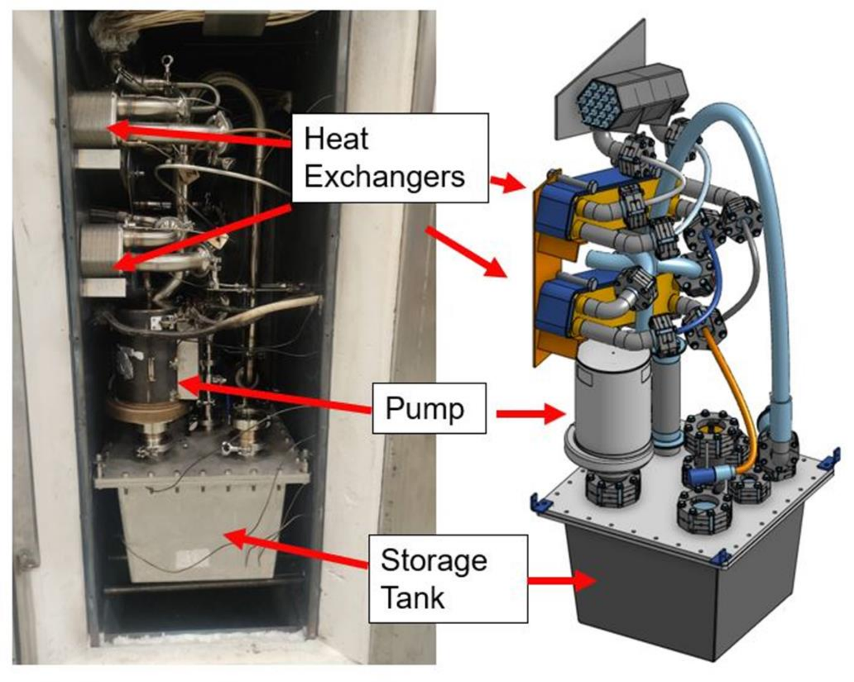


BSE Fe Ni

Cr Te Eu

Future Plans

- Further static tests
  - Uranium bearing salts
- Custom-built Copenhagen Atomics pumped molten salt loop to investigate
  - Flow conditions
  - Changes in temperature



Picture (left) and drawing (right) of pumped loop

Acknowledgements

This research is being performed using funding received from the DOE Office of Nuclear Energy's Nuclear Energy University Programs.

The authors acknowledge Connor Shamberger for his assistance with construction of the static testing apparatus, the financial support of the University of Michigan College of Engineering, NSF grant #DMR-1625671, and technical support from the Michigan Center for Materials Characterization.

October 25, 2023

Nidia C Gallego
Oak Ridge National Laboratory

Graphite-Salt Interactions: Overview of Research Activities at ORNL

2023 MSR Workshop

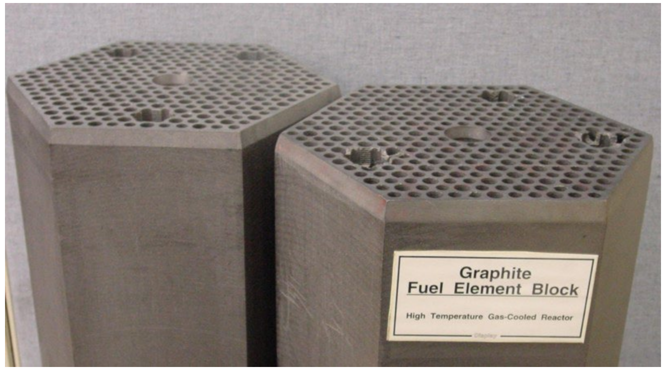
Oak Ridge National Laboratory

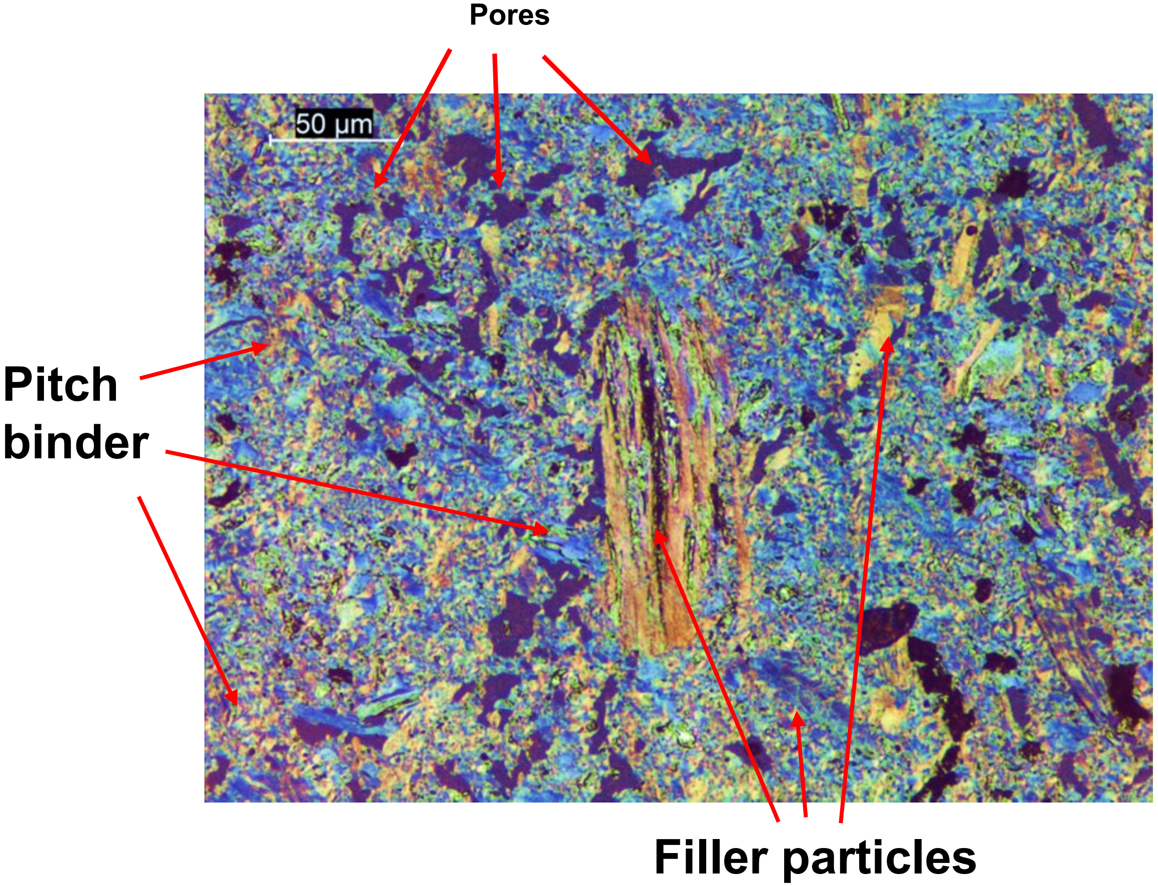
ART Advanced Reactor Technologies

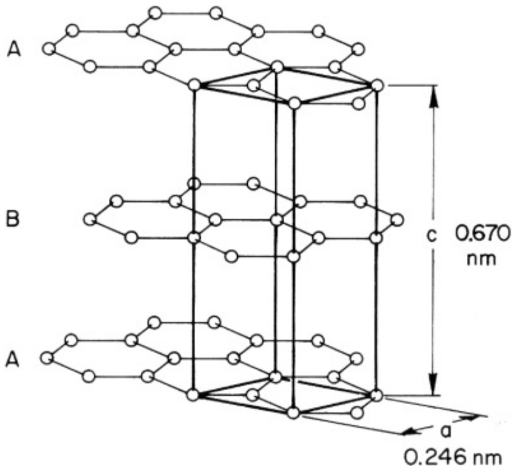
Current Research Focus of Graphite-Salt Studies at ORNL

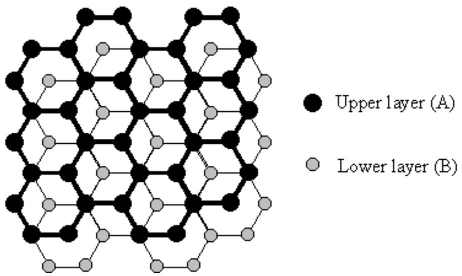
- Understanding salt intrusion (penetration depth and salt distribution) in a wide range of graphite grades (various microstructures) as a function of temperature, pressure and time.
- Studying wetting behavior of salt on graphite surfaces to develop predictive models for salt intrusion
- Studying wear and erosion behavior of graphite in molten salt
- Working with the ASTM community to develop standards to measure the effect of salt intrusion on graphite properties
- Working with the ASME Community to develop the needed knowledge to address the gaps in the ASME code and therefore assist in the near-term deployment of MSRs.

Understanding Manufactured Graphite



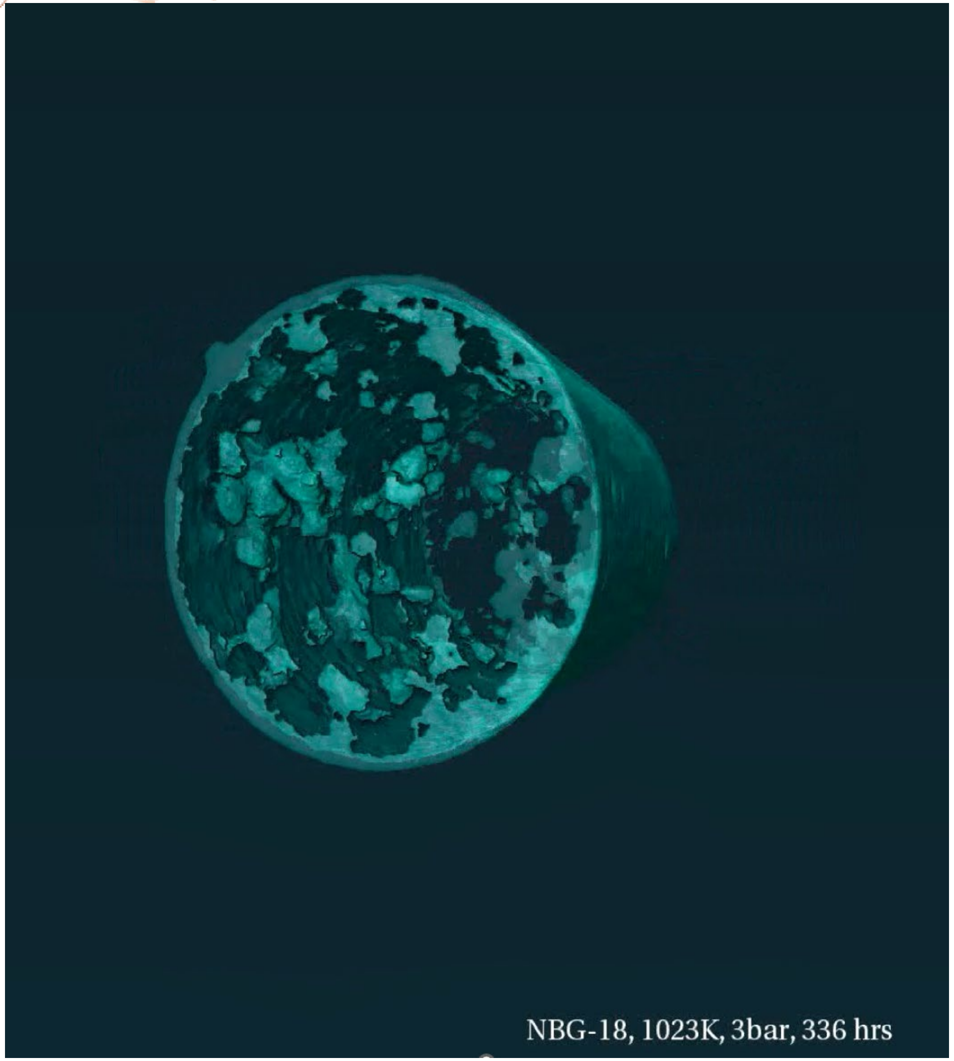






Manufactured Graphite has about **20 % porosity**

Salt intrusion into graphite porous structure



- Built capabilities for salt intrusion studies (FLiNaK, < 10 bar, < 750ºC) and conducted measurements on a wide range of graphite grades and intrusion conditions.
- Demonstrated and implemented the use of neutron imaging to study intrusion and determine **salt penetration and distribution.**
- Studying the effect of **P**ressure, **T**emperature and **t**ime for a wide range of graphite grades/microstructures.

Carbon 213 (2023) 118258

Contents lists available at ScienceDirect

Carbon

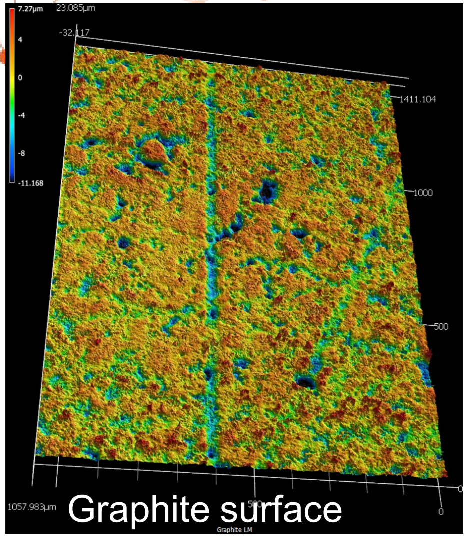
journal homepage: www.elsevier.com/locate/carbon

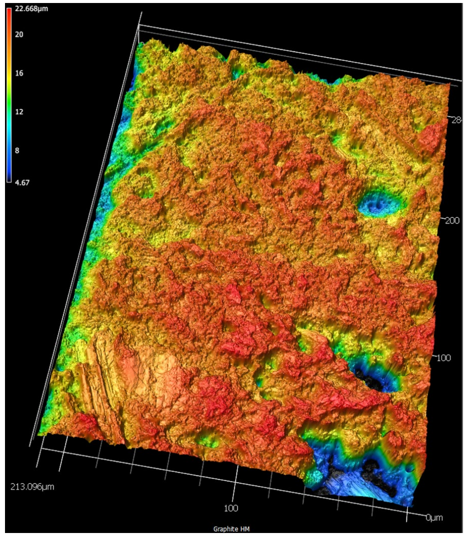
ELSEVIER

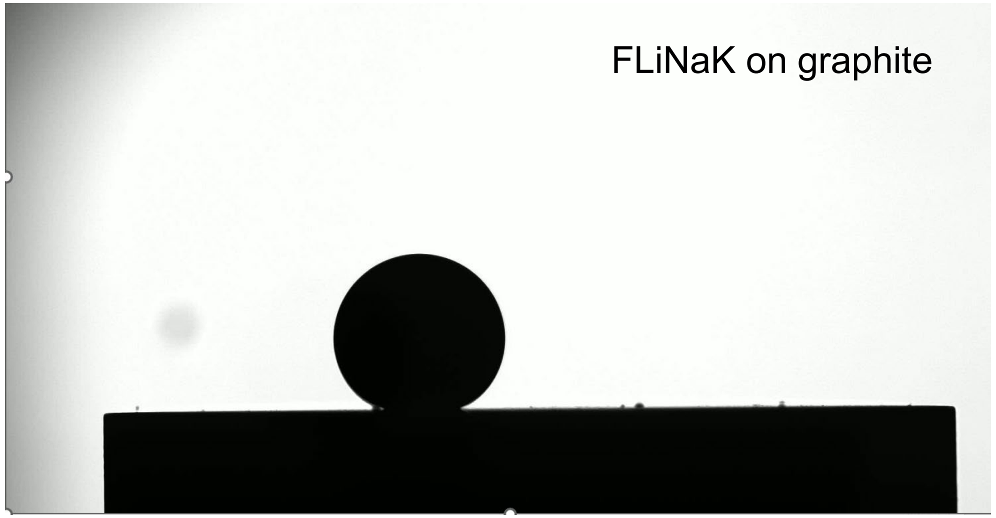
A neutron tomography study to visualize fluoride salt (FLiNaK) intrusion in nuclear-grade graphite

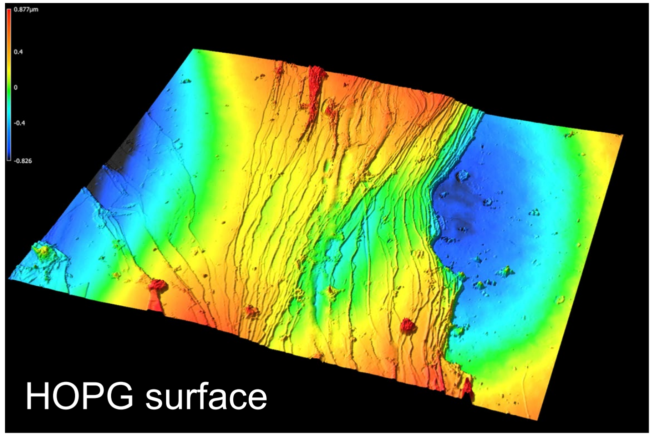
Jisue Moon [a,*], Nidia C. Gallego [b,**], Cristian I. Contescu [b], James R. Keiser [c], Dino Sulejmanovic [c], Yuxuan Zhang [d], Erik Stringfellow [d]

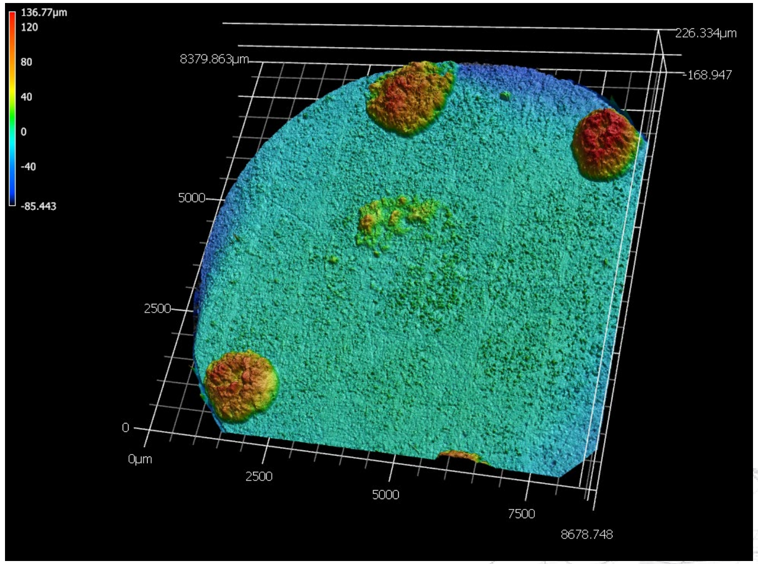
Wetting behavior of molten salt on graphite surface



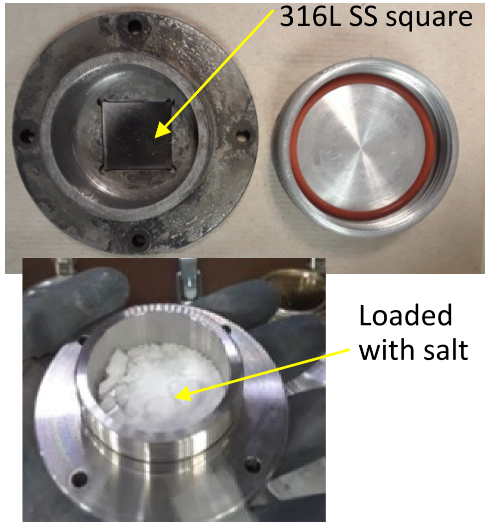




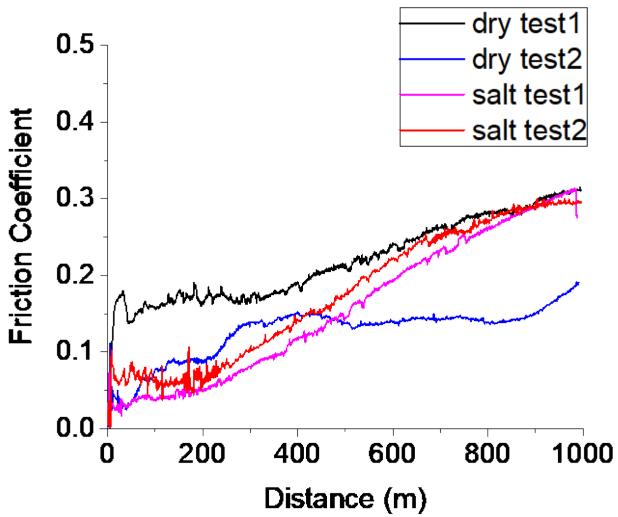


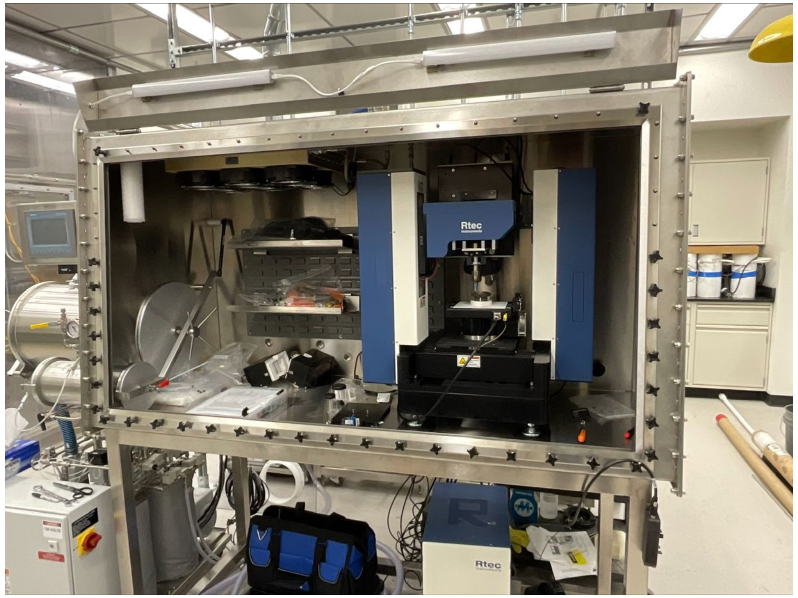


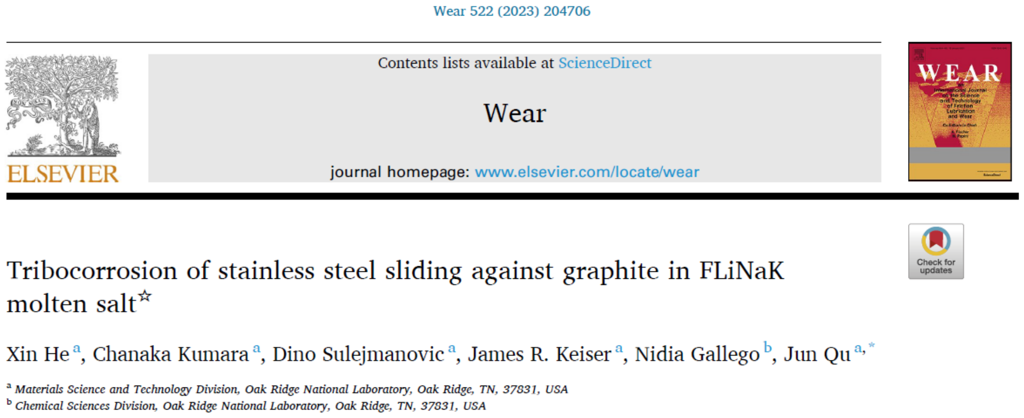
Tribological properties of graphite in molten salt



- Completed initial scoping studies of the wear behavior of graphite in molten FLiNaK salt.
- Commissioned new wear facilities to have better environmental control.






Wear 522 (2023) 204706

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Tribocorrosion of stainless steel sliding against graphite in FLiNaK molten salt☆

Xin He [a], Chanaka Kumara [a], Dino Sulejmanovic [a], James R. Keiser [a], Nidia Gallego [b], Jun Qu [a,*]

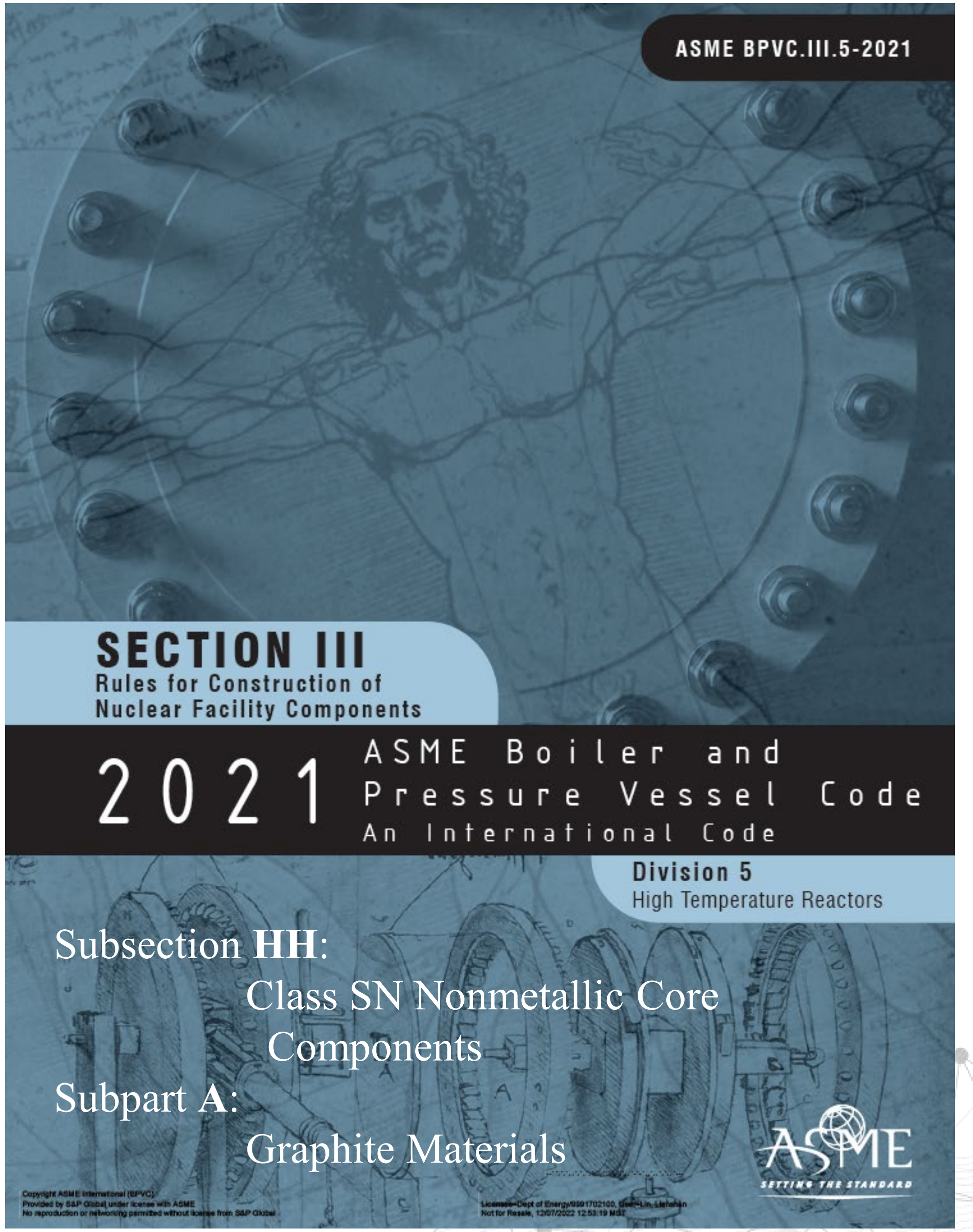
[a] Materials Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, TN, 37831, USA
[b] Chemical Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN, 37831, USA

ASME SEC III Division 5
High Temperature Reactors

The current HHA does not address any coolant salt interactions with graphite.

Chemical attack, salt infiltration and retention as well as wear and erosion aspects need to be incorporated in the design rules.

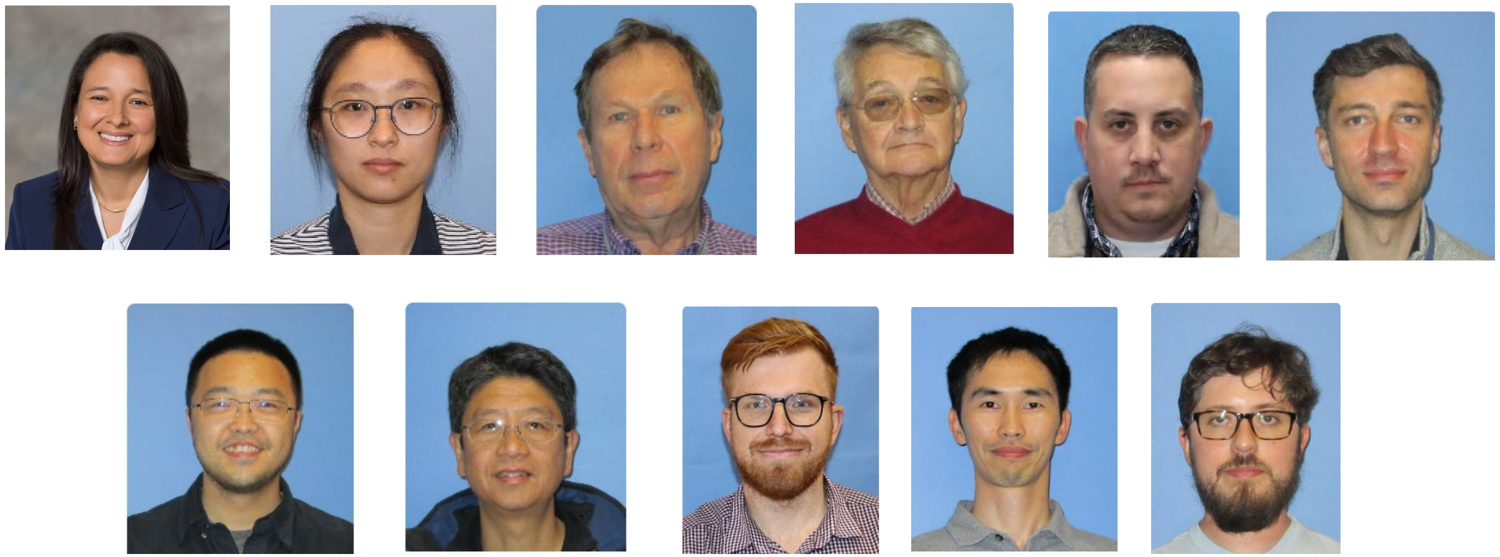
Standards:
D02.F0 on Manufactured Carbon and Graphite Products



Team Effort – ORNL Contributors

Nidia Gallego
Jisue Moon
Jim Keiser
Cristian Contescu
Yuxuan Zhang
Adam Willoughby
Dino Sulejmanovic
Jun Qu
Xin He / Tomas Grejtak
Lianshan Li
David Arregui-Mena

Many others around ORNL and collaborators at INL and other organizations



Financial Support from US DOE-NE Advanced Reactor Technology:
MSR and TRISO and Graphite Campaigns

This research used resources at the High Flux Isotope Reactor, a US DOE Office of Science User Facility operated by the ORNL

Publications

- Gallego NC, Contescu CI, Keiser JR, “Progress Report on Graphite-Salt Intrusion Studies” ORNL/TM-2020/1621 (August 2020)
- Gallego NC, Contescu C, Keiser J, Qu J, He X, Myhre K., “FY21 Progress Report on Graphite-Salt Interaction Studies” ORNL/TM-2021/2247 (October 2021)
- Moon J, Gallego NC, Contescu C, Keiser JR, Zhang Y, Stringfellow E, “Understanding FLiNaK salt intrusion behavior on nuclear grade graphite via neutron tomography” ORNL/TM-2022-2688 (September 2022)
- Vergari L, Gallego N, Scarlat S, et al., Infiltration of molten fluoride salts in graphite: phenomenology and engineering considerations for reactor operations and waste disposal. J Nuclear Materials, 154058. (2022)
- Myhre K, Andrews H, Gallego NC, et al., Approach to using Three-Dimensional Laser Induced Breakdown Spectroscopy Data to Explore the Interaction of Molten FLiNaK with Nuclear Grade Graphite (JAAS 37 (8), 2022, 1629-1641)
- Gallego NC, Contescu CI, Paul R, “Evaluating the Effects of Molten Salt on Graphite Properties: Gaps, Challenges, and Opportunities” In Graphite Testing for Nuclear Applications: The Validity and Extension of Test Methods for Material Exposed to Operating Reactor Environments, ASTM 2023
- He X., Qu J, et al., Tribocorrosion of stainless-steel sliding against graphite in FLiNaK molten salt (Wear 522 (1) 2023, 204706)
- Moon J, Gallego NC et al., A neutron tomography study to visualize fluoride salt (FLiNaK) intrusion in nuclear-grade graphite (Carbon 213, 2023, 118258).
- Moon J, Gallego NC, et al., Graphite-Salt Interactions: Summary of FY23 activities. ORNL/TM-2023/3144

Thank you!!

IAEA Safeguards

International Safeguards by Design

Traci Newton

Senior Safeguards Analyst, Division of Concepts and Planning
Department of Safeguards, IAEA
T.Newton@iaea.org

Overview

IAEA Safeguards

- Background: IAEA safeguards
- Safeguards considerations for Small Modular Reactors
- Safeguards by design

Role of IAEA safeguards

To verify that States are honouring their international legal obligations to use nuclear material and technology only for peaceful purposes

Comprehensive Safeguards Agreements

IAEA Safeguards

- Safeguards apply to all nuclear material in all peaceful activities in a State (INFCIRC/153 (Corr.))
- Concluded by the IAEA with Non-Nuclear-Weapons States (NNWS) party to the NPT
- Small Modular Reactors (SMRs) and related nuclear fuel cycle facilities built in States under a CSA – even prototypes – must be safeguarded, regardless of the size, technology, or State of origin of the SMR

Safeguards vs. proliferation resistance

IAEA Safeguards

Proliferation resistance:

"…that characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material or misuse of technology by the Host State seeking to acquire nuclear weapons or other nuclear explosive devices."*

- Safeguards provide **independent verification** ("*safeguardability*" is one aspect of PR)
- Higher proliferation resistance **does not necessarily mean simpler safeguards**

* Evaluation Methodology, Generation IV International Forum Working Group on Proliferation Resistance and Physical Protection (GIF-PRPPWG), https://www.gen-4.org/gif/jcms/c_40411/proliferation-resistance-physical-protection-working-group-prppwg, 2011

Safeguards challenges for SMRs

IAEA Safeguards

- **Advanced fuels and fuel cycles:** higher enrichment, pyroprocessing, …
- **Advanced reactor designs:** molten salt, fast reactors, pebble bed, …
- **Longer operation cycles:** continuity of knowledge between refuelling, high excess reactivity of core (target accommodation)
- **New supply arrangements:** factory sealed cores, transportable and floating power plants, transnational arrangements (need for design verification and sealing)
- **New spent fuel management:** storage configurations, waste forms
- **Small footprint:** access, design verification

Safeguards challenges for SMRs (cont'd)

- **Diverse operational roles:** district heating, desalination, hydrogen + electricity
- **Remote, distributed locations:** access issues, lack of "unannounced" visit deterrence, cost-benefit issues
- **Multiple-module plants:** continuity of knowledge, resource issues
- **Sheer number of designs!** (>80 in IAEA 2022 guide)
- **Lack of safeguards awareness** in design community (and difficulty in engaging directly with designers)

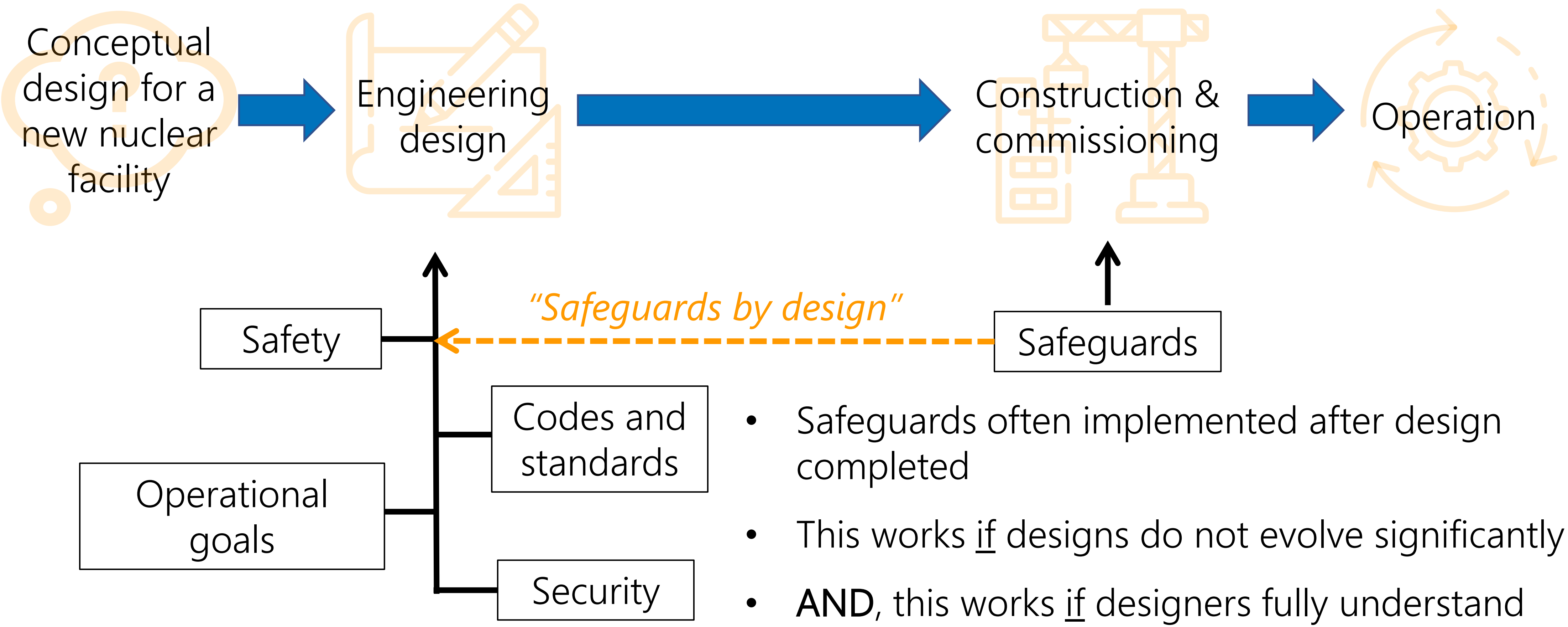
IAEA independent verification capabilities must be ready

Safeguards needs for SMRs

- **Unattended monitoring systems** (UMS) and **remote data transmission** (RDT)
- **Digital connectivity** coverage in remote areas (reliable, high bandwidth, secure)
- **Safeguards seals** on factory-sealed, transportable cores
- **Design verification**, particularly under transnational supply arrangements
- **New safeguards approaches**, including (potentially) joint-use instrumentation (e.g., thermal power monitor for microreactors, process monitoring)
- **State-level issues:** e.g., new or expanded nuclear capability
- **Training** for safeguards authority in emerging nuclear energy States

All of these need time for development:
"Safeguards by Design" Provides this

What is safeguards by design? (SBD)



- Safeguards often implemented after design completed
- This works <u>if</u> designs do not evolve significantly
- AND, this works <u>if</u> designers fully understand the requirements of international safeguards
- **Otherwise, safeguards by design is needed**

What is safeguards by design? (SBD)

IAEA Safeguards

- The **integration of safeguards considerations into the design process** (new or modified facility, at any stage of the nuclear fuel cycle), from initial planning through design, construction, operation, waste management and decommissioning
- **Awareness** by all stakeholders (State, designer, operator, regulator, other IAEA Departments) of IAEA safeguards obligations, and opportunities for **early discussion with the IAEA Department of Safeguards**
- A **voluntary process** that neither replaces a State's obligations for early provision of design information under its safeguards agreement, nor introduces new safeguards requirements

Benefits of safeguards by design (SBD)

- Reduce **operator burden** by optimizing inspections
- Reduce need for **retrofitting**
- Facilitate **joint-use equipment**
- **Increase flexibility** for future safeguards equipment installation
- Enhance possibility to use facility design/operator **process info**
- **Reduce risk** to scope, schedule, budget, and licensing

SBD benefits all parties involved, not just the IAEA

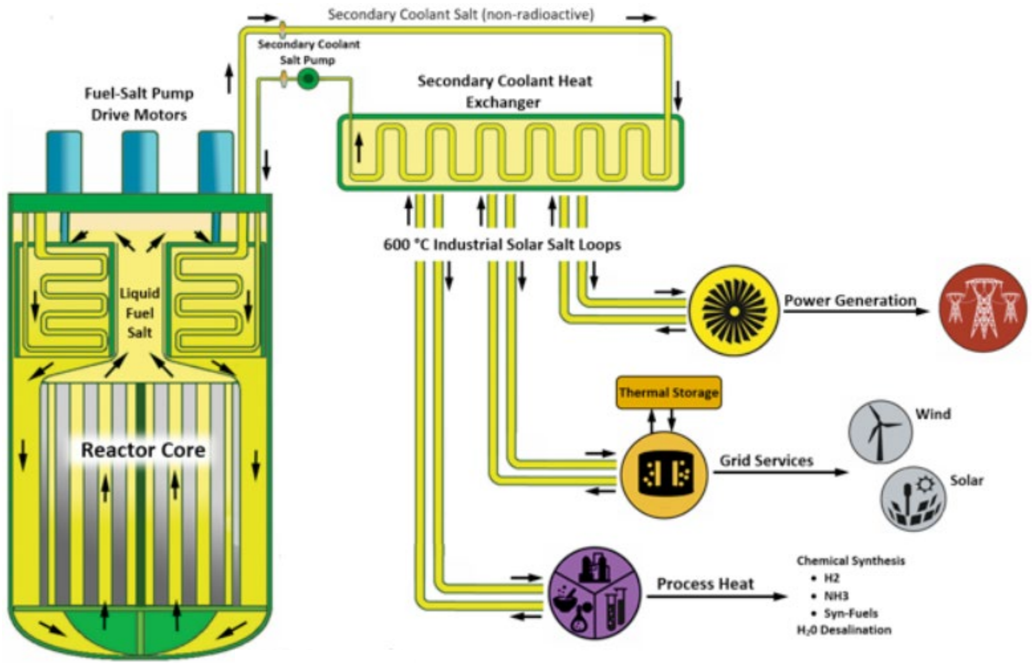
Challenges in implementing SBD

- IAEA lacks a **direct channel for initiating communication** with specific designers, particularly at the earliest stages when greatest SBD potential exists
- Designers/vendor companies lack a **uniform understanding** of international safeguards requirements – e.g., due to being:
  - new to the nuclear industry,
  - from a State where safeguards requirements aren't as widely known, or
  - relatively small and limited in engineering scope
- Safeguards **not seen as a design driver** – of relevance closer to operation
- **Inconsistent licensing practice** in addressing safeguards requirements
- **Proprietary / commercial concerns** affecting the early sharing of detailed design information

SBD example for molten-salt SMR

IAEA Safeguards

1. A designer of a molten-salt SMR, *as recommended in the 'pre-licensing review' process of the State nuclear regulator*, engages in early SBD discussions with the State safeguards authority (SRA) and the IAEA.
2. Safeguards measures are negotiated, involving IAEA unattended measurement systems (UMS), remote data transmission (RDT), and the secure sharing of operational data.
3. The designer works with the IAEA, SRA, and operator to incorporate these requirements, including development of customized equipment and analysis methods.
4. A prototype of the molten salt SMR is built, and an optimized, effective safeguards approach is implemented.



IAEA "SBD for SMRs" activities

- **SMR Member State Support Program tasks**
  - Canada, China, Finland, France, Russia, Republic of Korea, United States (extendable to other States)
  - Technologies include floating reactor, integral PWR, molten-salt reactor (MSR), pebble-bed reactor, microreactor (district heating)
  - Goal is to work with IAEA Member States to:
    - raise awareness of safeguards with technology designers
    - evaluate design aspects that could impact safeguards
    - investigate potential safeguards implementation strategies, or even design modifications

IAEA "SBD for SMRs" activities

IAEA Safeguards

- **Internal IAEA collaborations**
  - Agency-wide SMR Platform (co-ordination and efficiency for Agency interaction with Member States on SMR issues)
  - SBD Working Group and other collaborations with IAEA Departments of Nuclear Energy and Nuclear Safety and Security
- **External engagements:**
  - Raising awareness with stakeholders (e.g. SMR Regulators Forum)

How can stakeholders help?

- **Regulators**
  - **Raise awareness** of safeguards requirements, and the potential benefits of SBD to all licensees
  - Make safeguards considerations a **requirement of pre-licensing review**
  - **Encourage three-way discussion** with State authority responsible for safeguards (SRA), designer, IAEA
- **NGOs, R&D community**
  - **Raise awareness** of safeguards requirements and SBD through industry seminars and other events (invite safeguards experts/IAEA)

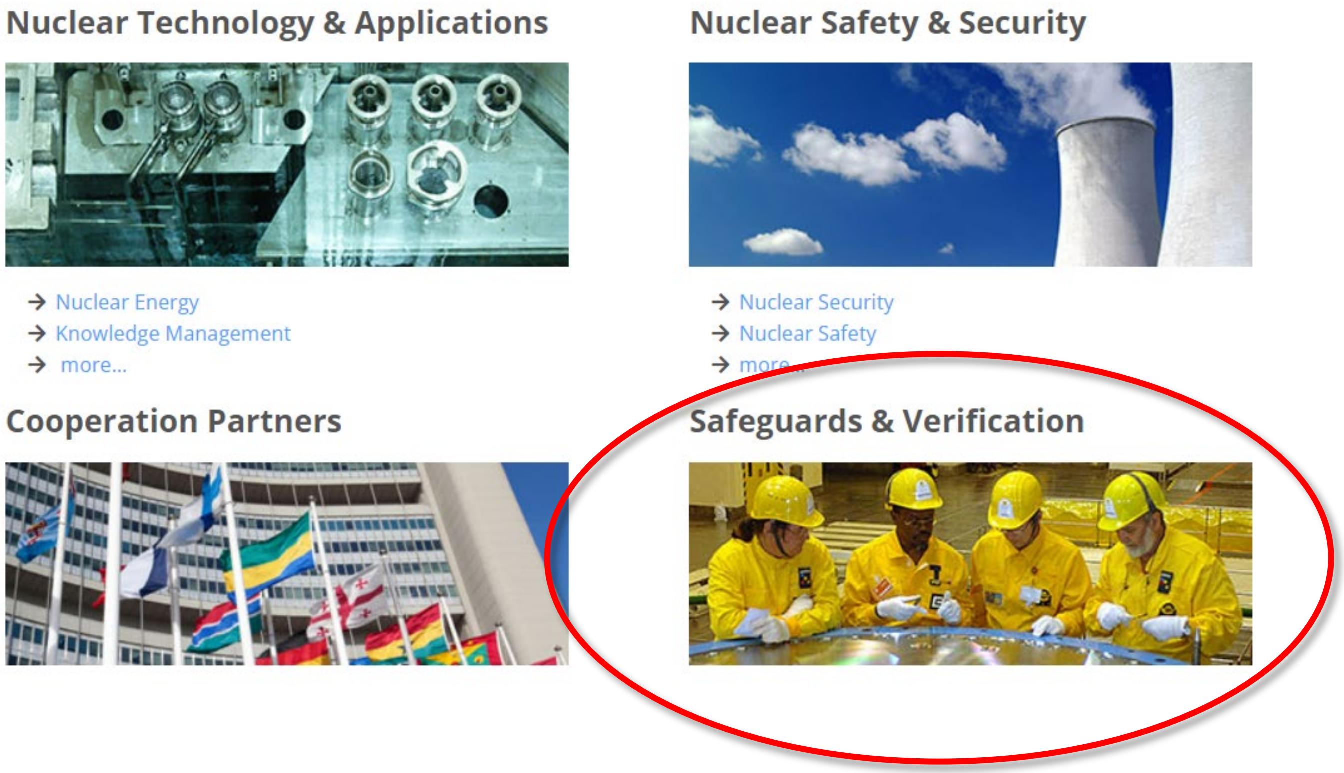
How can stakeholders help?

- **SMR developers**
  - **Increase awareness** of safeguards requirements and potential impact of State's safeguards obligations on operation of a new facility
  - **Incorporate safeguards considerations** along with safety, security, economics, and other factors
  - **Engage in early SBD discussions** with SRA, IAEA, or other experts

IAEA general safeguards training

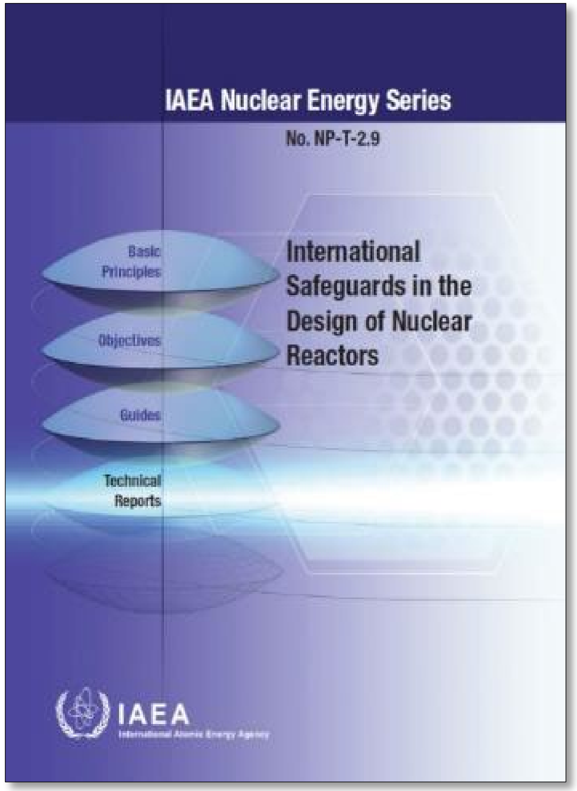
IAEA Open Learning Management System:

https://elearning.iaea.org



IAEA safeguards-by-design guidance

IAEA | Safeguards



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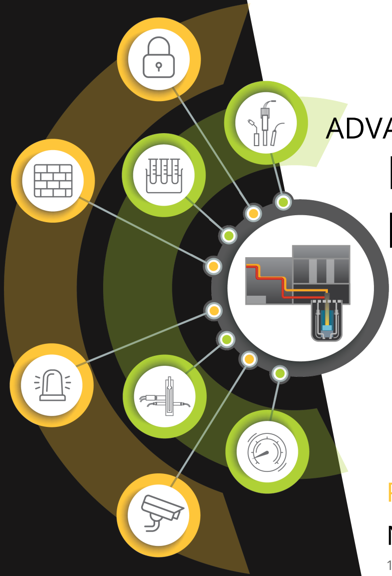


ADVANCED REACTOR SAFEGUARDS

Novel strategies for MC&A of liquid-fueled MSRs

An overview of current literature

Presented by:

Nathan Shoman[1]

[1]Sandia National Laboratories

October 25, 2023

Contact: nshoman@sandia.gov

SAND NO. 2023-10208C

Unique MSR features necessitate NMA strategies that differ from LWRs

MSRs:

- Fuel is in bulk form
- Constant feed and removals
- Constant depletion and decay
- Salt volume estimation
- Potentially heterogeneous samples
- Strong radioactive source terms

Conventional Nuclear:

- Fuel is in discrete items
- No feeds and removals outside of outages
- Many fuel assemblies with potentially different burnup and enrichment
- Factors that impact burnup well characterized (axial and radial effects)
- Have methods to ensure spent fuel is present when too hot to measure (i.e. Cherenkov)

Material balances are key NMA components at bulk facilities

- Material balance (MB) is used to quantify nuclear material for accountancy
- Sometimes called Inventory Difference (ID) or Material Unaccounted For (MUF)
- Basis for more complex statistical tests
- Since liquid-fueled MSRs have bulk fissile material, bulk techniques are appropriate

MB calculation

$$MB_t = (\Sigma_{t-1}^{t}\text{inputs}) - (\Sigma_{t-1}^{t}\text{outputs}) - (\text{inventory}_{t-1} - \text{inventory}_t) \quad (1)$$

MB for MSRs can be formulated using time-differenced measured and observed values

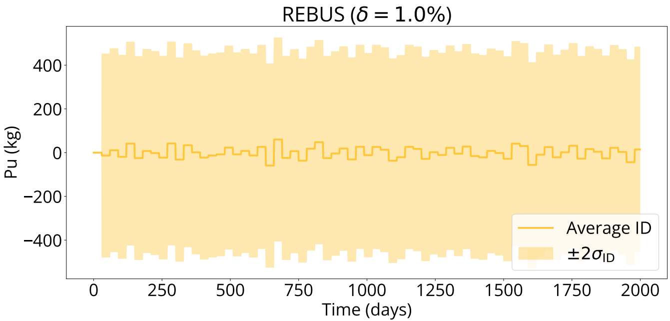
MSR material balance

$$\mathrm{MB}_t = \left(\sum_{i=1}^{n_\mathrm{I}} I_{i,t-1} + \cancelto{0}{\sum_{i=1}^{n_\mathrm{in}} Tin_{i,t}} - \cancelto{0}{\sum_{i=1}^{n_\mathrm{out}} Tout_{i,t}} \right) - \sum_{i=1}^{n_\mathrm{I}} I_{i,t} \tag{2}$$

$$\begin{aligned} \mathrm{MB}_t &= \left(I_{m,t} - I_{m,t-1} \right) - \left(I_{c,t} - I_{c,t-1} \right) \\ &= \left(C_{m,t}B_t - C_{m,t-1}B_{t-1} \right) - \left(C_{c,t}B_t - C_{c,t-1}B_{t-1} \right) \end{aligned}$$

Where $I_{m,t}$ is the measured quantity and $I_{c,t}$ is the calculated quantity, terms C and B refer to the concentration and bulk measurement respectively.

Bulk material balances are never zero



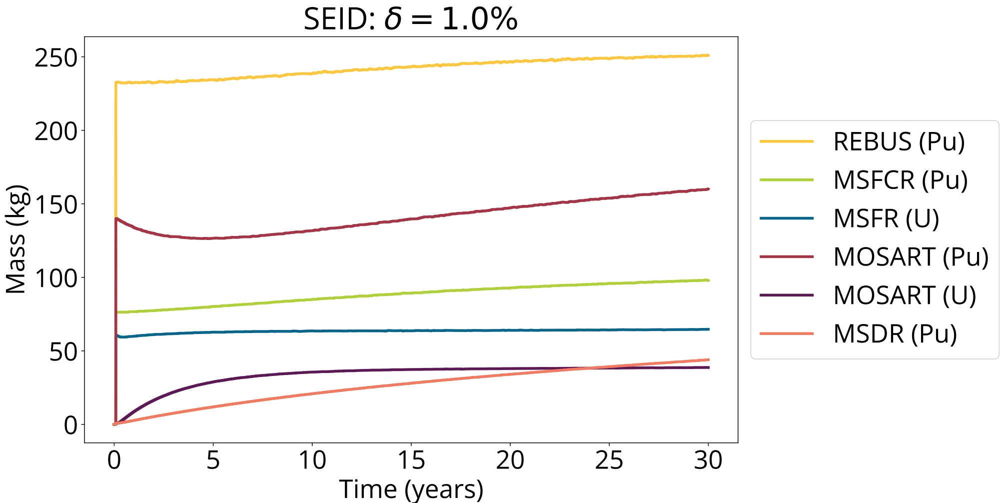
Measurements are never perfect

Measurements are never perfect which lead to non-zero material balances. Consequently, the material balance uncertainty plays an role in the ability of techniques to detect potential material loss.

Prior work considered several different designs

MSR parameter summary					
Parameter	**MSDR**	**MOSART**	**REBUS**	**MSFR**	**MCSFR**
Th Pwr (MWth)	750	2400	3700	3000	6000
F Salt Comp (mol%)	$LiF-BeF_2-ThF_4-UF_4$ (71.5-16-12-0.5)	$LiF-BeF_2-ThF_4-TRUF_3$ (69.72-27.1.28)	NaCl + (0.711% ^{235}U + 16.7 at.% TRU)Cl_3 (55-45)	$LiF-ThF_4-^{233}UF_4$ (77.5-19.9-2.6)	$NaCl-UCL_3-^{239}PuCl_3$ (60-36-4)
F Feed	3.08%^{235}U	0.711%^{235}U + TRU	0.711%^{235}U	^{233}U + ^{232}Th	0.711% ^{235}U + Pu
F Mass (MTIHM)	121.0	28.83507	114.62944	43.33535	67.78803
B Salt Comp	-	-	-	$LiF-ThF_4$ (77.5-22.5)	$NaCl-UCl_3$ (60-40)
B Feed	-	-	-	^{232}Th	0.711% ^{235}U
B Mass (MTIHM)	-	-	-	17.57098	133.76272
Fuel Cycle	U/Pu	U/Pu+Th/U	U/Pu	Th/U	U/Pu
Spectrum	Thermal	Fast	Fast	Fast	Fast

Large inventories create material accountancy challenges



Could fission product be directly used to detect signs of material loss?

- Soares et al.[1], considered the impact of nuclear data uncertainty on material loss detection
- If so, process monitoring might be able to provide real-time assurances for material accountancy
- Considered the Molten Salt Demonstration Reactor (MSDR) with continuous feeds and removals
- Analyzed largest isotopic changes under material loss and compared it to nuclear data uncertainty
  - Important to note this is the floor of measurement uncertainty that would be encountered in practice

[1] https://doi.org/10.1016/j.anucene.2023.109881

Even at 10SQ level losses, change in isotopics likely too small to detect

Nuclide	Atom density (atoms/barn-cm)		Rel. change	ND Unc.
	No diversion	10SQ		
^{89}Sr	1.0444×10^{-7}	1.0555×10^{-7}	1.06%	0.55%
^{142}Nd	4.0164×10^{-8}	4.0568×10^{-8}	1.00%	5.19%[a]
^{91}Y	1.6957×10^{-7}	1.7113×10^{-7}	0.92%	0.41%[a]
^{91}Sr	1.1793×10^{-9}	1.1900×10^{-9}	0.91%	0.42%
^{92}Sr	3.5560×10^{-10}	3.5830×10^{-10}	0.76%	0.50%
^{92}Y	4.7025×10^{-10}	4.7382×10^{-10}	0.76%	0.45%
^{93}Y	1.5104×10^{-9}	1.9850×10^{-9}	0.58%	0.35%
^{157}Gd	1.0522×10^{-9}	9.9431×10^{-10}	−5.51%	5.69%
^{113}Cd	7.0709×10^{-10}	6.7170×10^{-10}	−5.00%	3.24%[a]
^{155}Gd	1.7189×10^{-9}	1.6524×10^{-9}	−3.87%	23.01%
^{151}Eu	1.05498×10^{-9}	1.0095×10^{-9}	−3.84%	2.69%
^{149}Sm	3.4962×10^{-8}	3.3793×10^{-8}	−3.34%	1.93%
^{152}Eu	1.2780×10^{-9}	1.2419×10^{-9}	−2.82%	4.30%[a]

Could changes be detected if the ND uncertainty was improved?

- In practice, cross-sections can be calibrated to reduce uncertainty
- Kovacevic et al., used GADRAS to simulate gamma spectra from a computational MSDR model to consider the changes under material loss conditions [2]
- Similar to the previous work, a MSDR model with continuous feeds and removals were used as to model changes during a material loss
- GADRAS simulation ignored ND uncertainty, but did include Poisson statistics
    - Optimistic as in practice ND uncertainty will never be zero, but important exploratory work

[2] Gamma-ray Signatures for Identifying Plutonium Diversion in Molten Salt Reactors, JNMM 2023, vol 50

It is difficult to detect a 10SQ loss even neglecting ND uncertainty

Table 4: Uncertainty analysis of Compton-subtracted peak areas for the case of 10 SQ Pu removal sample of 1 Curie of activity, decayed 1.2 hours. Count time is 3600 seconds.

Peak channel energy, keV	Dominant Isotope	Total number of Counts in Peak	Number of Compton Subtracted Counts	Peak Area Uncertainty, %	Peak Area Difference, %
555.2	^{91m}Y	2,778,541	438,856	0.08	0.89
749.7	^{91}Sr	1,098,268	366,374	0.18	1.05
1023.8	^{91}Sr	1,053,473	132,823	0.13	0.83
1383.6	^{92}Sr	1,855,367	81,165	0.08	0.76
1835.9	^{88}Rb	45,349	16,287	1.06	1.15
2195.7	^{88}Kr	31,902	11,156	1.12	1.07
2483.4	^{84}Br	6,738	3,255	3.45	0.91
2569.8	^{89}Rb	7,382	2,152	2.10	1.08
2695.7	^{127}Sn	2,729	1,889	7.96	-0.62

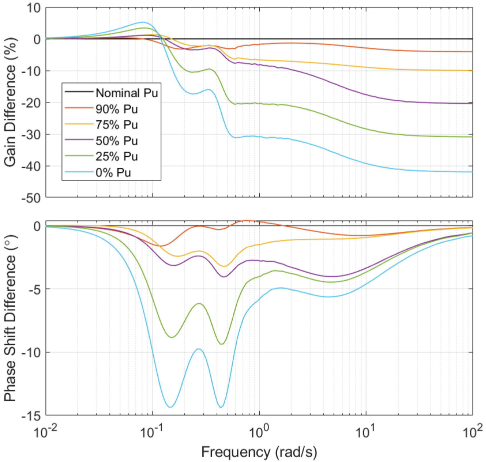
Could there be feedback in the reactor neutronics under loss conditions?

- Operator required measurements (e.g., reactivity, power, temperature, flows) might exhibit transient behavior under material loss
- Wheeler et al.[3], hypothesized that material loss in a LEU system would change the fission contribution ration between U and Pu
- The work considered a generic MSR system inspired by the Molten Salt Reactor Experiment (MSRE) and modeled precursor drift, delayed neutron fractions, resonance frequencies and material feeds and removals
- Frequency response to a sinusoidal reactivity insertion was considered

[3] https://doi.org/10.1016/j.anucene.2021.108370

Frequency response does exhibit a transient, but, it is dependent on total Pu inventory

Note: Pu inventory was on the order of 10s of kgs.

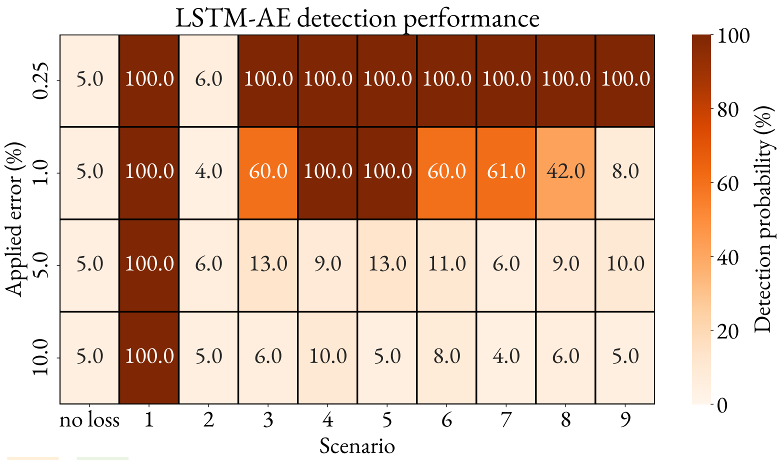


Could other process signals be indicators of material loss?

- Shoman considered [4] using flowrates and temperatures from a dynamic model of the MSDR to flag indicators of material loss
- These signals would already require operator monitoring and could have lower uncertainty than nuclear material measurements
- Modeled material losses in scale with feeds and removals
- Analyzed dynamic responses using both parametric and non-parametric models

[4]Forthcoming

Best model only detected losses at relatively low measurement uncertainties



Currently no technique to detect loss of significant quantity in liquid-fueled MSRs with large fissile inventory

- SEID alone, even with conservative uncertainty estimates, is multiple times larger than a significant quantity
- Few fission product indicators are available to detect large losses of material
  - This holds true even when only considering a single uncertainty source at a time (e.g., nuclear data uncertainty or counting statistics)
- Neutronics-based techniques could be viable for relatively large losses of material
- Other process signals (e.g., temperature and pressure) might be viable at 1% measurement uncertainty levels
  - Full study points out several limitations that would need to be resolved before a conclusive evaluation could be undertaken
- Performance-based approach might be more effective for large, liquid-fueled MSRs
  - Consideration of radioactivity of fuel, fissile density, accessibility of area, etc.

Acknowledgements

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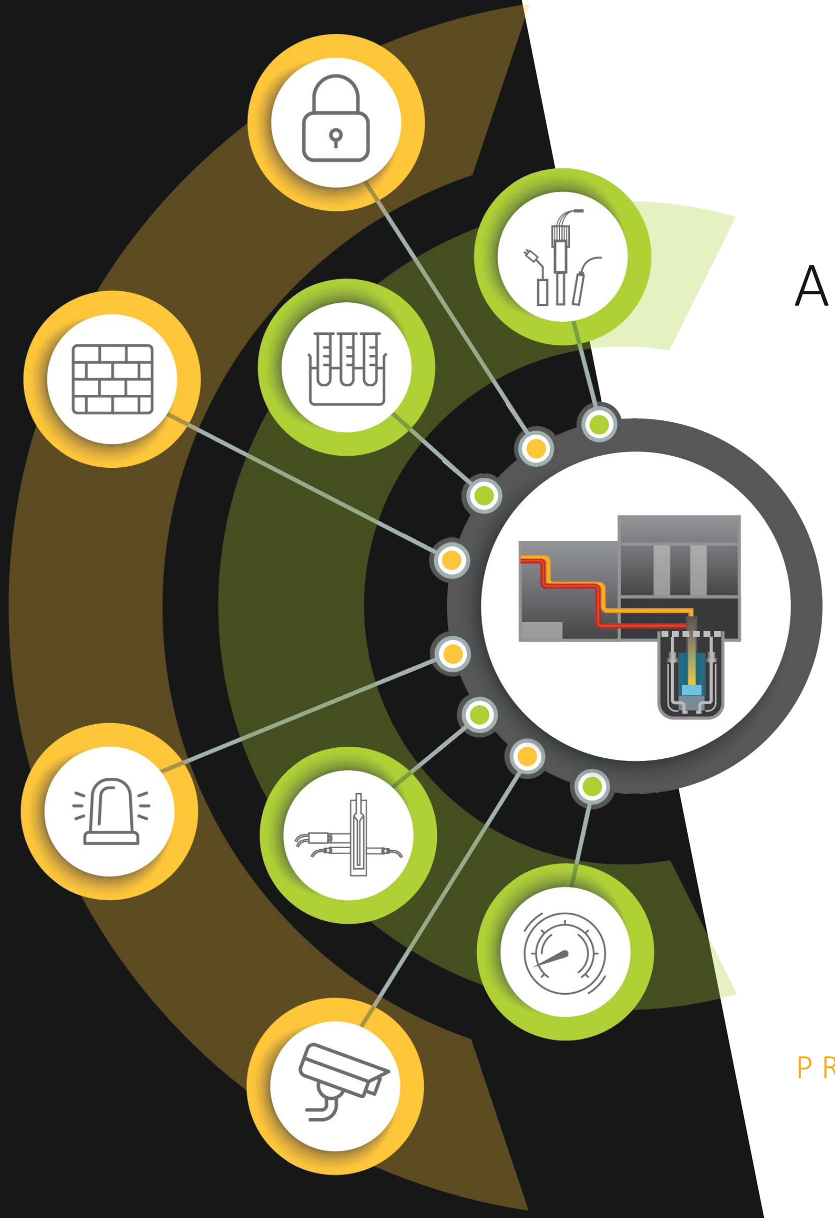


ADVANCED REACTOR SAFEGUARDS

Material Control and Accountancy for US NRC License Applications for a Liquid-Fueled MSR

PRESENTED BY Karen Koop Hogue, ORNL

Nicholas Luciano, Matthew Krupcale, Rabab Elzohery

November 2, 2023

U.S. DEPARTMENT OF ENERGY

Introduction

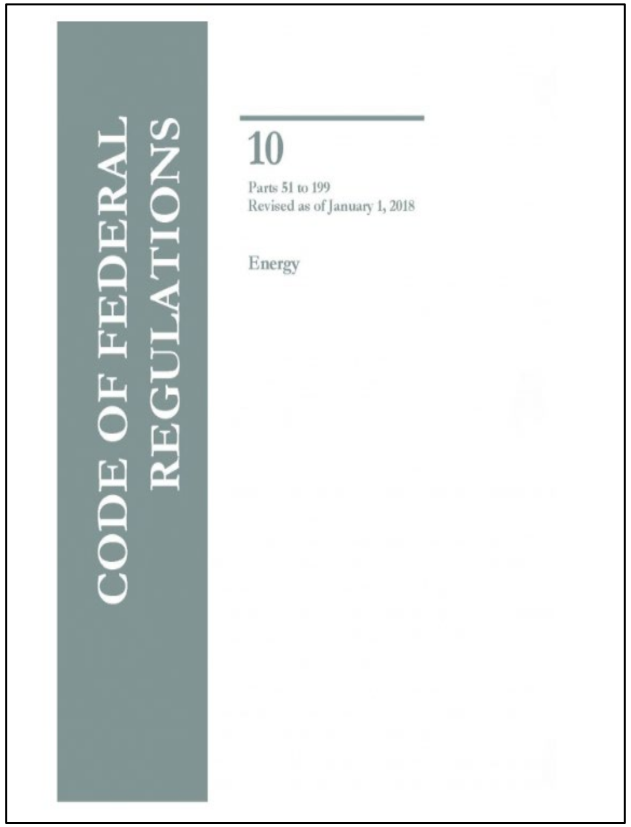
BLUF: We recommend a general MC&A approach that divides the MSR facility into three MBAs, with item accounting on the front- and back-ends and diversion monitoring while the SNM is in difficult to access areas.

Definition: MC&A is a system of material control measures and material accounting measures to prevent, deter, and detect theft or loss of SNM (U enriched in ^{235}U, Pu, ^{233}U).

- Outline
  - NRC Licensing Context for MSRs
  - Our Recommended Approach for MC&A of MSRs
  - Performance Based Regulation and Diversion Path Analysis
  - Conceptual Implementation of MC&A

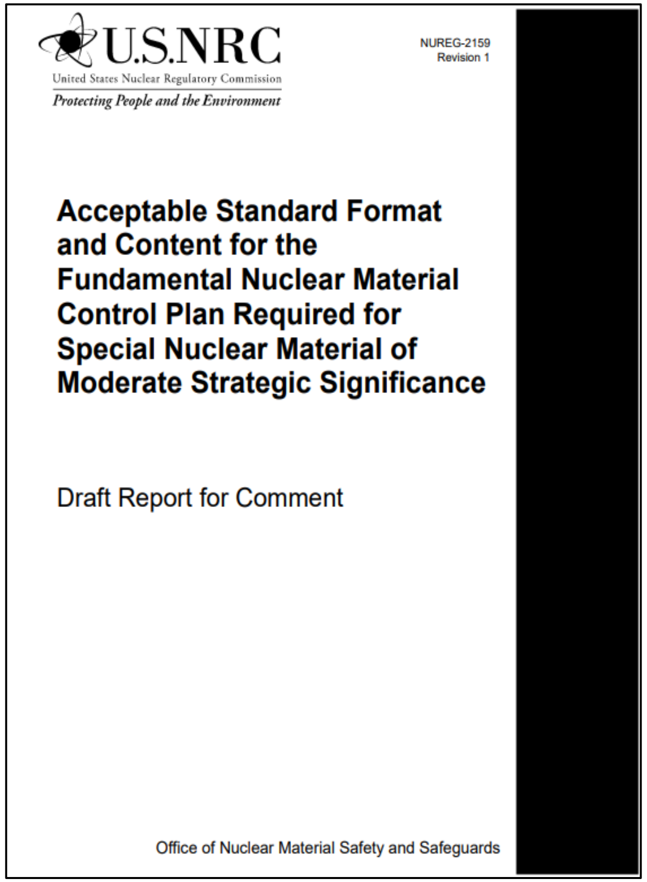
NRC Licensing for Conventional LWRs

- License applicants for conventional LWRs do not submit a Fundamental Nuclear Material Control (FNMC) plan
  - Exclusion in 10 CFR part 74 for *Utilization Facilities* licensed under 10 CFR part 50.
- LWR assemblies are large, heavy, items with incapacitating dose rates (post-irradiation)
  - Many theft scenarios are not highly credible
- Fresh fuel assemblies are inventoried, loaded into the reactor, and sealed for years, then offloaded to a pool.
  - Used fuel assemblies are inventoried (counted).
  - Once offloaded, SNM is “put on the books” using quantities using computational models.



NRC Licensing Context for MSRs

- Fuel fabrication and enrichment facilities **do** submit FNMC plans
  - Bulk facilities with SNM in powder or gaseous form.
  - No transmutation, depletion, and only limited losses due to decay
- MSRs are bulk facilities and will very likely need to develop, submit, and implement FNMC plans
  - No current plans for NRC to develop a modified approach for MSRs
  - No current FNMC template for MSRs


U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

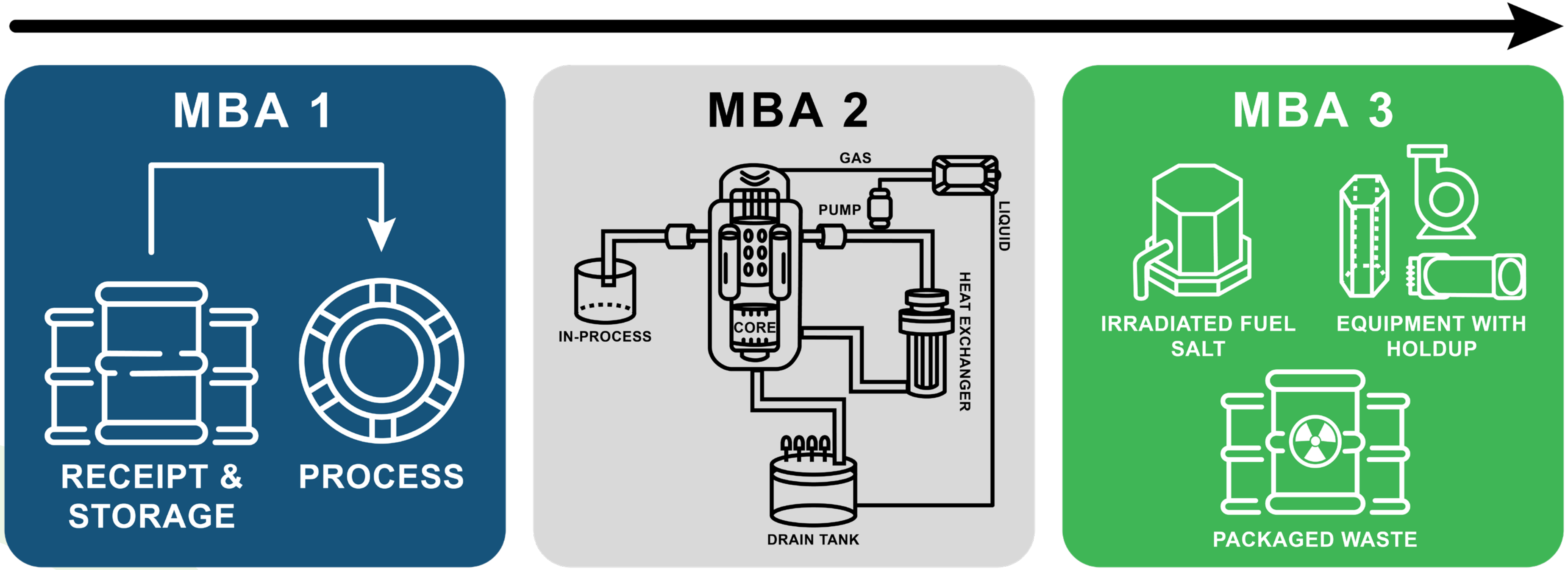
NUREG-2159
Revision 1

Acceptable Standard Format and Content for the Fundamental Nuclear Material Control Plan Required for Special Nuclear Material of Moderate Strategic Significance

Draft Report for Comment

Office of Nuclear Material Safety and Safeguards

Recommended MC&A Approach



Periodic inventories performed, IDs and SEIDs calculated
(follows Part 74 requirements)

Monitoring performed to detect diversion

Periodic inventories performed, IDs and SEIDs calculated
(follows Part 74 requirements)

Process Monitoring Would Be Difficult

- Alternative Approach: treat a liquid-fueled MSR like any other bulk facility and apply 10 CFR Part 74 requirements
  - MSRs aren't the same as fuel fab or enrichment facilities;
    - SNM in process is **highly radioactive** material and not accessible
  - **Inconsistent** with NRC's approach for other reactors
  - Likely **not attainable** with current technologies
    - Thought experiment – consider all parameters necessary to monitor
    - Uncertainties (measurement precision, nuclear data,…) and biases (sensor drift, hold-up,…)
    - If expected and measured don't agree for inventory, NRC notified of "loss or theft"
  - Full process monitoring would be **expensive** to implement, even if possible
  - High level of resources devoted to MC&A is **not necessary** to prevent or detect diversion

Measuring Inputs & Outputs are not enough

- Alternative Option: Only look at material transferred between MBAs (inputs & outputs)
  - SNM in MSRs is not in large, heavy countable items
  - Fuel is not stationary and sealed in one location
  - Sampling ports, etc. are possible pathways for material diversion
  - Timely detection of material loss or theft unlikely
  - Would not achieve the purpose of MC&A

Performance-Based Regulation

"A regulatory approach that focuses on **desired, measurable outcomes, rather than prescriptive processes, techniques, or procedures**. Performance-based regulation leads to defined results without specific direction regarding how those results are to be obtained. At the NRC, performance-based regulatory actions focus on identifying performance measures that ensure an adequate safety margin and offer incentives for licensees to improve safety without formal regulatory intervention by the agency."

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

	Safety	Physical Security	*MC&A*
Tools	Probabilistic Risk Assessment	Design Basis Threat	*Diversion Path Analysis?*

Already in use by the NRC (Safety, Physical Security)

Proposed by ORNL (MC&A)

Diversion Path Analysis

Purpose

- Identify potential pathways SNM might be diverted in each process stream by assessing:
  - Approximate quantities of SNM that could be diverted
  - Technical difficulty
  - Indicators of diversion

Methodology

- Held 3 separate 4-hour brainstorming workshops (in a classified environment)
- ORNL team included SMEs in nuclear engineering, mechanical engineering, chemistry, and safeguards; all familiar with MSRs

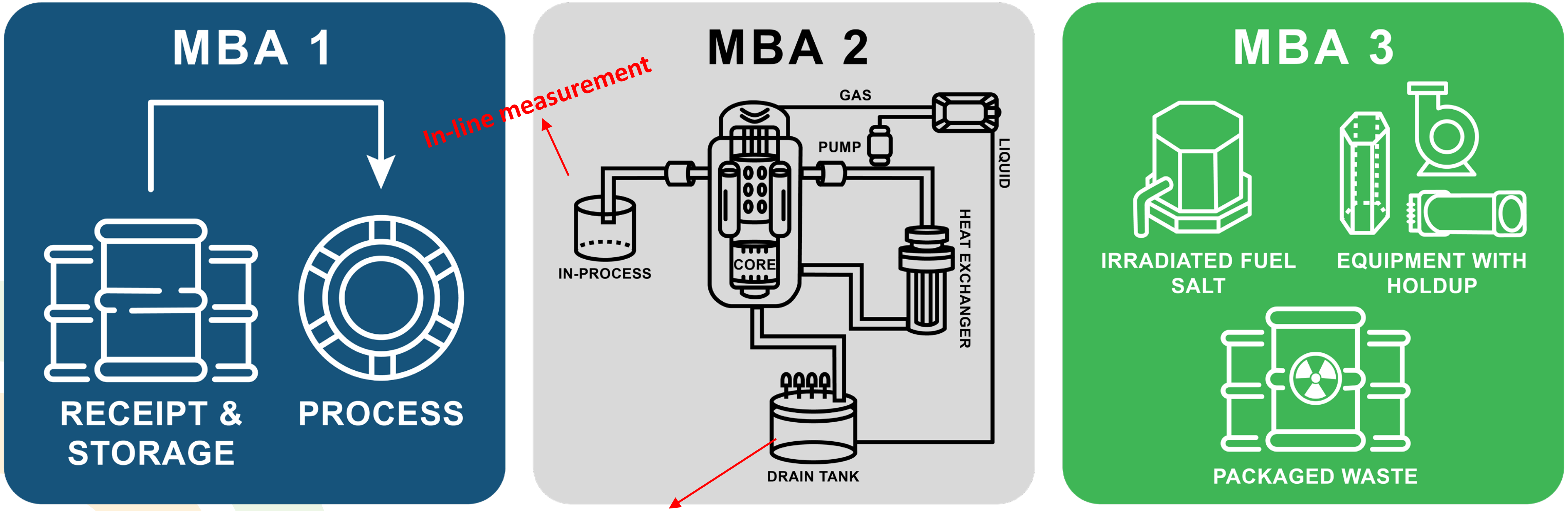
Outcomes

- List of MC&A technical objectives that need to be achieved by MC&A plan
  - E.g., Detect diversion of SNM in containers of fresh fuel salt in storage (or salt components like UCl_3), Quantify SNM in used filters from the off-gas system

Conceptual Implementation of MC&A

- Gross net weight of containers and transfer tanks
- Gamma spectroscopy on outside of containers
- Verifying TIDs on containers

- Gross net weight of any containers and tanks
- NDA measurements on outside of containers
- NDA measurements to quantify residual material
- TID verification on containers



- Gross net weight of containers upon receipt
- Verification of serial numbers, TIDs

- Gross net weight of tank
- Sample line with mass spec. analysis or in-tank measurements

- Gross net weight of containers prior to shipment
- Verification of serial numbers, TIDs

Note: this is conceptual draft of proposed MC&A elements.

Conclusions and Future Work

- We recommend a general MC&A approach that divides the MSR facility into three MBAs, with item accounting on the front- and back-ends and diversion monitoring while the SNM is in process.
  - Satisfies the goals of MC&A without process monitoring and ensures diversion pathways are analyzed and monitored
  - Consistent with conventional LWR and bulk facility MC&A
- Future work will include methods to:
  - Quantify hold-up in used equipment
  - Practical containment and surveillance
  - Quantifying SNM in fresh fuel in pipes and tanks

References

DOE ARSS Website

Material Control and Accounting Approaches for Molten Salt Reactors

- Material Accountancy for Molten Salt Reactors: Challenges and Opportunities
- Domestic MC&A Recommendations for Liquid-Fueled MSRs
- Limitations of Overall Measurement Error for Molten Salt Reactors
- Assessment of Flow-Enhanced Sensors for Actinide Quantification in MSRs
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Thank You

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Oak Ridge National Laboratory

An Example of Data-Driven Safeguards and Security by Design

Karen Koop Hogue, PhD, ORNL

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Peter Sobel, PhD, ORNL
Steve Skutnik, PhD, ORNL
Mathew Swinney, PhD, ORNL

Safeguards and Security by Design is: **A PRIORITY**

> New reactor types, especially small modular reactors, or SMRs, and advanced reactors… will also require new safeguards and security approaches. With advanced reactors in the early stages of development, there is an opportunity for governments, regulators, and the nuclear industry to work together not only to strengthen safety features, but also security and safeguards features of nuclear reactors and their associated fuel cycle facilities.

-Jill Hruby
National Nuclear Security Administrator

Safeguards and Security by Design is: **A PRIORITY**

"The International Atomic Energy Agency (IAEA) and the Department of Energy (DOE) should identify the funding, personnel, regulatory analyses, and key technology gaps for pilot programs in international safeguards for advanced reactors."

- National Academies
Laying the Foundation for New and Advanced Nuclear Reactors in the U.S.

Safeguard and Security by Design is: **CHALLENGING**

What is required

What exists

What developers would like

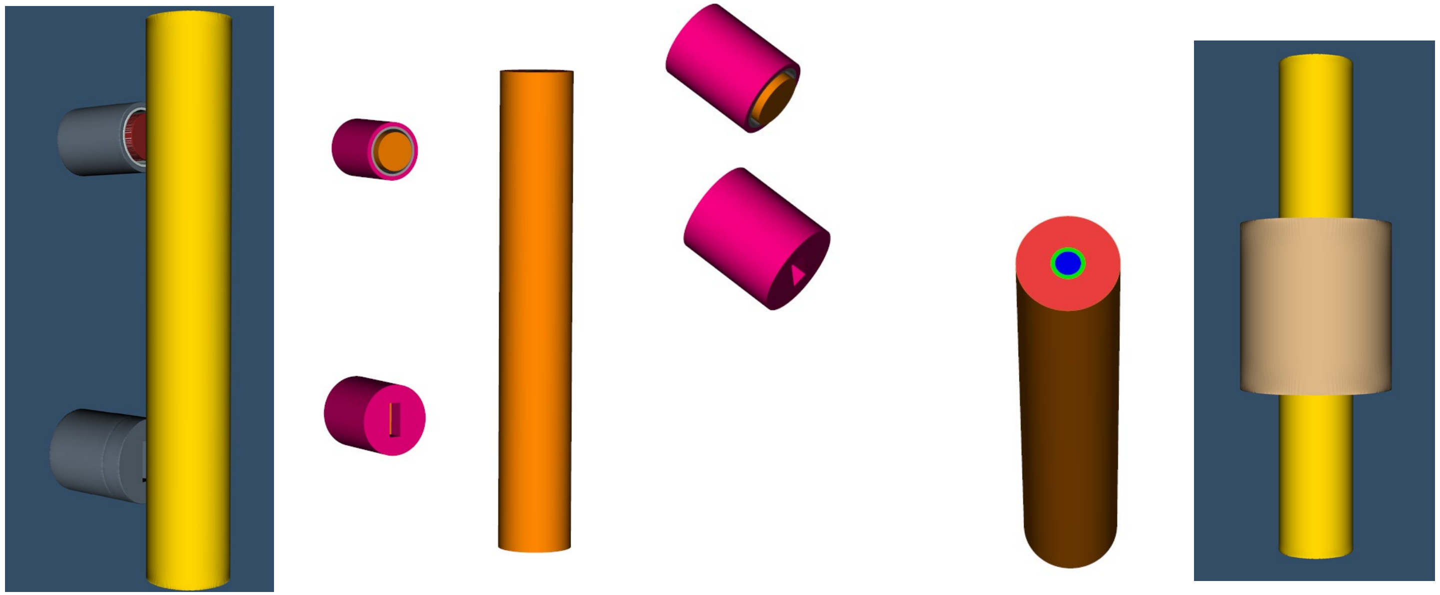
Safeguards and Security by Design:
MY APPROACH

Start by defining the objective(s)

- Define nuclear material control and accountancy objectives across a prospective liquid-fueled MSR facility, e.g.
  - Quantify nuclear material as it enters “difficult to access areas”
  - Detect nuclear material on used filters removed from off-gas system
- Identify which I felt was the most pressing R&D need
  - Nearest-term challenge
  - Gap in current technologies
  - Importance to safeguards and security

CASE STUDY: Exploring in situ feed monitoring

- Are there signatures to quantify, or monitor, nuclear material in fuel salt feed that can be measured from the outside of piping?



PARAMETRIC STUDY: MSR Design

Parameter	Options	Reference
Salt	FLiBe-based *$LiF-BeF_2-UF_4-ZrF_4$ (65-29.1-0.9-5 mol%)* Cl-based *$NaCl-UCl_3$ (66-34 mol%)*	MSRE MCFR
^{235}U Enrichment (wt%)	NU 2 5 19.75	MCFR makeup salt? ThorCon, IMSR ThorCon, IMSR MCFR, Seaborg, MSRR
Pipe material	Hastelloy N Inconel 625	MSRE, ORNL-TM-0728 MCRE?
Pipe OD (in)	12 8 2 1	 TerraPower IET ORNL molten salt test loops
Pipe thickness (in)	1 0.25 0.1	ORNL molten salt test loops

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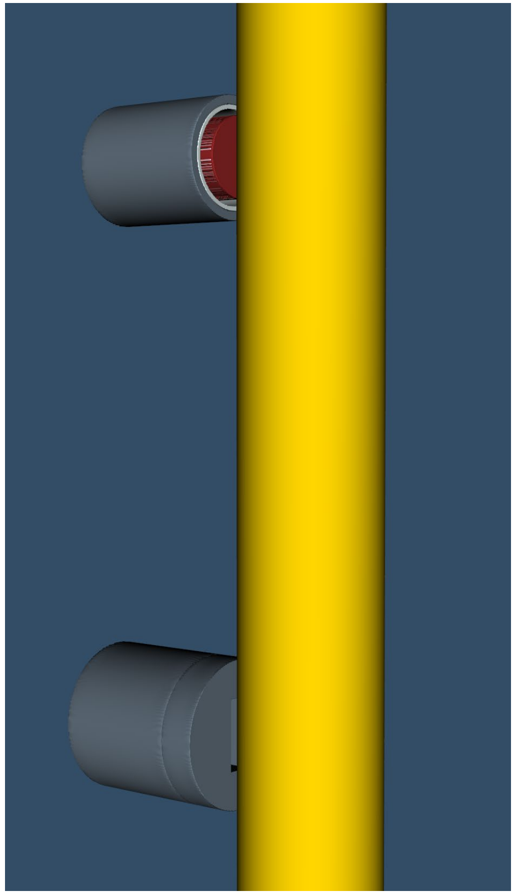
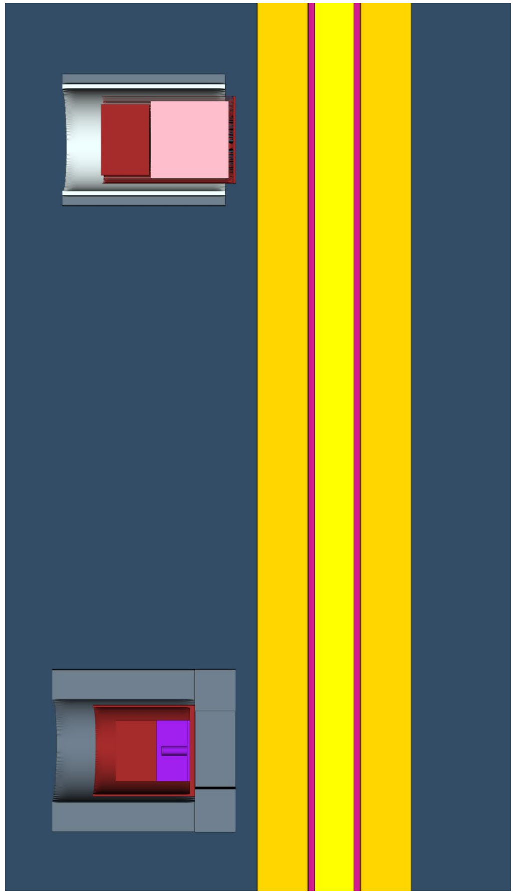
PARAMETRIC STUDY: Detectors

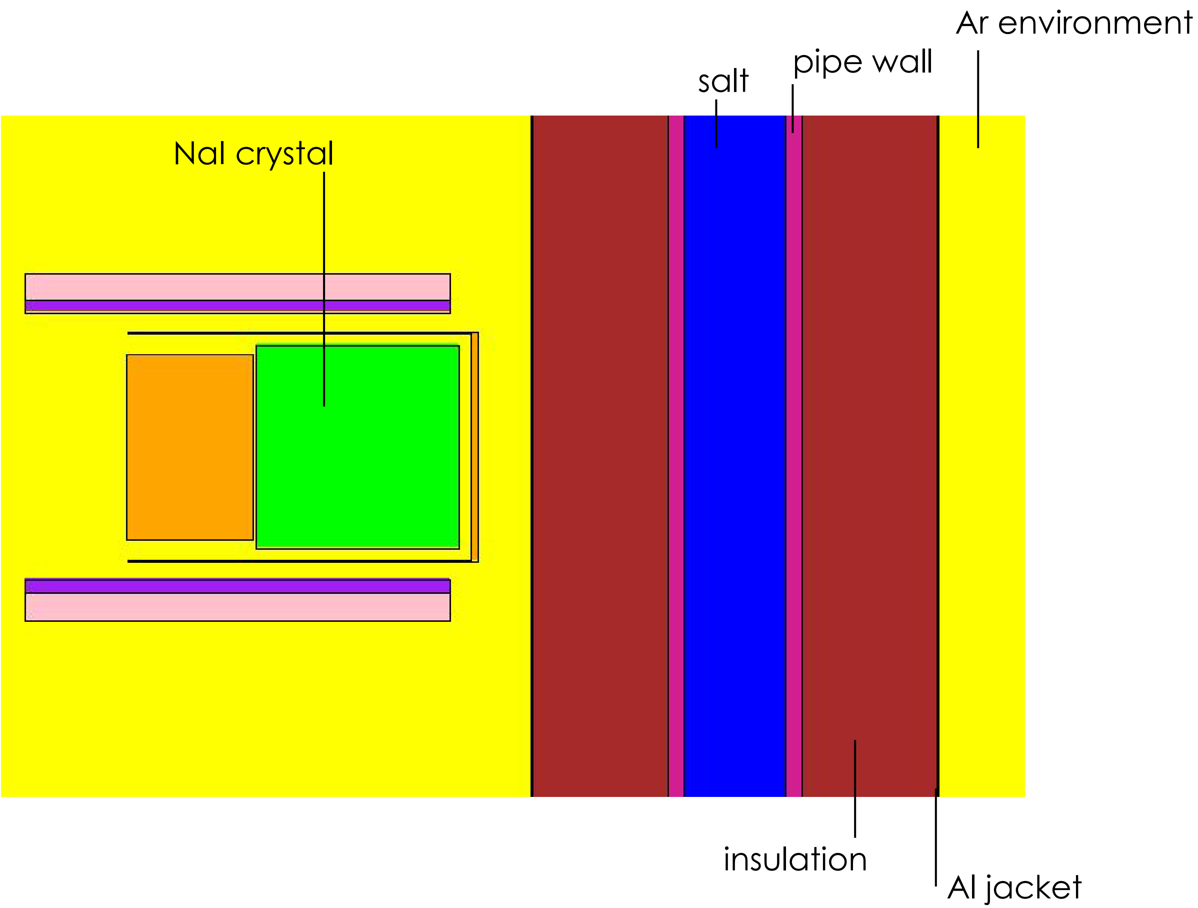
Detector	Reference	Reference
gamma: NaI	continuous enrichment monitor (CEMO)	3 in. diameter, 3 in. height NaI crystal W collimator, Fe lined
gamma: HPGe	cascade header enrichment monitor (CHEM)	6 cm diameter, 3 cm height coaxial Ge crystal W collimator with slit
passive neutron	active well coincidence counter (AWCC)	full collar detector two rows of ^{3}He tubes in HDPE
active neutron with AmLi interrogation	active well coincidence counter (AWCC)	half collar detector- two rows of ^{3}He tubes in HDPE AmLi source next to pipe

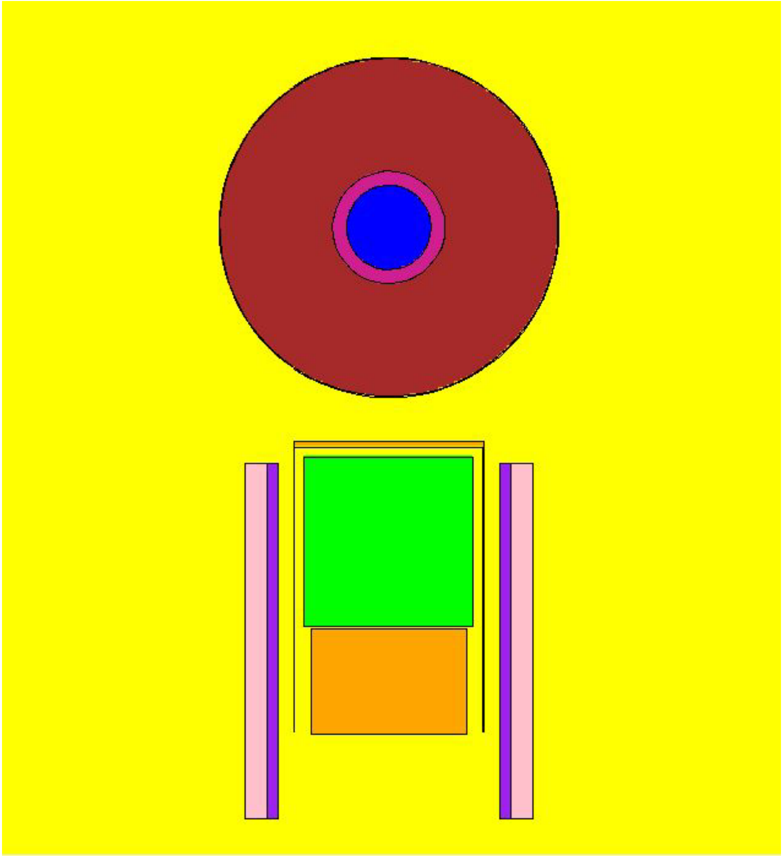
Gamma detectors



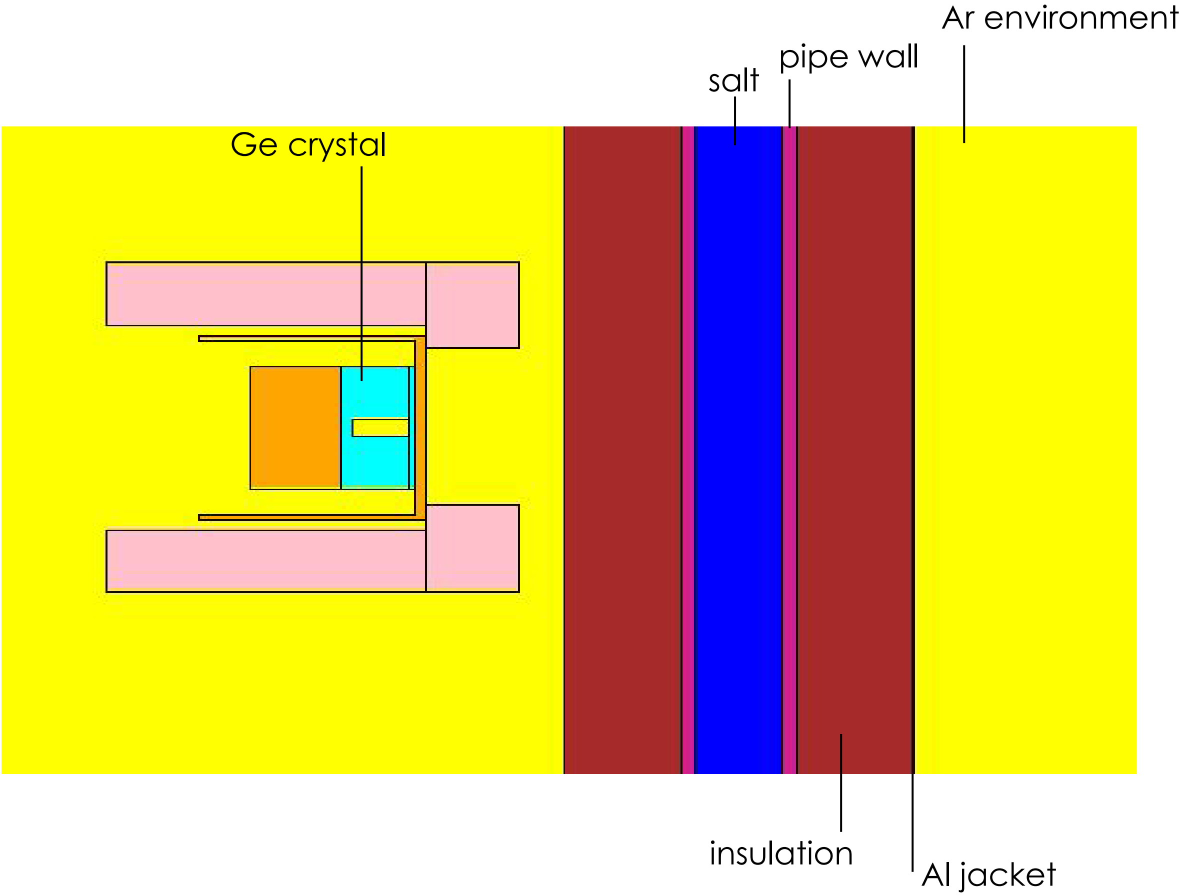


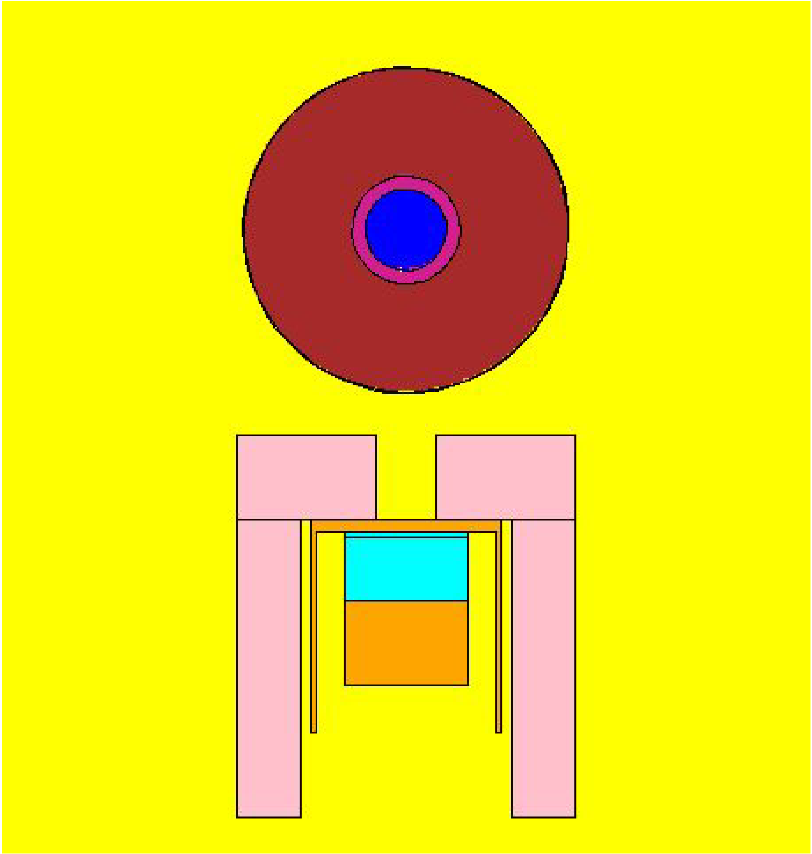
NaI detector



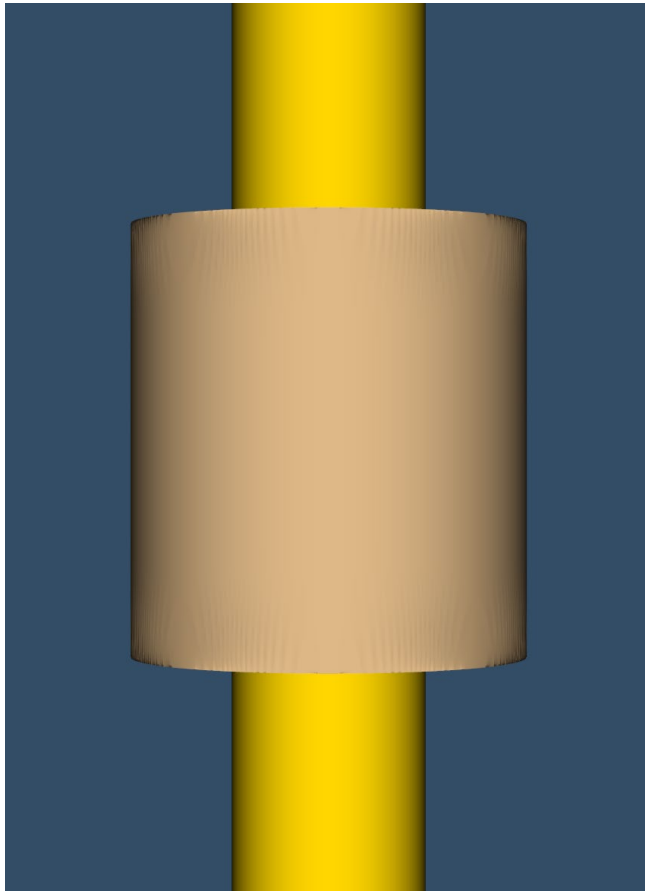


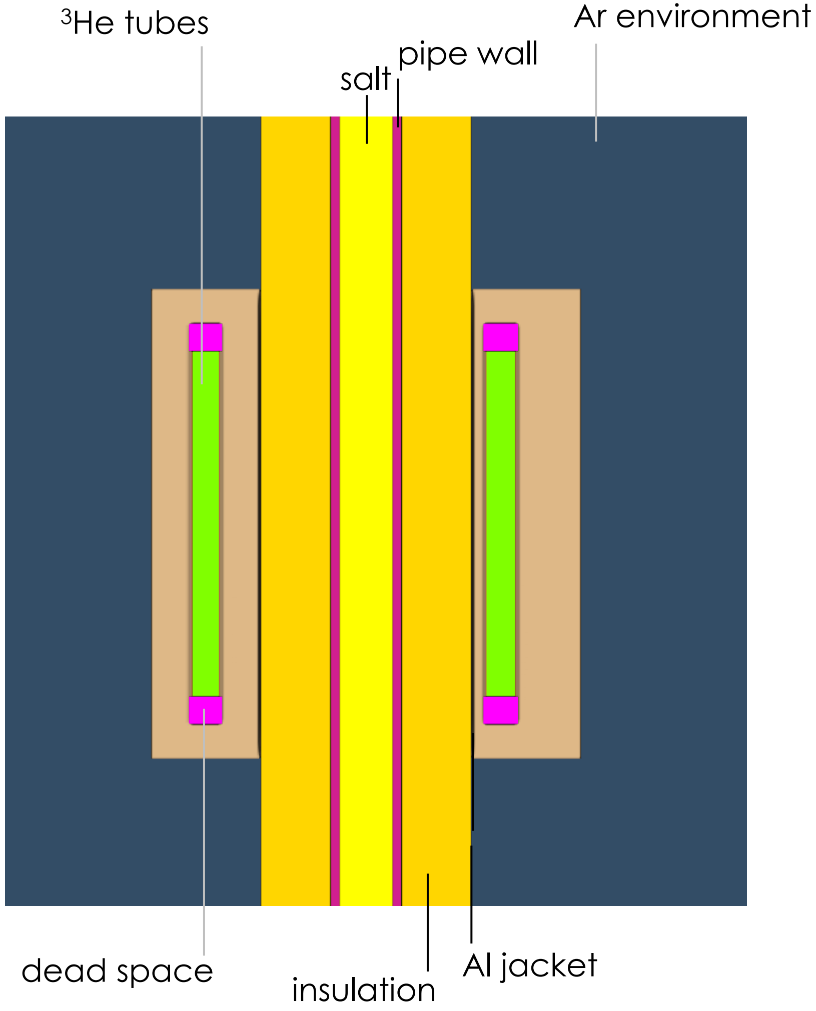
HPGe detector

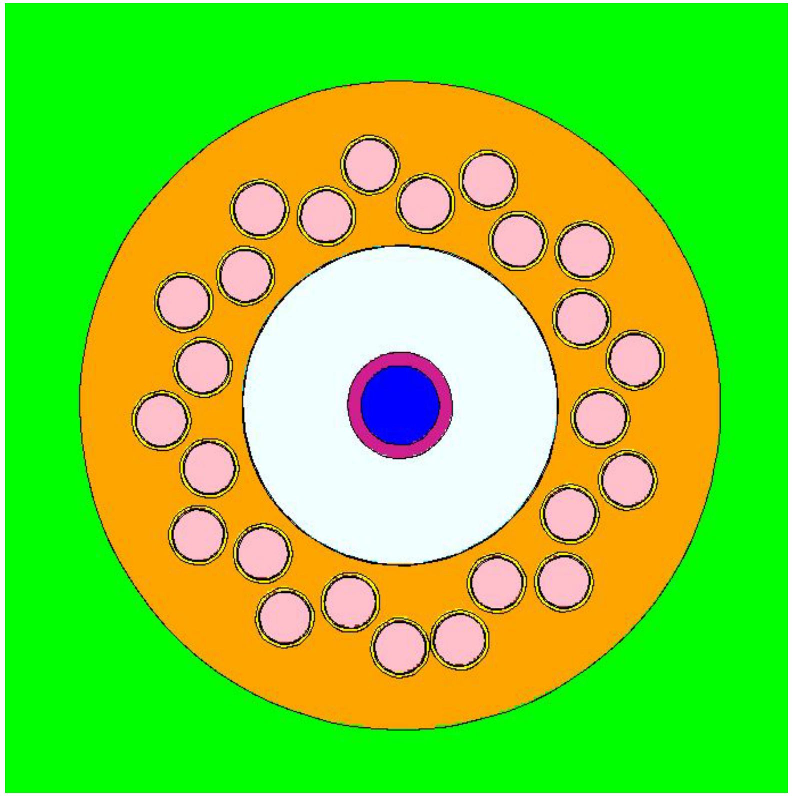




^{3}He neutron collar







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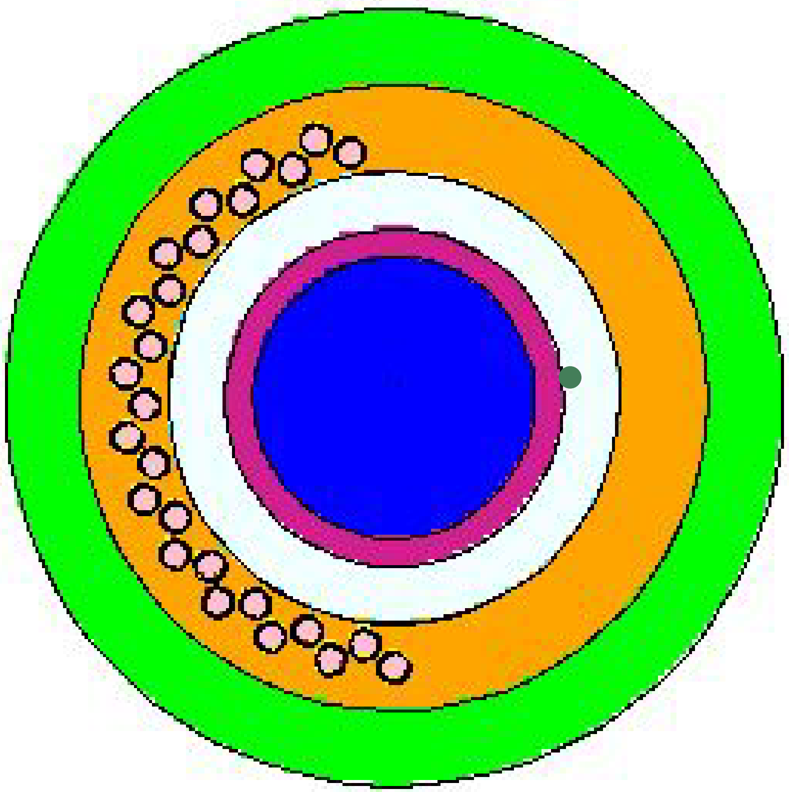
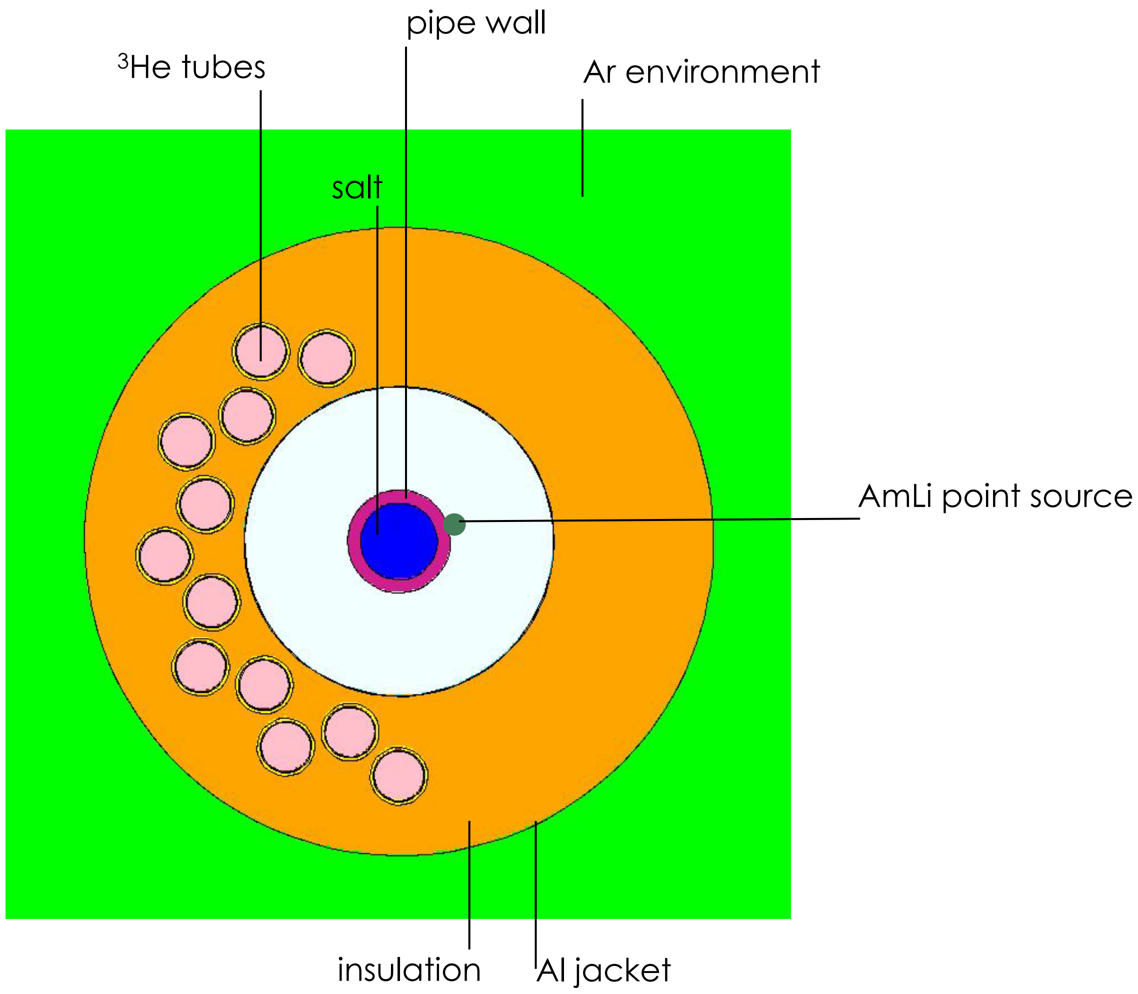
^{3}He neutron half-collar





Summary of findings

	Method	Information gained	F salt feasibility	Cl salt feasibility
γ	186 keV photopeak	m_{235_U} in visible volume	all E, D, all t	HALEU(except large D), 5%, 2%(in Hast)
	1001 keV photopeak	m_{238_U} in visible volume	2%, HALEU(large D)	NU, some HALEU
	186 keV/1001 keV	E	2%, HALEU(large D)	some HALEU
n	Passive: total n	m_{234_U} in visible volume	HALEU	HALEU(large D)
	Passive: coincidence	m_{235_U} in visible volume	HALEU(large D)	HALEU(very large D)
	Active: coincidence	m_{235_U} in visible volume	HALEU(very large D, small t)	HALEU(very large D, small t)

Conclusions

- Penetrating radiation can be a useful signature for both safeguards and security to **quantify** and **monitor** unirradiated fuel salt entering an MSR
- Gamma and neutron detectors can be placed outside of insulation
  - Allows for typical detector materials to be used
- No detection system analyzed works for all potential MSR designs, but HPGe detectors and passive total neutron counting work for most
- Design decisions impact feasibility of instrumentation
  - salt chemical composition, pipe diameter, pipe material, ^{235}U enrichment

Conclusions

- Goal is to drive security regulations and safeguards-by-design best practices toward technical recommendations
- Requires early engagement – when designs can still be changed
- Define the safeguards or security objective first
- Leverage modeling and simulation in an iterative process to assess impact of design choices on safeguards and security and vice versa

CURRENT WORK

FEED MONITORING:
considerations for measurement options

Methodology for selecting a potential monitoring system for additional R&D

1. Define the safeguards technical goals across process streams in a liquid-fueled MSR.
2. Identify potential key measurement points to meet these goals. Define the measurement environment at each point.
3. Consider all instruments and measurement techniques that could be implemented to meet each goal.
4. Survey each instrument/technique using standardized safeguards-relevant metrics (figures of merit).

Example figures of merit

Capital equipment cost

Measurement time to achieve reasonable uncertainty

Reasonably achievable uncertainty

Operator burden

Maintenance intensity

Reliability

QUESTIONS?

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Molten Chloride Reactor Experiment

ARDP Risk Reduction

ORNL MSR Workshop
October 2023

Dan Walter, PhD
MCRE Project Engineer

Subject to DOE Cooperative Agreement No. DE-NE0009045

Agenda

I. Project Status
II. Safety
III. Site & Plant Layout
IV. Reactor Design
V. Fuel Handling Design
VI. Testing

MCRE Mission Statement

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).

Objective 1 Safely **achieve criticality** with the first fast spectrum molten salt fueled reactor

Objective 2 Experimentally determine **reactor physics and kinetics parameters** to reduce uncertainty and gather data

Objective 3 Demonstrate the **fuel** loading, fuel salt sampling/analysis, offloading, and general **handling strategy** for chloride fuel salt

Objective 4 Initiate development of industry **supply chain** for key molten salt components operated in a high temperature and radioactive environment

Objective 5 Collect operational/testing data to lay foundation for an operating license for MCFR-D under a risk-informed performance-based **(RIPB) licensing framework**

21 Reactor Experiments Planned

Criticality	1	**Approach to Criticality (~650℃)**
Reactor Characterization	2	Determination of Reaction Rates of Fissionable Materials via Wire/Foil Irradiation
	3	Determination of the Neutron Spectrum via Wire/Foil Irradiation
	4	Measurement of the Gamma Flux outside the Neutron Reflector
	5	Differential and Integral Control Rod Worth with no Forced Flow
	6	Differential and Integral Control Rod Worth at Multiple Flowing States
	7	Differential Control Rod Worth at Multiple Fuel Salt Temperatures
	8	Determination of the Dynamic Reactivity Response during Pump Startup
	9	Determination of the Dynamic Reactivity Response during Pump Coastdown
	10	Isothermal Temperature Coefficient
Neutron Kinetics	11	β_{eff} Determination with no Forced Flow
	12	β_{eff} Determination at Multiple Flow Rates
	13	Kinetics Measurements using Alpha (Prompt Neutron Decay Constant) Measurement Techniques
	14	Kinetics Measurements using Noise Analysis
	15	Periodic Perturbations for Stability Analyses
Reactivity Feedback	16	Dynamic Response to Reactivity Insertions
	17	Demonstration of the Load Following Response
	18	Dynamic Reactivity Response during Pump Startup and Coastdown with Thermal Feedback
	19	Dynamic Reactivity Experiments via Rapid Step Control Element Insertions
	20	Unprotected Loss of Forced Flow
	21	Demonstration of the Transition to Low Power Critical

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TerraPower

MCRE is in Preliminary Design Phase and focused on construction of a non-nuclear Mockup at TerraPower's Everett, WA Lab

2020 | 2021 | 2022 | 2023 | 2024

Conceptual Design

Preliminary Design

MCRE Mockup

Construction

Salt Ops

Operator Training

- Safety Design Strategy (SDS) submitted to DOE
- Conceptual Design Safety Report (CSDR) submitted to DOE
- Preliminary Document Safety Analysis (PDSA) planned to be submitted to DOE

Mockup Objectives

1. Confirm engineering design
2. Validate thermal-fluid models
3. Inform operational procedures
4. Support INL field operator training
5. Support INL Operational Readiness Review (ORR)

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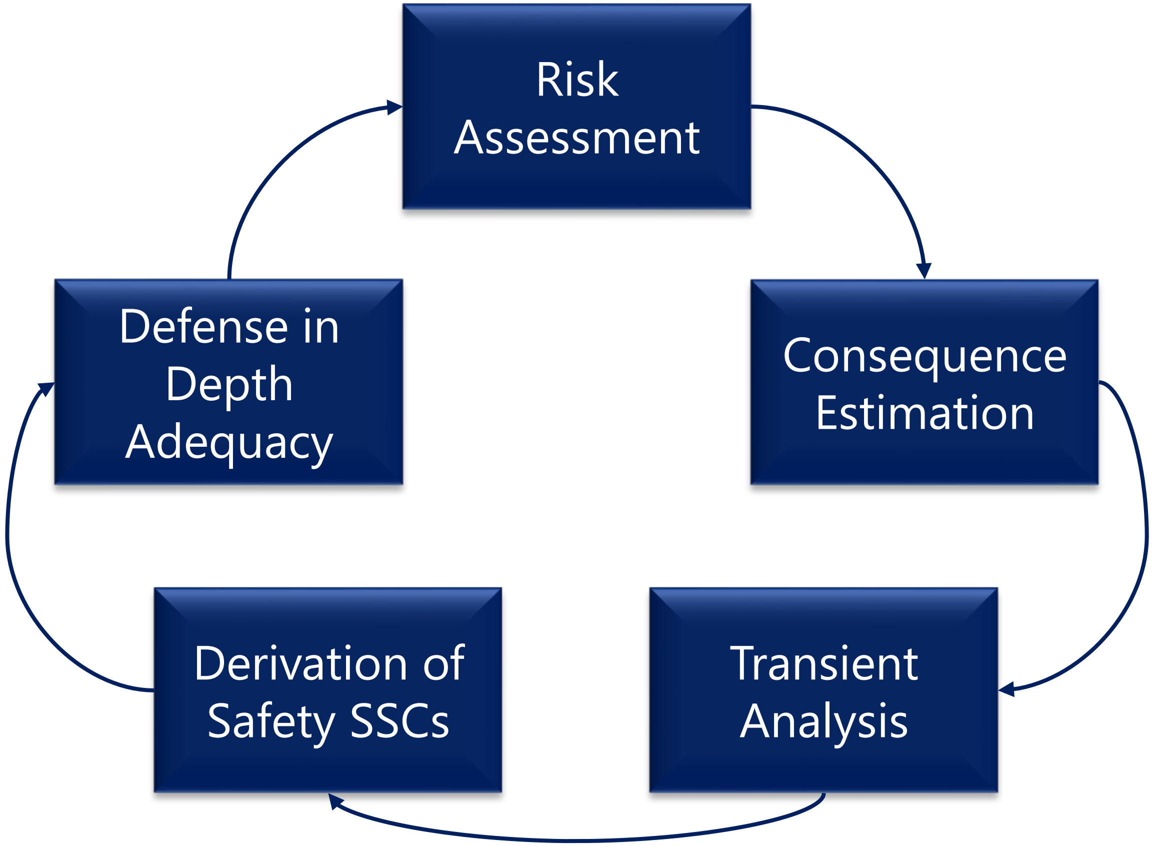
Nuclear Safety

Subject to DOE Cooperative Agreement No. DE-NE0009045

Reactor Safety Philosophy

- Built around satisfying 4 Fundamental Safety Functions
  1. Control of heat generation
  2. Control of heat removal
  3. Retention of radionuclides
  4. Shielding* (project decision to add for worker protection)

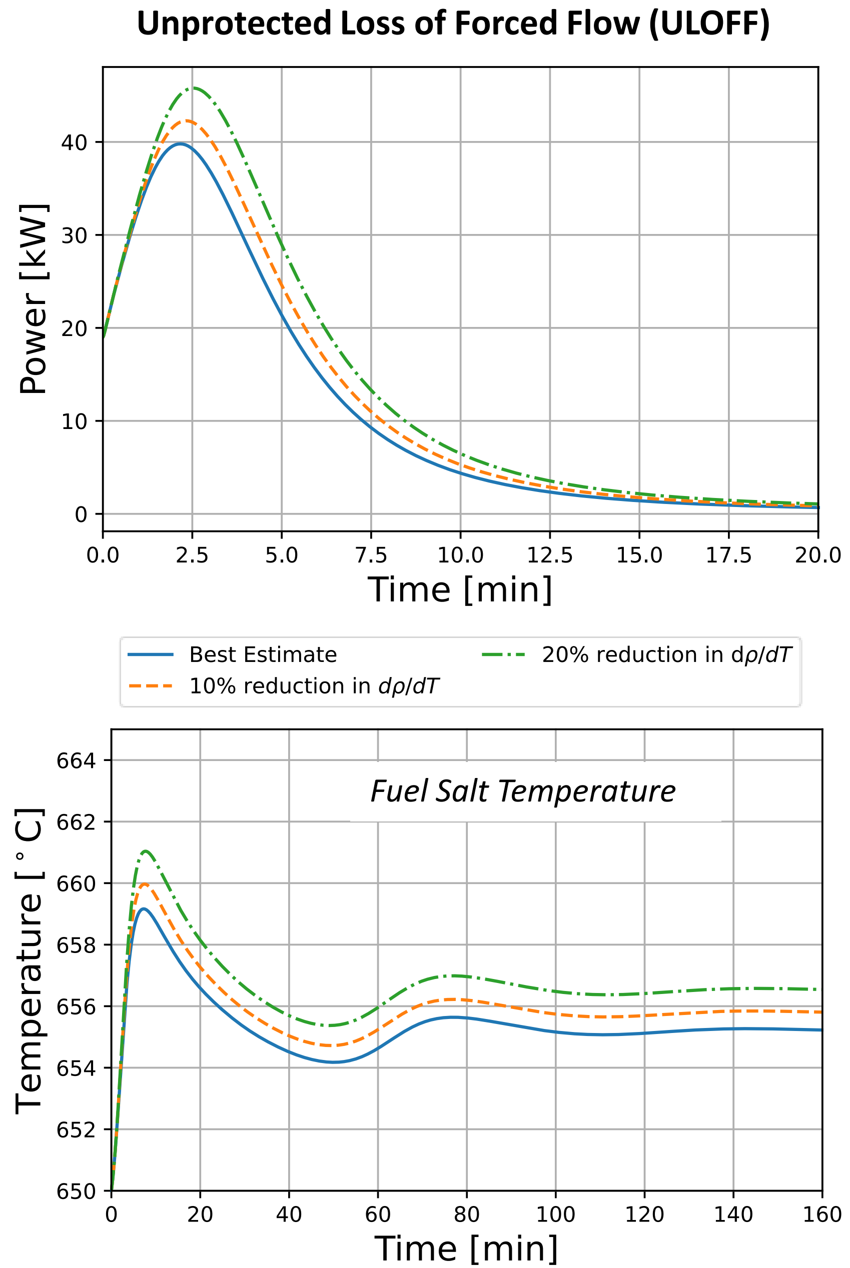
- Utilizing the LMP methodology Described in NEI 18-04 to develop a RIPB safety case
- Integration of safety in the design
  - Consideration of both safety and experimental requirements
  - Coordination with operations to ensure experiments can be conducted safely



<u>First time for a liquid-fueled MSR</u>
The TP, SCS, INL Safety Team has completed a *full cycle* of the RIPB approach to systematically investigate the safety of MCRE and continuously integrate safety into the design

One full *cycle* of the risk-informed licensing process completed

- Probabilistic Risk Assessment (PRA) derive Safety Basis Events (SBE)
  - 17 SBEs evaluated explicitly – **all remain under the 700°C design temperature**
- Dose consequence compared with likelihood of events
  - To determine Frequency-Consequence plots
- All used to derive Structures, Systems, Components (SSC) Classification and show Defense in Depth (DID) adequacy
- Safety Design Integration Team (INL + SO + TP) convened to agree on SSC Classification proposed
- Conceptual Safety Design Report (CSDR) was submitted to DOE June 2023



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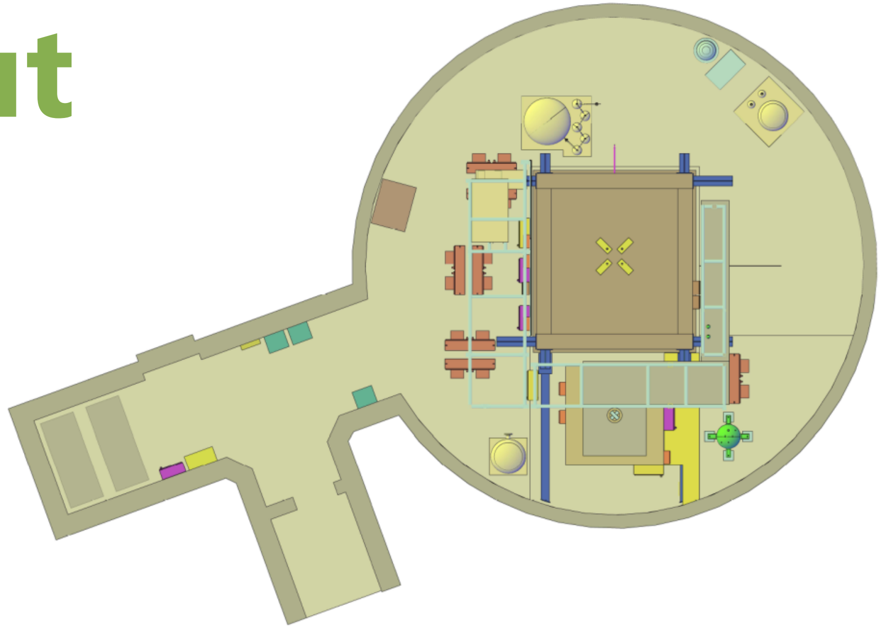
Site & Plant Layout



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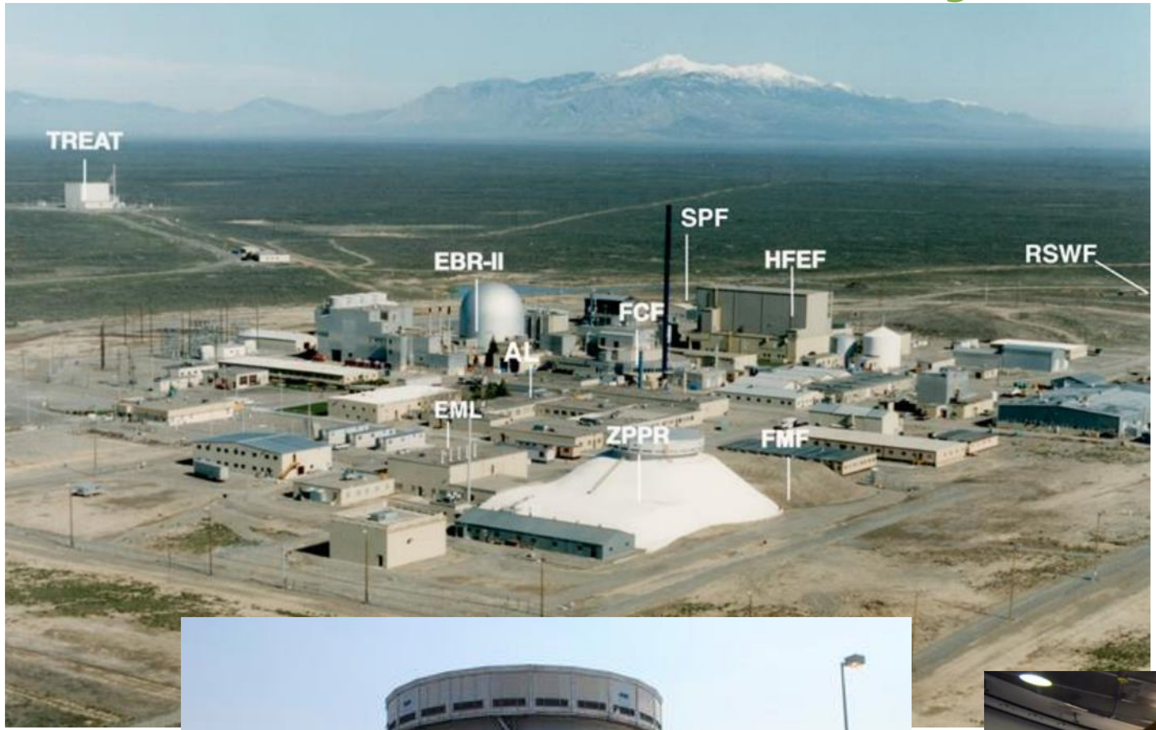
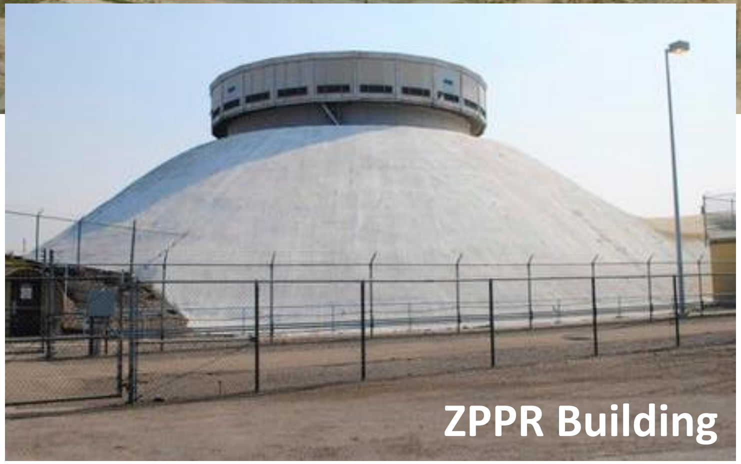
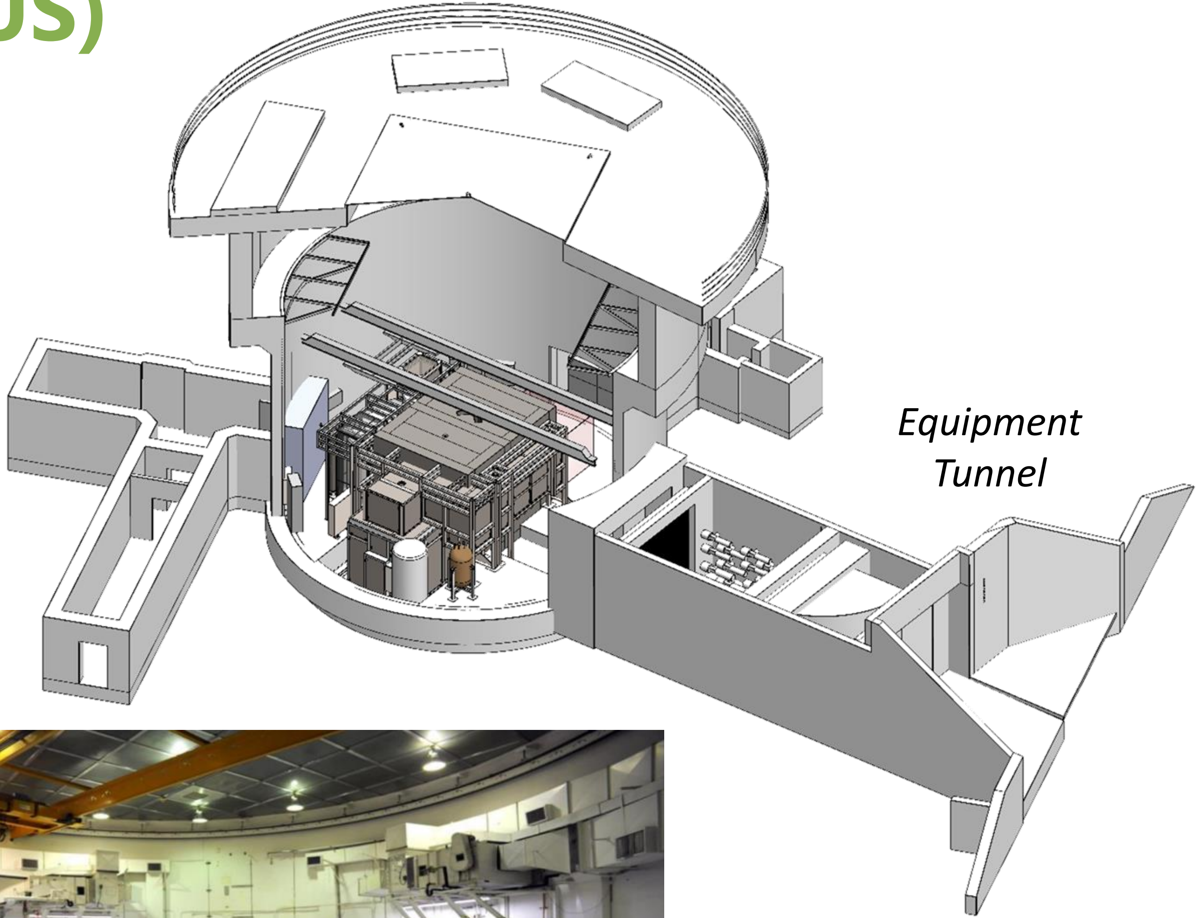
MCRE is planned to be DOE Authorized at INL ZPPR Cell/Facility (LOTUS)





ZPPR Building

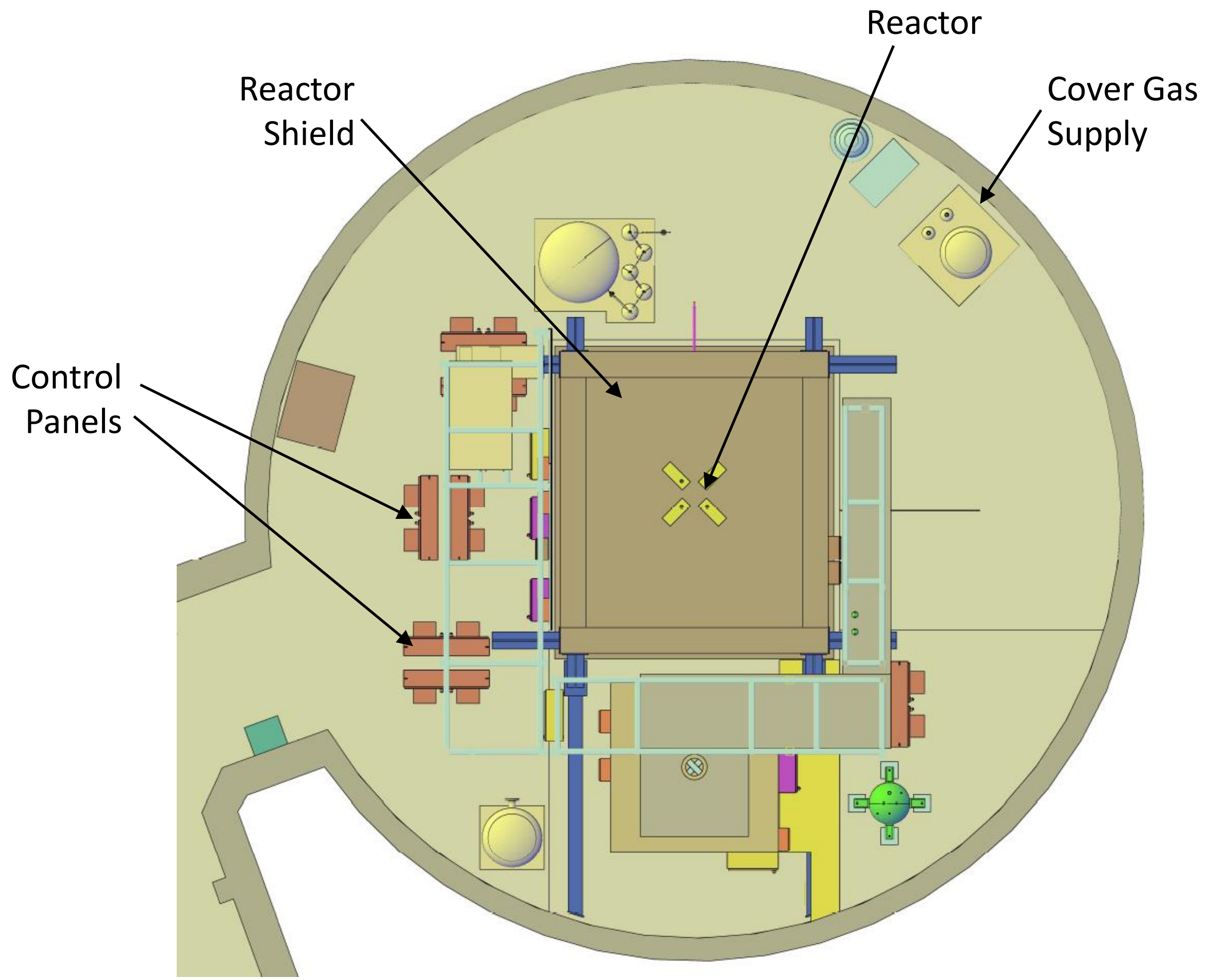
ZPPR Cell

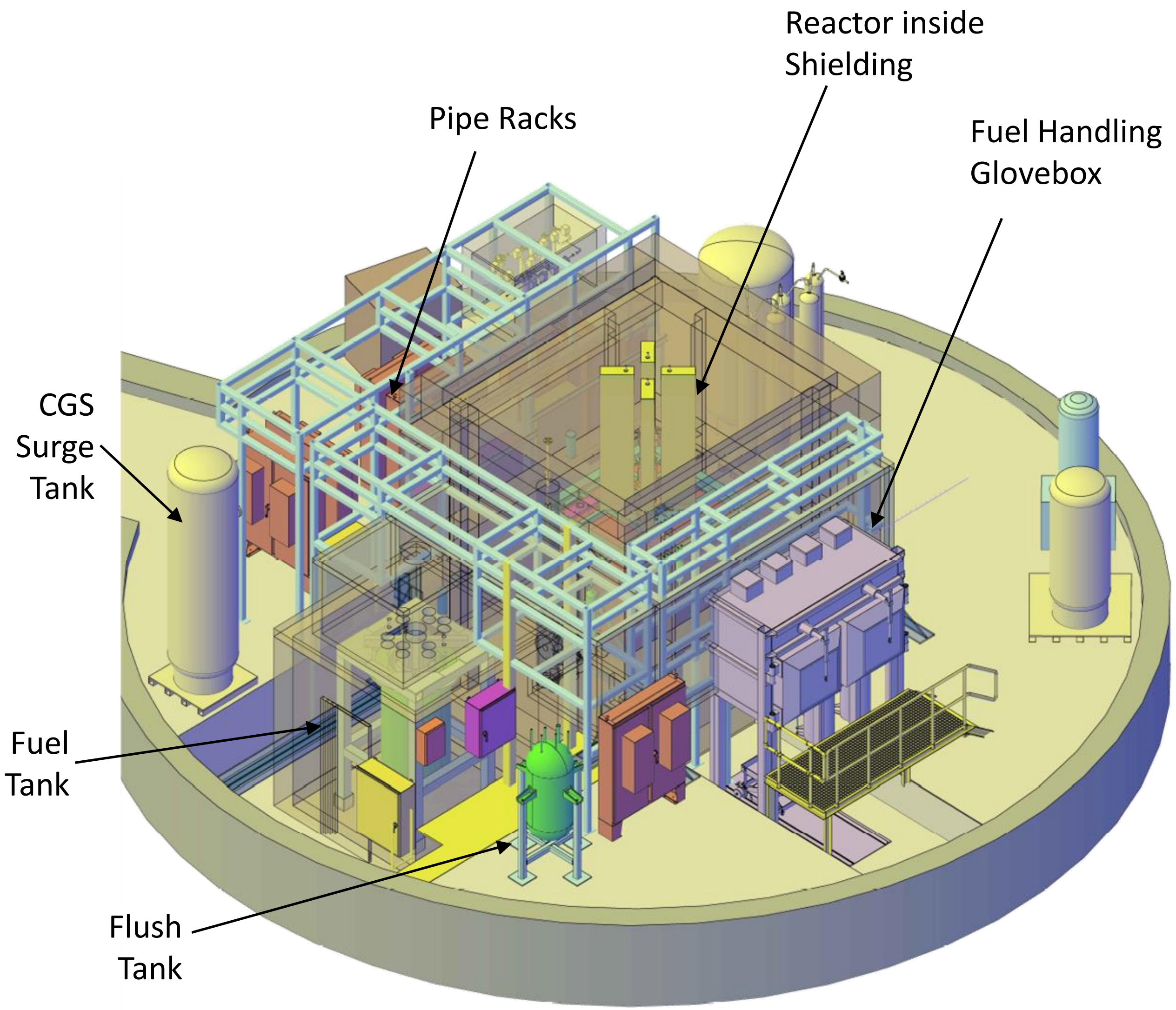


Equipment Tunnel

MCRE is in the Preliminary Design Phase (60%)

- LOTUS cell is quickly filling up
  - 90+% of equipment has been located within LOTUS plant model





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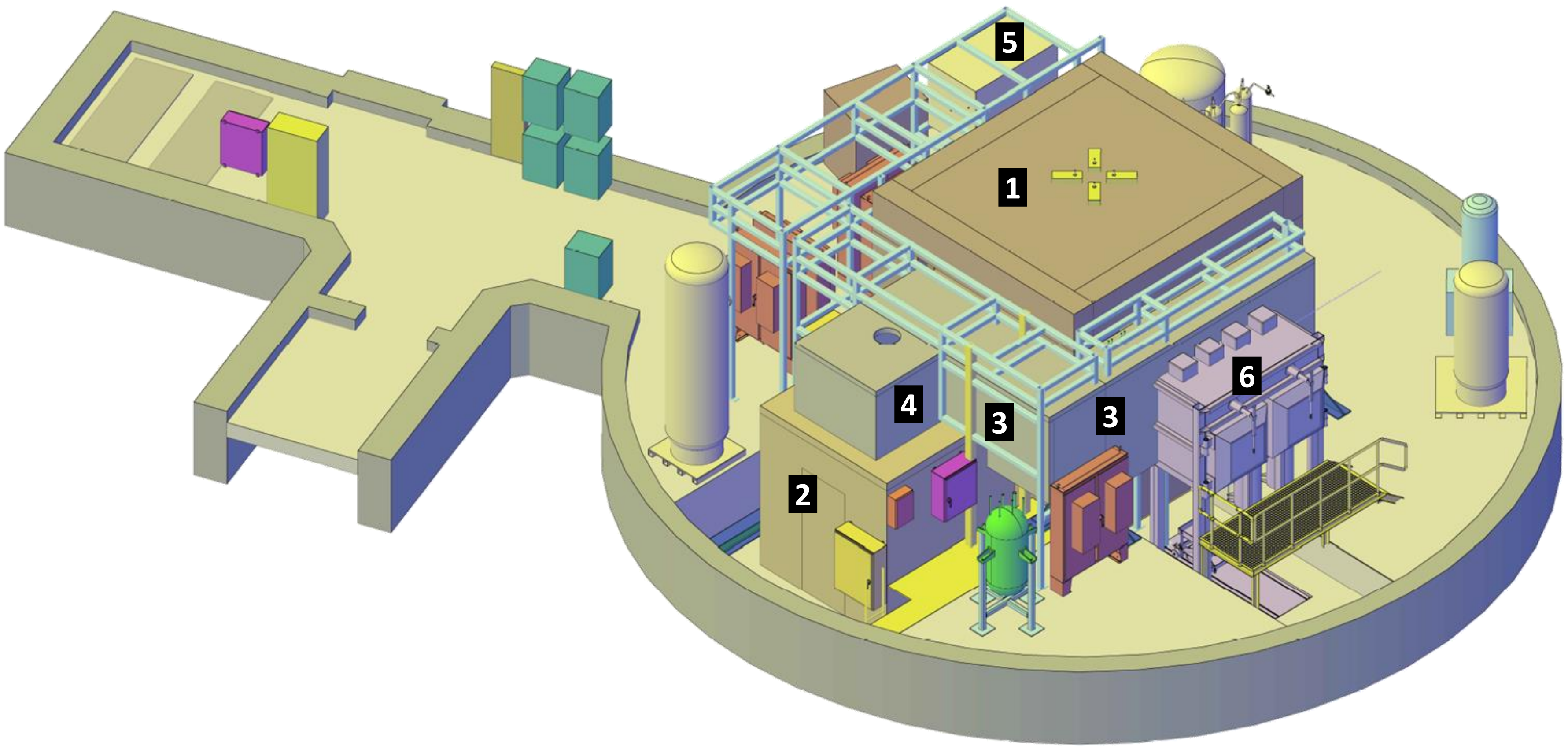
Shielding located around reactor, fuel tank, fuel piping, CGS condensers, CGS scrubber, and fuel handling glovebox



1 Reactor
2 Fuel Tank
3 Fuel Piping
4 CGS Condenser
5 CGS Scrubber
6 Fuel Handling Glovebox

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Reactor Design

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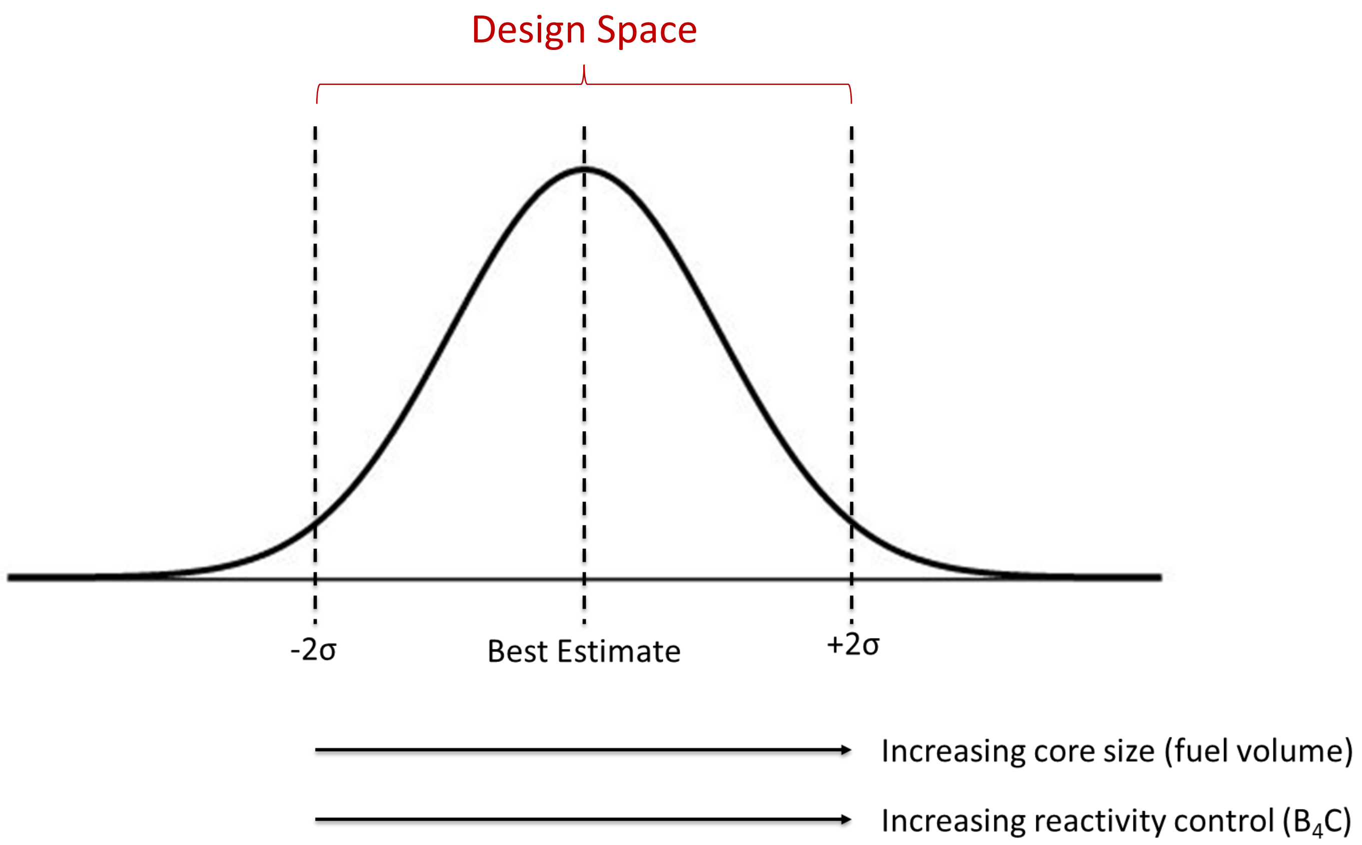
Uncertainty in where MCRE goes critical is calculated and factored into the design

- This is why we are doing MCRE → **find critical point**
- Reactor is oversized
- Reactivity control is oversized

Primary Contributors (the first three rows of the table: ^{35}Cl Nuclear Data, Fuel Salt Density, Nuclear Data (all other))

DOE GAIN Voucher – LANL measured ^{35}Cl cross sections in MCRE's energy range (the ^{35}Cl Nuclear Data row)

Components of Uncertainty
^{35}Cl Nuclear Data
Fuel Salt Density
Nuclear Data (all other)
UCl_3 Molecular Composition
Uranium Enrichment
Active Core Diameter
Active Core Height
Vessel Thickness
Alloy 625 Composition
Lower Vessel Head Thickness
Upper Vessel Head Thickness
Monte Carlo Statistics



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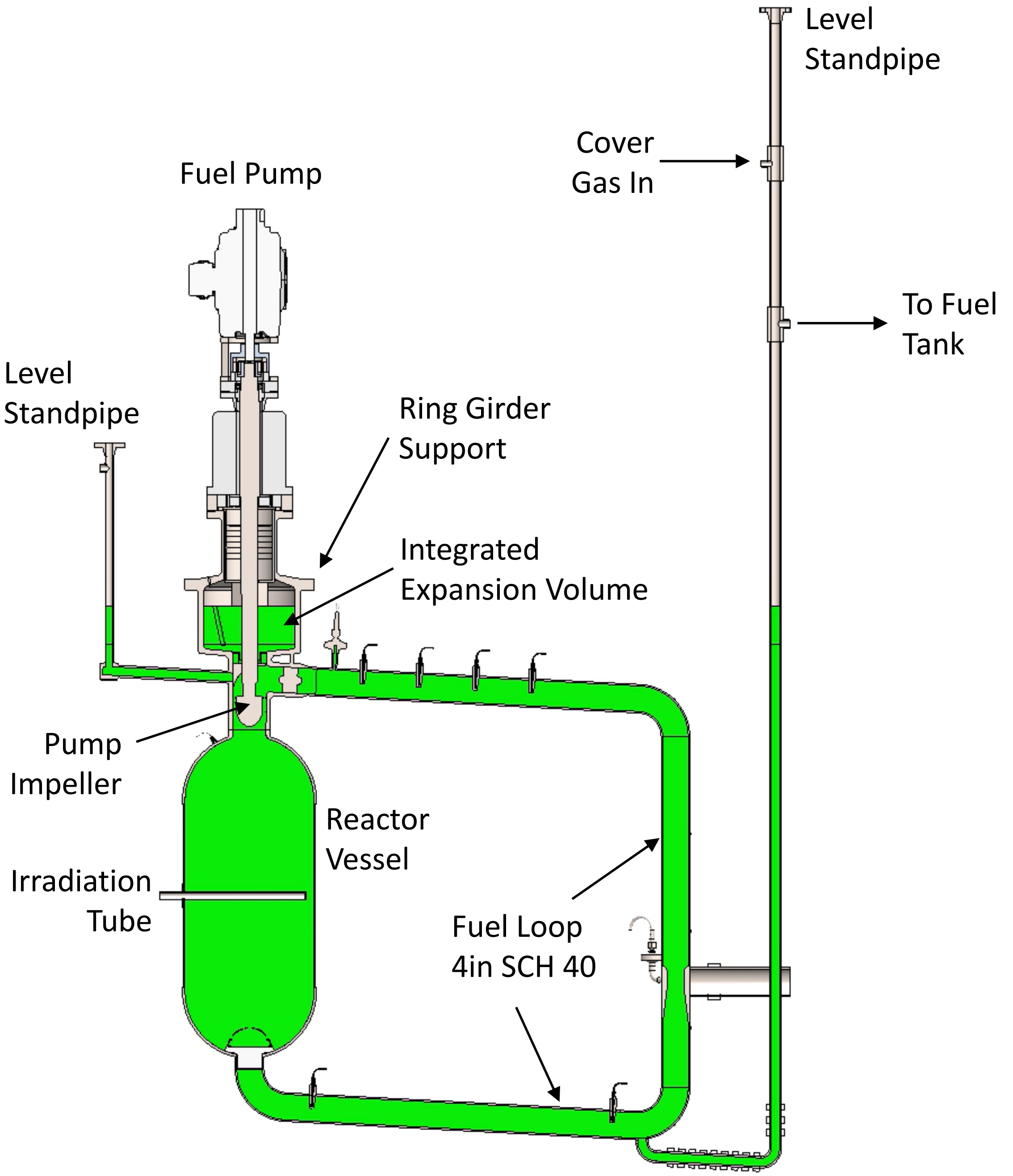
Reactor Design

Parameter	Value
Rated Thermal Power	150 kW
Design Temperature	700°C
Design Pressure	500 kPa-g
Fuel Salt Mass Flow Rate	25-100 kg/s
Operating Temperature	600-650°C
Fuel Salt Melting Temperature	525°C
Fuel Salt Composition	NaCl-UCl_3 (67-33mol%) 93.2 wt% U-235
Fuel Salt Volume	0.302 m^3
Fuel Salt / HEU Mass	~1000 kg / ~500 kg
Neutron Reflector	82% dense MgO
Reactivity Control	Four rods w/ B_4C 80 wt% B-10
ASME BPVC	Section III Division 5
Material	UNS N06625 Grade 2



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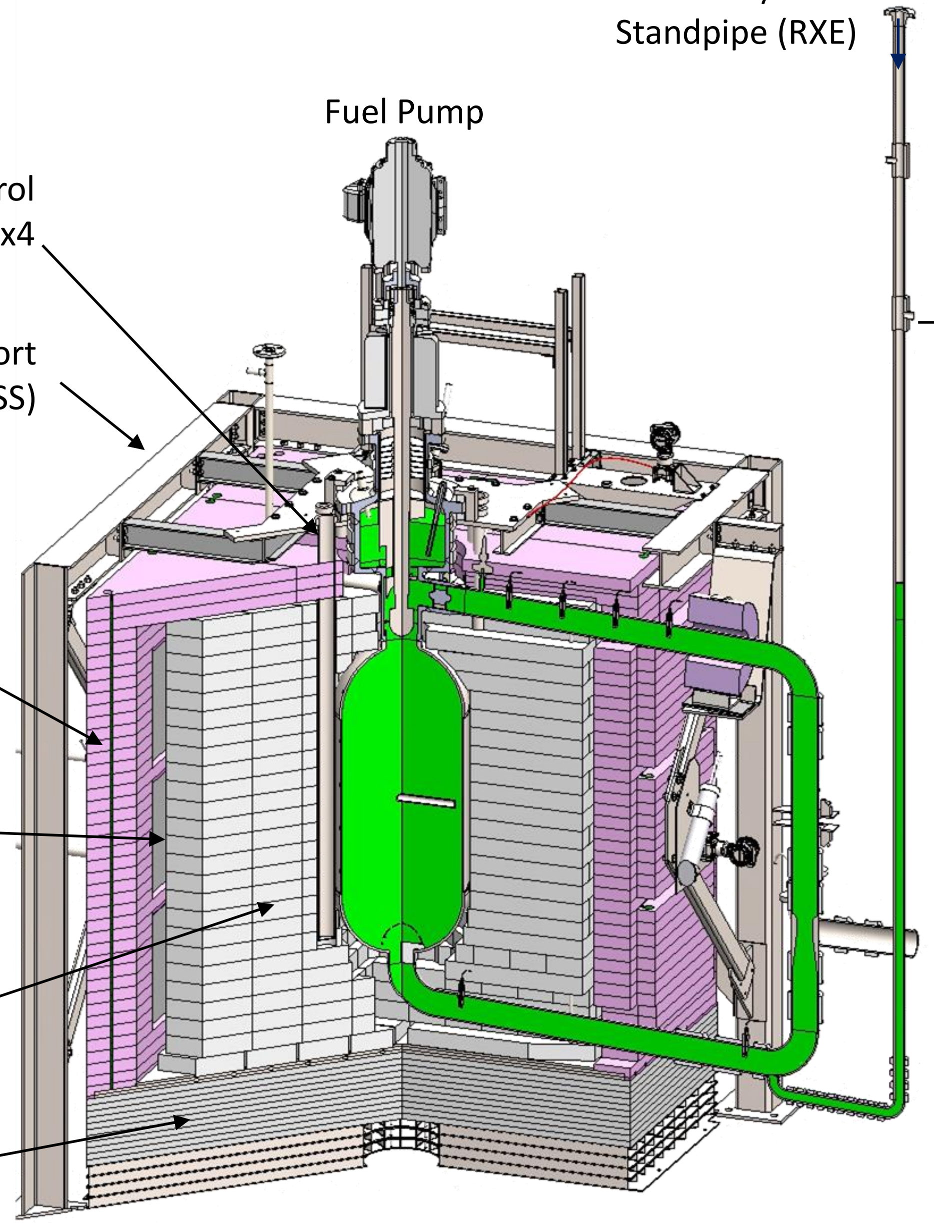
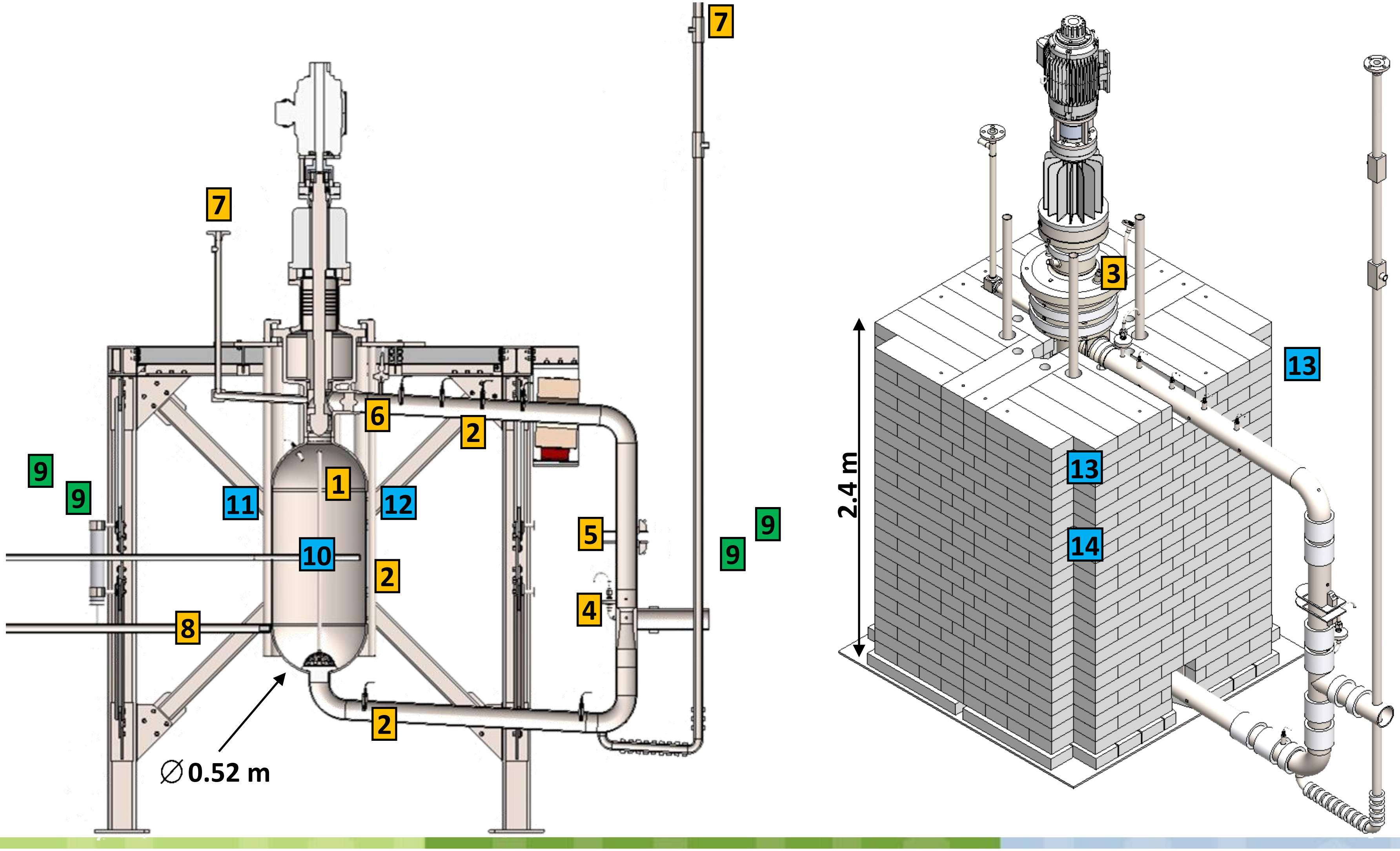
Reactor Design

Reactor Core System (RCS)
- Reactor Enclosure System (RXE)
  - Vessel & loop
  - Fill/drain standpipe
- Neutron Reflector System (RFL)
  - High density, high purity MgO bricks
- Reactor Support System (RSS)
  - Reactor support
  - Reflector support
- Core Heating System (CHT)
  - Radiative heater panels
  - Rigid insulation

- Fuel Pump
  - Pump case
  - Rotating assembly
  - Level standpipe



Operational, safety, and experimental instrumentation incorporated into the MCRE reactor design



1 In-Core Multipoint Thermowell
2 Vessel/Loop Thermowell
3 Pump Bowl Thermowell
4 Venturi Flow Meter
5 Ultrasonic Flow Meter
6 Pressure Differential Indicating Transmitter
7 Guided Wave Radar Level Transmitter
8 Startup Source Tube
9 Wide-Range Fission Chamber x4
10 In-Core Irradiation Tube
11 Fission Chamber x2
12 Ta-SPND x2
13 Ion Chamber x2
14 Gamma Dosimeter

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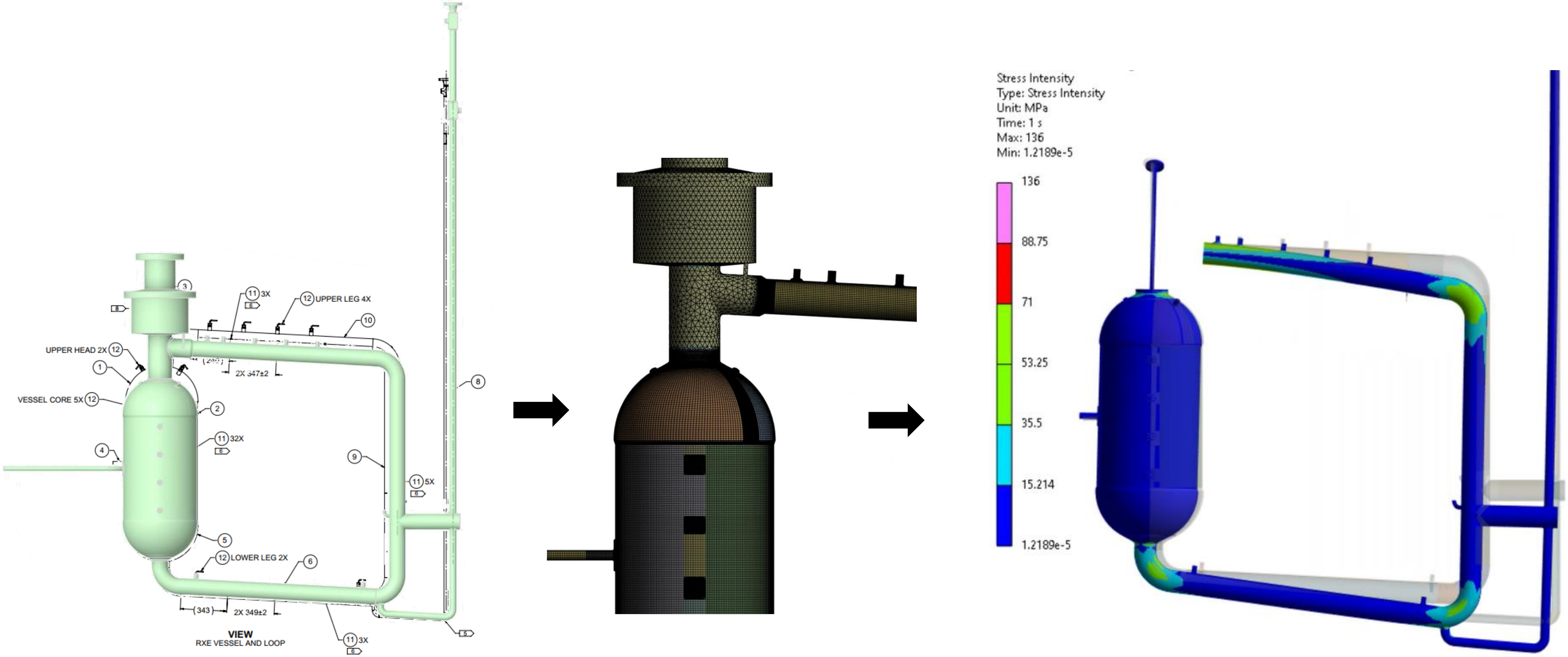
Reactor Enclosure System (RXE)
ASME Section III.5 design & analysis by **Energy Steel** and **Prime Engineering**



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Reactor Enclosure System (RXE)
Fabrication by Energy Steel

Elbows

Thermowell

Plate for Vessel Heads

Upper & Lower Loop

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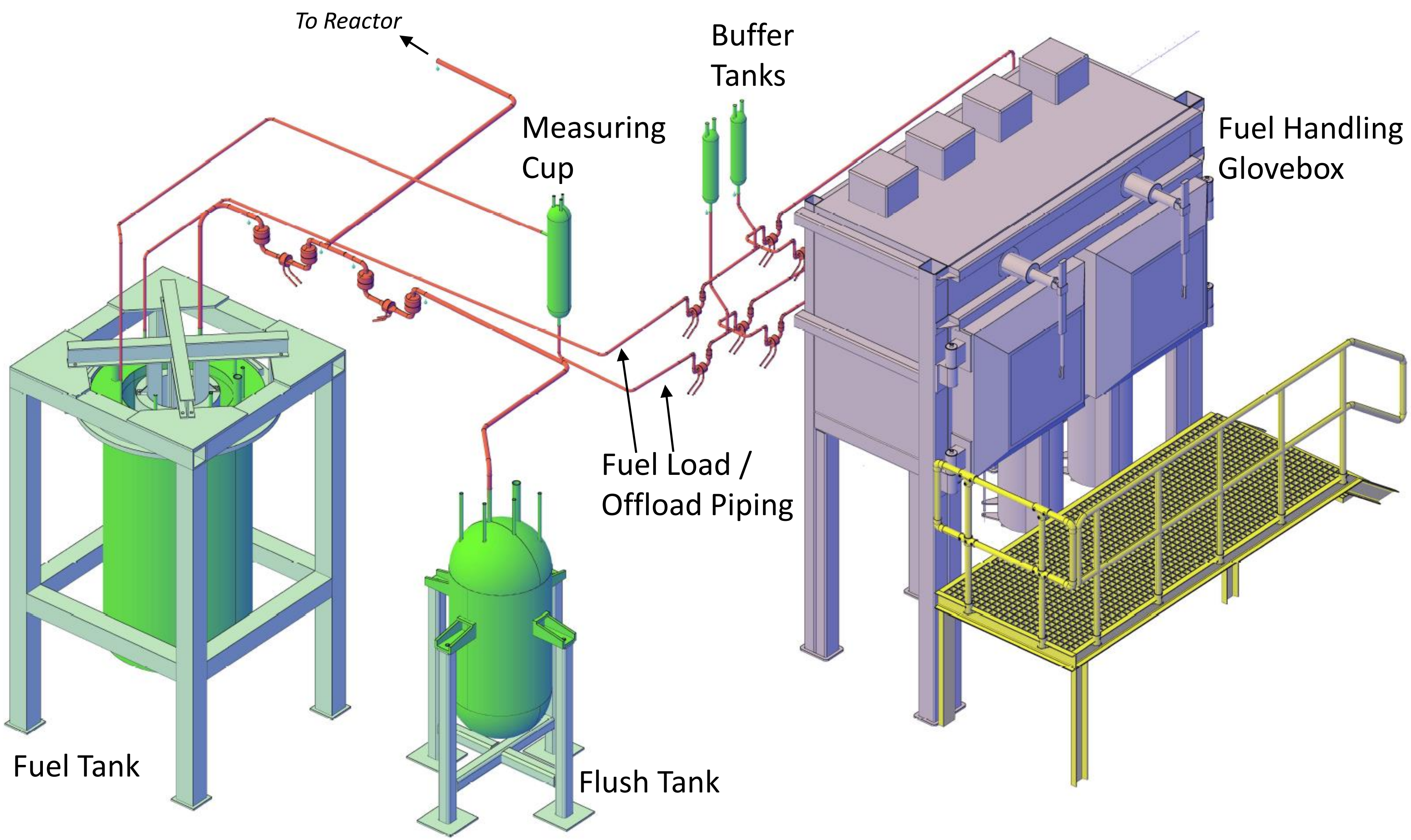
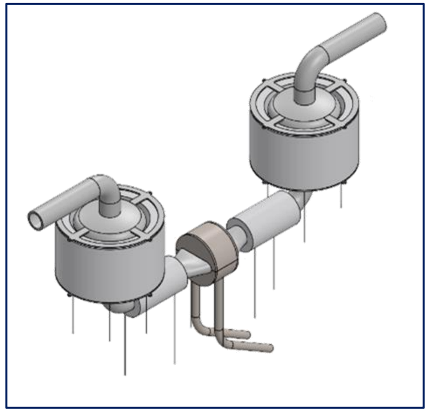
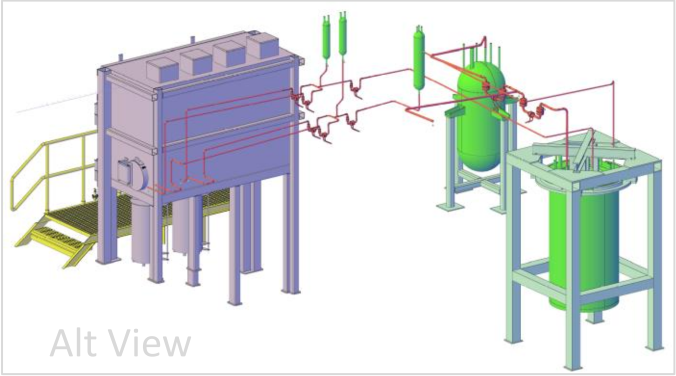
Fuel Handling Design

Fuel Handling Design

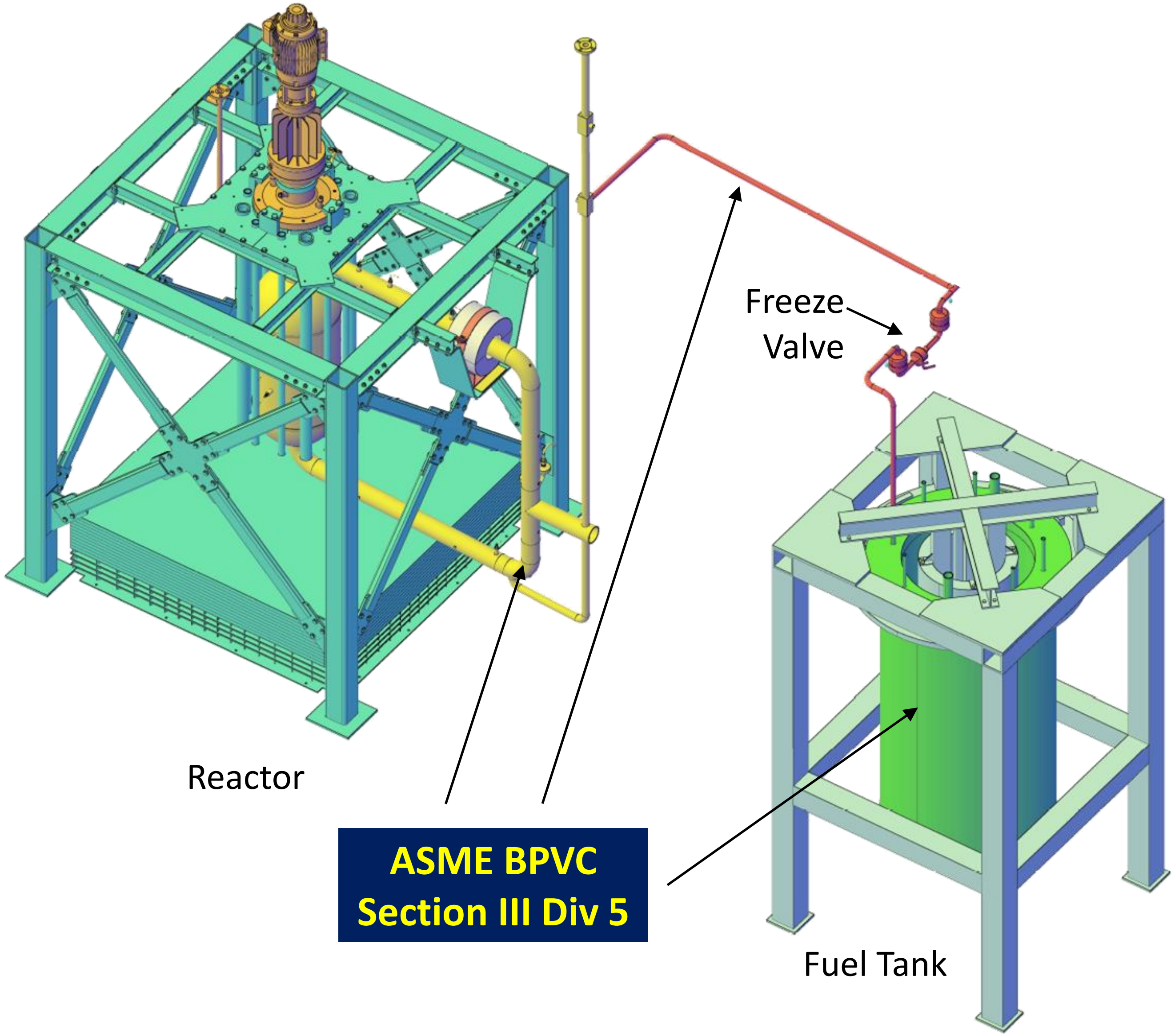


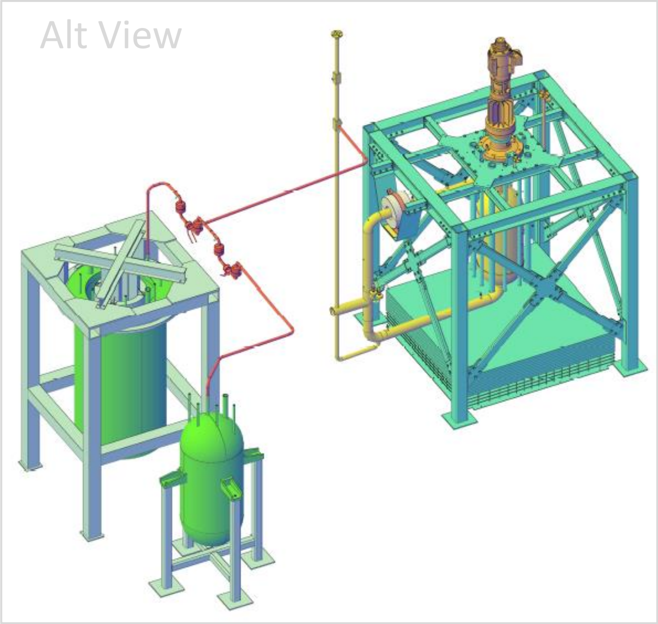


8 Freeze Valves to accomplish fuel load/offload and reactor fill/drain



Fuel Handling Design





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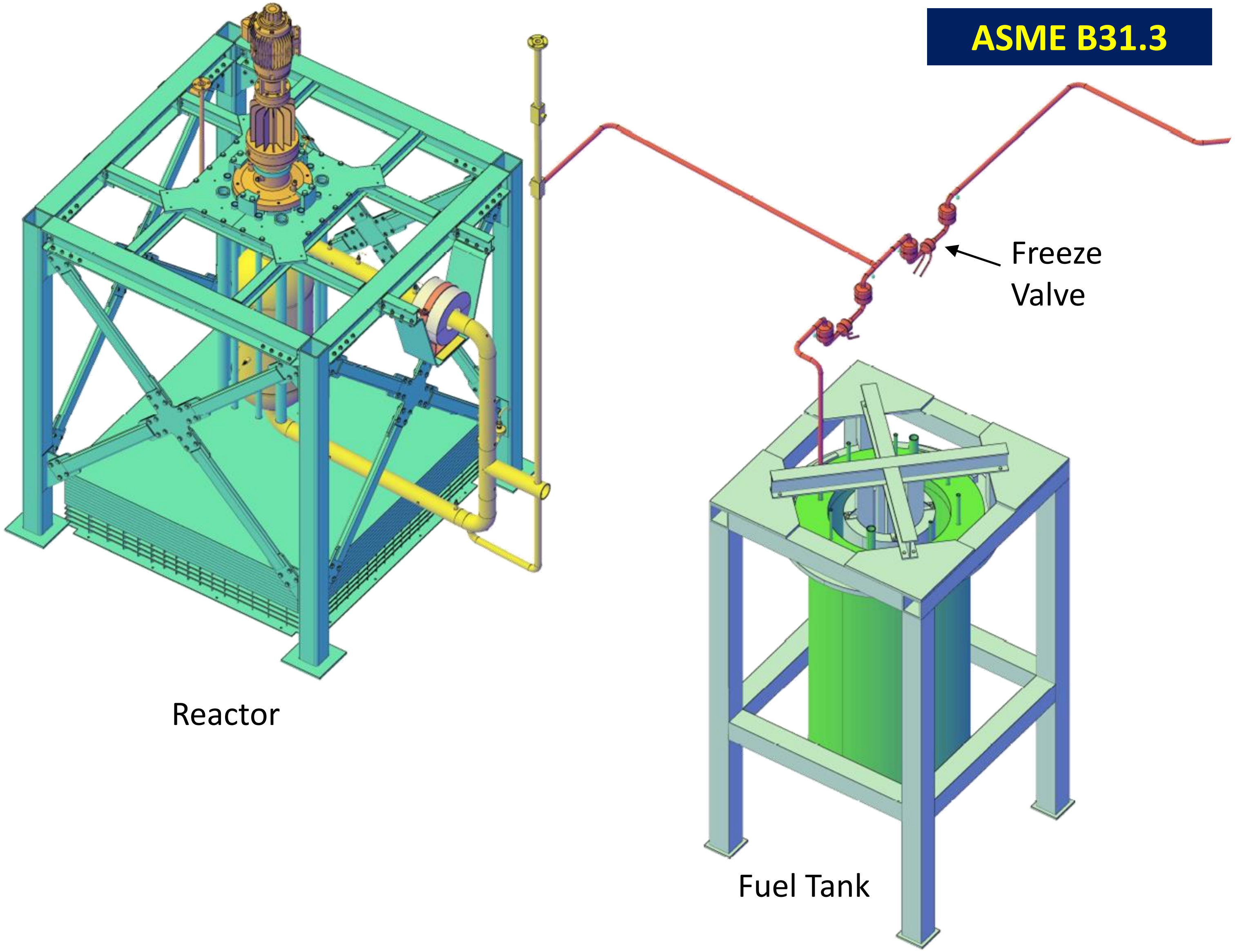
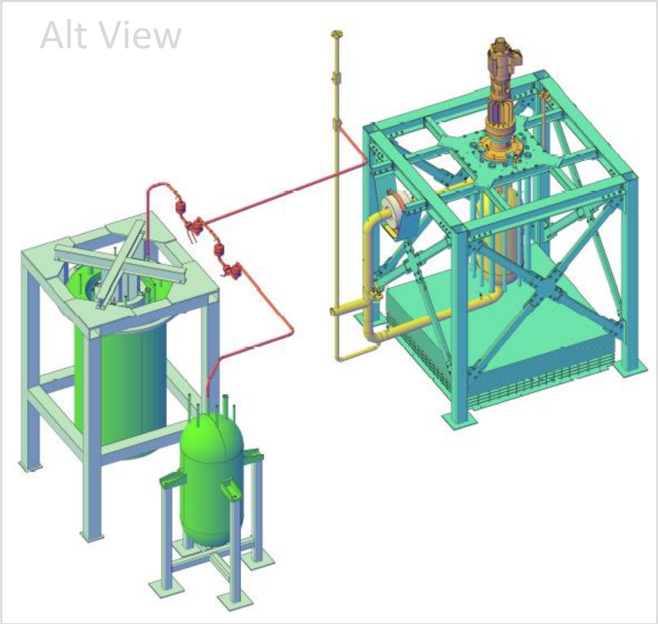
Fuel Handling Design





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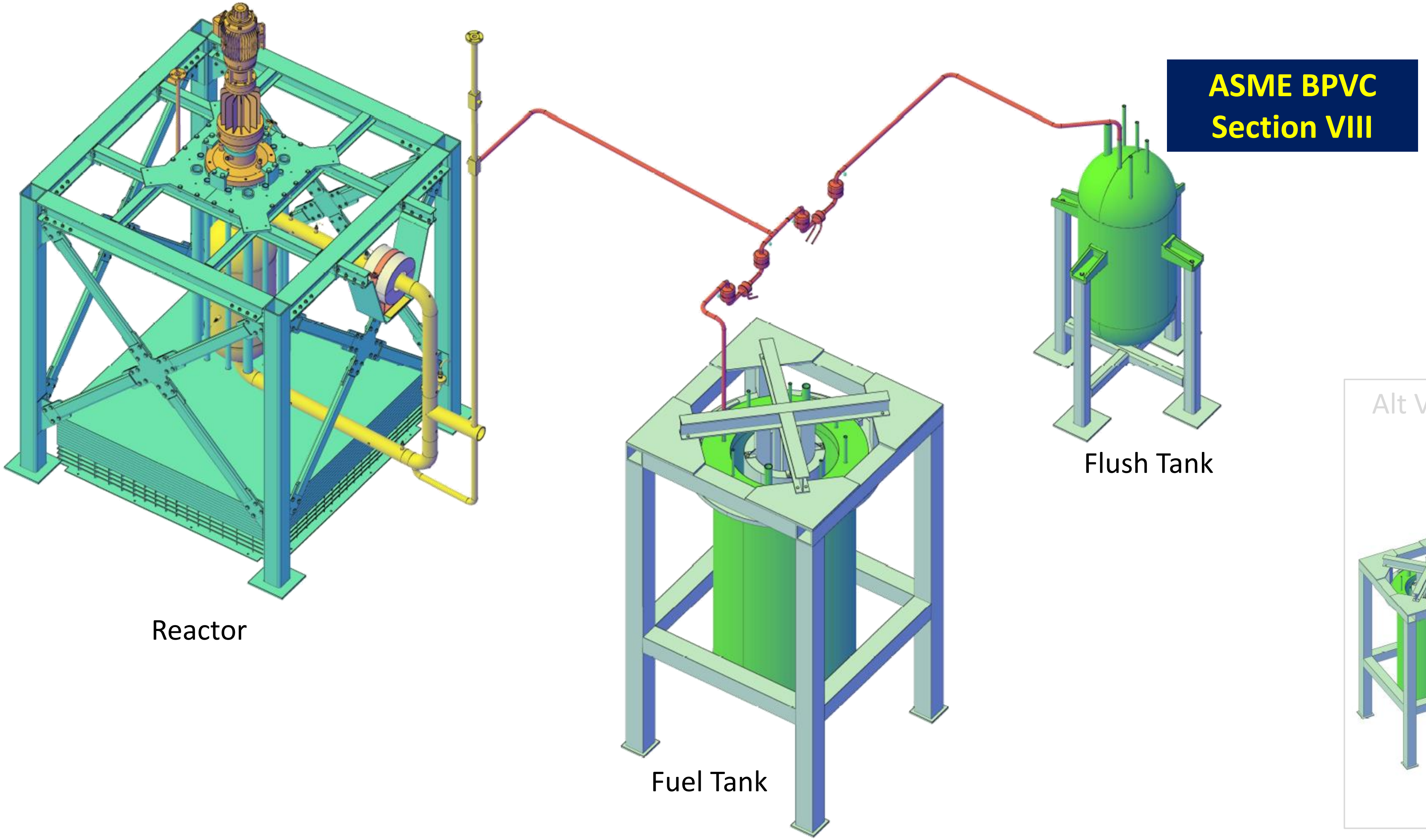
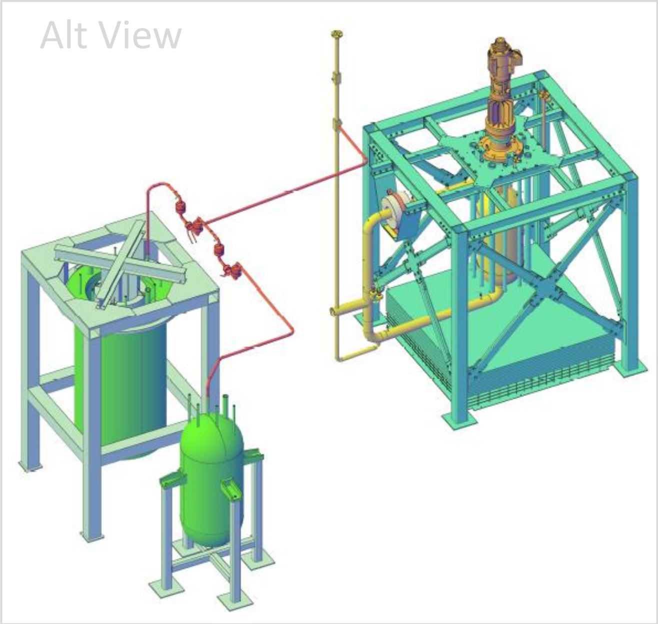
Fuel Handling Design





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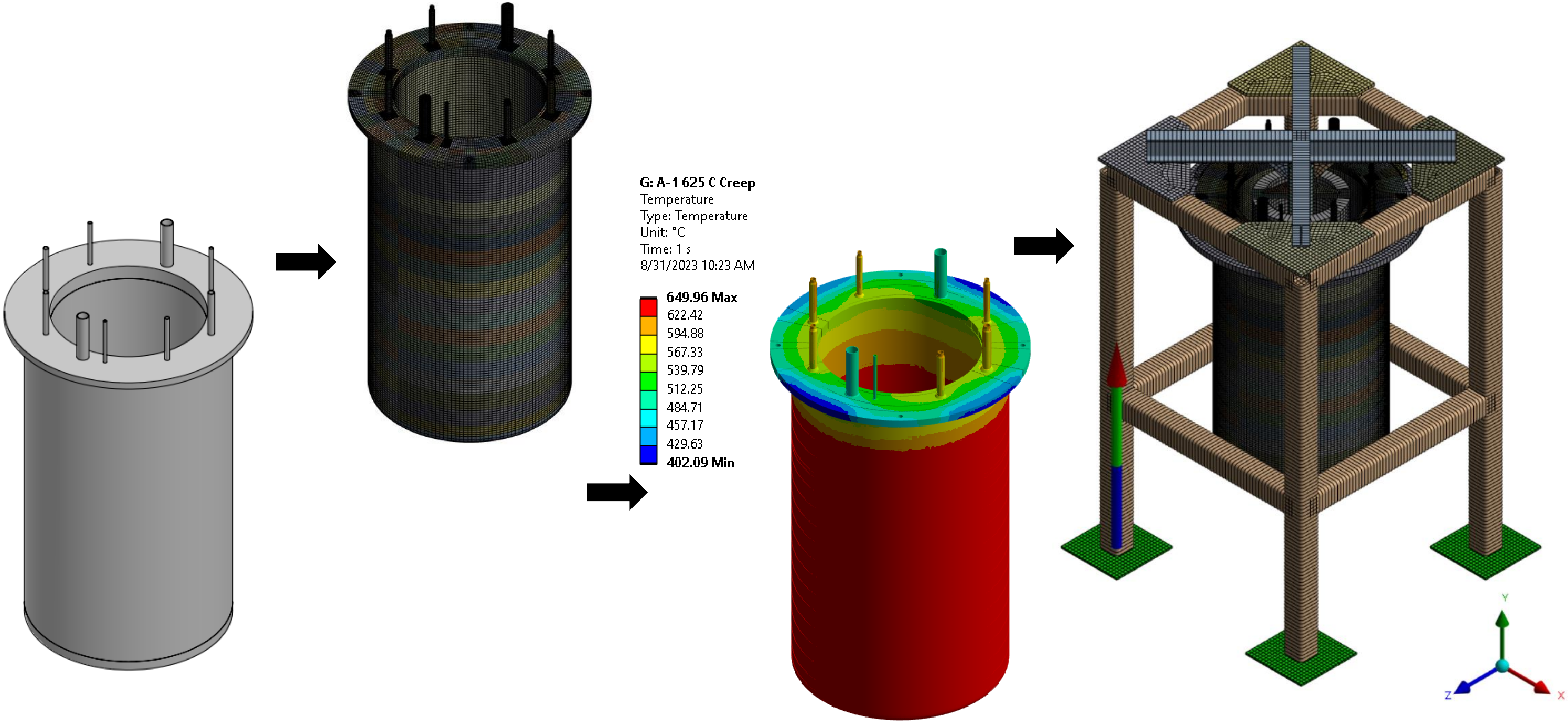
Fuel Tank

ASME Section III.5 design & analysis by Energy Steel and Prime Engineering



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Testing

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Small Isothermal Molten salt Pumped Loop

Chloride salt loop for testing corrosion-erosion phenomena

- ~3 kg NaCl-$MgCl_2$ (58-42 mol%)
- ¾" tube
- ≤ 10 gpm
- ≤ 2 m/s (on coupon face)
- ≤ 700°C
- 15 psig

Mag-Coupled Salt Pump

<u>Testing Summary</u>

- Pumped salt for 2000 hours
- 3 bearing failures, likely from overloaded lower bearing
- Pump/bearing design being re-evaluated
- Expected to resume operations at reduced pump speed

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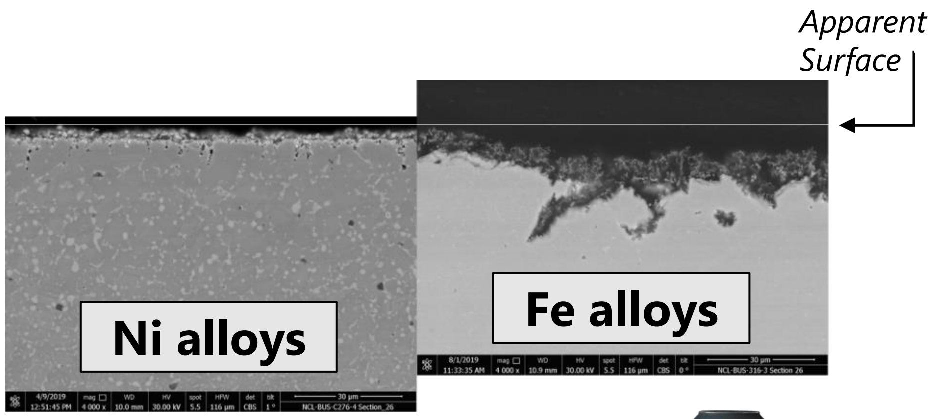
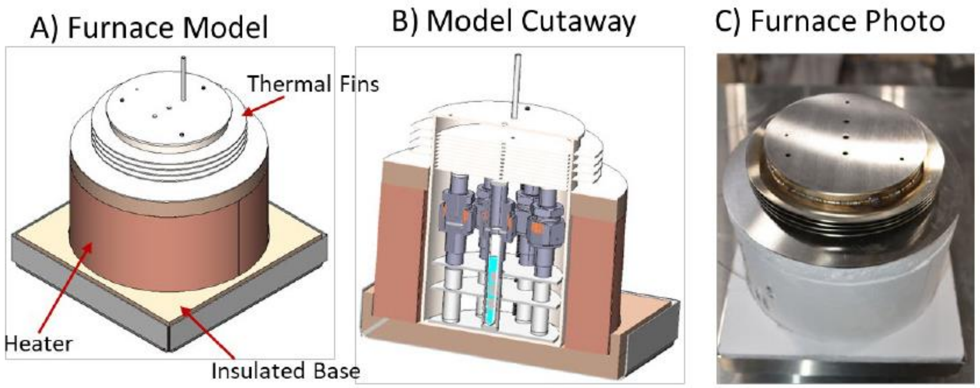
Material Compatibility Testing



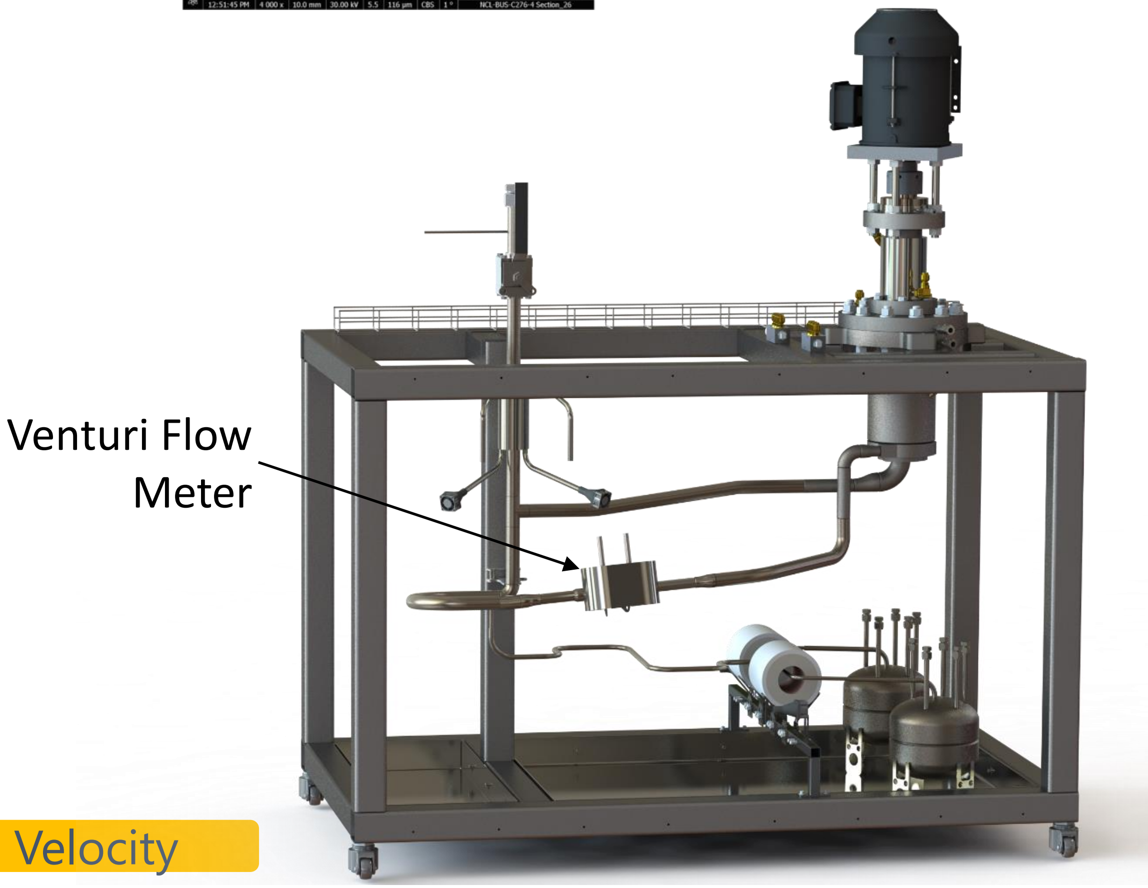
DU Corrosion Static Testing (DUCS)

(uranium-nickel intermetallic investigation)



Depleted Uranium SIMPL

- ~10 kg NaCl-UCl_3 (67-33 mol%)
- 1″ tube
- ≤ 4 m/s (on coupon face)



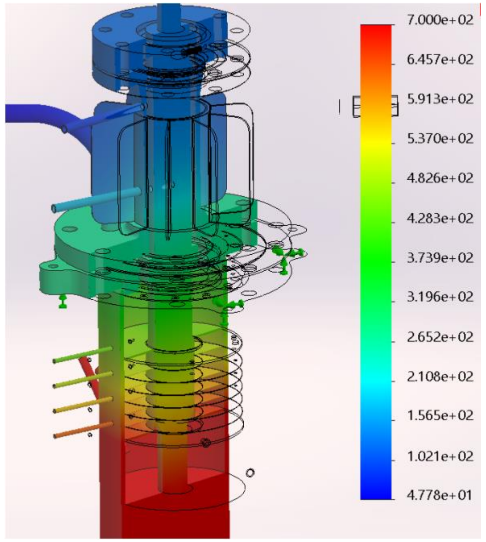
✓ Salt ✓ Material ✓ Temperature ✓ Velocity

Subject to DOE Cooperative Agreement No. DE-NE0009045

Fuel Pump Testing by Hayward Tyler

1. Hydraulic Test Unit (HTU)



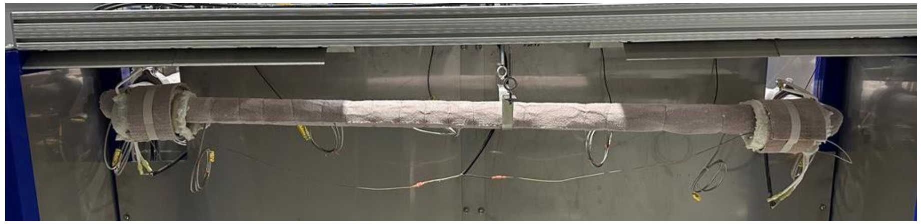


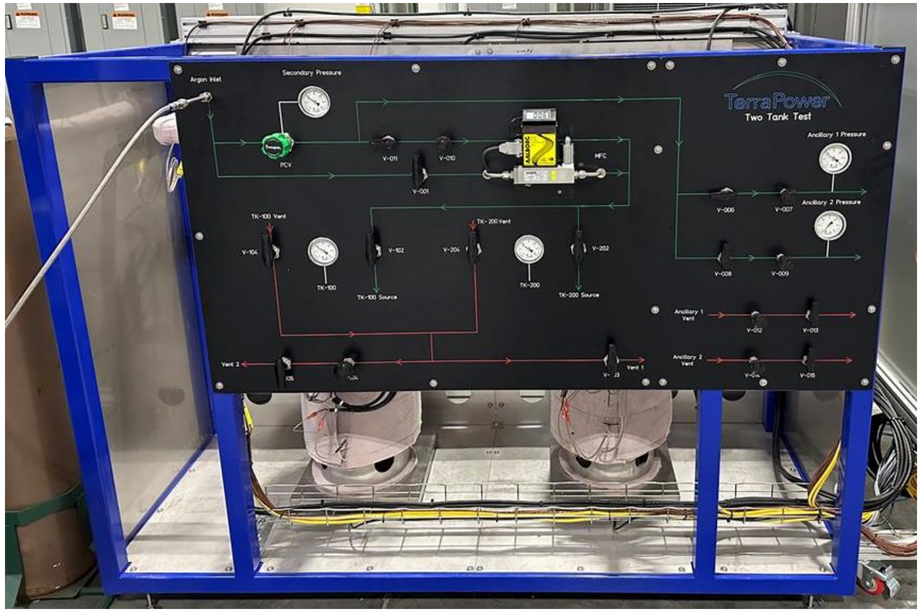
2. Thermal Management Mockup of Magnetic Coupler and high temperature Bearings (TM3B)
   - Multiple bearing types and lubricants are being hot tested without salt before moving to salt testing

3. Prototype Test Unit (PTU) (for Mockup)

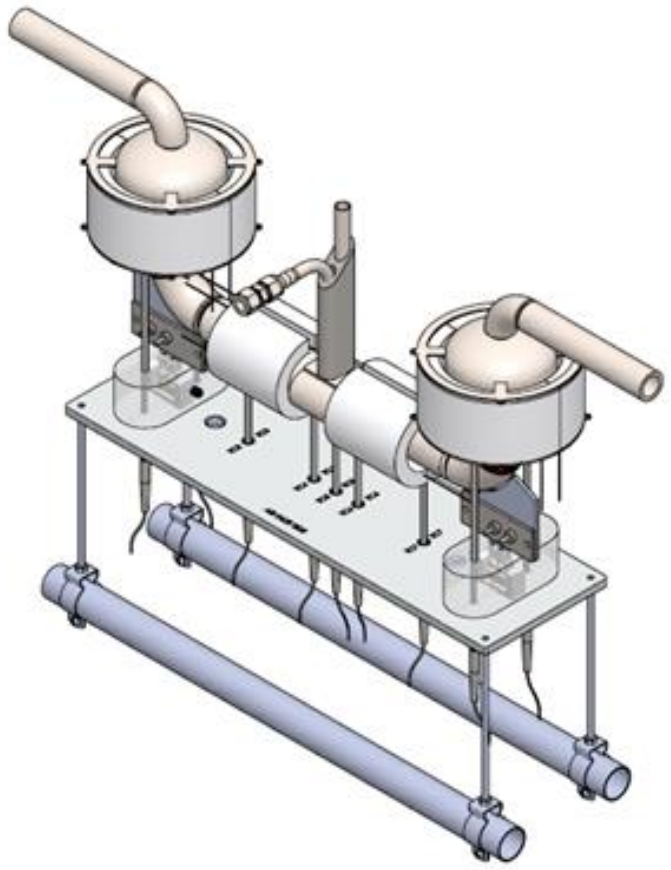
Instrument Testing

Two Tank Test (TTT)





Freeze Valve Test (FVT)



Subject to DOE Cooperative Agreement No. DE-NE0009045

Alloy 625 mechanical properties testing

- All fuel salt-wetted components/equipment will be fabricated from **Alloy 625 (UNS N06625)**
- Alloy 625 is not an ASME BPVC Section III Div 5 qualified material
- High temperature testing of **Solution Annealed Grade 2** will be used to confirm properties found in literature

Category ID	Tests	Key Test Outputs	Total No. of Samples	Note	Target Temperatures (°C)
1	Tensile (Aged)	Yield strength Ultimate tensile strength Total elongation Uniform elongation	26	2 heats	550, 650, 700, 750
2	Stress rupture (Cross weld)	Stress to rupture Time to rupture	8	2 heats	750
3	Creep rupture (As Received Base Metal)	Time to 1% strain Time to failure (select samples) Strain as a function of time	26	2 heats	650, 700, 750, 800
4	Fatigue (As Received)	Cycles to failure	25	2 heats, 1 repeat	750
5	Creep-fatigue (As Received)	Cycles to failure Time to failure	17	1 heat, 1 repeat	750

Subject to DOE Cooperative Agreement No. DE-NE0009045

TerraPower

Thank You

Dan Walter
dwalter@terrapower.com

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Hermes Reactor Update

ANNE DEMMA, SENIOR MANAGER, KAIROS POWER

MOLTEN SALT REACTOR WORKSHOP, OCTOBER 25-26, 2023

Kairos Power's mission is to enable the world's transition to clean energy, with the ultimate goal of dramatically improving people's quality of life while protecting the environment.

In order to achieve this mission, we must prioritize our efforts to focus on a clean energy technology that is *affordable* and *safe*.

Overview of Kairos Power

- Nuclear energy engineering, design, and manufacturing company ***singularly focused*** on the commercialization of the fluoride salt-cooled high-temperature reactor (FHR)
  - Founded in 2016
  - 368 Employees (~90% Engineering Staff)
- Novel approach to nuclear development that includes iterative hardware demonstrations and in-house manufacturing to achieve disruptive cost reduction and provide true cost certainty
- US demonstration by 2030 and rapid deployment ramp in 2030s
- Cost targets set to be competitive with natural gas in the US electricity market

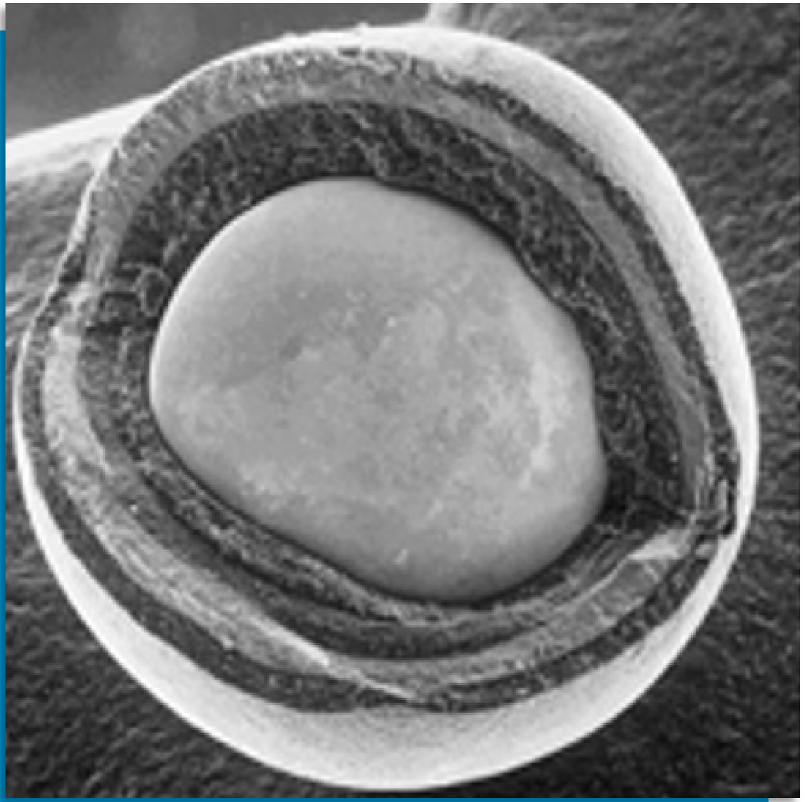
Kairos Power Headquarters

Kairos Power Team

kai·ros (def.): the right or opportune moment

Fluoride Salt-Cooled High Temperature Reactor

Technology Basis



Coated Particle Fuel
TRISO

Liquid Fluoride Salt Coolant
Flibe ($2LiF\text{-}BeF_2$)

Kairos Power Workstreams

Reduce risk and build cost certainty

- KP-X Design
- Test Program
- Licensing
- Fuel Development
- Salt Development

→

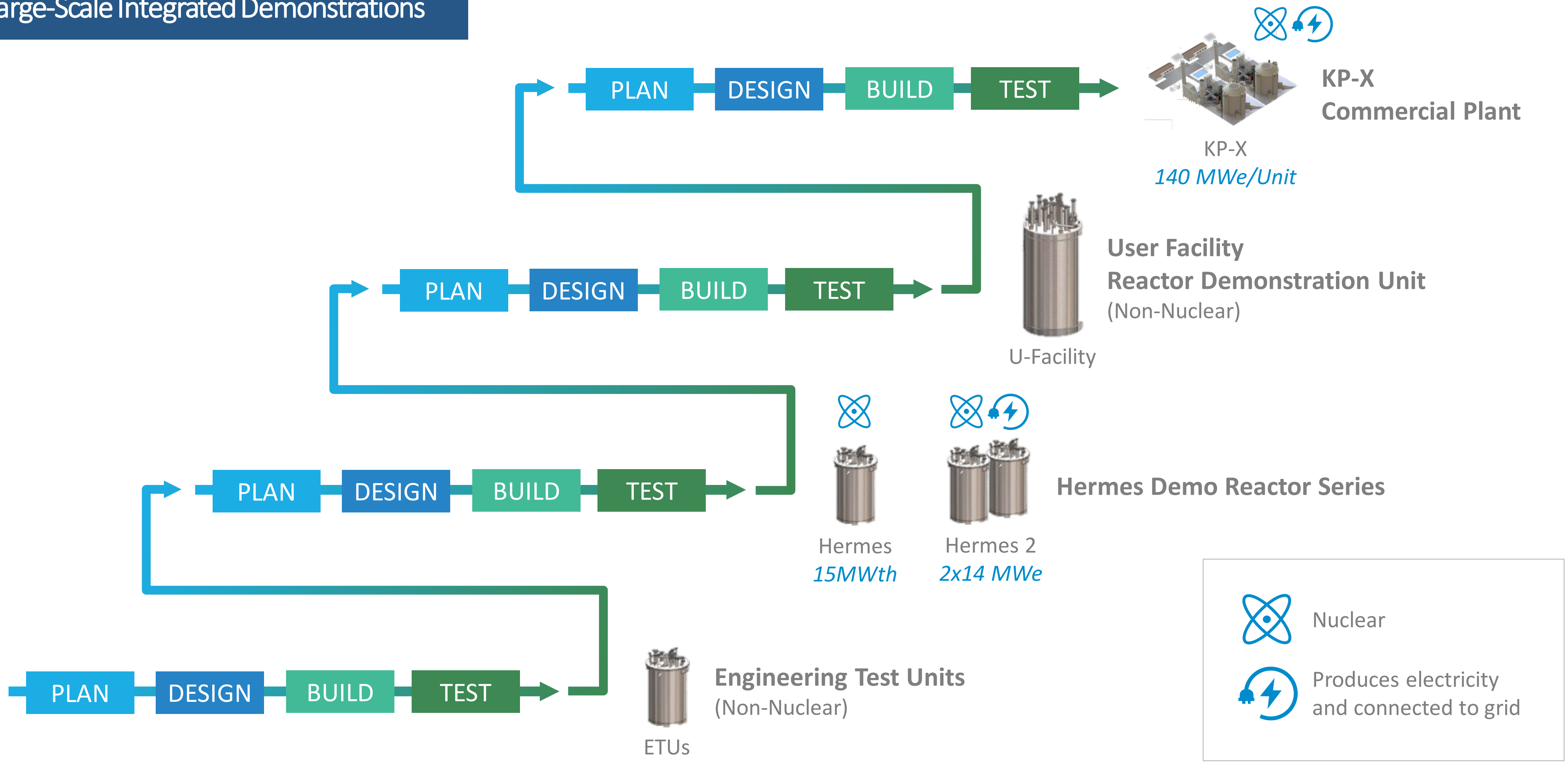
- Technology Certainty
- Licensing Certainty
- Supply Chain / Manufacturing Certainty
- Build Certainty

→

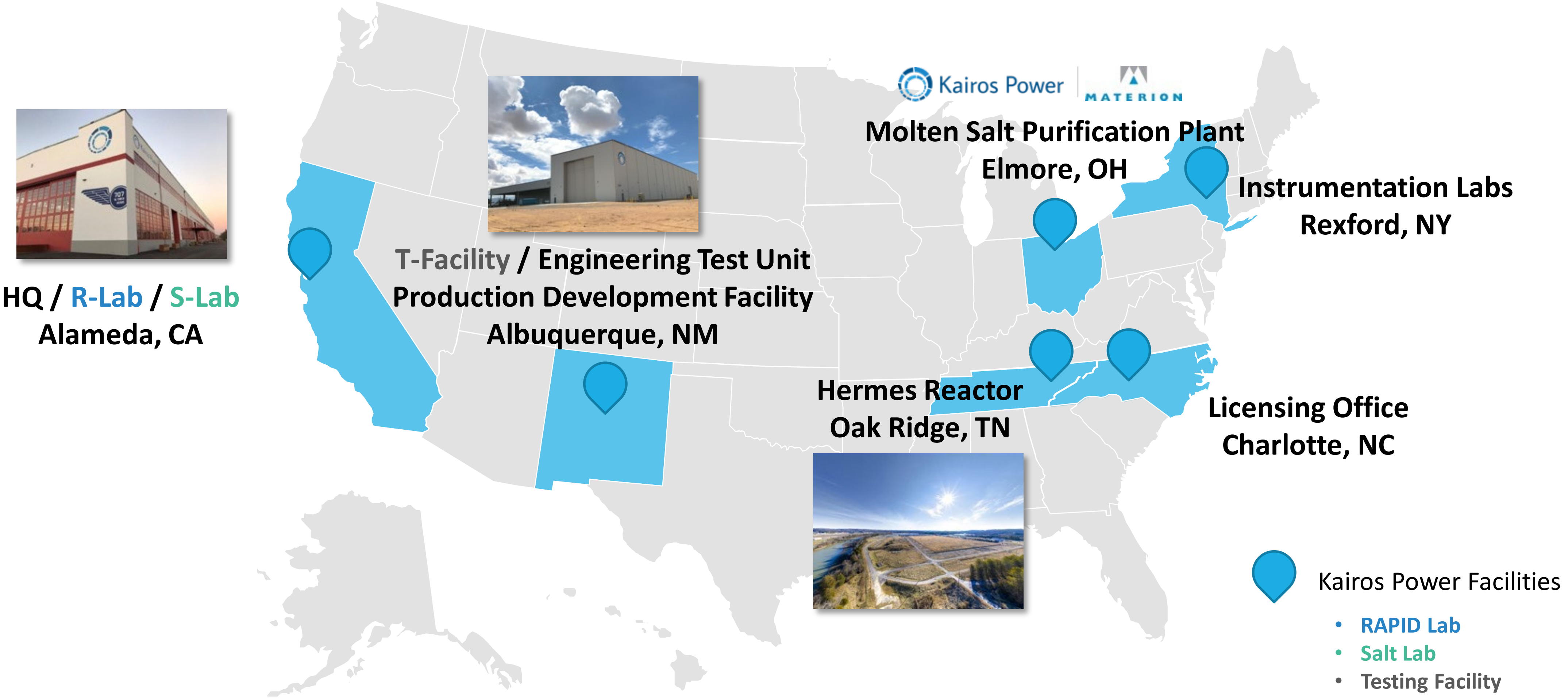
- Cost Certainty

Kairos Power Path to Commercialization

Successive Large-Scale Integrated Demonstrations



Kairos Power Locations and Infrastructure



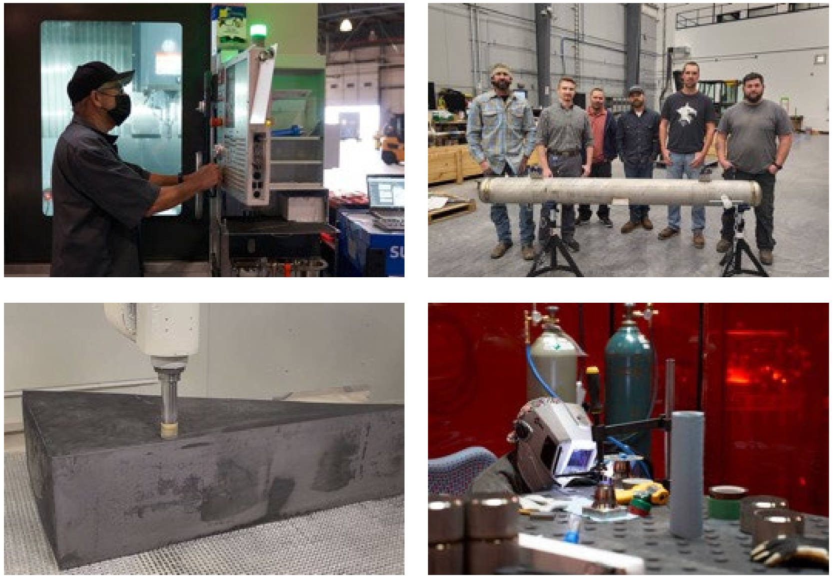
Vertical Integration

Delivering Cost Certainty

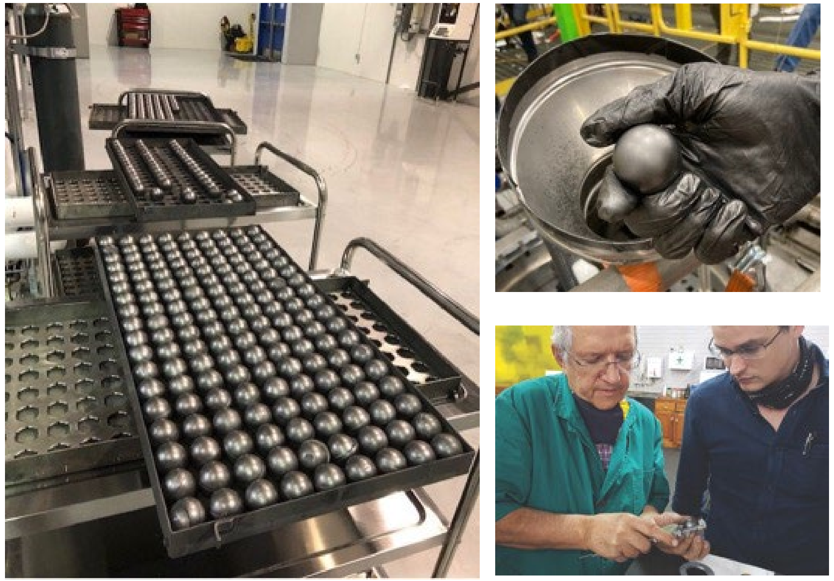
Kairos Power has made significant investments in infrastructure to de-risk the supply chain and deliver cost certainty, vertically integrating production or assembly of components and materials that are:

1) related to salt   2) safety-related   3) not available off-the-shelf

KP Southwest Manufacturing Facility	Pebble Development Lab & TRISO Development Lab	Molten Salt Purification Plant



In-house manufacturing of specialized components



Fuel development

Commercial-scale Flibe production

Engineering Test Unit

Albuquerque, NM

Graphite Reflector Installation

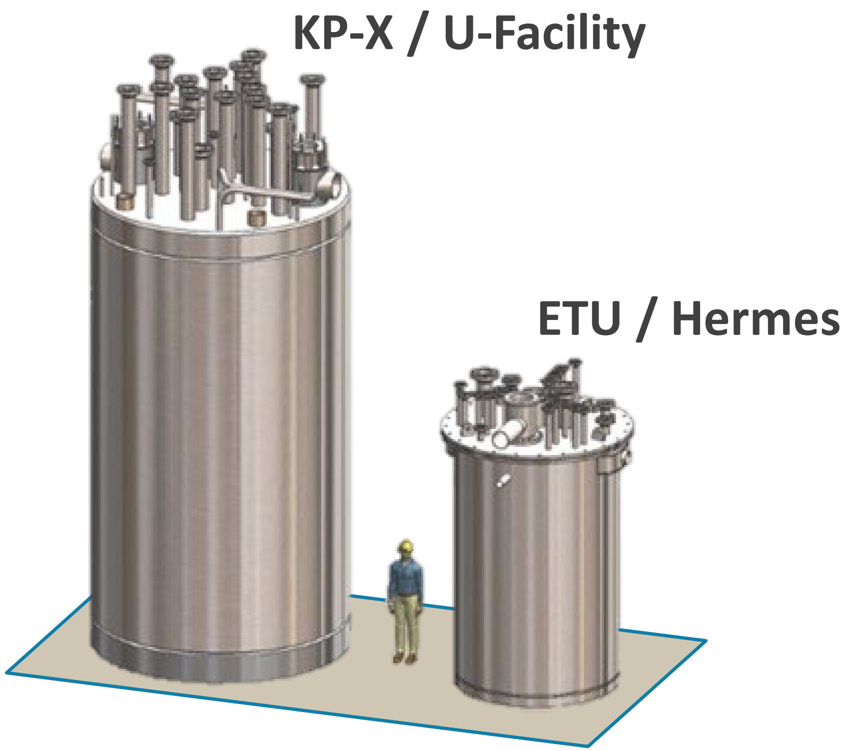
Entrant Training

Control Room

Kairos Power Hermes Reactor Overview

Oak Ridge, TN

- What?
  - A **low power reactor** that will prove Kairos Power's capability to deliver low-cost nuclear heat
- Why?
  - **Cost:** Establish competitive cost through iterative learning cycles
  - **Supply Chain:** Advance the supply chain for KP-FHR specialized components and materials while vertically integrating critical systems
  - **Design / Test**: Deliberate and incremental risk reduction
  - **Licensing Approach:** NRC license for Hermes as a non-power reactor and facilitate licensing certainty for KP-FHR
  - **Operations:** Provide a complete demonstration of nuclear functions including reactor physics, fuel and structural materials irradiation, and radiological controls



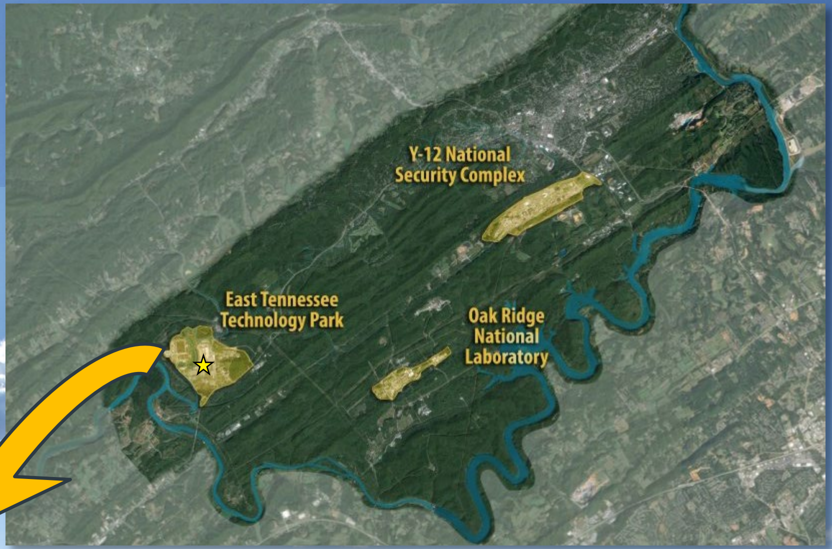
Hermes will ultimately demonstrate our aptitude to license an advanced reactor in a timely manner

U.S. DOE Selects Kairos Power for ARDP Award

- Kairos Power has been selected for an **Advanced Reactor Demonstration Program (ARDP)** Risk Reduction Award to support development of the Hermes reactor
- This is a partnership between the DOE and industry to mature advanced nuclear technology
- Hermes is a collaborative effort with Oak Ridge National Laboratory, Idaho National Laboratory, and Electric Power Research Institute
- Hermes leverages proven technologies that originated in Oak Ridge with the Molten-Salt Reactor Experiment (MSRE) in the 1960s

Former K-33 Building Site

Heritage Center / Oak Ridge, TN



Hermes Construction Permit Application

Leading the Way in Advanced Reactor Licensing

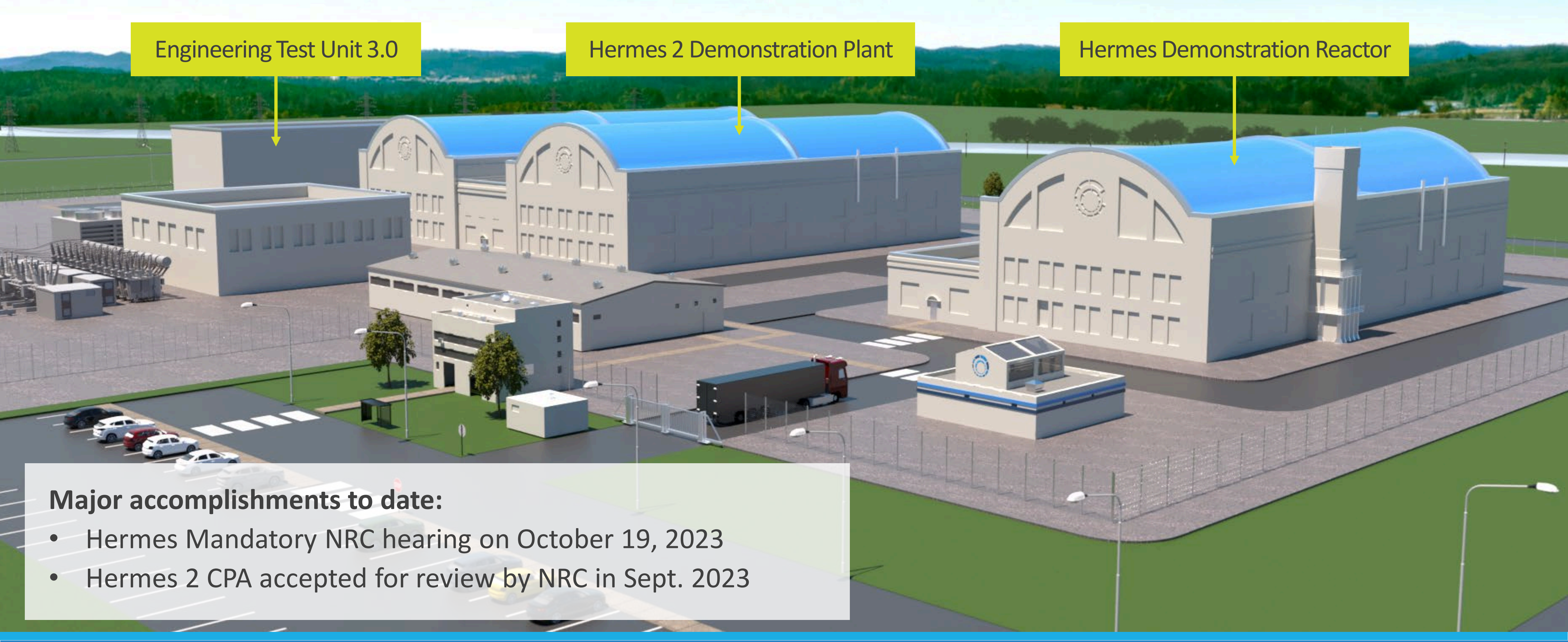
- The U.S. Nuclear Regulatory Commission accepted the Hermes CPA for review in November 2021 following robust pre-application engagement with 11 topical reports and several technical reports supporting the CPA.

- **CPA review progressing ahead of schedule:**
  - ✓ **Draft Environmental Impact Statement Finalized**
  - ✓ **ACRS Safety Evaluation Review Completed**
  - ✓ **Final Safety Evaluation Report Issued**
  - ✓ **Mandatory NRC Hearing on October 19, 2023**
  - ✓ **On track to receive Construction Permit in Fall 2023**

Hermes project status dashboard:
https://www.nrc.gov/reactors/non-power/hermes-kairos/dashboard.html

Hermes Demonstration Reactor Series

Heritage Center K-33 Site / Oak Ridge, TN



Major accomplishments to date:

- Hermes Mandatory NRC hearing on October 19, 2023
- Hermes 2 CPA accepted for review by NRC in Sept. 2023

KP-OMADA Advanced Nuclear Alliance

The Kairos Power Operations, Manufacturing and Development Alliance brings together leading North American utilities and generating companies to collaborate on the advancement of KP-FHR technology.

Bruce Power

Constellation

Kairos Power

Southern Company

TVA TENNESSEE VALLEY AUTHORITY

Kairos Power's Commitment to the Community

Embedded in Our Mission

Everything we do at Kairos Power is driven by our mission to **improve people's quality of life while protecting the environment**

Our Commitment:

- Engage and support local communities
- Prioritize diversity, equity, and inclusion
- Selectively build on brownfield sites
- Deliver high energy density with low land use

1 fuel pebble = 4 tons of coal

Headquarters
Alameda, CA

KP Southwest
Albuquerque, NM

K-33 Site
Oak Ridge, TN


Kairos Power
Enabling the world's transition to clean energy
while improving people's quality of life
and protecting the environment

Development of Robust High-Temperature Reference Electrodes for Molten Salts

Jim Steppan, Tom Meaders, Byron Millet, Lee Sorensen
HiFunda LLC

Mike Simpson, Matthew Newton, Sydney Dowben, Olivia Dale, Suhee Choi, Sang-Eun Bae
University of Utah (UofU)

Guy Fredrickson, Guoping Cao, Richard Skifton
Idaho National Laboratory (INL)

Outline:

1) Introduction to molten salts and HTREs
2) Materials selection challenges of working in HTMS
3) High-Temperature Reference Electrode (HTRE) design
4) HTRE experimental test setups
5) HTRE test results
6) Summary
7) HTRE brochure

hifunda
Innovative Energy & Materials Solutions

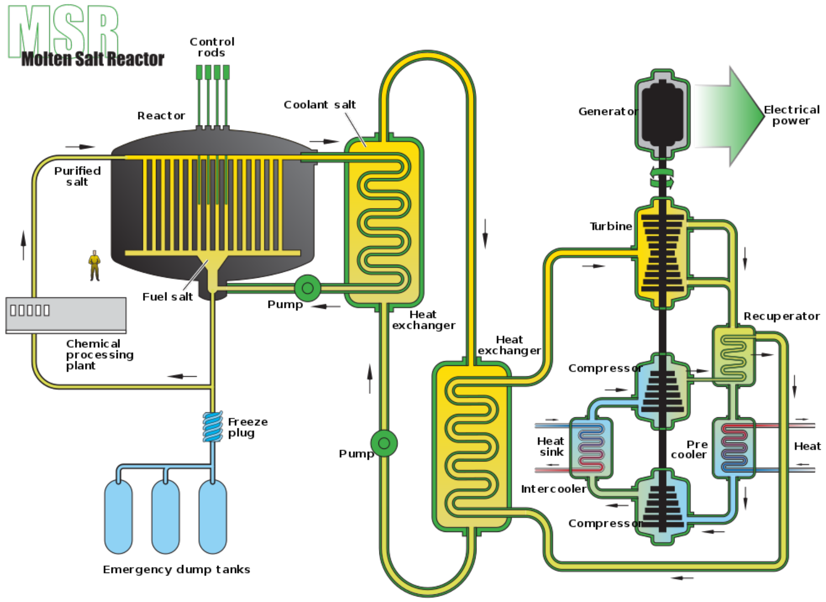
THE UNIVERSITY OF UTAH

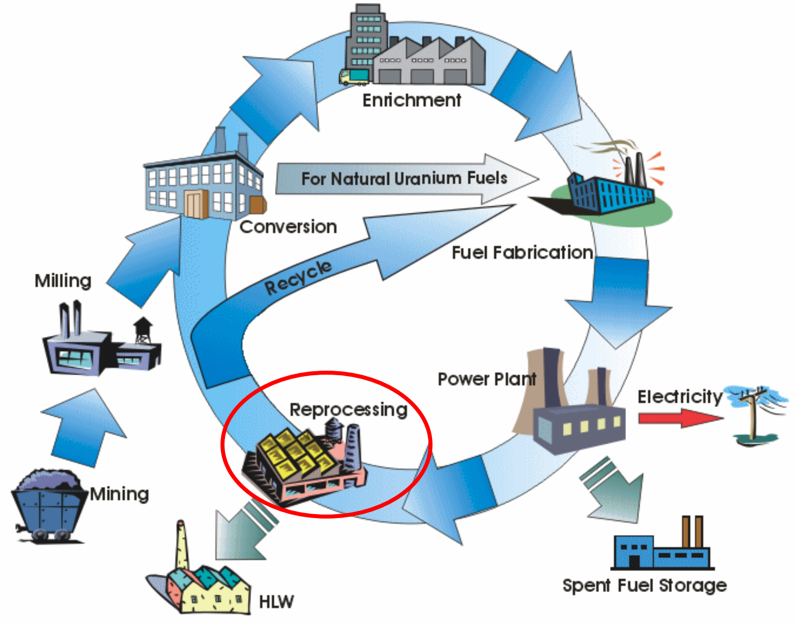
DOE SBIR Phase II, DE-SC0020579, "Stable High-Temperature Molten Salt Reference Electrodes"

Idaho National Laboratory

Uses and Importance of Molten Salts

- **Radiation resistant** with stable operating temperature range from about 400 to 800°C
- **Molten salt mixtures can be tailored** to achieve desired properties: liquidus temperature, reactivity, vapor pressure, etc. and can dissolve fissile and fertile actinides
- **Several applications** for nuclear energy and fuel cycle technology
  - **Pyroprocessing** of spent nuclear fuel
  - **Liquid fuel/coolant** for molten salt reactors
  - **Tritium breeding blankets** for sustainable fusion systems
- **HTMS enable electrochemical methods for separations, corrosion control, and real time composition monitoring**





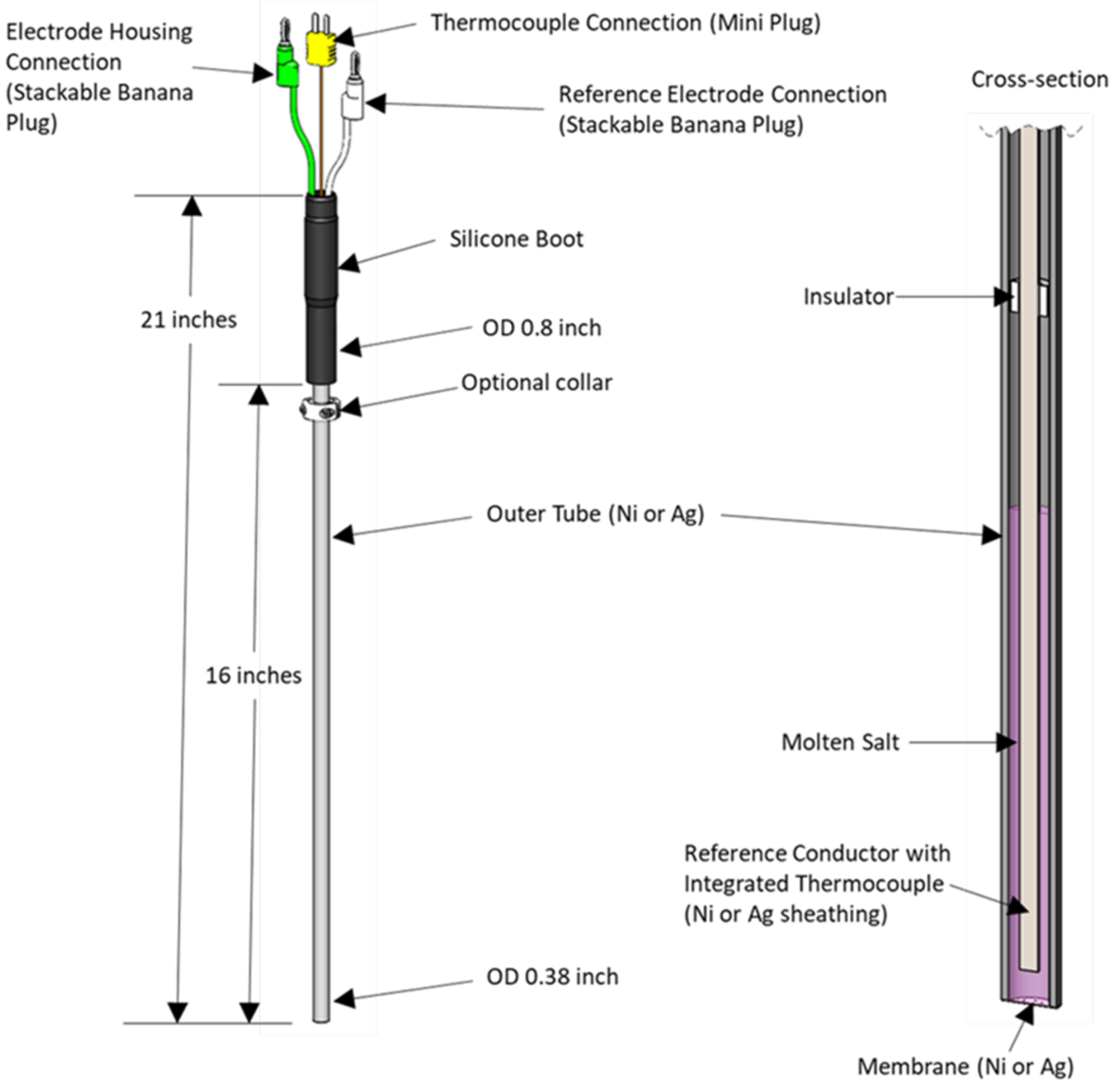
High-Temperature Reference Electrodes (HTRE) for Molten Salts

- Known, fixed, **thermodynamic reference potential** is critical for MS electrochemical analyses and sensors

- HTREs consist of 3 essential components
    1) Metallic reference conductor (**Ni**)
    2) Reference molten salt mixture (**NiF_2/FLiNaK**)
    3) Ion conductive membrane (**Controlled porosity Ni**)

- HiFunda's HTREs have 3-fold functionality:
    1) Stable thermodynamic reference potential
    2) Integral temperature sensor
    3) Redox sensor

- Materials challenges for HTRE components in fluorides



Chemical Compatibility of HTRE Materials in FLiNaK

- Materials tested in FLiNaK at 750 °C for 500 hours
- ***Ni, Ag, and graphite are suitable for use in FLiNaK***
- ***Mullite, quartz, and alumina*** membranes are good for chloride melts, but ***are not compatible with FLiNaK***

Sample images before/after 500-hours corrosion test at 750°C in FLiNaK
Top image is pretest and bottom image is posttest

Table 1. Pretest and posttest masses for each corrosion sample

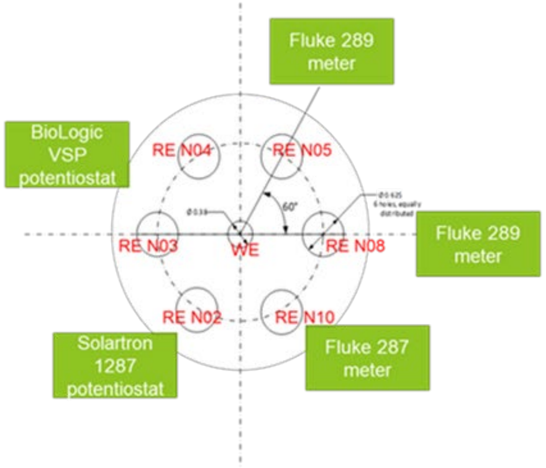
Sample	Pre Sample (g)	Post Sample (g)	Delta (g)	Delta (%)
AX05	2.4399	2.4358	0.0041	0.17%
Ni Frit	0.3894	0.3943	-0.0049	-1.26%
Pure Ni	2.2116	2.2069	0.0047	0.21%
Alumina	0.7892	0.908	-0.1188	-15.05%
Porous Ni	0.141	N/A		
Mullite	1.4196	N/A		
Quartz	0.9134	N/A		
PBN	0.22	0.2034	0.0166	7.55%
ZXF	15.2874	15.2909	-0.0035	-0.02%
Ni201	12.5637	12.5413	0.0224	0.18%
Ag	22.5602	22.5642	-0.004	-0.02%

A negative delta indicates a mass gain

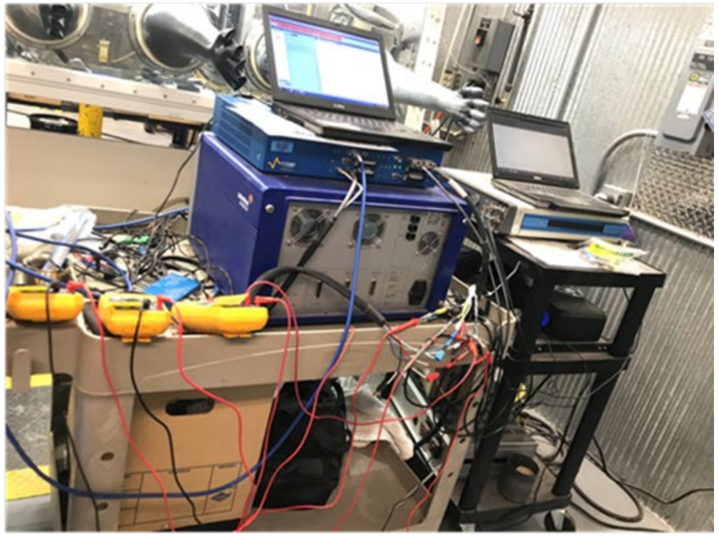
Table 2. ICP data results of FLiNaK melt after 750°C corrosion testing

	750°C Corrosion Test ICP Data Average (Wt% in Salt)							
Sample	B	Ni	Al	Si	Ag	Fe	Mn	Cu
AX05	0.2257%							
Ni Frit		0.0083%						
Pure Ni		0.0109%						
Alumina			0.7067%					
Porous Ni								
Mullite			0.4587%	1.2992%				
Quartz		0.0038%	0.0194%	2.1120%				
Empty Control	Below Limit			1.5723%	0.0033%	Below Limit	0.0354%	Below Limit
PBN	0.0060%							
ZXF	Below Limit	0.0070%	0.4392%	1.1578%	0.0101%		0.0617%	Below Limit
Ni201		0.0113%		1.7929%		0.0800%	0.0246%	Below Limit
Ag					0.0057%			

Experimental Test Setups for HTRE Testing in FLiNaK

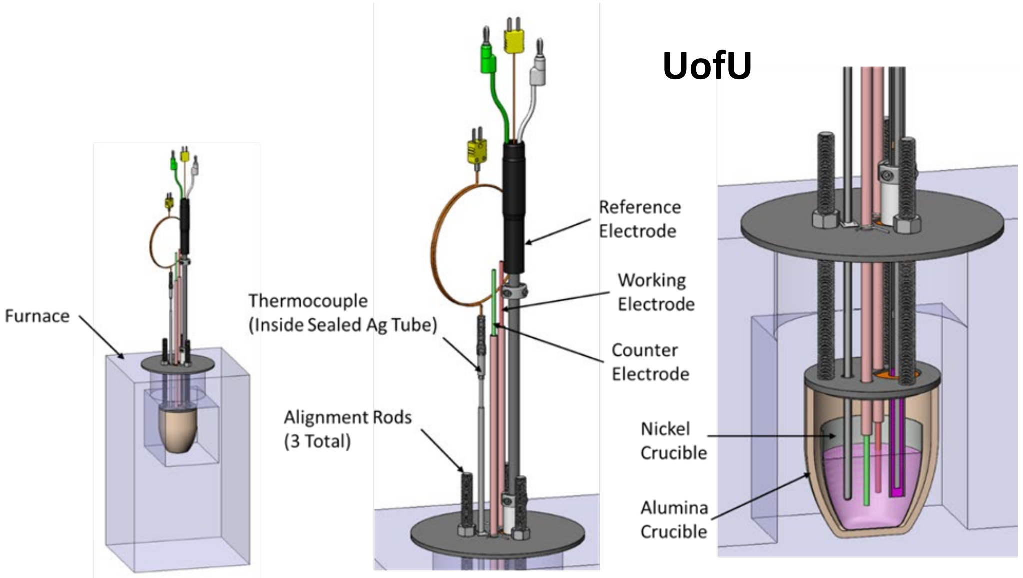


INL



Data acquisition challenging in glove box with multiple measurement instruments

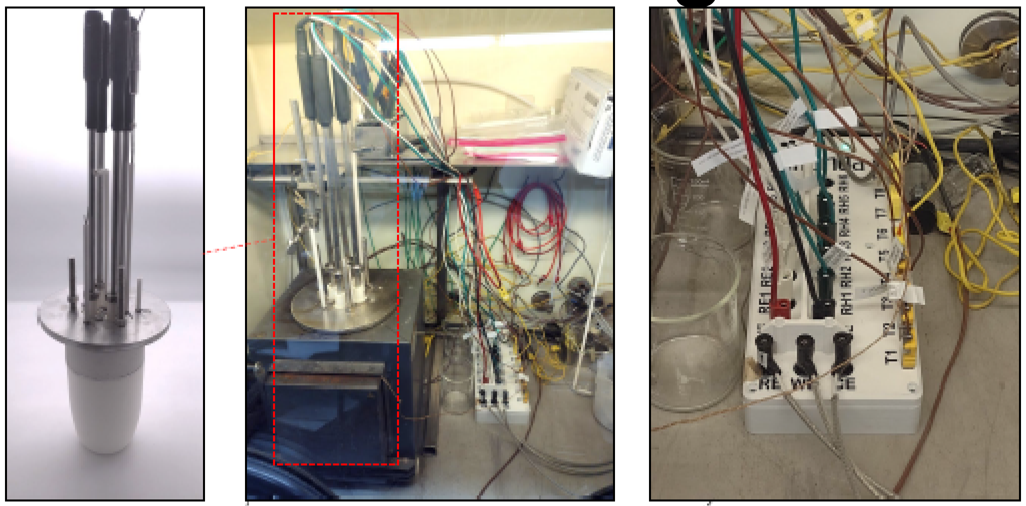
UofU

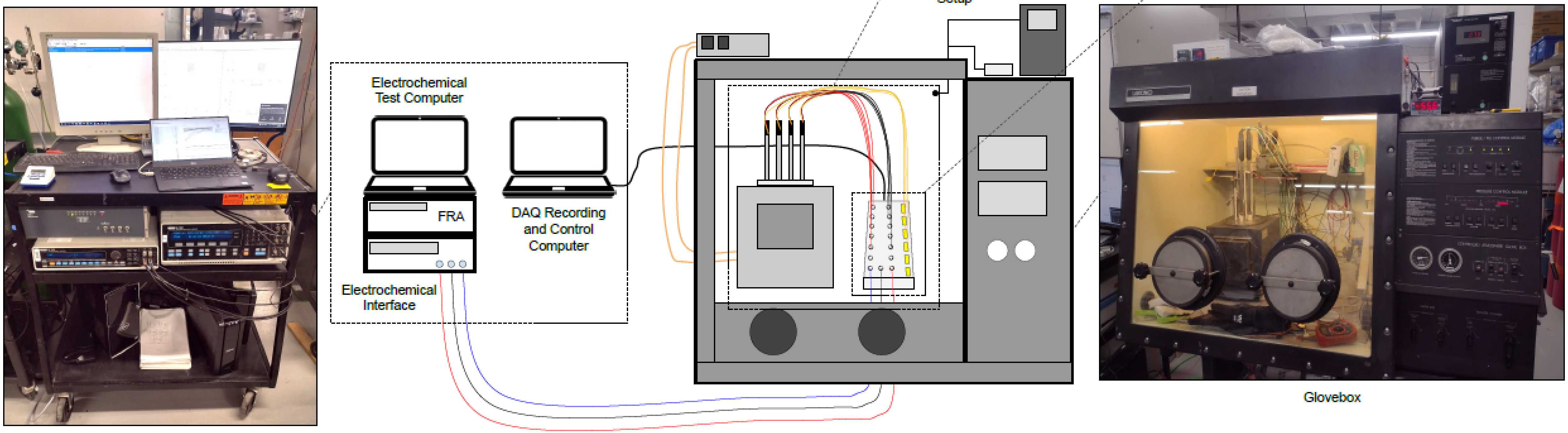


100 cc Ni crucible size

Experimental Test Setups for HTRE Testing in FLiNaK

- HiFunda established **custom data acquisition system (DAQ) for long-term testing**
- **Single USB feed-through** for monitoring 10 thermocouples (TCs), WE, CE, 6 HTREs, and 6 HTRE housings vs. time
- **Configurable** sampling rate, Inputs/Outputs (I/O) for electrochemical testing (EIS, CV, SWV, etc.)

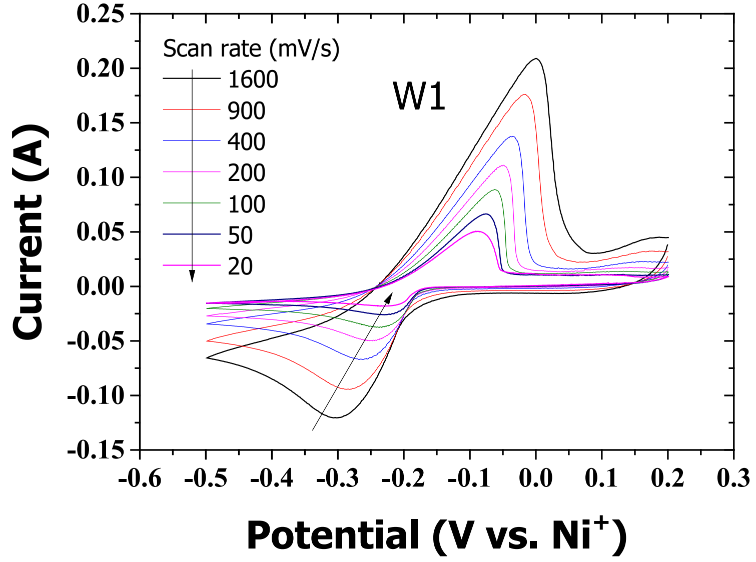


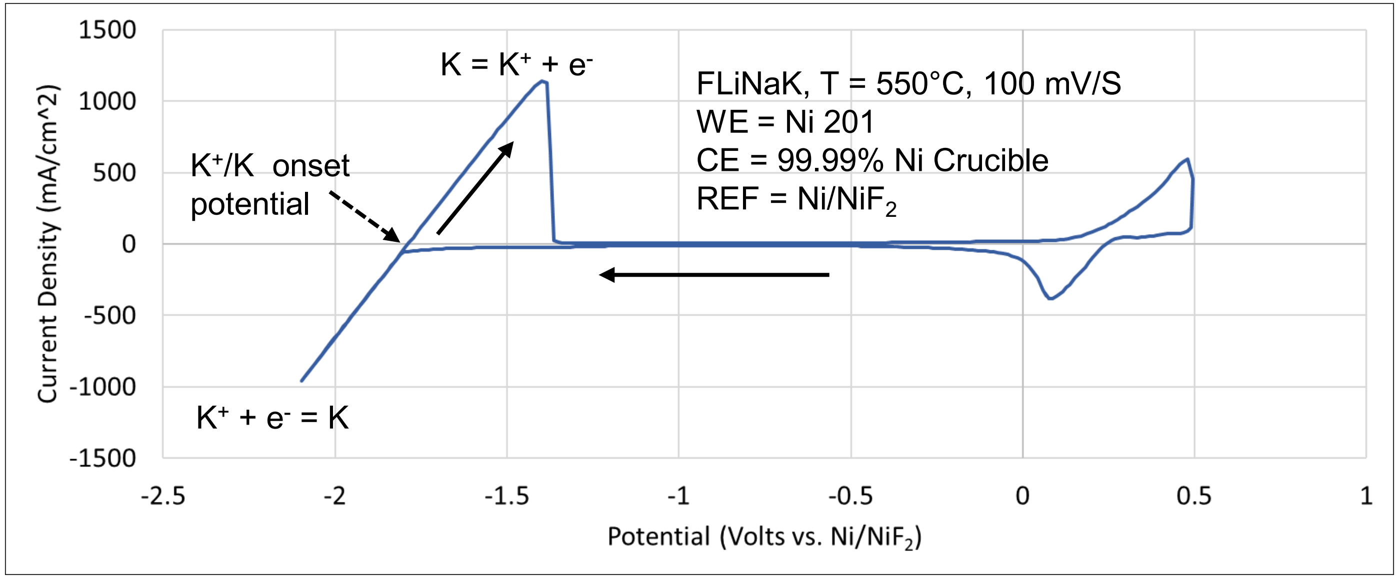


Electrochemical Test Results with Ni/NiF_2 HTREs in FLiNaK

- CV and EIS measurements
  - Onset potential for K/K^+
  - Vary sweep rate to determine diffusion coefficients and/or concentrations
- 90-days long-term HTRE test underway
  - FLiNaK, T= 550°C
  - WE = Ni 201
  - CE = 99.99% Ni crucible
  - REF = Ni/NiF_2 (4 each)
- OCP measurements
  - WE vs. HTREs, WE vs. CE, Housing vs. HTREs, between HTREs
  - Challenge tests: T, O_2, sequential NiF_2 additions

$Fe^{2+} + 2e^- \rightarrow Fe\ (s)$



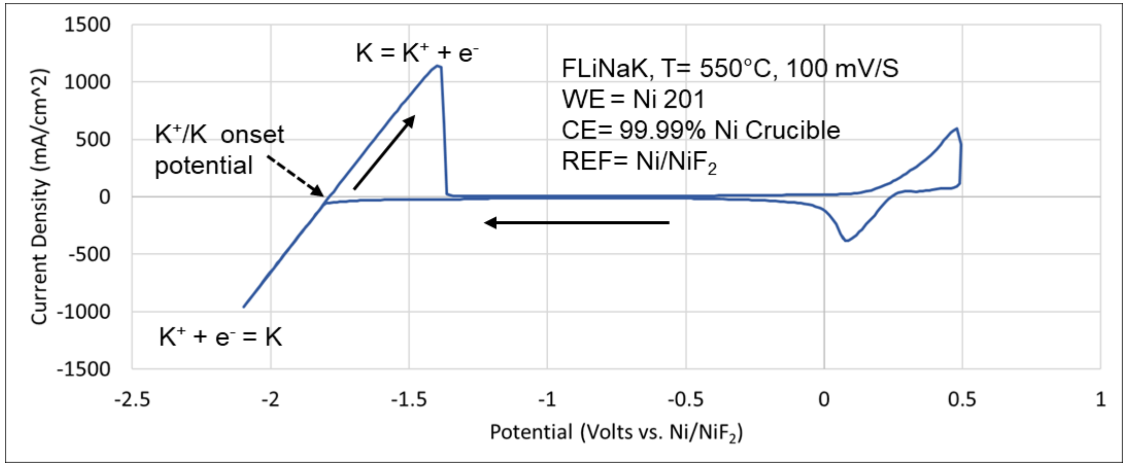


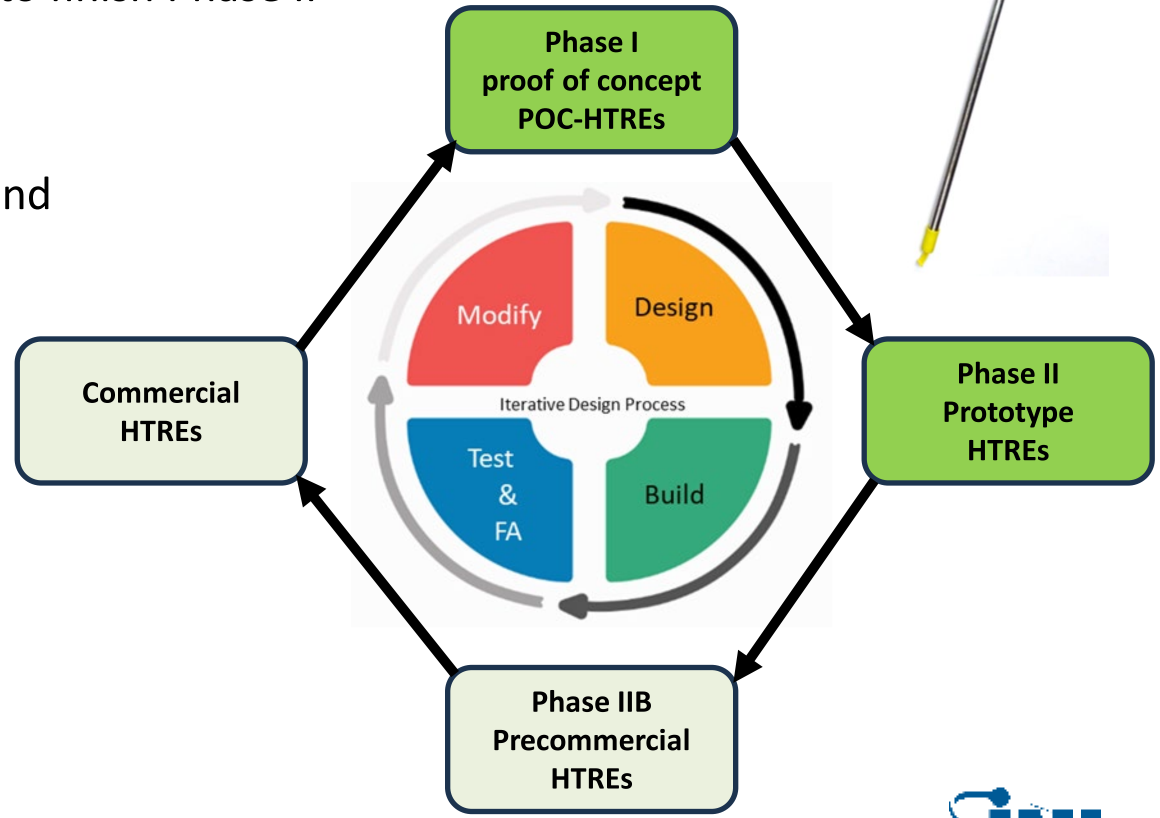
Berzins-Delahay equation

$$i_p = 0.61 \left(\frac{F^3}{RT}\right)^{1/2} n^{3/2} A D^{1/2} C v^{1/2}$$

Summary

- Designed, developed, and tested **prototype Ni/NiF_2 HTREs with 3-fold functionality**:
  1) Stable thermodynamic reference potential
  2) Integral temperature sensor
  3) Redox sensor
- Performed chemical compatibility tests of HTRE materials in FLiNaK up to 750°C
- Electrochemical measurements (OCP, CV, and EIS) indicate **HTREs are performing well**
- Long-term (90 days) testing and evaluation of HTREs underway to finish Phase II
  - Challenge tests are next (NiF_2 additions and vary T)
- HTREs can be customized (See brochure)
- **Additional funding required** to further develop, demonstrate, and commercialize HTRE technology
- **Submitting Phase IIB SBIR proposal** in December, 2023





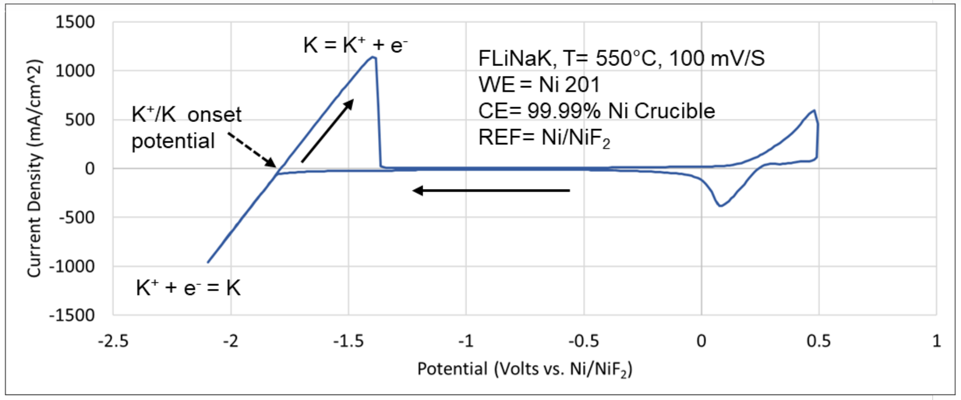
Custom High-Temperature Reference Electrodes

HiFunda has developed and demonstrated a robust thermodynamic high-temperature multi-functional reference electrode (HTRE) for performing electrochemical measurements in molten salt applications.

Until now, there have not been commercially available robust HTREs, causing scientists to make their own HTREs with inherent variability due to differences in design and fabrication methods. HiFunda can provide standard or custom HTREs for your application so your team can focus on electrochemical processing and product development.

HiFunda's Ag/AgCl, Ag/AgF, and Ni/NiF_2 HTREs are designed, built, and characterized for your application. Each HTRE has three-fold functionality 1) stable thermodynamic reference potential, 2) integral temperature sensor, 3) redox sensor.

The HiFunda HTRE technology was developed as part of DOE SBIR projects where we teamed with Idaho National Laboratory and the University of Utah to test and demonstrate HTREs for operation in molten chloride and fluoride salts.



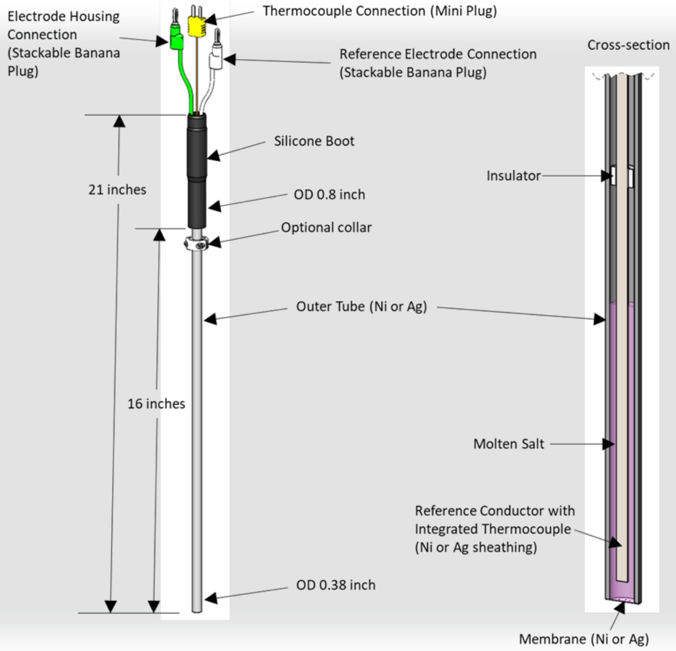
SBIR Projects and Technical Presentations:

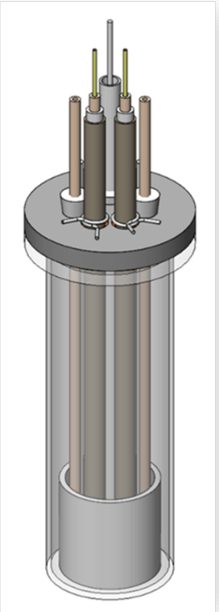
1) Robust, Standardized High-Temperature Molten Chloride Salt Reference Electrodes, DE-SC0021439 https://www.sbir.gov/sbirsearch/detail/2056865
2) Stable High-Temperature Molten Salt Reference Electrodes, DE-SC0020579 https://www.sbir.gov/sbirsearch/detail/2104123
3) "Robust and Standardized High-temperature Molten Chloride Salt Reference Electrode," 2022 TMS Annual Meeting & Exhibition
4) "Long Term Stability of Ag/AgCl Reference Electrode in Molten Chloride Salt," Log 254, 12th International Conference on Methods and Applications of Radioanalytical Chemistry 2022
5) "Long Term Stability of Mullite and Magnesia-Encased Ag/AgCl Reference Electrodes in Molten $MgCl_2$-KCl-NaCl," J Electrochemical Society, 170, 057505, (2023).
6) "Comparison of Ni/NiF_2 and Ag/AgF for a Stable Redox Couple for Molten Fluoride Salt Reference Electrodes, 2023 American Nuclear Society Annual Meeting, June 11-14, (2023), Indianapolis, IN.
7) "Material Challenges for Development of Long-Term Stable Reference Electrodes," The American Ceramic Society, Materials Challenges in Alternative & Renewable Energy (MCARE), August 21, 2023.

HiFunda can help to solve your greatest electrochemical and materials challenges

CONTACT:
Jim Steppan, VP R&D
801-750-4928
jsteppan@hifundallc.com

Customized HTREs for Your Molten Salt Applications





Standard HTREs

HTRE Type	Reference Wire	Housing	Membrane	Reference Melt	Wire Length (inches)	Thermocouple	HTRE length (inches)	Max Use T (°C)	Immersion Depth (Inches)	Interface	Part No.
Ni/NiF_2	Ni201	Ni201	Ni201	NiF_2/FLiNaK	36	Type K	21	750	4	Collar	Ni/NiF2-2222-3223-222-1111
Ag/AgF	Ag99.9	Ag99.9	Ag99.9	AgF/FLiNaK	36	Type K	21	750	4	Collar	Ag/AgF-1211-2123-222-1111
Ag/AgCl	Ag99.9	Ag99.9	Ag99.9	AgCl/$MgCl_2$, NaCl, KCl	36	Type K	21	750	4	Collar	Ag/AgCl-1211-2323-222-1111
Ni/$NiCl_2$	Ni201	Ni201	Ni201	$NiCl_2$/MgCl2, NaCl, KCl	36	Type K	21	750	4	Collar	Ni/NiCl2-2222-3423-222-1111

HTRE Customization Options

Feature	Description	1	2	3	4	5	6	7	8	9	Comments
A	Reference conductor	Ag99.9	Ni201	other customer specified (OCS)							Options highlighted in green correspond to standard Ag/AgF HTRE
B	Housing Diameter	0.5	0.38	0.25							
C	Housing Material	Ag99.9	Ni201	OCS							
D	Membrane type	Ag99.9	Ni201	Mullite	MgO	OCS					Mullite and MgO are not compatible with fluorides
E	Membrane leak rate (MLR, sccm)	0.0	0.1	1	10	OCS					Ni, Ag, and MgO MLR can be customized. Mullite MLR = 0
F	Reference melt	AgF/FLiNaK	NiF_2/FLiNaK	AgCl/Chloride solar salt (Future2B)	NiCl2/Chloride solar salt (Future 2b)	Nitrate solar salt (Future2B)	AgF/FLiBe (CDS)	OCS			Test melt plus reference salt
G	Reference salt composition (mol%)	0.1	1	100	OCS						Reference salt = AgF, NiF_2, AgCl, or $AgNO_3$
H	Wire length (inches)	12	24	36	OCS						
I	Thermocouple Type	None	K: single	K: triple profile	N	OCS					
J	Immersion depth (inches)	2	4	6	8						Immersion depth and total length are linked.
K	Total HTRE length (inches)	19	21	23	27						Total length is linked to maximum use temperature
L	HTRE Interface	SS316 collar for height adjustment	Isolated swagelok fitting	Nonisolated swagelok fitting							OCP of HTRE housing independent of piping OCP when isolated and the same as piping when OCP not isolated
M	Characteristic CV	T=550°C	T=650°C	T=750°C							CV at 550°C included with 3 sweeps, additional cost for other temperatures
N	Verification testing	0	1	12	24	100					Additional cost for verfiication testing (~$100/hr)
O	CofC	Not required	Required								Additional cost for CofC (~$50)
P	*Custom development services (CDS) available to benchmark or optimize the RE and to demonstrate electroanalytical determination of Cr or Fe for each customer's salt mixture of interest*										
Q	*Turnkey services available to design and build HT electrochemical test setups*										

HiFunda works with customers to solve their most demanding technical challenges to develop and commercialize new materials and technologies

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Control Valve Material Combinations in 750^{o}C chloride molten salt

Jeff Parish – R&D Valve Technology Principal

Flowserve

Background – Driving Research Factors

Based on a DOE desire to develop control valves that can safely operate in a ternary molten chloride salt at 750 °C for Gen 3 Concentrated Solar Power (CSP) applications, an extensive material screening study was performed under static conditions with valves constructed from the down selected materials and tested under dynamic environmental conditions in a custom flow loop.

Selected materials must allow the valves to provide the following:
- Flow and pressure control at full temperature and pressure
- Be leak resistant
- Be freeze recoverable
- Easy to maintain
- Scalable to commercial sizes

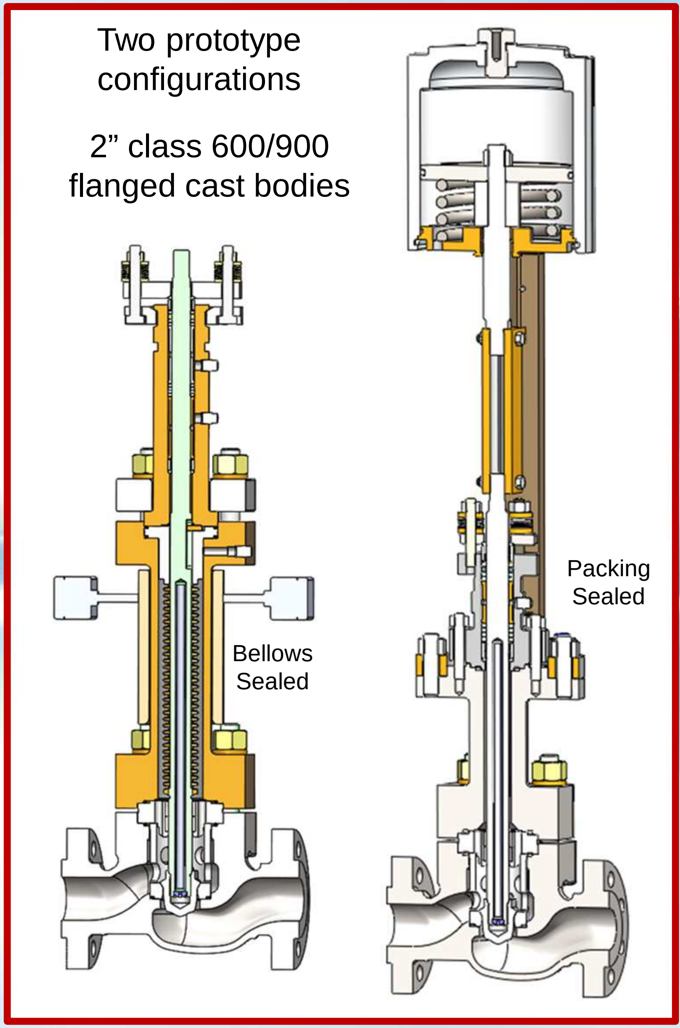
To avoid high temperature and ion migration galling under dynamic actuation, at least three different materials of construction (metallic and/or ceramic) are required for proper control valve design. Candidate materials must demonstrate corrosion resistance and maintain adequate strength at 750 °C.

Material applications include these primary functions:
- Pressure containing shell
- Trim material
- Guide and seat material
- Sealing material

[1] Text Bottom of chart

Based on these criteria up to 12 materials were tested at the same time in a static salt pot test to evaluate the interactions between them in a common salt environment.

Funding for this project was supported by SNL Award # 36335 and DE-EE0002064-2260.



FLOWSERVE

Experimental Setup and Design

Static Corrosion Tests

- 500 hour test with an Alumina crucible
- Best performing materials down selected
- 1300 hour test with a 6%NiWC crucible
- Atmospheric pressure
- Nitrogen gas purge
- $750^{o}C$
- NaCl-KCl-MgCl

[1] Text Bottom of chart

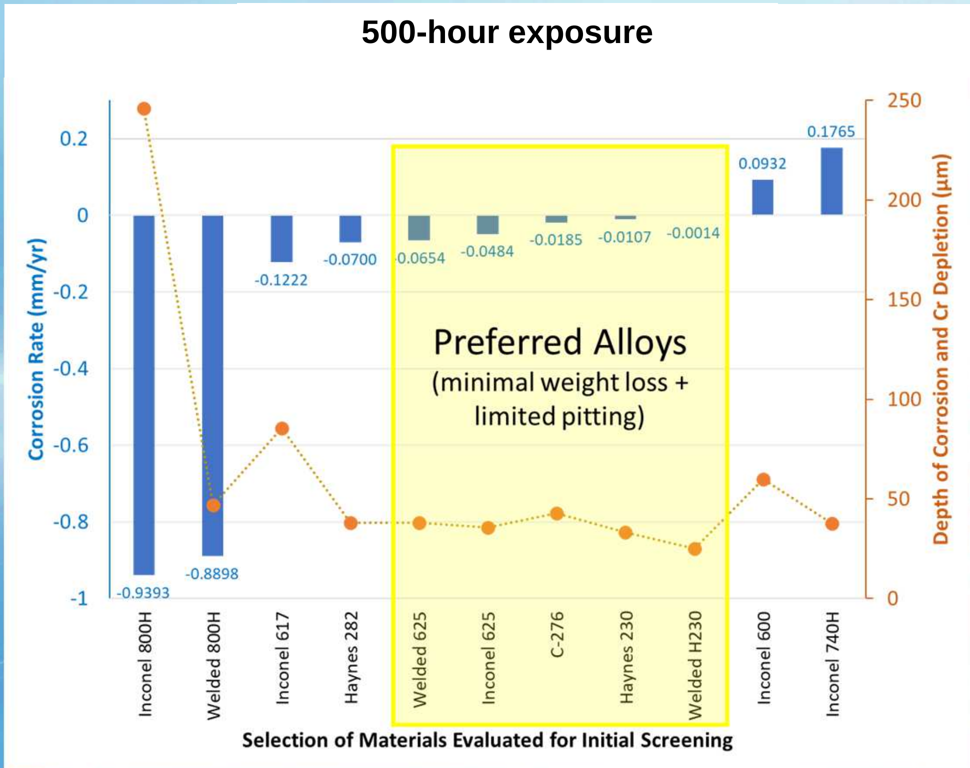
Dynamic Flow Loop Tests

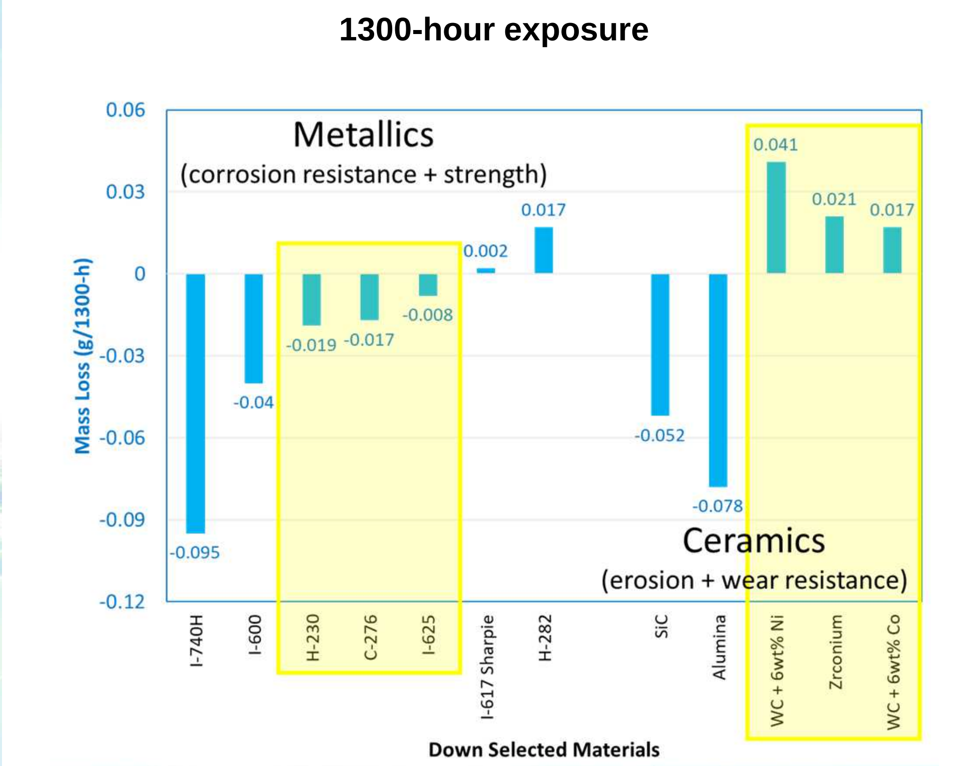
- 3 testing stations
- 2 direct contact pressure sensors
- 2 control valves and 1 sampling spool
- 15 gpm mag drive pump at 1 Bar
- 1-10 Bar system pressure with N2
- $530^{o}C$ - $750^{o}C$ up to 11 Bar total pressure
- NaCl-KCl-MgCl

Flow Loop Test Results

- ~500 hours of operation
- No leaks at flanges, seals, and packing
- Reached full temperature and pressure
- Thermal profile matched predicted
- Valves operated well
- No material issues with the valves
- 316/304 is not to be used even on cold salt side

Selected Results of the Static Corrosion Tests





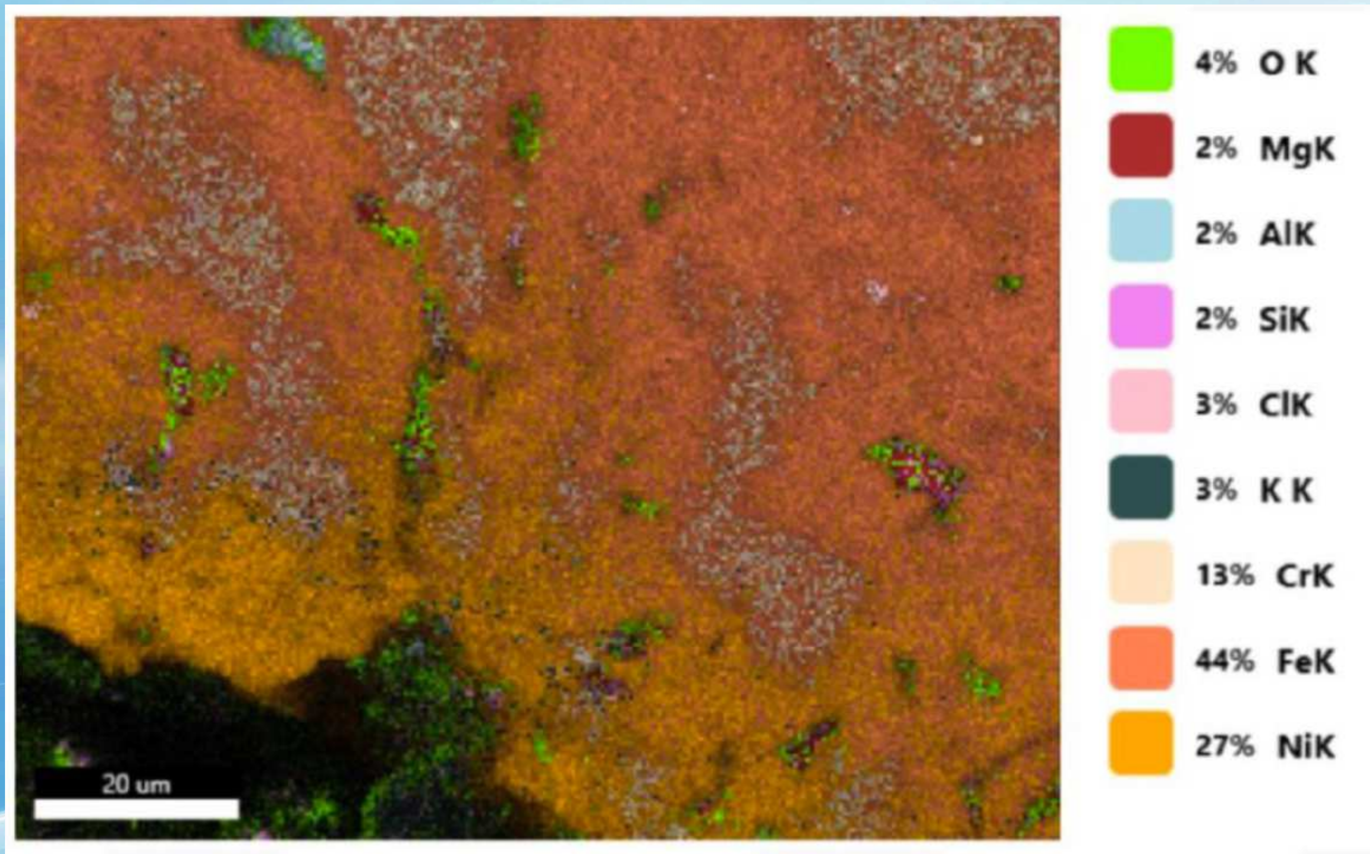
[1] Text Bottom of chart

Selected Comparison of Material Compositions

Alloy (UNS)	Ni	Cr	Mo	W	Nb (Cb) + Ta	Ti	Co	Mn	Cu	Al	Fe
I-600 (N06600)	bal.	14.0 to 17.0						1.0 max.	0.50 max.		6.0 to 10.0
H-282 (N07208)	bal.	20	8.5			2.1	10	0.3 max.		1.5	1.5 max.
I-617 (N06617)	bal.	20.0 to 24.0	8.0 to 10.0			0.6 max.	10.0 to 15.0	1.0 max.	0.5 max.	0.8 to 1.5	3 max.
I-740H (N07740)	bal.	23.5 to 25.5	1.0 max.		0.5 to 2.5	0.5 to 2.5	15.0 to 22.0	1.0 max.	0.50	0.2 to 2.0	3 max.
I-800 (N08810)	30.0 to 35.0	19.0 to 23.0				0.15 to 0.60	0.15 to 0.60				bal.
H-230 (N06230)	bal.	22	2	14	0.5 max.	0.1 max.	5 max.	0.5		0.3	3 max.
I-625 (N06625)	bal.	20 to 23	8 to 10		3.15 to 4.15	0.4	1	0.5		0.4	5
C-276 (N10276)	bal.	16	16	4			2.5 max.	1.0 max.	0.5 max.		5

Selected Results of the Static Corrosion Tests

Inconel 800H (500-h)



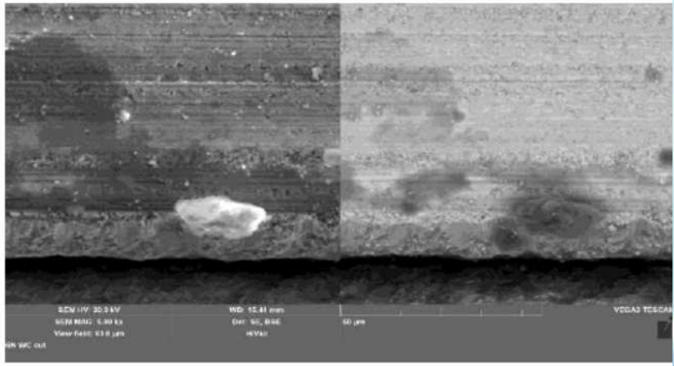
High Cr & Fe wt% likely contributed to enhanced corrosion of 800H.

Whisker Deposits

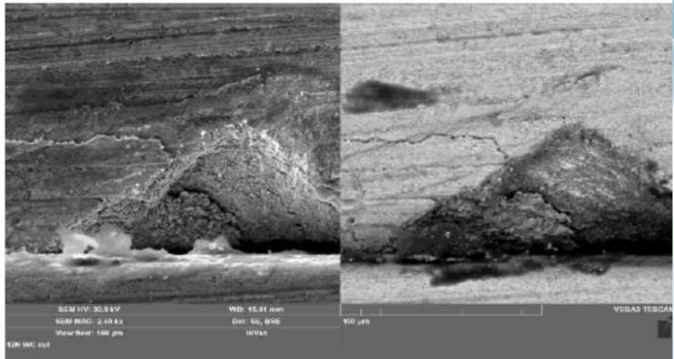
FLOWSERVE

Selected Results of the Static Corrosion Tests

6% Nickel Binder Tungsten Carbide



12% Nickel Binder Tungsten Carbide



Whisker reinforced PSZ

Mica Windings

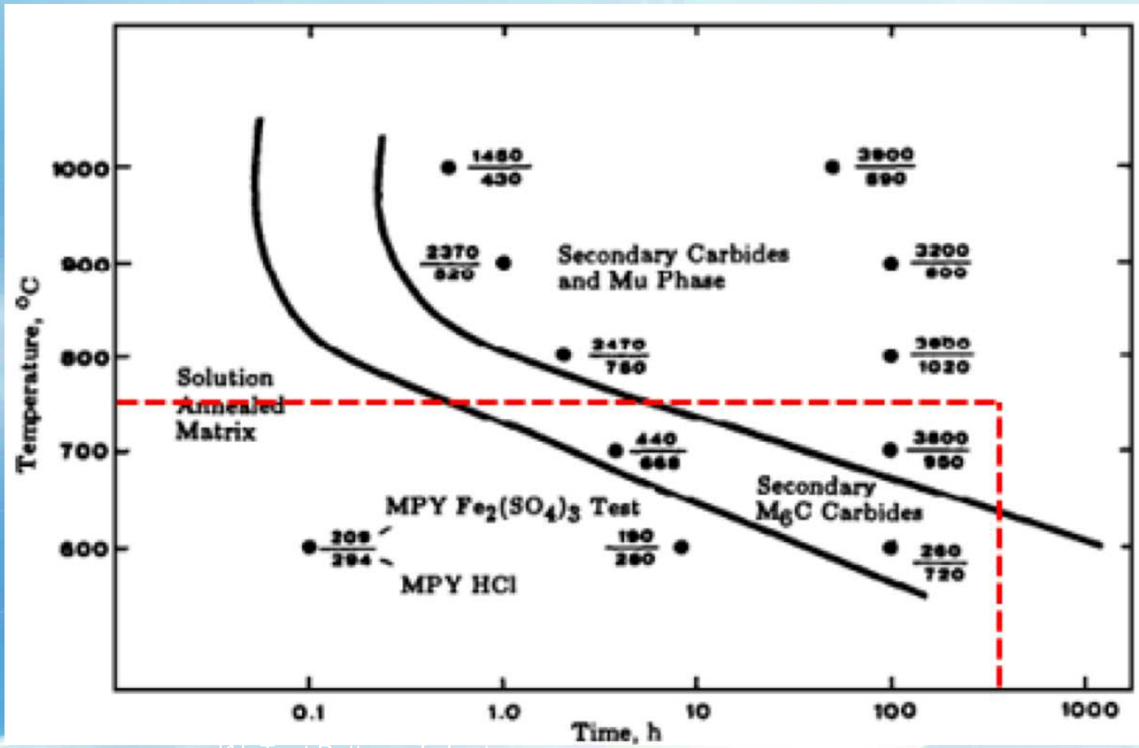
Graphite

Thermiculite

FLOWSERVE

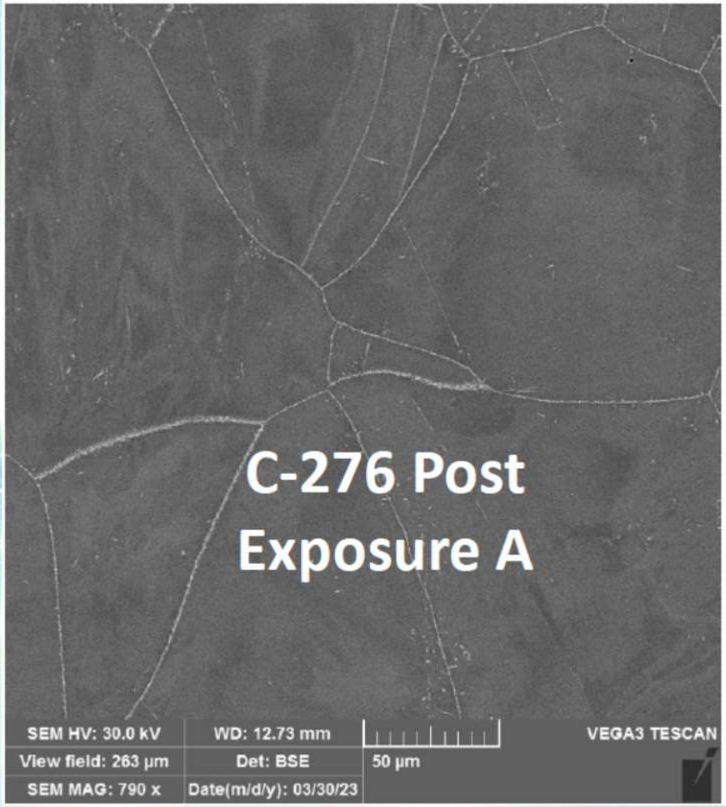
Selected Results of the Static Corrosion Tests

Hastelloy C-276



[1] Text Bottom of chart

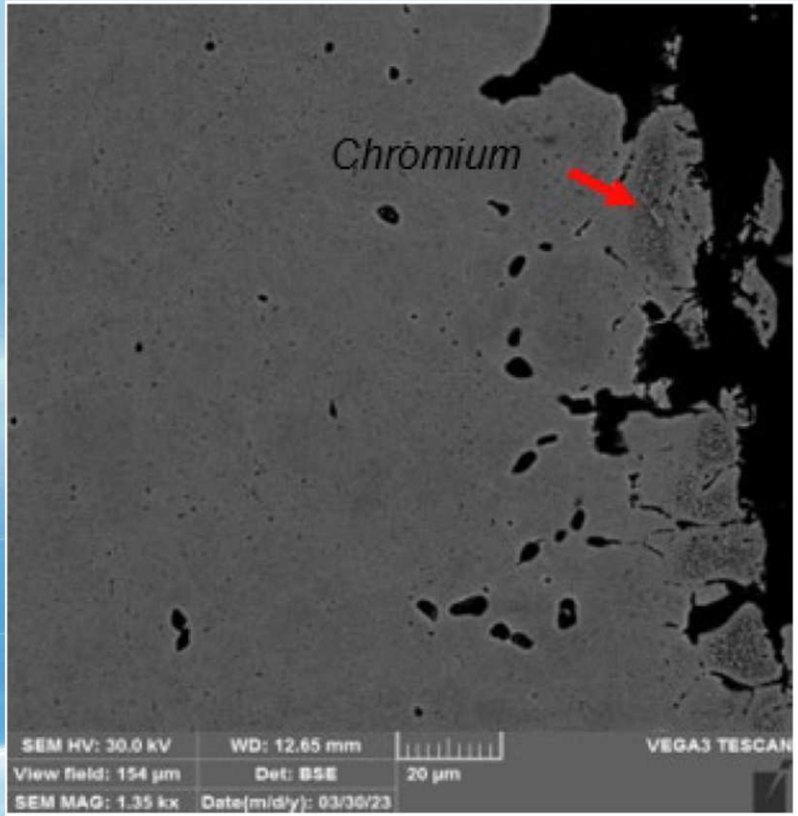
Chromium Carbides



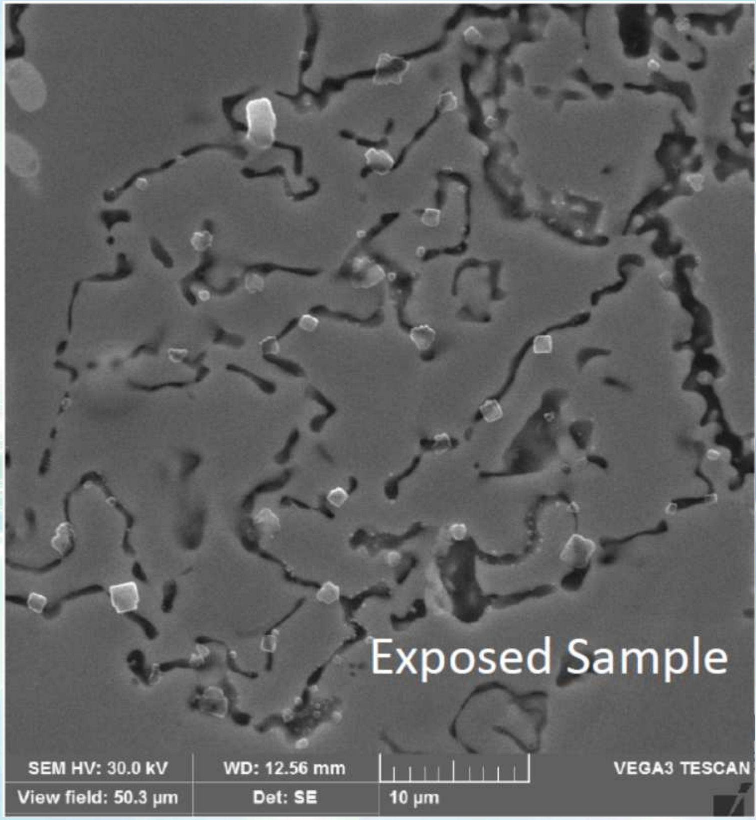
At 750 °C, C-276 is susceptible to chrome carbide sensitization.

Selected Results of the Static Corrosion Tests

Inconel 600 SEM



Haynes 230 SEM



Conclusions

- Of the metals tested, H-230 and I-625 performed best, demonstrating both the *lowest corrosion rate* and *highest mechanical strength*.
- C-276 had an unexpected corrosion resistance on par with H-230, although not nearly the strength post-test.
- At 750 °C, alloy sensitization, leading to loss of strength, occurred within the first 500 hours, but eventually leveled off; this must be considered during design.
- Of the ceramics evaluated, 6%NiWC showed remarkable performance as did whisker reinforced PSZ.

While enough questions were answered to validate a functional material combination for manufacturing control valves for use in 750ºC chloride molten salt, a lot more questions were generated that could feed years of additional research.

Flowserve at a Glance

Over 50 Countries

~16,000
Employees

5,000,000+ Assets
(Installed Base)

FLOWSERVE

Over 50 Leading
Product Brands

163
Aftermarket QRCs
(Quick Response Centers)

10,000+
Customers Annually

FLOWSERVE

Global Reach and Local Presence

GLOBAL REACH
AND LOCAL PRESENCE

Flowserve people, processes and experience are keys to providing critical local support for customers in more than **50** countries. Flowserve has **180 quick response centers** and **75** manufacturing facilities across the world.

*Excludes non-consolidated Joint Venture operations

- **World Headquarters**
- **Sales Offices**
- **Service Centers & Quick Response Centers**
- **Manufacturing Plants & Regional Operations Centers**

FARADAY TECHNOLOGY, INC.

Overlays for Improved Corrosion Resistance During MSR Operation

T.D. Hall[1], B.A., Pint[2], H. Garich[1], M. Inman[1], D. Sulejmanovic[2], and C. Beamer[3]

[1] Faraday Technology Inc., Englewood, OH, USA
[2] Oak Ridge National Laboratory, Oak Ridge, TN, USA
[3] Quintus Technologies, LLC, Columbus, OH, USA

2023 Molten Salt Reactor Workshop

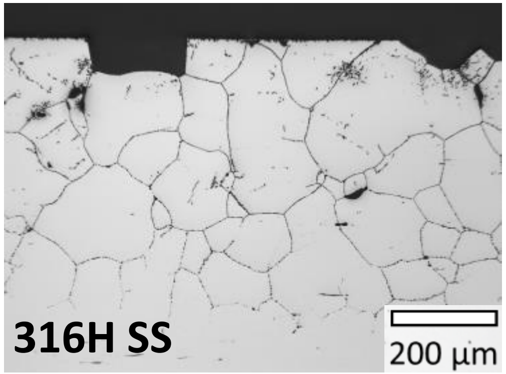
October 26, 2023

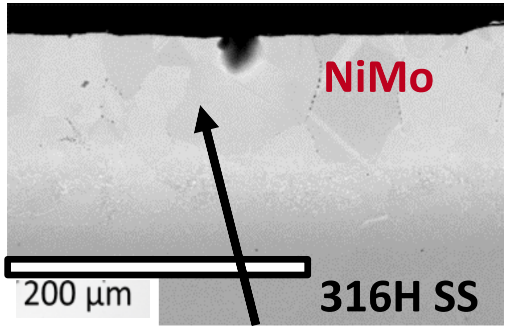
OAK RIDGE National Laboratory

Quintus TECHNOLOGIES

Bottom Line Up Front

- Motivation to enable higher temperature nuclear reactor operation and use of molten salts
- Electrodeposition of functionally graded NiMo overlay for corrosion protection of 316H SS in molten salts
  - Scalable for MSR components including internal surfaces
  - Enables lower cost, ASME-certified boiler materials
- Post-deposition Hot Isostatic Pressing (HIP) creates a diffusion bond between overlay and substrate
- Significant improvement in corrosion resistance of 316H SS substrate after exposure to FLiNaK up to 750^{o}C / 1,000 hr (static corrosion tests)
- Functionally graded NiMo overlays deposited on 8" pipe segments for flowing loop test
- Preliminary estimates show significant cost savings for NiMo overlays on 316H SS (vs Hastelloy N)





Functionally graded, diffusion bonded NiMo overlay

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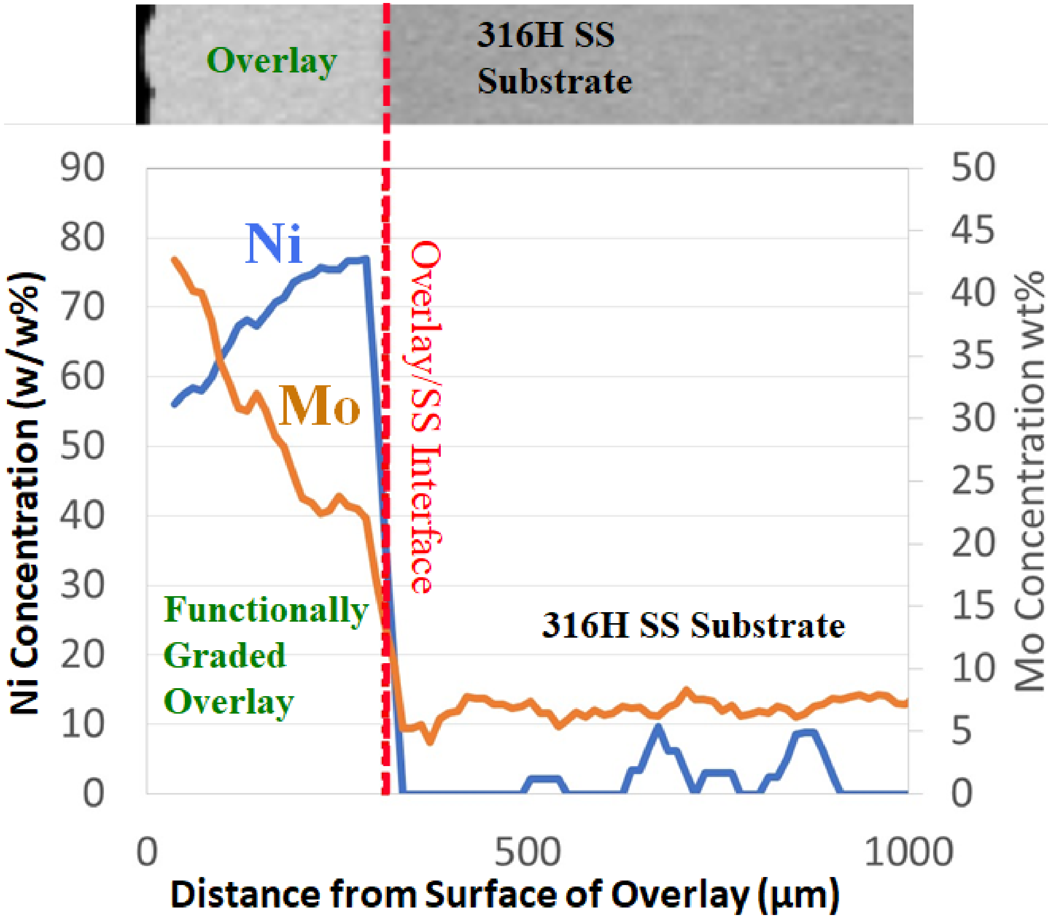
US Patent Application: 63/502,767; 5/17/2023

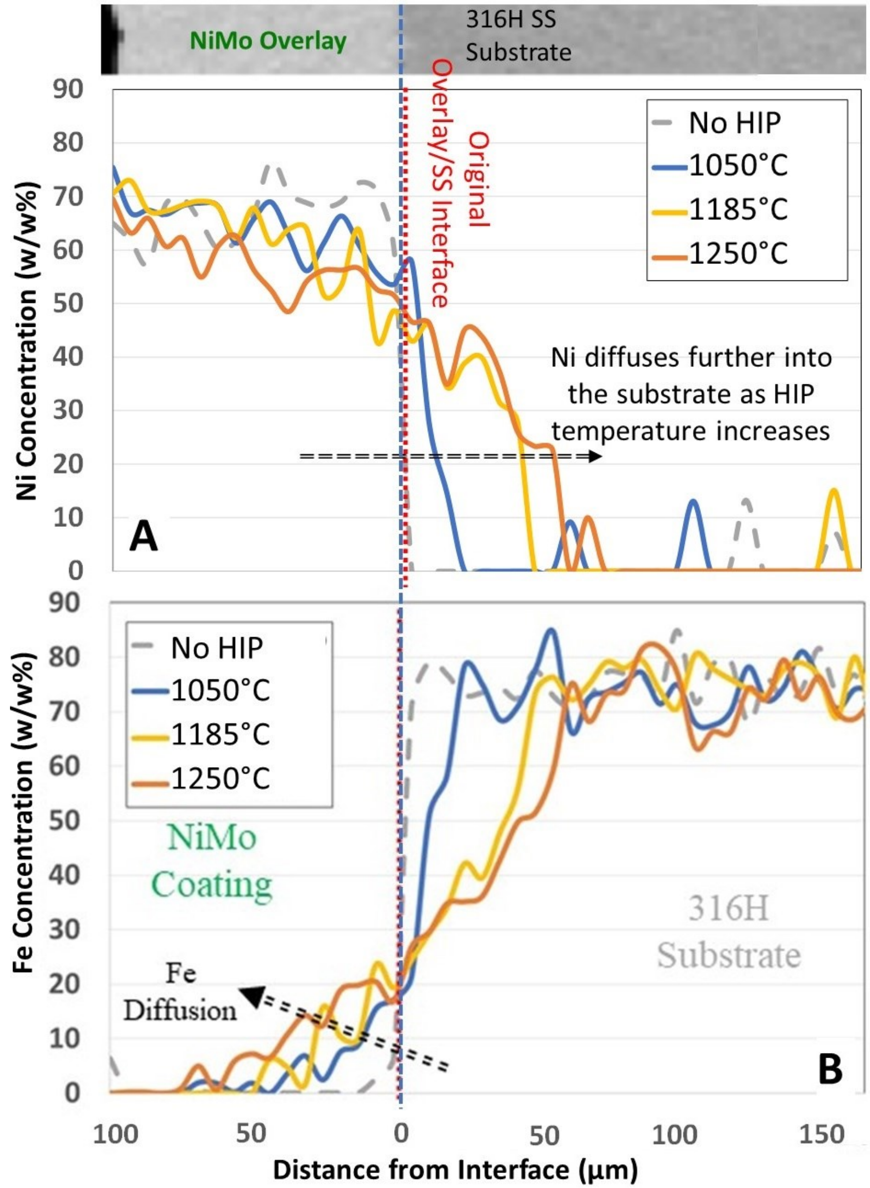
Electrodeposited Functionally Graded Overlay

- Functional grading of composition
  - Reduces CTE mismatch between substrate and overlay
  - Ni-rich at the 316H SS (or Ni alloy) substrate and Mo-rich at the surface



Diffusion Bonded Functionally Graded Overlays

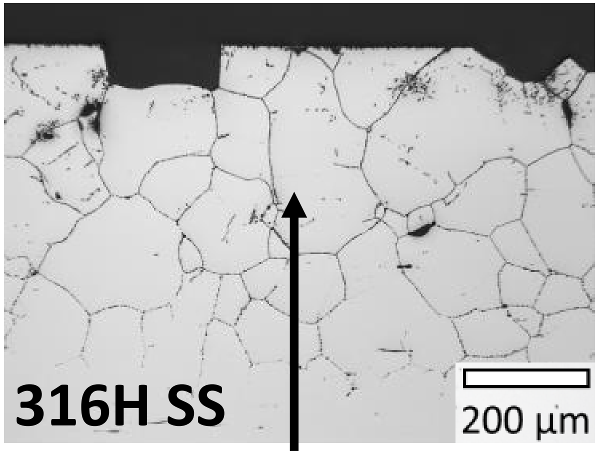
- Diffusion bonding creates a metallurgical bond
  - ➢ Diffusion of species in and out of substrate is evidence of diffusion bonding
  - ➢ Ni and Mo diffuse into the 316H SS
  - ➢ Fe and Cr diffuse out of 316H into NiMo
- ➢ Effect of Variables
  - ➢ Higher temperatures increases diffusion of species (1050 to 1250^{o}C) (next slide)
  - ➢ Longer soak time increases diffusion of species (1.75 to 7 hours)
  - ➢ HIP pressure (14,500 vs. 22,000) has minimal effect



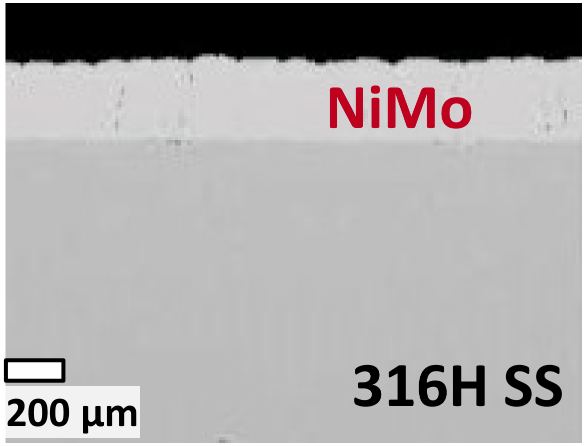
Static Pipe Test Setup

- Static testing prior to flowing loop test
- Performance of overlays on 316H SS pipe
  - Compared to coupons: 700°C/500 h in FLiNaK
  - Several thicknesses
  - At maximum flowing test conditions: 750°C/1000 h
- Demonstrate butt-weld performance
  - Coated pipe to coated pipe
  - Coated pipe to uncoated pipe

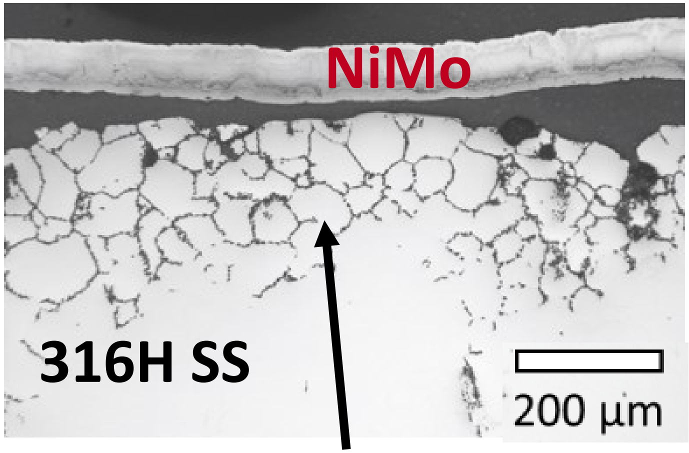
Exposure to FLiNaK at 700°C for 500 hours (ORNL)



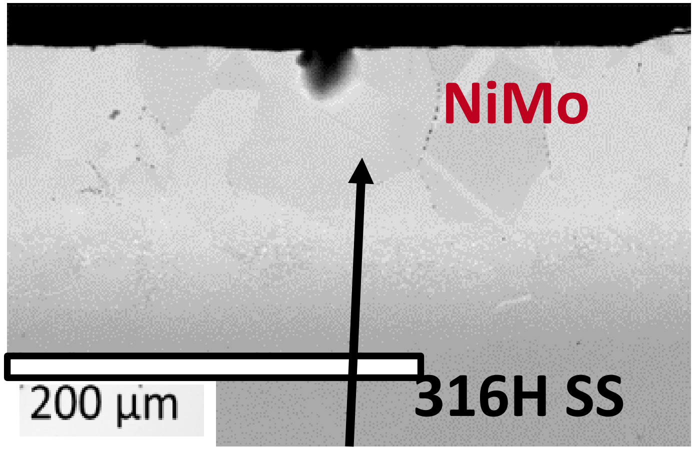
Substrate attack on bare 316H SS



Electrodeposited overlay, before diffusion bonding – no corrosion test



Substrate attack on 316H SS with functionally graded overlay

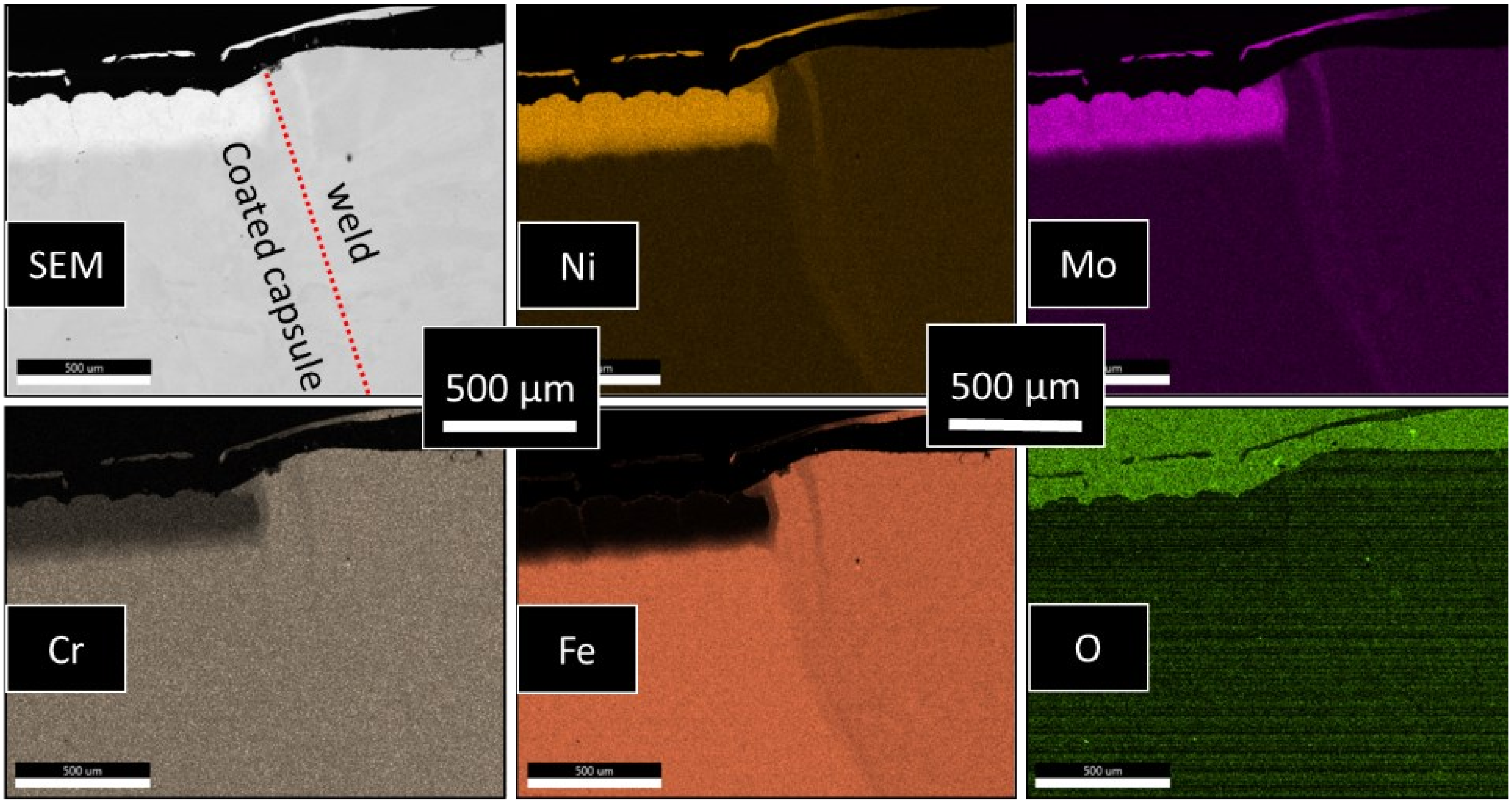


No substrate attack on 316H SS with functionally graded, diffusion bonded NiMo overlay

FARADAY TECHNOLOGY, INC.

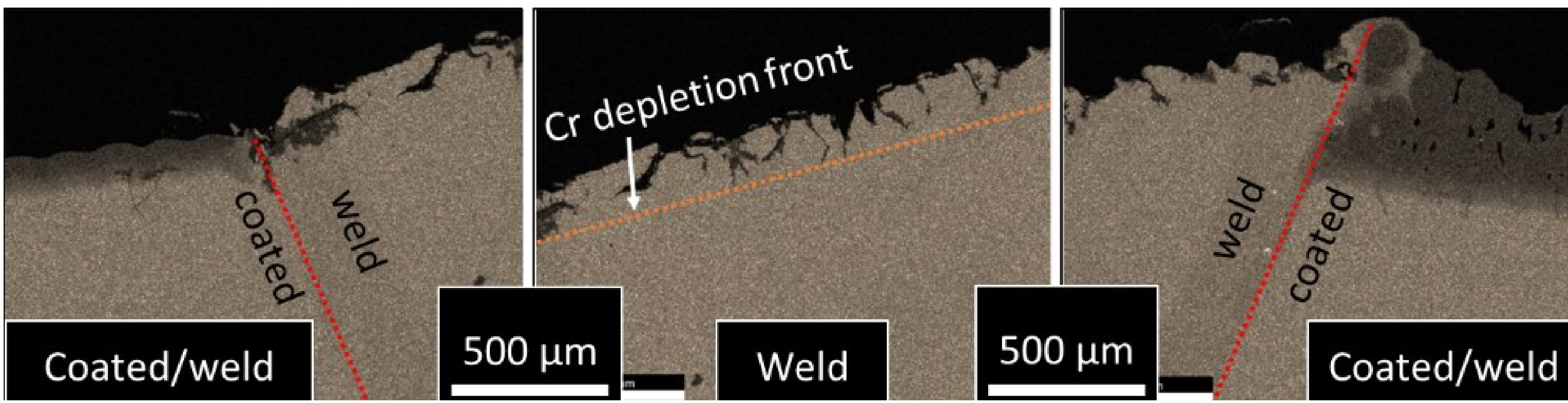
Overlay Adhesion Post-Welding

- After welding coated pipe-uncoated pipe, diffusion-bonded NiMo overlay remains intact



Overlay Adhesion Post-Welding/Corrosion Testing

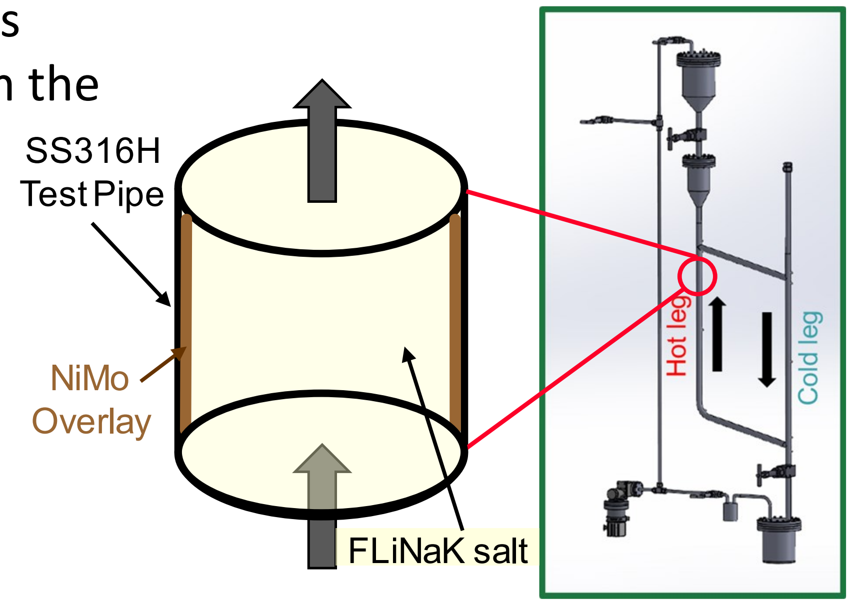
- After static pipe corrosion test (700 hrs, 500^{o}C, FLiNaK)
  - Cr depletion front observed in weld section of coated pipe--coated pipe
  - 316H SS is being etched away



- May be able to “heal” the weld seam
  - Brush overlay deposition

Continuous Flowing Loop Corrosion Testing

- Alloy degradation in molten fluoride salts primarily driven by dissolution of Cr from the alloy into the salt
- Flowing loop test creates more realistic corrosion environment:
  - Dissolution of Cr on hot side of loop
  - Precipitation of Cr on cold part of loop
  - Effect of flowing molten salt solution
  - Effect of molten salt on a weld joint
- Supplied four 8-inch lengths of pipe with diffusion bonded NiMo overlay to ORNL
- Ran flowing loop corrosion test for ~50 hours (salt pot weld failure)
- Awaiting extraction of pipe lengths from the test for analysis



Thermal convection loop at ORNL containing FLiNaK salt

OAK RIDGE
National Laboratory

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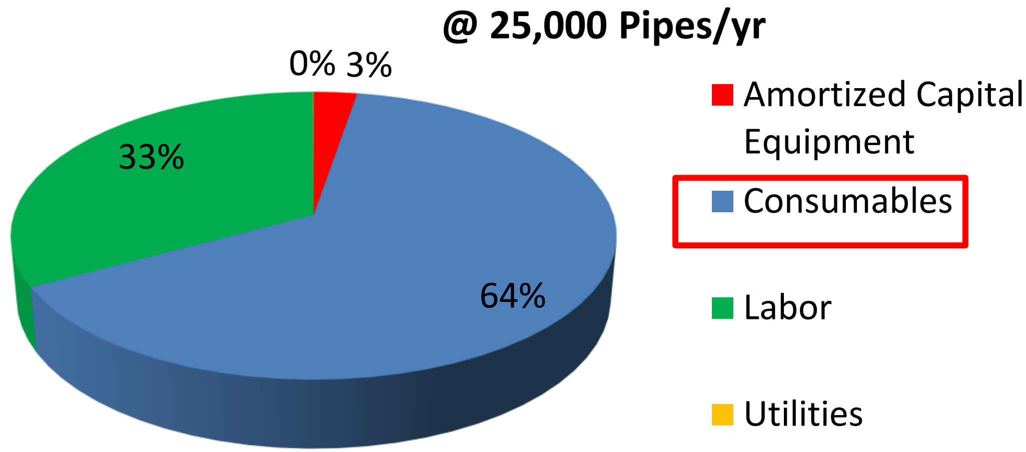
Preliminary Electrodeposition-Based Economic Analysis



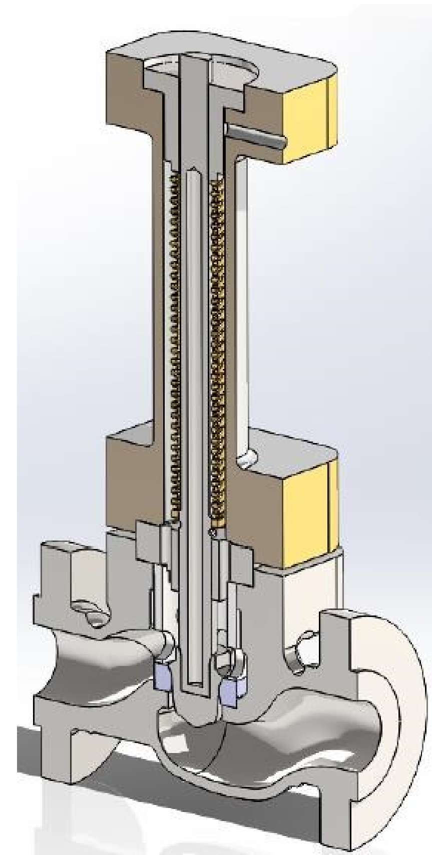
- 200 µm overlay cost estimate based on a 3 m x 2.5 cm pipe
  - $230 for 316H SS pipe
  - $940 for Hastelloy N pipe
- Diffusion bonding not included in cost estimate

Line No.	Plant Parameters	5,000 Pipes	10,000 Units	25,000 Units
1	Cylinder Size	4751 cm^2	4751 cm^2	4751 cm^2
2	Run Time (h)	18	18	18
3	Total Pipes/Hr	1	1	3
4	Total Hours worked per day	24	24	24
5	Pipes/Day (24 hr.)	16	32	72
6	Days worked per year	348	348	348
7	Units/Yr. (348 days)	5,568	11,136	25,056
8	Plating Line Cost ($/pipe)	$6.07	$3.04	$2.02
9	Material Cost ($/pipe)	$56.51	$50.87	$49.00
10	Labor Cost ($/pipe)	$112.50	$56.25	$25.00
11	**Total Cost ($/pipe)**	**$175.08**	**$110.16**	**$76.02**

Next Steps

- Investigate other substrates: IN625 and IN800HT
- Explore corrosion resistance in FLiBe, FLiNaU, KCl-NaCl-$MgCl_2$, and/or FLiNaTh
- Investigate higher operation temperatures (1000^{o}C) in FLiNaK
- Assess capabilities under thermal cycling
- Design tooling to apply overlays onto components of interest to our partners
- Ready technology for manufacturing transition:
  - Develop standards, technical data sheets and preferred operating procedures
  - Develop bath maintenance procedures

Heat exchanger bundle built for installation into fluoride salt-cooled high temperature reactor.



2” Flowserve valve for controlling flow of molten salts from Gen3 CSP

FARADAY TECHNOLOGY, INC.

The financial support of DOE Contract No. DE-SC0019602 is acknowledged.

THANK YOU FOR YOUR ATTENTION!
QUESTIONS?

Contact Information:
Tim Hall or Maria Inman
Ph: 937-836-7749

timhall@faradaytechnology.com
mariainman@faradaytechnology.com

OAK RIDGE National Laboratory

Advancements and Challenges for MSR Chemistry in MELCOR

Matthew S. Christian, Lucas I. Albright, David L. Luxat

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY
NNSA
National Nuclear Security Administration

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SAND-1726161

MELCOR for Advanced Nuclear Energy Technologies

Fully integrated, engineering-level code

- Thermal-hydraulic response of reactor coolant system, reactor cavity, rector enclosures, and auxiliary buildings
- Core heat-up, degradation and relocation
- Core-concrete interaction
- Flammable gas production, transport and combustion
- Fission product release and transport behavior

Level of physics modeling consistent with

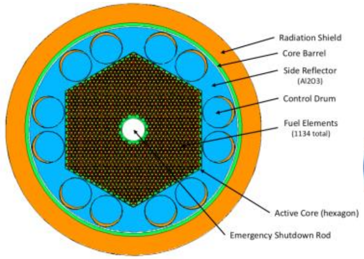
- State-of-knowledge
- Necessity to capture global plant response
- Reduced-order and correlation-based modeling

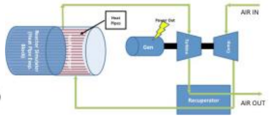
Traditional application

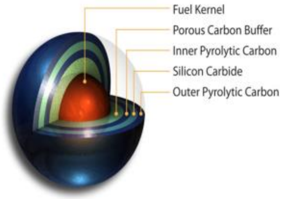
- Models constructed by user from basic components (control volumes, flow paths and heat structures)
- Demonstrated adaptability to range of reactor designs – LWR, LWR-SMR, FHR, HPR, HTGR, MSR, SFR, ATR, VVER, SFP…

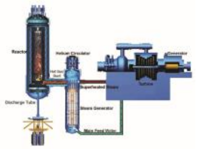
MELCOR Non-LWR Modeling

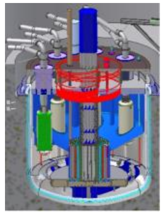
- Hydrodynamic modeling
  - Generalized working fluid treatment
  - Conduction heat transfer within working fluids
  - Generalized convection and flow models to capture flow through new core geometries (e.g., pebble beds)
  - Multi-fluid modeling
- Core models
  - TRISO pebble and compact core components
  - Heat pipe reactor core component
  - Graphite oxidation
  - Intercell and intracell conduction
  - Fast reactor core degradation
  - Fission product release
  - Generalized release modeling for metallic fuels
  - Radionuclide transport and release from TRISO particles, pebbles and compacts
  - Generalized Radionuclide Transport and Retention (GRTR) model
  - Tritium transport modeling
- Simplified neutronic modeling
  - Solid fuel core point kinetics
  - Fluid point kinetics (liquid-fueled molten salt reactors)
  - Integration with ORIGEN

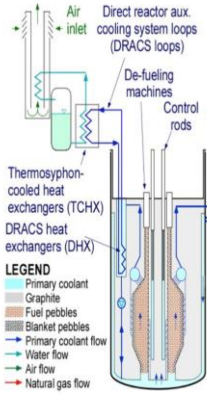


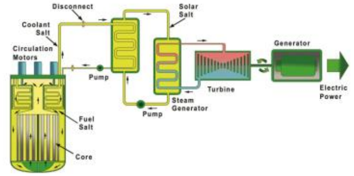






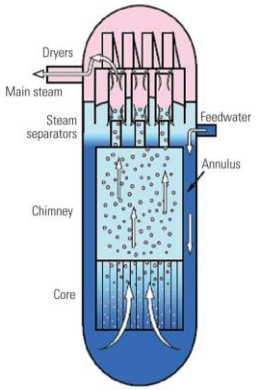


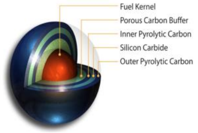


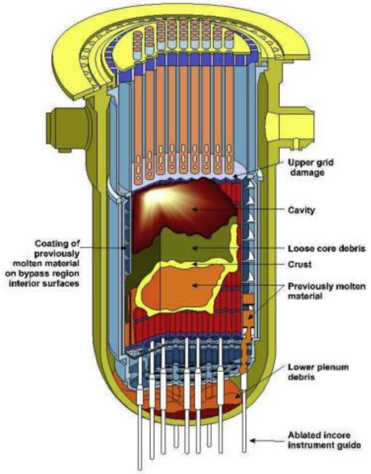


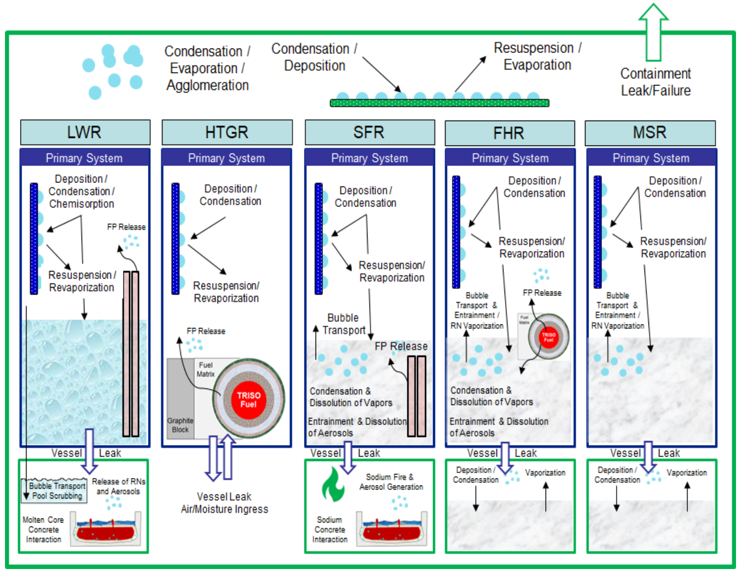
MELCOR Modeling Scope

- Thermal hydraulics
- Fuel thermal-mechanical response
- Core degradation
- Ex-vessel damage progression
- Fission product release and transport
- Reactivity Effects

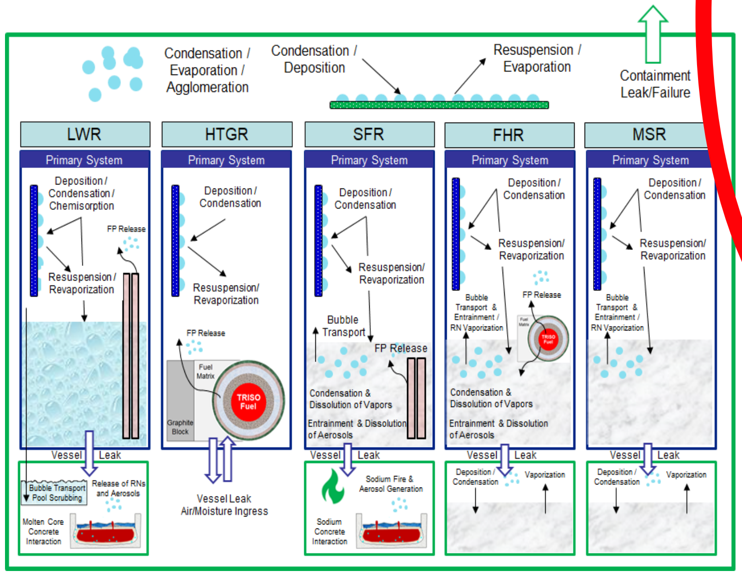


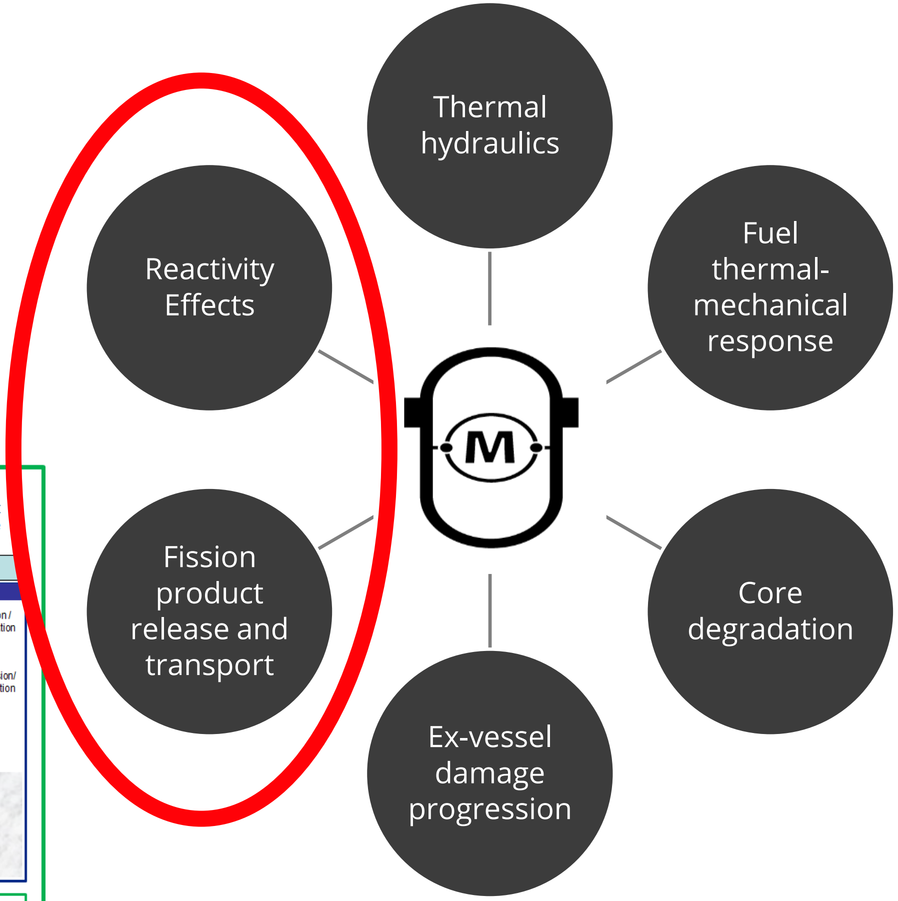






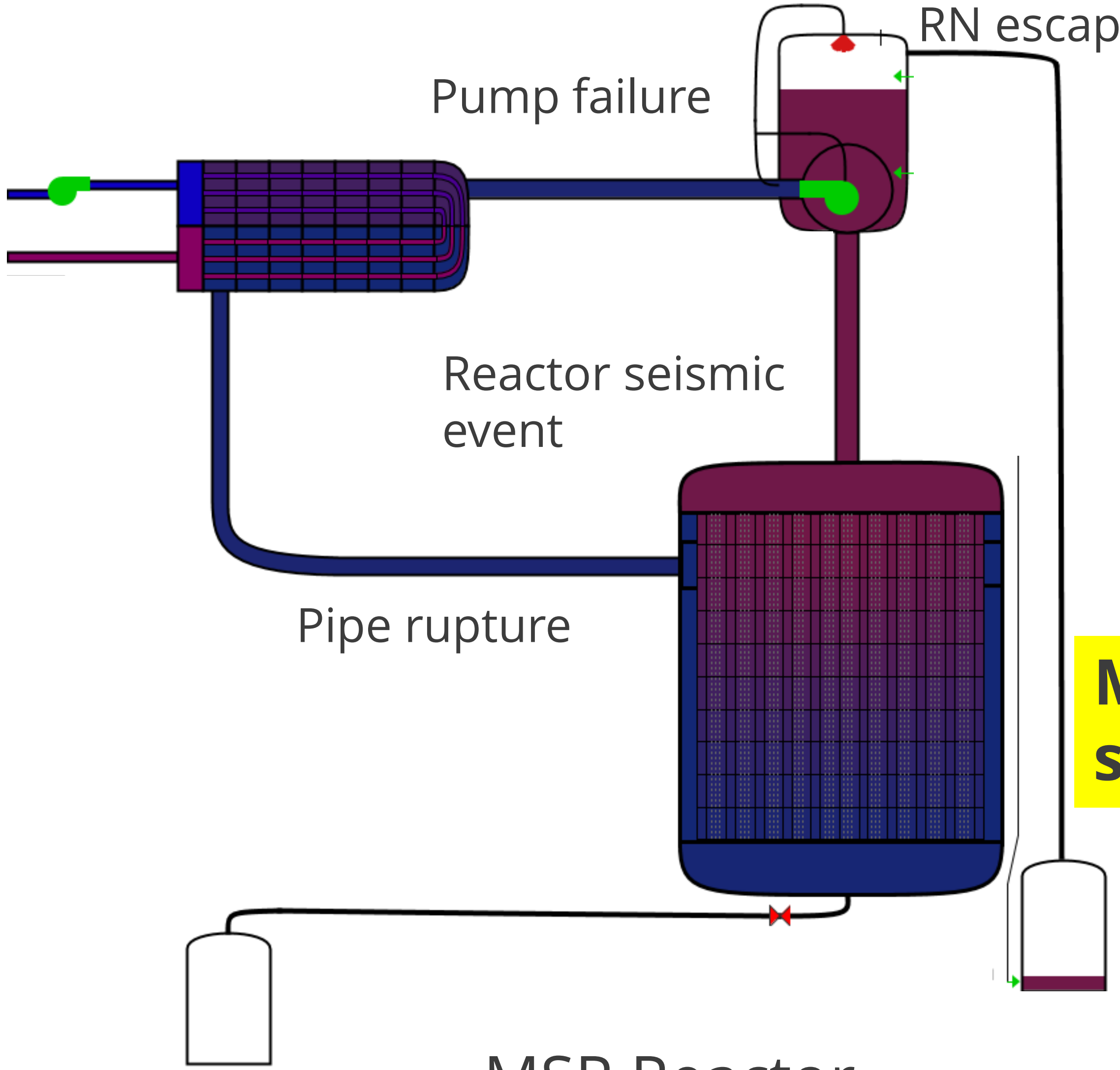
MELCOR Modeling Scope





Talk concentrates on reactivity and RN release for MSRs

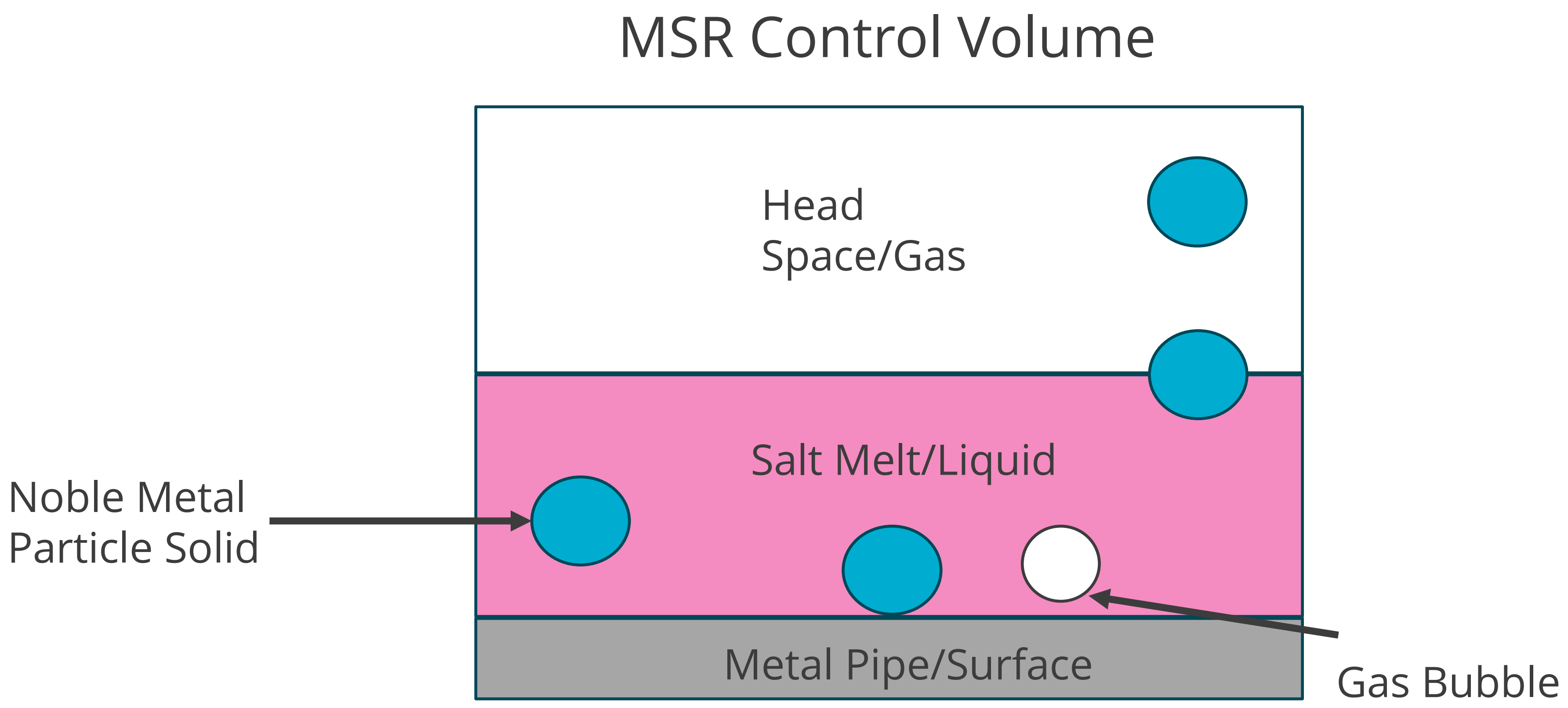
Many Severe Accidents can Result From Chemical Processes



Many possible accident scenarios

MSR Reactor

Reactor Control Volumes Create Many Interfaces for Chemical Reactions and Mass Transfer



Many different chemical processes can occur in one MELCOR control volume

Many Chemical Reactions can Occur in MSRs

- Oxidation/reduction of metal species in melt
  - Plating/settling of neutral RN metals (Mo, Ru, Rh, Pd, Te)
  - Corrosion (Ni, Fe, Cr)
  - Halogen species (F, Cl, I)
- Formation of insoluble metal-halides
  - Corrosion products
- Vapor/Aerosol Formation
  - Noble gas diffusion (Kr, Xe)
  - Aerosolization from spray jets (RN species)
- Deposition of Species on Surfaces
  - RN metal plating (Mo, Ru, Rh, Pd, Te)
  - Corrosion product build up
  - Diffusion of gases into moderator
  - Splattering of species from bubble bursting/splashing/aerosolization

Chemistry must be reflected in MELCOR

Reactions are Chemical, Mechanical and Heat Induced

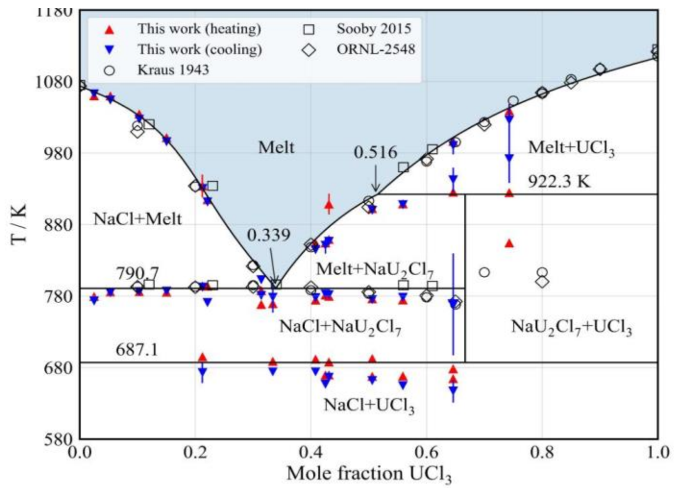
- Chemical processes involve the transfer and interaction of electrons (bond breaking/making, surface adsorption)
- **Chemical Reactions:** oxidation/reduction, sublimate and bubble formation (decay to gas species), precipitation, adsorption
- Mechanical processes involve a physical force (gravity, pump spray)
- **Mechanical:** aerosolization (spray nebulization), bubble bursting, liquid splattering
- Heat processes involve the exchange of energy (temperature)
- **Heat processes:** Melt, crystallization, gas condensation

Reactions and Speciation can be Handled by Thermochemical Databases and Gibbs Energy Solvers

- Speciation within each MELCOR node could be handled by thermochemical databases (MSTDB-TC) coupled with a solver (Thermochimica)
- Proof of concept demonstrated by Fred Gelbard for cesium
- Calling Thermochimica + MSTDB-TC for all MELCOR nodes for simulation duration would be expensive

Can chemical speciation be simplified?

T. Besmann (UofSC)



Yingling et al., J Chem. Thermo 2023, 179, 105974

Application of MELCOR for Simulating Molten Salt Reactor Accident Source Terms

Fred Gelbard,[a*] Bradley A. Beeny,[a] Larry L. Humphries,[a] Kenneth C. Wagner,[a] Lucas I. Albright,[a] Max Poschmann,[b] and Markus H. A. Piro[b]

[a] *Sandia National Laboratories, 1515 Eubank SE, Albuquerque, New Mexico 87123*
[b] *Ontario Tech University, 2000 Simcoe St. N., Oshawa, Ontario, Canada*

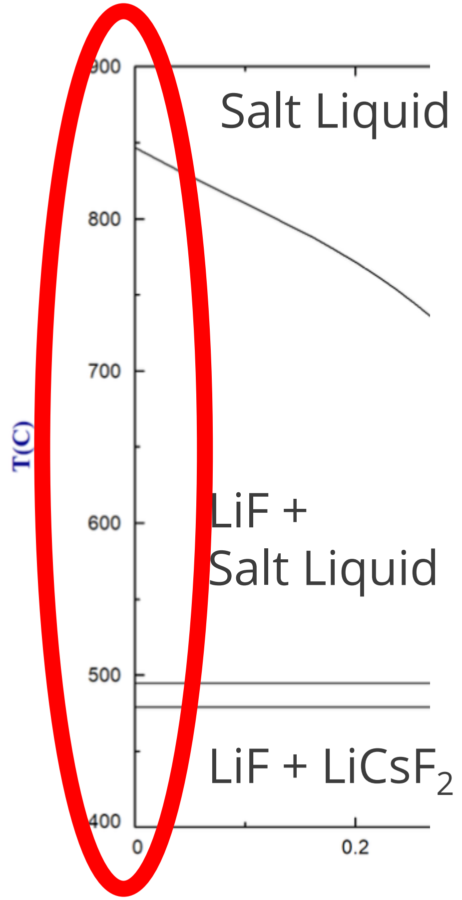
Nuc. Sci. and Engin 2023, 197, 2723-2741

Thermochimica

M. Piro (OT)

Radionuclide Masses Should Minimally Affect Thermochemical Properties in MSR Fuel Loop

- Carrier and fuel salt mass is thousands of kgs while radionuclides (RNs) will be a few kgs
- RNs will quickly form products related to phase speciation, having little affect on bulk properties
- RNs can be treated in system as atomic defects



1% CsF mol frac with LiF

Verifying assumption with calculated RN inventories in Thermochimica

Indications/Hypothesis for MELCOR MSR Fuel Chemistry Modeling

- Do all relevant RN systems need to be included in MSTDB-TC for MELCOR
  - **No because RNs can be treated as a dispersed presence in MSR**
  - **However, inclusion would reduce MELCOR speciation routines**
- How often should MELCOR call Thermochimica?
  - **For speciation: 0.1-0.3 mol fraction changes in RN inventory**
  - **For thermodynamic properties : 0.01-0.05 mol change in RN inventory**
  - **For speciation quantities: Any time-step of interest, TBD**
- What radionuclide information does MELCOR need if not in MSTDB-TC?
  - **Incorporation of other published chemical databases**
  - **Diffusion coefficients of RNs in working fluid**
  - **Vapor species of radionuclides in working fluid**
  - **Adsorption energies in cladding**

Assumptions need to be tested with MELCOR calculations

MELCOR can Utilize "Frozen Chemistry" if Element Speciation is Static

- MELCOR groups compounds by representative classes and species (right table)
- Frozen chemistry key for calculation speed
- Representative element has similar properties as others in grouping (reactivity, system diffusion)
- Current grouping works for light-water reactors, but likely not for MSRs due to different chemistry

Need to find elemental grouping for MSRs

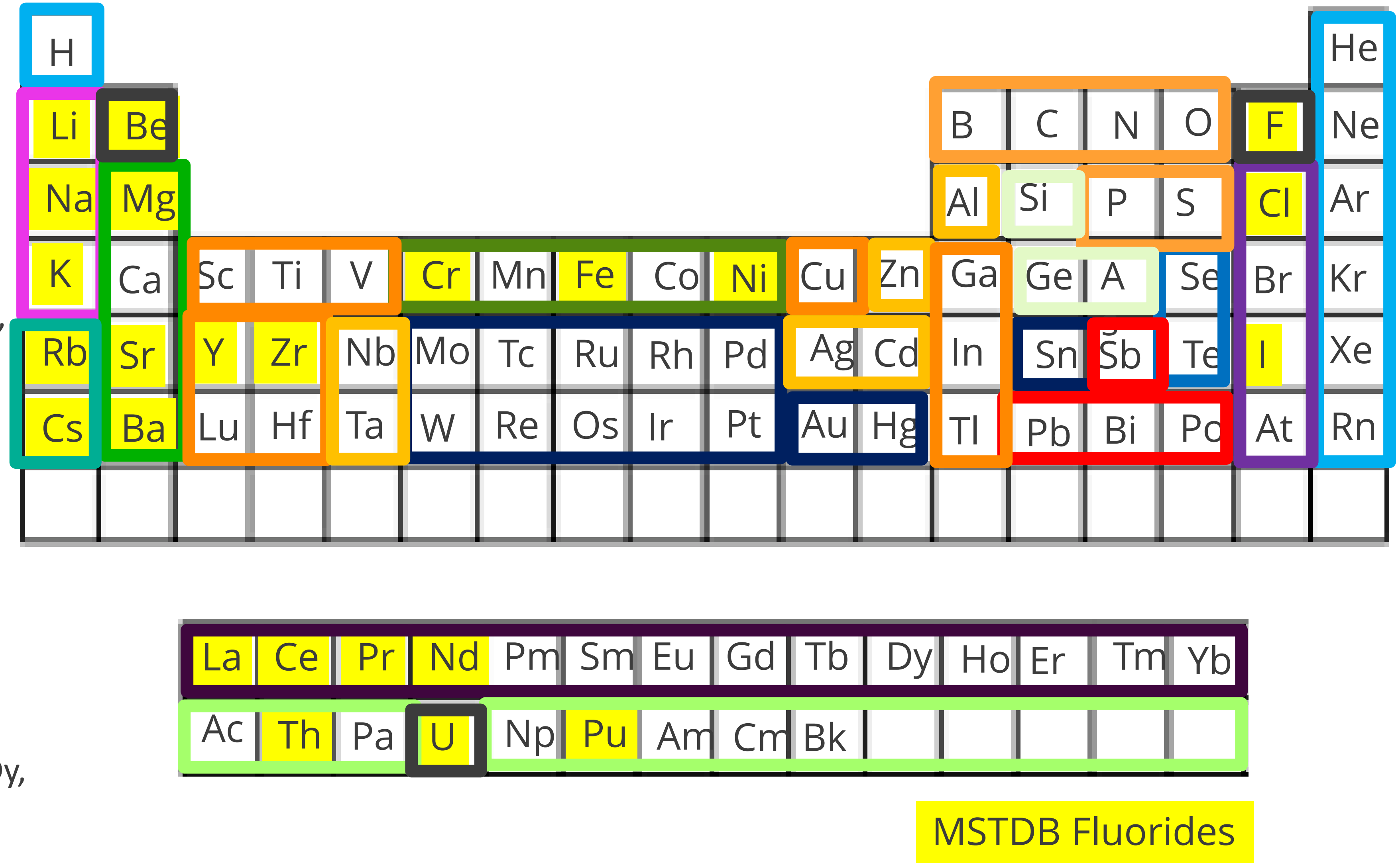
Current MELCOR Elemental Grouping

Xe : He, Ne, Ar, Kr, Xe, Rn, H, N
Cs : Li, Na, K, Rb, Cs, Fr, Cu
Ba : Be, Mg, Ca, Sr, Ba, Ra, Es
I : F, Cl, Br, I, At
S : S, Po
Re : Re, Os, Ir, Pt, Au, Ni
V : V, Cr, Fe, Co, M, Ta, W
Mo : Mo, Tc, Ru, Rh, Pd, Ag, Ge, As, Sn, Sb
Nb : Nb, Zn, Cd, Se, Te
Ce : Ti, Zr, Hf, Ce, Th, Pa, Np, Pu, C
La : Al, Sc, Y, La, Ac, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Am, Cm, Bk, Cf
U : U
Cd : Hg, Ga, In
Ag : Pb, Tl, Bi
B : B, Si, P

A Possible Element Grouping for Fluorides

MELCOR Elemental Grouping

Li: Li, Na, K,
Cs : Rb, Cs, Fr
Be: Be
Ba : Mg, Ca, Sr, Ba, Ra, Es
Zr : Sc, Ti, V, Cu, Ga, Y, Zr, In, Lu, Hf, Tl
Cd: Al, Zn, Nb, Ag, Cd, Ta
Mo : Mo, Tc, Ru, Rh, Pd, Sn, W, Re, Os, Ir, Pt, Au, Hg
Ni : Cr, Mn, Fe, Co, Ni,
O : B, C, N, O, S, P
Ge: Si, Ge, As
Te : Se, Te
Pb : Sb, Pb, Bi, Po
F : F
I : Cl, Br, I, At
Xe : He, Ne, Ar, Kr, Xe, Rn, H
Ce : La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb
Pu : Ac, Pa, Np, Pu, Am, Cm, Bk
U : U



Grouping based on fluoride species solubility

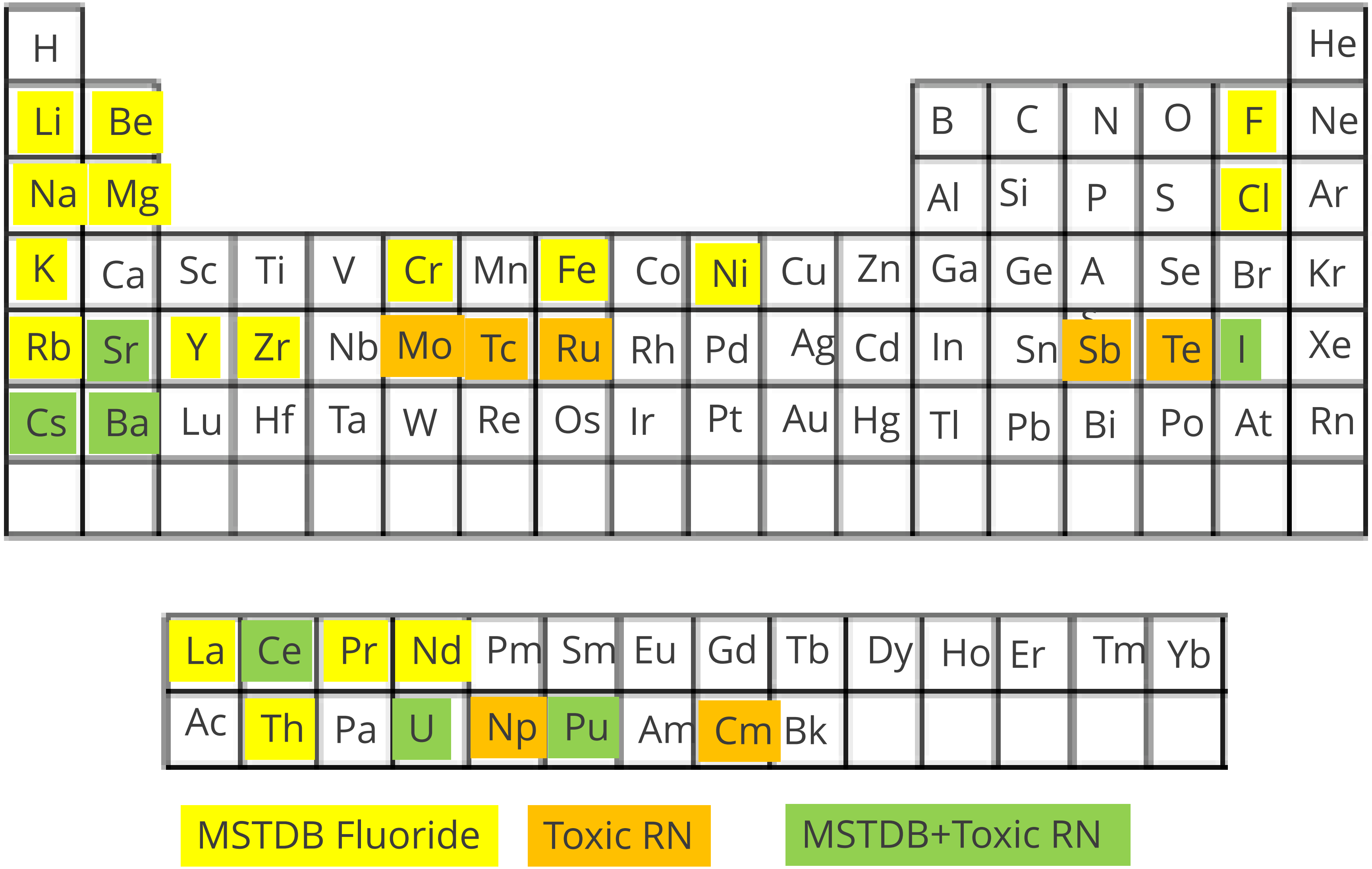
"Frozen Chemistry" Requires Rudimentary Experimental Knowledge

- "Frozen Chemistry" requires transferability of chemical/physical/thermal properties across the grouping
- Possible groupings: halogen solubility, redox potentials, melting point…
- Speciation grouping must not significantly change any calculation outcome (MELCOR or Thermochimica)

Assumptions requires testing and validation

Many Health-Consequence Systems Still Need Investigation

- Large focus has been on fuel salts and corrosion products
- Many fission product systems remain to be investigated
- Chemical and mechanical understanding of fission products is important



Authoring road map with focus on severe accident systems

Conclusions

- MELCOR is adding methods to handle chemistry in the MELCOR package
- Chemical speciation will be handled by using Thermochimica with MSTDB-TC
- RNs not in MSTDB-TC will be treated as dilute and dispersed in system
- Applicability of “frozen chemistry” is being investigated for MSRs
- Additional knowledge of health hazardous RNs are required to ensure accurate models
- Authoring road map for systems that need understanding for severe accident modeling

Acknowledgements

- Sandia MELCOR Team
- Ted Besmann/Juliano Schrone-Pinto and team (USC)
- Markus Piro (OT)
- Joanna McFarlane (ORNL)
- Patricia Paviet (PNNL)
- **YOUR NAME HERE**

WE WANT TO WORK WITH YOU!!!

mschris@sandia.gov

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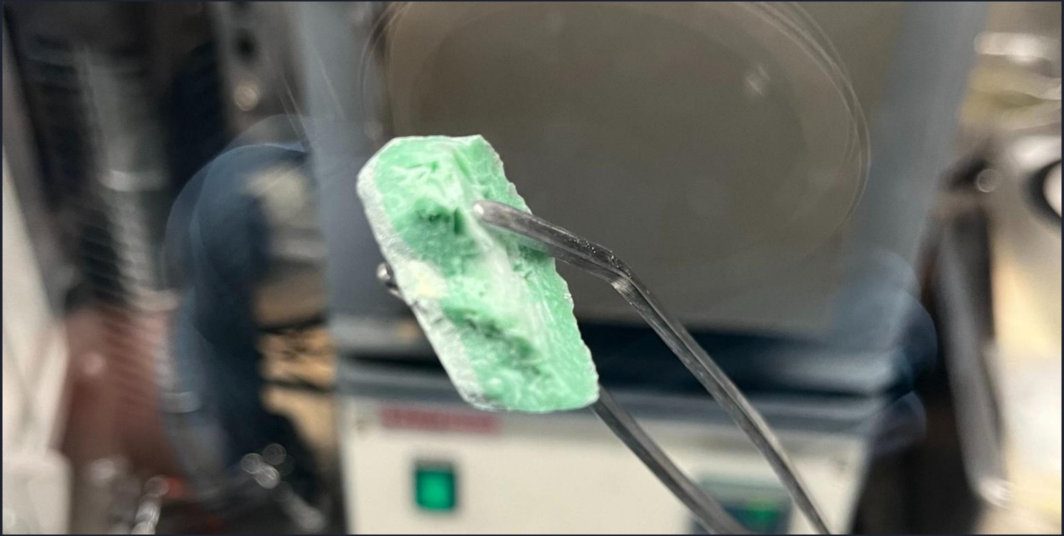
ORNL Molten Salt Reactor Workshop

Developer Forum

DJ Hanson - COO

25 October 2023

Guess The Salt

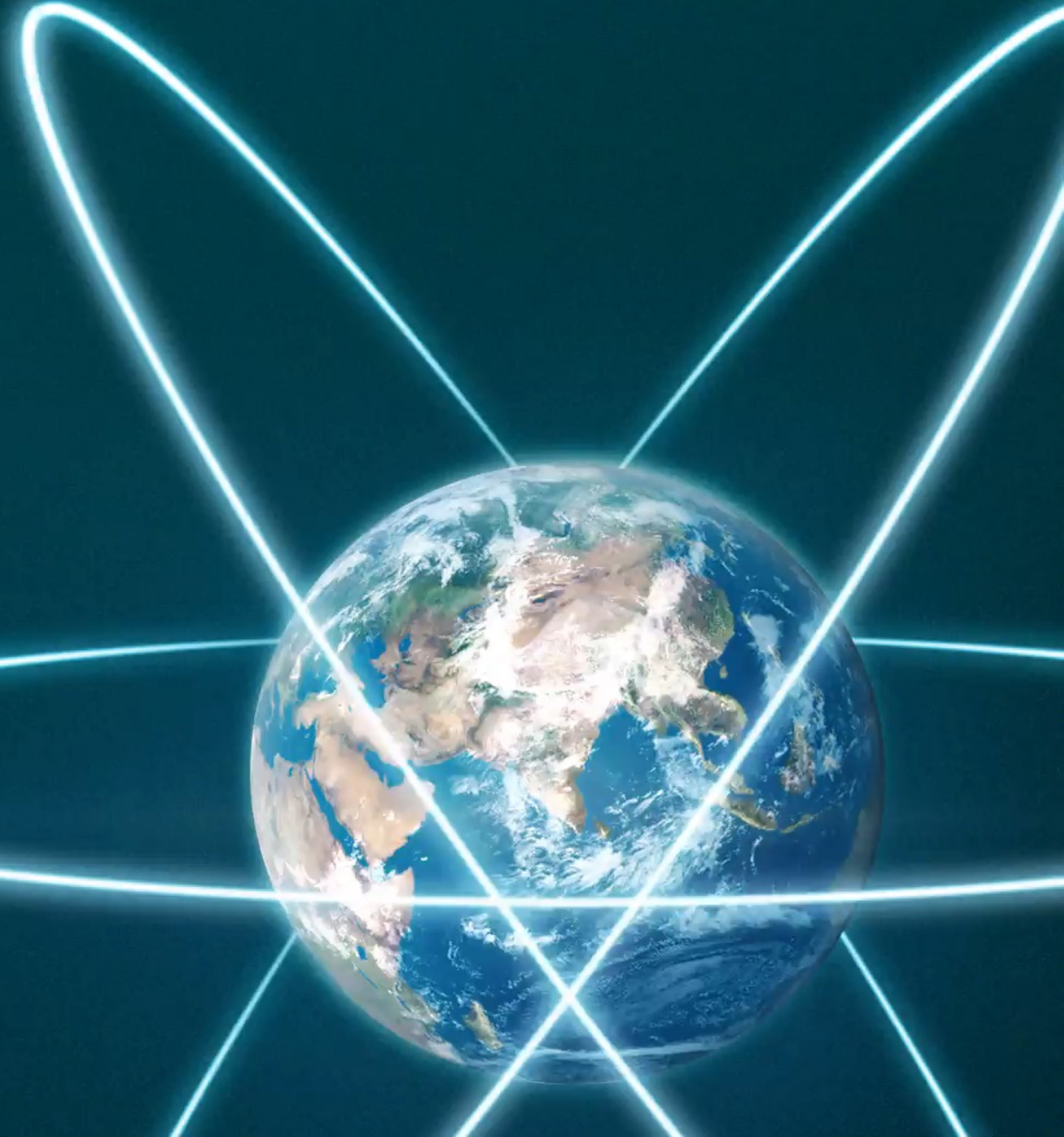


SEABORG

Compact Molten Salt Reactor (CMSR) Power Barge

Progress & status

26 October 2023
ORNL MSR Workshop



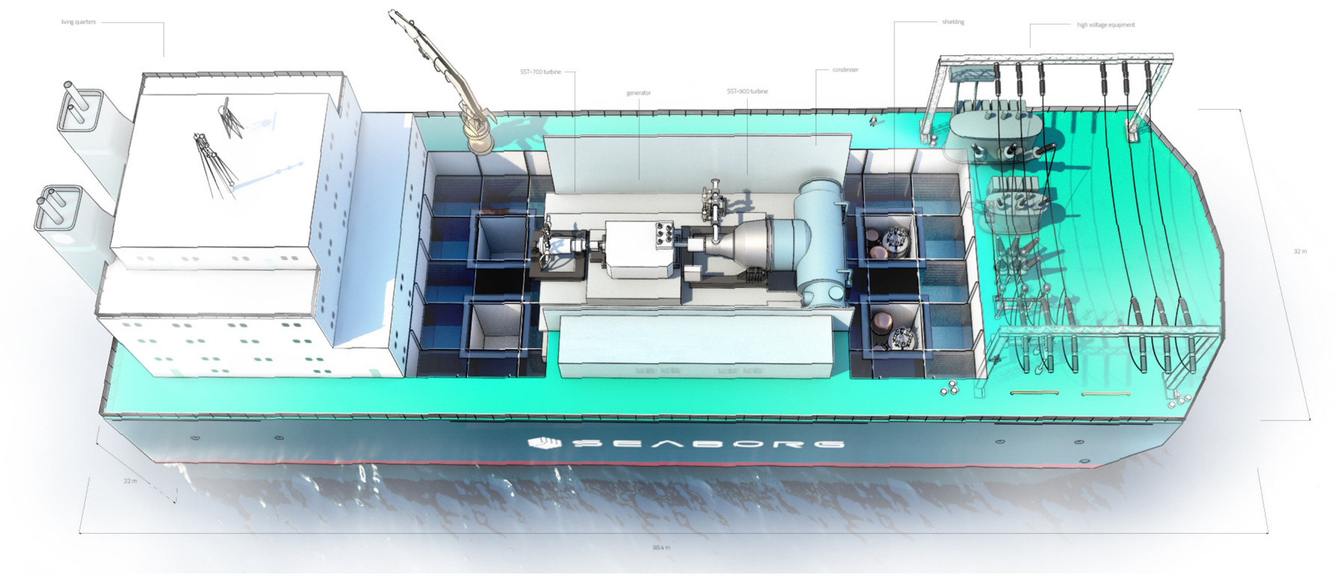
Federico PUENTE-ESPEL, PhD
Global Manager, Strategic Programs

Andreas Vigand Schofield, PhD
CTO & Co-founder

A sincere and profound appreciation to Dr. Robb, Ms. Setzer, & the ORNL for their most valuable consideration.

A great recognition as well to the ORNL for their exceptional work.

Outline



Context of the CMSR Power Barge

Deployment model

CMSR: Progress & Status

Introduction to SeaSalt

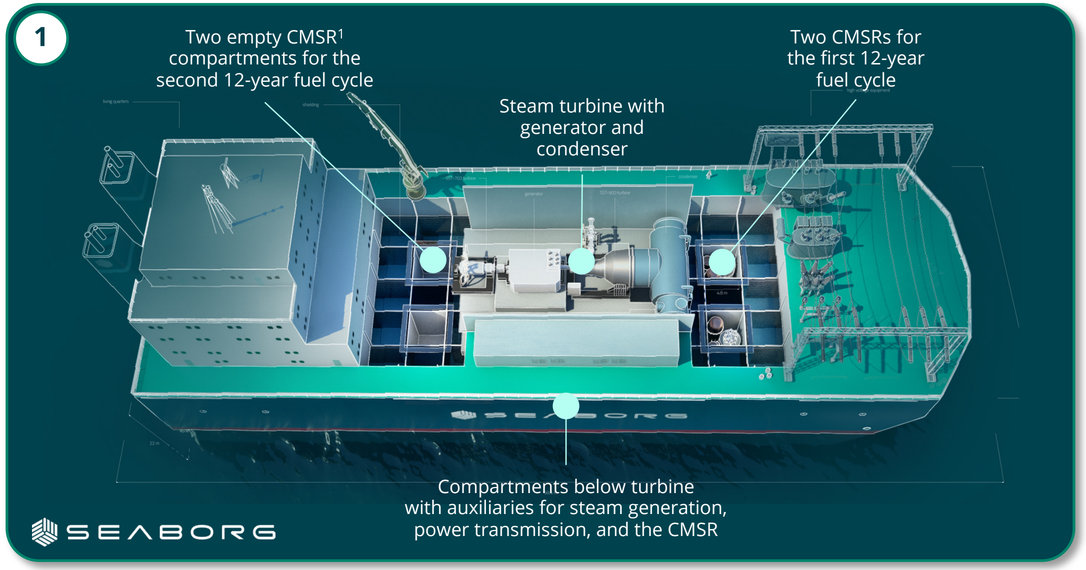
- Around 100 employees from +25 countries, including +30 PhDs.
- HQ and laboratories in Denmark and business office in South Korea and Singapore.

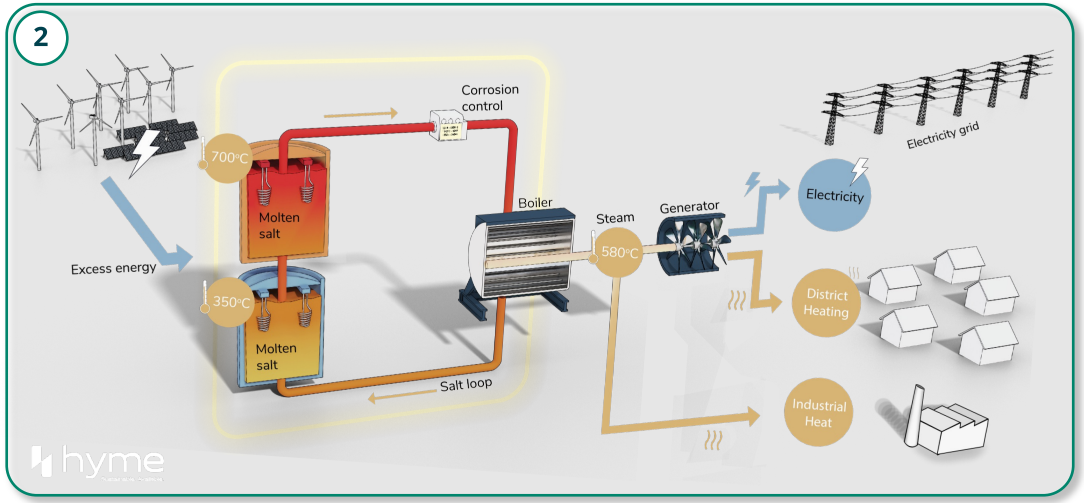
<u>SeaSalt is comprised of two distinct entities</u>

1. **Nuclear energy** technology company (Seaborg) developing a safe nuclear compact molten salt reactor to be deployed on power barges on a global scale.

2. **Energy storage** technology company (Hyme) set to deploy hydroxide salts as a grid scale energy storage system to complement the energy transition.

- Significant synergy potential between the two entities in relation to molten salt research and innovation and IP co-operation and commercial opportunities.





CONTEXT OF THE CMSR POWER BARGE

We will only reach our goals for **decarbonisation** if the alternative is **cheap** enough and scales **fast**.

VISION

Transform energy markets and **out-compete fossil fuels** to create a bright future with abundant clean energy for everyone.

UNPRECEDENTED OPPORTUNITY

Executing a rapid **world-wide deployment** of the Compact Molten Salt Reactor via **shipyard serial production** of Power Barges.

Export of Factory Build Nuclear Power Plants

Designed by

SEABORG

Built by

SAMSUNG

SAMSUNG HEAVY INDUSTRIES

Operated by

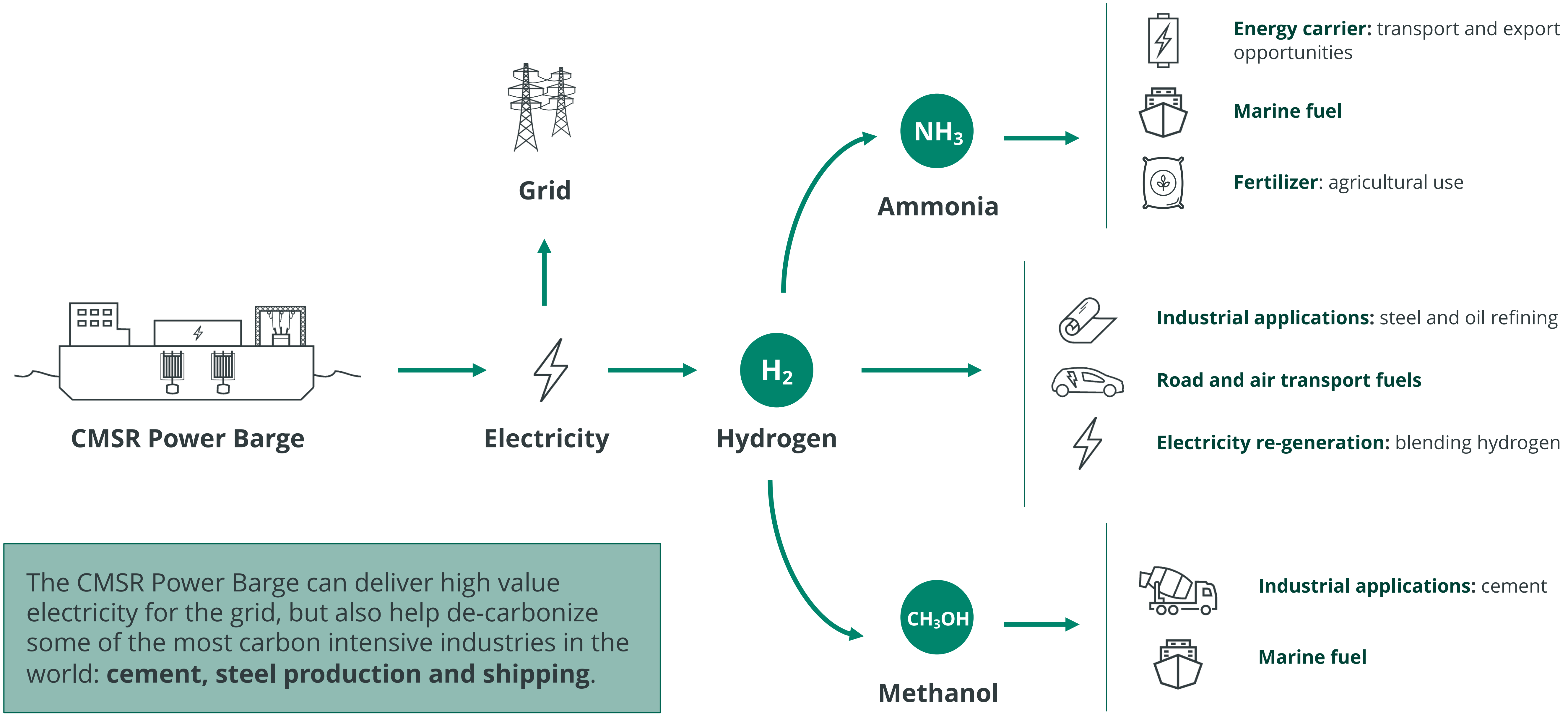
KHNP

Variant	Electric Power
2x CMSR	200 MW_e
4x CMSR	400 MW_e
6x CMSR	600 MW_e
8x CMSR	800 MW_e

Standardized modular design

- Turnkey energy solution
- Shipyard construction
- Leveraging Korean expertise in nuclear and offshore
- High quality and safety
- Global deployment and operation

Commercial use cases for the CMSR Power Barge



The CMSR Power Barge can deliver high value electricity for the grid, but also help de-carbonize some of the most carbon intensive industries in the world: **cement, steel production and shipping**.

SEABORG

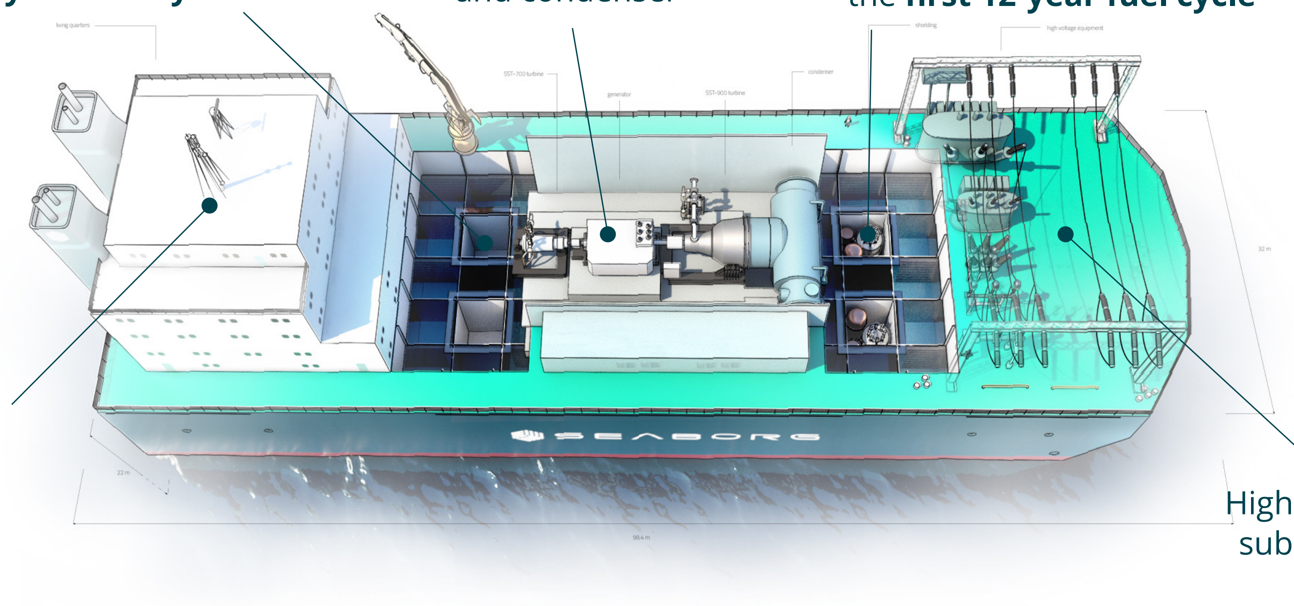
Floating aspects

Centralized lifecycle activities

Modular + centralized plant construction	Centralized commissioning and testing	Centralized dismantling
High quality assurance and control	Faster construction time	Standardized commissioning procedures
Centralized workforce	Rapid site remediation & restoration	Standardized dismantling for all barges

- Key benefits of Floating Nuclear Power Plants.
- Further, **combining of maritime and nuclear frameworks** can enable seamless and rapid **export** of CMSR Power Barges across the globe.

CMSR Power Barge



Plant

- Floating Nuclear Power Plant
- Non-self-propelled
- 25-year lifetime
- 200 MW_e dual unit plant sharing balance of plant
- 40% thermal efficiency
- Passive decay heat removal
- Designing for no off-site EPZ

Reactor

- Thermal spectrum molten salt reactor
- 250 MW_{th}
- Fluoride salt (eutectic UF_4-KF-NaF)
- Graphite moderated
- Loop type
- Hydrostatic operating pressure, ~ 650 C operating temperature

Fuel cycle

- Fuel enrichment – LEU (<5%)
- 12-year fuel cycle
- No external refueling or reprocessing schemes
- Decommissioning carried out at central facility after end-of-life

Consortium agreement between KHNP, Samsung and Seaborg
signed April 20th 2023

Key objective

Enable the deployment of the CMSR Power Barge and expedite export globally

Consortium Roles & Scope

Nuclear energy technology company developing a safe nuclear compact molten salt reactor to be deployed on power barges on a global scale.

SEABORG

Overall Licensing and Safety Case

Design, development and integration of CMSR

Fuel cycle development & Qualification

Develop decommissioning path

World leading **Shipbuilding and offshore construction** company.
SHI has decades of experiences in engineering, manufacturing, commissioning of ships and offshore constructions in the highest quality.

SAMSUNG HEAVY INDUSTRIES

Design, build and outfitting of power barge

Installation of all vendor systems and packages

Non-nuclear commissioning

World leading
nuclear power operator
KHNP is renown for the safe and reliable operation of nuclear power plants in Korea and abroad.

KHNP

Fuel loading

Nuclear commissioning

Power barge operation

Regulatory and licensing → **CMSR** → **Power Barge** → **Fuel Cycle** → **Nuclear Test site** → **Nuclear test and commissioning** → **Operations and Maintenance** → **Decommissioning**

MoU for Fuel Salt Production

Signed 7th June 2023

GS E&C Corporation

One of South Korea's largest **construction** companies with experience in many sectors, including nuclear.

KEPCO NF

South Korea's only nuclear fuel company, with forty years of specialization in the design and manufacture of nuclear fuel and provision of related services.

SEABORG

Nuclear energy technology company developing a safe nuclear compact molten salt reactor to be deployed on power barges at a global scale.

Pre-feasibility → **Feasibility** → **Demonstration Plant** → **Enriched Uranium** → **Production Facility** → **Transportation**

First steps between Fuel Salt Production Partners

Seaborg's change from HALEU to LEU fuel

Beginning of 2023, Seaborg took the major technical and business decision to change from High Assay Low Enriched Uranium (HALEU) to Low Enriched Uranium (LEU) fuel

- Geopolitical situation poses **substantial risk** associated with HALEU availability before 2035 (Possibly 2040)
- Fuel enrichment switch to LEU keeps focus on the **ability to scale fast** and deliver on Seaborg's vision to transform the global energy market
- LEU enrichment requires a **change of moderator** from sodium hydroxide (NaOH) to graphite for the first Seaborg product line
- The CMSR remains a thermal spectrum molten salt reactor, with all the related **inherent safety characteristics**

CMSR Context

Summary of R&D Challenges

- Fuel Salts
  - Thermophysical properties, chemical properties or radionuclides, modeling and simulation
  - Understanding composition evolution with operation qualification of fuel
- Materials
  - Balance of mechanical properties, irradiation performance, and corrosion resistance
- Moderator (graphite)
  - Performance under irradiation and interaction with fuel salt
- Sensors and Instrumentation
  - Applicability from conventional NPP are limited in MSRs
  - MSR specific technologies require extensive development and qualifications
- Chemical Modeling
  - Structural-thermodynamic model for fuel for enabling accurate prediction of properties
- Multidisciplinary Modeling and Simulation
  - Highly dynamic system; coupling chemical and physical tools of low and high fidelity that are regulatory compliant
- Safety Demonstration
  - Tools required to model severe accident progression based on data for V&V from experiments and modeling

Research Approach

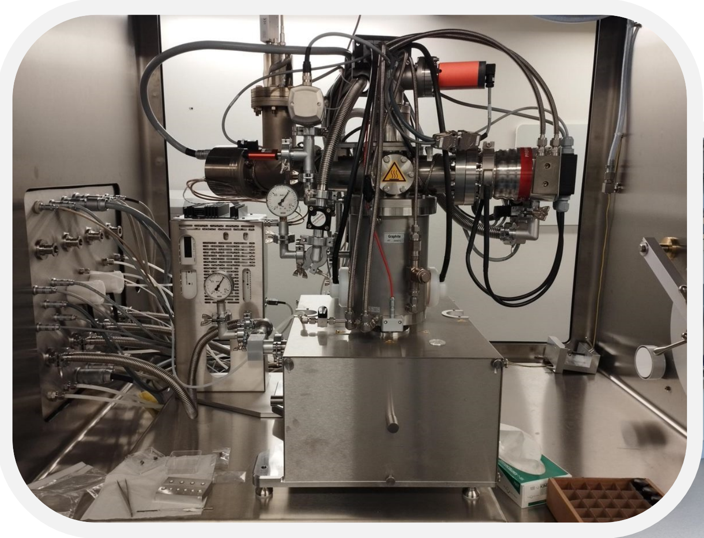
Research in parallel to product development

- Early focus on de-risking and concept verification
- Transition to high quality validation when direction is established
- Initiate long lead-time activities early

Research partnerships are essential – we cannot do this alone

- Collaboration as well as outsourcing research
- Mutual development of expertise
- Access to specialised facilities
- External validation of data
- Important to gain hands-on understanding and feed this directly into the design
- Strengthen IPR via internal lab facilities

3rd generation natural convection flow loop. Currently developing forced convection (pumped) flow loops.



In-house radioactivity lab facilities, including gloveboxes with integrated furnaces (right) and thermal analysis instrumentation (left).

Seasalt facilities
Enabling R&D and Testing

Extensive R&D is essential for the development of the CMSR. Seaborg is tackling this both internally and externally

SEABORG
Copenhagen facilities
Offices, laboratories and prototyping facilities

hyme
Esbjerg site
The world's first hydroxide molten salt energy storage plant

hyme
Bornholm site
First grid-connected project repurposing old coal power block

Symbion Facilities
- Fluoride salt laboratories
- Electrochemistry
- Thermal analysis
- Radiolab under commissioning

Titanhus Facilities
- HQ offices
- 330 m² Hydroxide laboratories
- Ongoing expansion of laboratory facilities (1,200 m²)

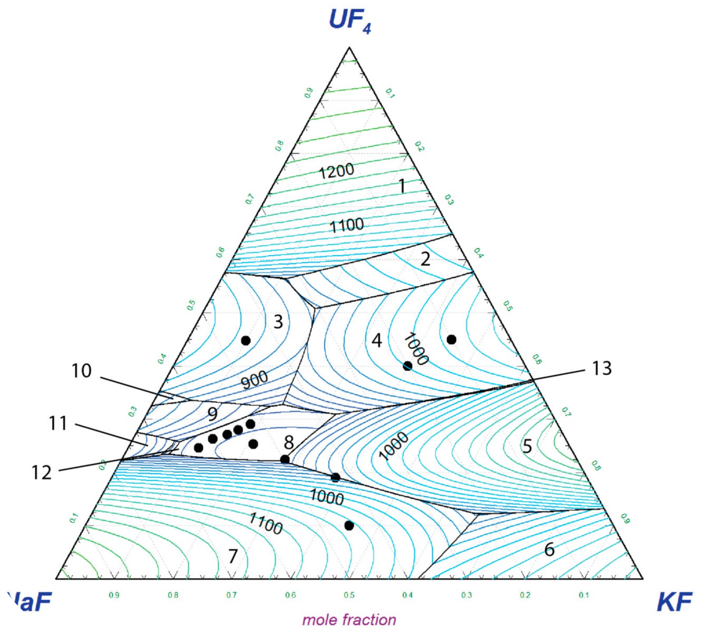
Amager Facilities
- Large scale salt components testing
- Prototyping

Fuel qualification R&D I

Institute	R&D Activity	Item	Status	Timeline
Seaborg Technologies	Fuel qualification	Strategy - Leader	Ongoing	Continuos
	Fuel composition	BoC selection	Complete	Complete
European Joint Research Centre, Karlsruhe (DE)	Thermophysical property measurements	Phase diagram exploration	Complete	Complete
		Melting point - FUNaK	Complete	Complete
		Vapour pressure - FUNaK	Complete	Complete
		Heat capacity - FUNaK	Ongoing	Q4 2023
		Density - FUNaK	Ongoing	Q4 2023
Delft University of Technology (NL)	Thermophysical property modelling	Predictive model for thermophysical properties of FUNaK	Ongoing	Q4 2023 Expansion of technical activities in planning

Seaborg Technologies **overall fuel salt qualification leader** with extensive outsourcing to highly estimated external labs.

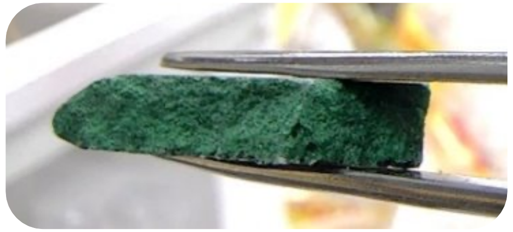
Following methodology outlined by Oak Ridge National Lab and endorsed by the NRC (Nureg – 2246)



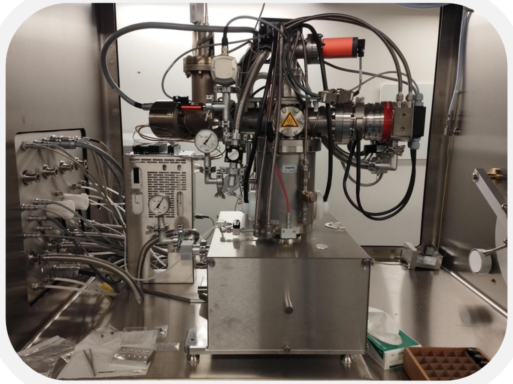
Partners for fuel salt projects, solidified NaF-KF-UF_4 fuel, phase diagram.

Fuel qualification R&D II

Institute	R&D Activity	Item	Status	Timeline
Idaho National Laboratory (US)	Thermophysical property measurements (FUNaK)	Phase diagram exploration	Complete	Complete
		Density - binary eutectics	Ongoing	Complete
		Density	Ongoing	Expected Q4 2023
		Viscosity	Ongoing	Expected Q4 2023
		Heat capacity	Ongoing	Expected Q4 2023
		Enthalpy of fusion	Ongoing	Expected Q1 2024
		Thermal expansion	Planned	Expected Q1 2024
		Thermal diffusivity	Planned	Expected Q1 2024
Seaborg Technologies	Mechanistic Source Term Methodology Prep	Strategy - Leader	Ongoing	Continuos
		Sourcing of salt (including uranium)	Complete	Complete
		Establishing radiolab facilities	Ongoing	Expected Q4 2024
Seaborg Technologies	Mechanistic Source Term Methodology	FP retention experiments and data	Planned	TBD
		Modeling and simulation	Planned	TBD



Solidified NaF-KF-UF_4 fuel (Fuel Qual. Experiment at INL)



In-house radioactivity lab facilities (under commissioning), including gloveboxes with integrated furnaces (bottom) and thermal analysis instrument (top).

Global Strategic Programs

IAEA
International Atomic Energy Agency

GEN IV International Forum
Expertise | Collaboration | Excellence

NEA
NUCLEAR ENERGY AGENCY

WORLD NUCLEAR ASSOCIATION

European Commission

Academic collaborations and fully outsourced R&D

Enabling scale & speed

Fuel qualification and salt properties

Fuel salt
Partnerships on thermophysical properties:
experiments, irradiation, modelling

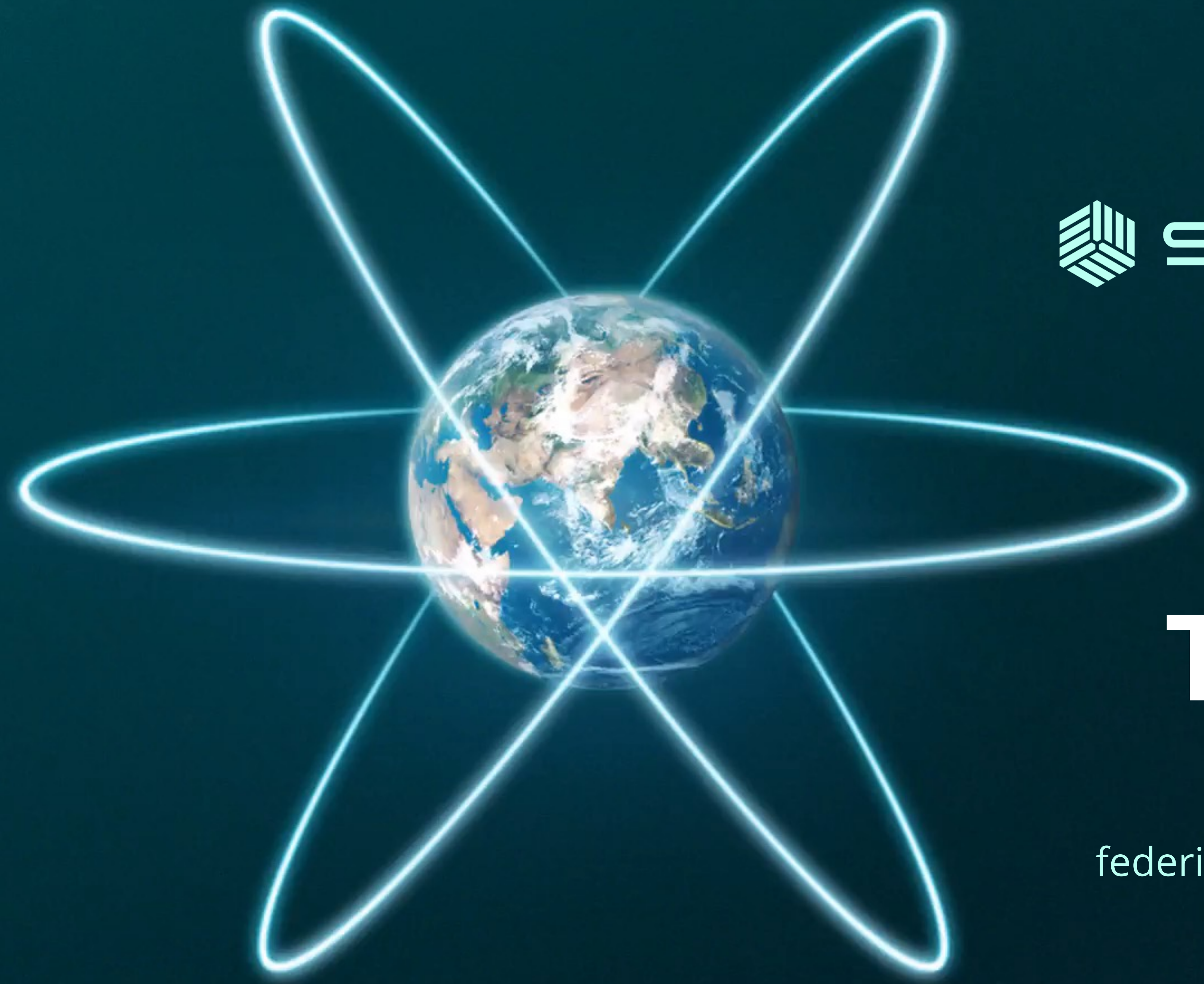
Tertiary salt (former moderator)
Partnerships on thermophysical and neutron scattering properties:
experiments, irradiation.

Modelling, simulation and V&V

Chemistry Control, Materials and Moderator

Fuel salt chemistry control
Redox and corrosion control of fuel-facing materials.

Structural materials
Ion-beam irradiation, experiments.



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Rethinking nuclear

Thank you

www.seaborg.com

federico.puente-espel@seaborg.com

ThorCon: Status 2023

Dane Wilson, ThorCon US, Inc.

October 26, 2023

2023 Hybrid Molten Salt Reactor Workshop

dwilson@thorcon.us

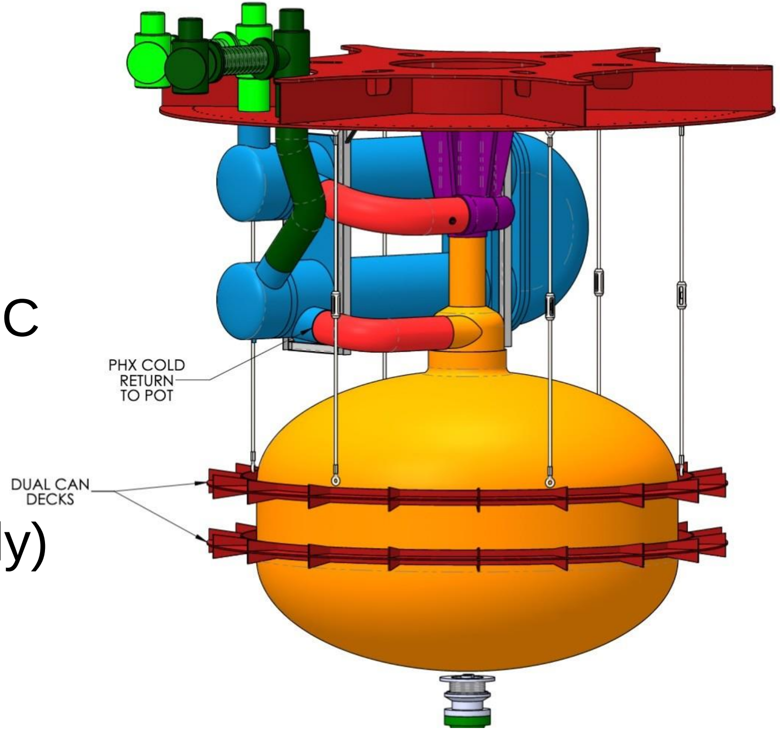
Two 500 MWe ThorCon liquid fission power plants

During 2023, Several Organizations Facilitate The Development Of ThorCon Fission Reactor, Including

- ❖ Milano Multiphysics (MMP)
- ❖ Empresarios Agrupados (EA)
- ❖ PLN Engineering
- ❖ Virginia Tech
- ❖ University of California, Berkeley

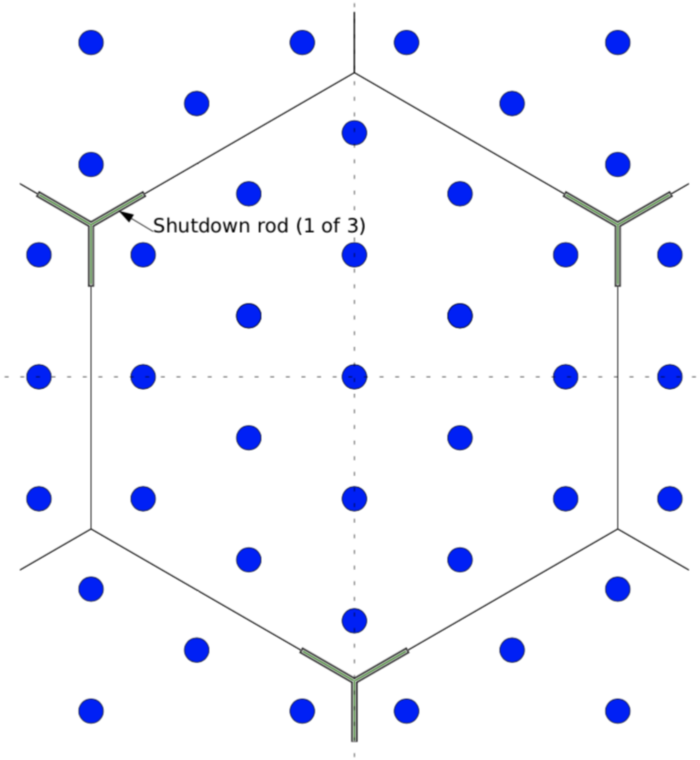
ThorCon Is a Thermal Spectrum, Molten Fluoride Salt Reactor In a Can

- Pot (Vessel) (316 SS)
  - Pressure: 3.5 bar (0.33 Mpa)
  - NaF-BeF_2-UF_4 (72-16-12 mol %)*
  - Temperature: inlet/outlet 564/704°C
  - Graphite moderator (4 y lifetime)
  - Converts some U-238 to Pu-239 (makeup fuel is added continuously)



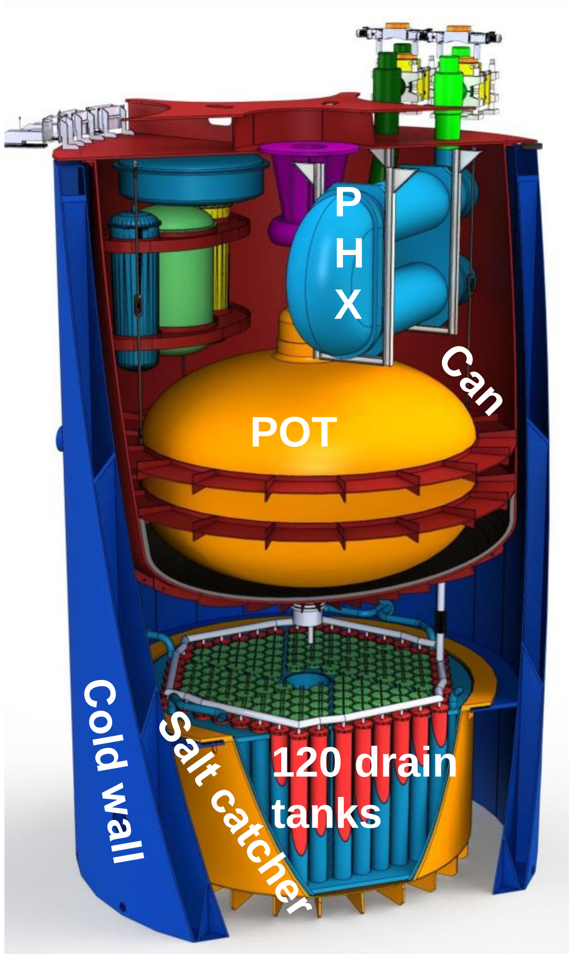
Control of ThorCon Is Achieved via:

- Negative temperature coefficient (−6 to −2 pcm/K)
  - Increased temperature reduces reactivity
- Drop of any one of 3-control rods
- Drain of fuel-salt to drain tank
  - Loss of heat sink or loss of flow that results in a temperature rise of ~120K
- Redox control
  - Minimized corrosion (general & localized)
  - Avoid carbide precipitation ….
- Removal of Xe (transient response) via Off-gas system

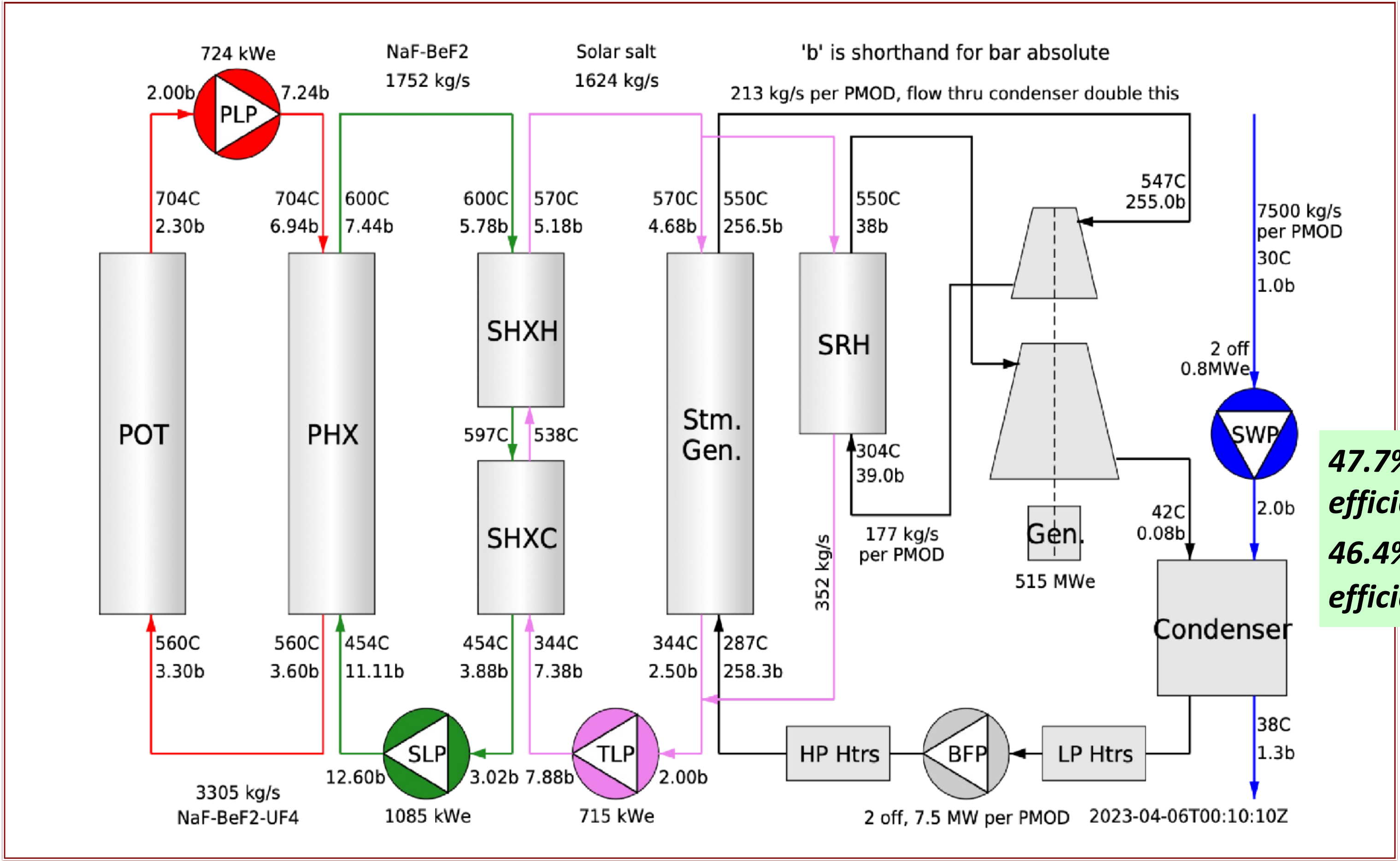


Cooling Is Achieved By Housing Can Unit Within A Cold Wall

- Cold wall (25 mm 316 SS/500 mm water/25 mm 316 SS) continuously absorbs heat
  - Radiated from the Pot
  - Radiated from the drain tanks
- Cold wall is cooled by water thermal-convective circulation



ThorCon Employs Three Salt Loops To Generate Power

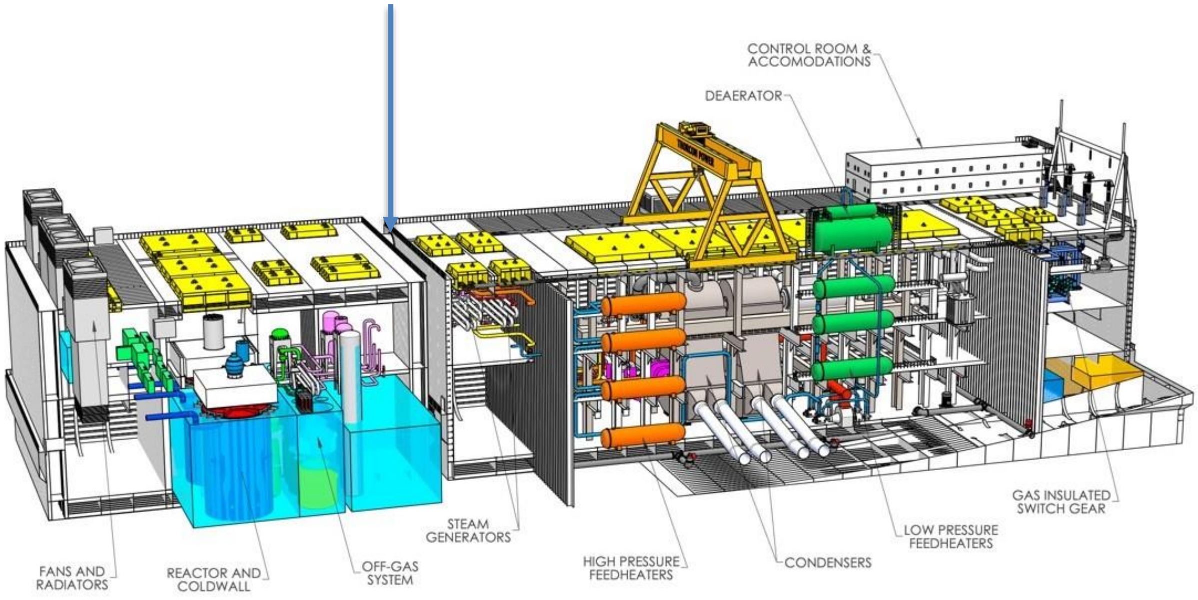


47.7% thermal efficiency @ 20C

46.4% thermal efficiency @ 30C

ThorCon Has Split the Isle into Two Vessels: Fission Island and Balance of Plant

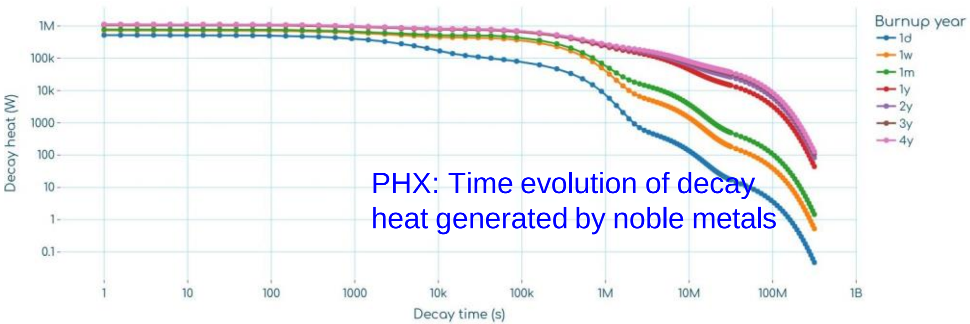
- ❖ Split between the SHX and the steam generator

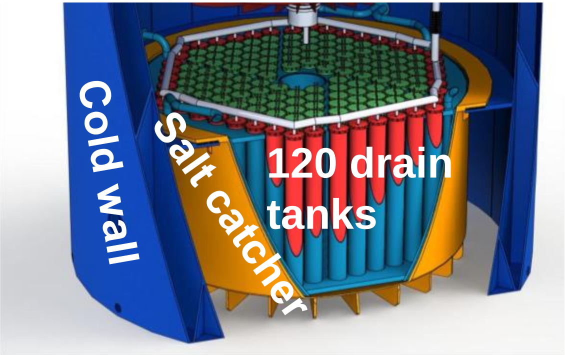


- ❖ Fission island (FI) contains the fuel, fission products
- ❖ FI returns to recycling center
- ❖ Blackstart
- ❖ Load following @ 5%/min

MMP Performed Extensive Neutronic And Heat Flow Analyses That Supports 2023 Design Modifications

- ❖ Modifications to shielding and flow paths that allow for:
  - ♦ Improve materials performance
    - Irradiative and thermal-mechanical
  - ♦ Reduced post-power production radioactivity issues
  - ♦ Significantly reduced worker exposure



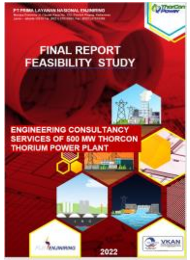


Empresarios Agrupados (EA) Has Forged Forward

- Targets July 2024 to complete the preliminary design of the ThorCon 500 MWe demo plant, which
  - Supports the procurement of components and materials
  - Supports development of preliminary safety analysis report (PSAR)
- Is establishing a procurement plan to qualify, select and manage suppliers, and conduct a local content evaluation in Indonesia in 2024
- Is developing a roadmap with European partners to secure fuel supply in 2024

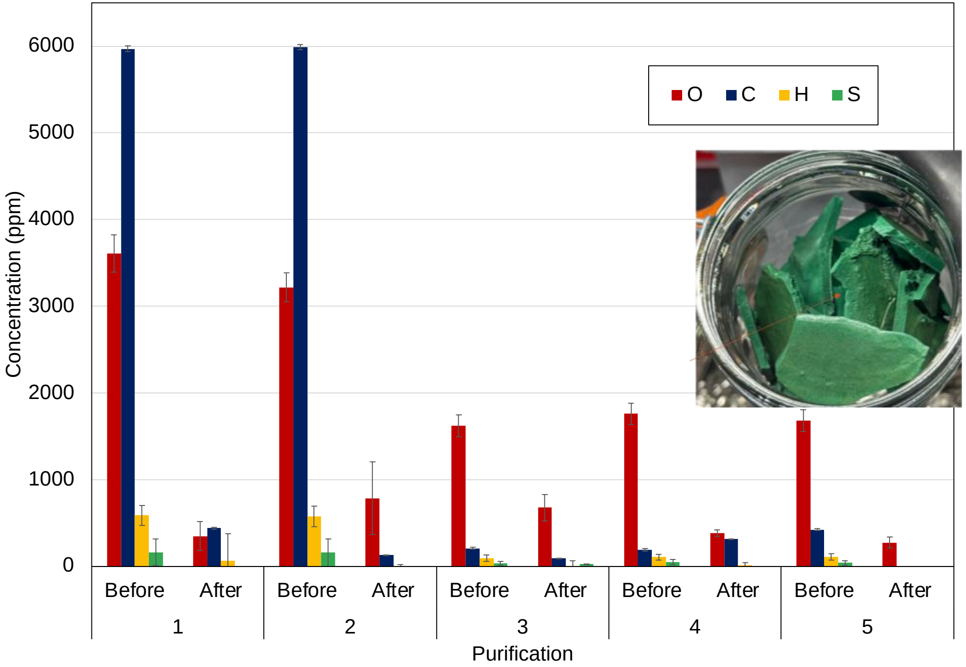
Indonesia Continues To Be Supportive of ThorCon

- Government of Indonesia has embraced fission power to meet the needs for clean and dispatchable power
  - ThorCon has been evaluated within the National Electricity Master Plan (RUKN) 2023-2060
  - Kelasa Island, Bangka-Belitung Province, has been approved by the Province and the Regency for theThorCon 500 MWe demo plant
- PLN-Engineering has completed the site and grid feasibility study
  - Recommended the project to go forward
  - PLN Bangka will lease their land in Pangkalpinang to ThorCon for the salt processing facility
- BAPETEN, the national nuclear regulator, has signed a first-ever pre-licensing consultation agreement



Virginia Tech Has Provided Research Support

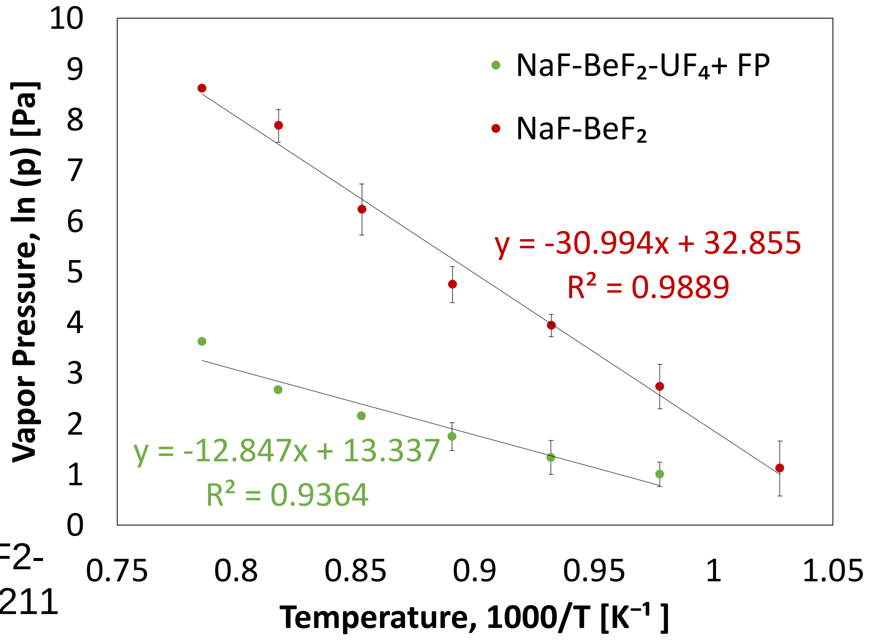
- Salt purification and scale-up
  - Different flow rates and purification times
  - Ni200 and pure Cu crucibles
- Techniques/procedures for elemental analyses including O, C, H and S



*Before purification salts were estimated based on weight percentages of individual salts

Virginia Tech Has Completed Several Properties Measurements

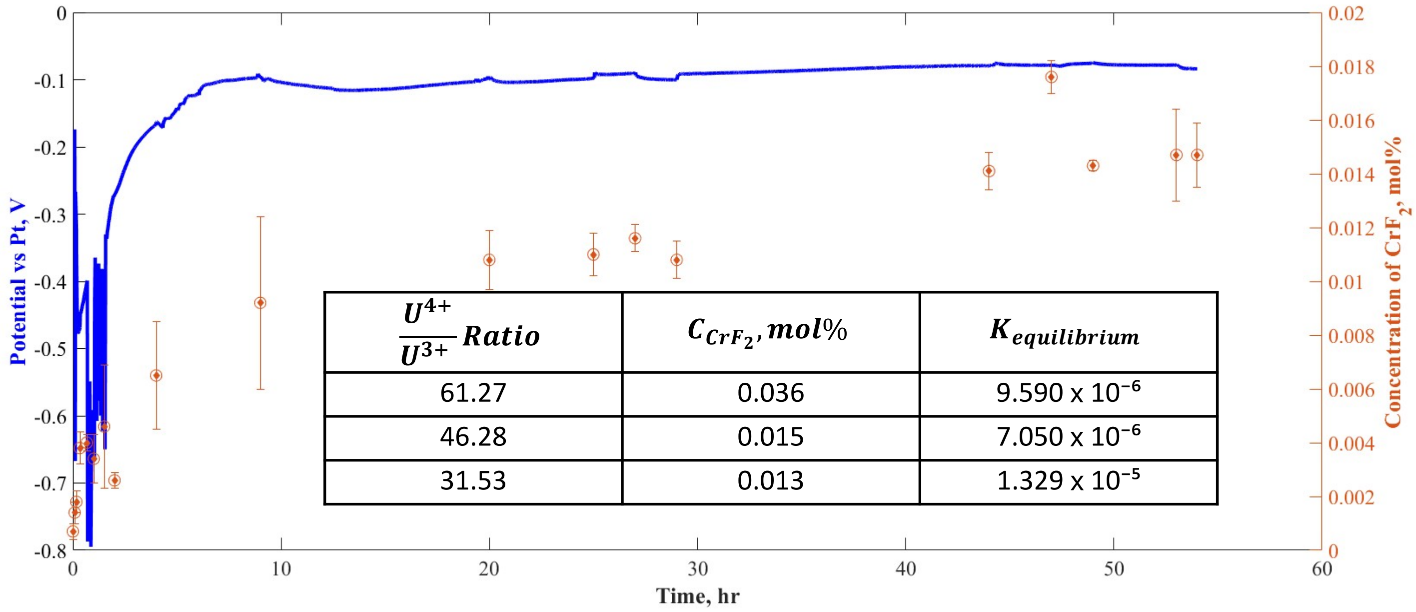
- Fuel salt ($NaF\text{-}BeF_2\text{-}UF_4\text{-}ZrF_4$) and Secondary salt ($NaF\text{-}BeF_2$)
  - Melting Point
  - Density
  - Heat Capacity
  - Vapor Pressure
  - Contact Angle (Fuel Salt)



J. Park, W. Zhuo, C. Ridder, A. Leong et J. Zhong, Thermophysical and thermodynamic properties of NaF-BeF2-UF4-ZrF4 fuel salt, Materials Today, Vol 37 Dec 2023, 107211

Virginia Tech Has Measured Effect of Redox Potential on Chromium Dissolution at a Few UF_4/UF_3 ratios

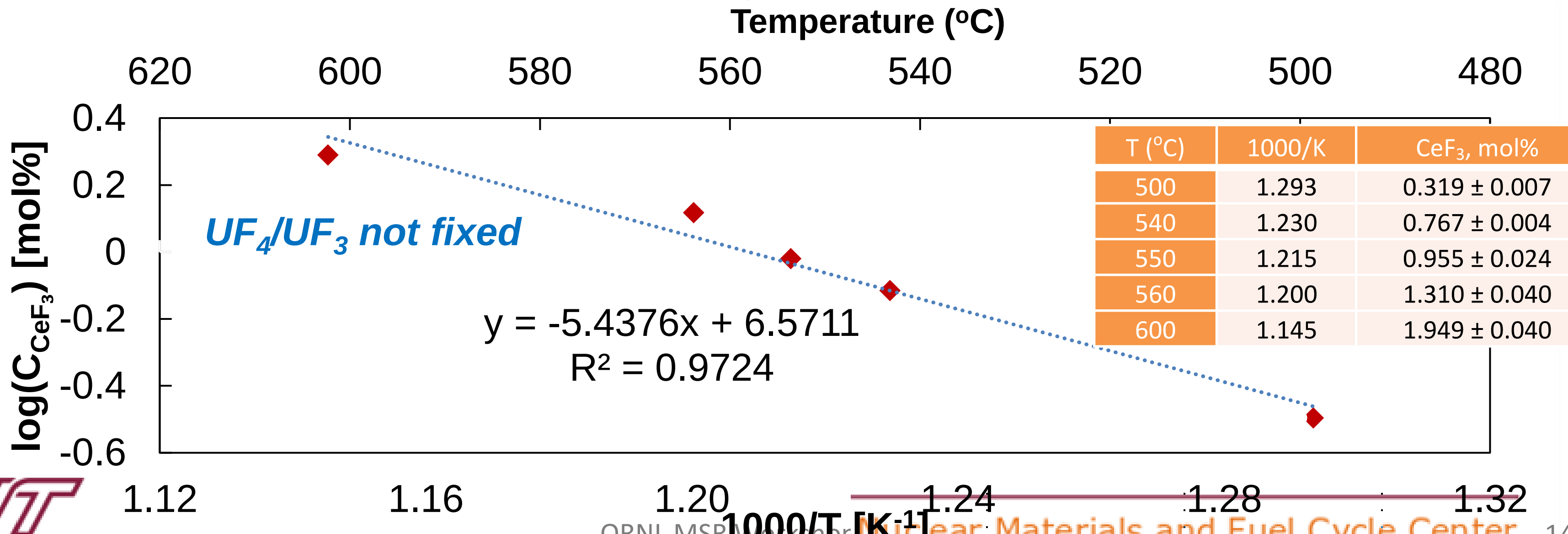
- ❖ UF_4/UF_3 Upper Limit – Dissolution of Chromium
  - ♦ $NaF\text{-}BeF_2\text{-}UF_4\text{-}ZrF_4$ fuel salt at 704°C $Cr + 2UF_4 \rightarrow CrF_2 + 2UF_3$
    - • Dissolution of Cr monitored using OCP and ICP-MS.



$\frac{U^{4+}}{U^{3+}}$ *Ratio*	C_{CrF_2}, *mol%*	$K_{equilibrium}$
61.27	0.036	9.590×10^{-6}
46.28	0.015	7.050×10^{-6}
31.53	0.013	1.329×10^{-5}

Virginia Tech Has Measured Effect of Redox Potential on Trifluoride Solubility (CeF_3)

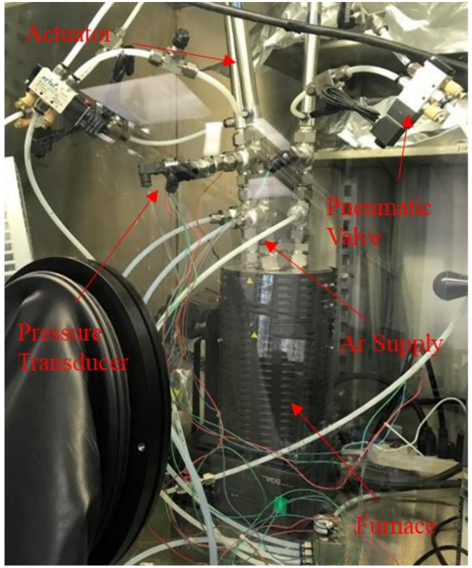
- UF_4/UF_3 Lower Limit – Trifluoride Solubility
- $NaF\text{-}BeF_2\text{-}UF_4\text{-}ZrF_4$ at 500, 540, 550, 560 and 600°C.
  - Dissolution monitored using OCP and ICP-MS.

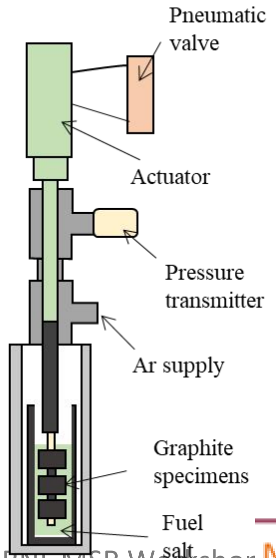


T (°C)	1000/K	CeF_3, mol%
500	1.293	0.319 ± 0.007
540	1.230	0.767 ± 0.004
550	1.215	0.955 ± 0.024
560	1.200	1.310 ± 0.040
600	1.145	1.949 ± 0.040

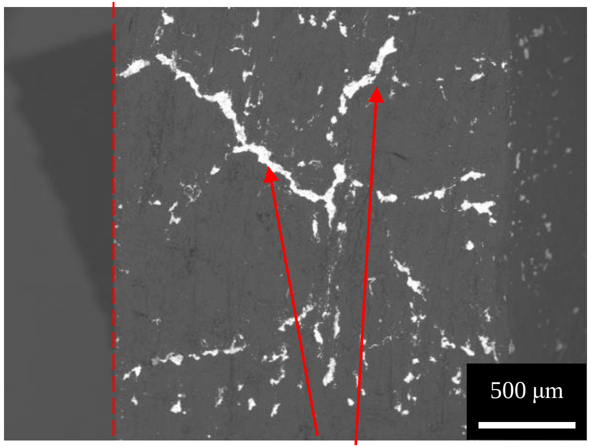
Virginia Tech Is Developing Graphite/Salt Infiltration Test System and Evaluation Procedures

- ❖ Specimens connected to actuators
  - ♦ Specimens retracted from salt without depressurizing the system
- ❖ NaF-KF-UF_4 infiltrated graphite (1-2 μm pore size, 8% porosity) at 41-150 psig and 704°C





Cross section of post-test graphite at 120 psig



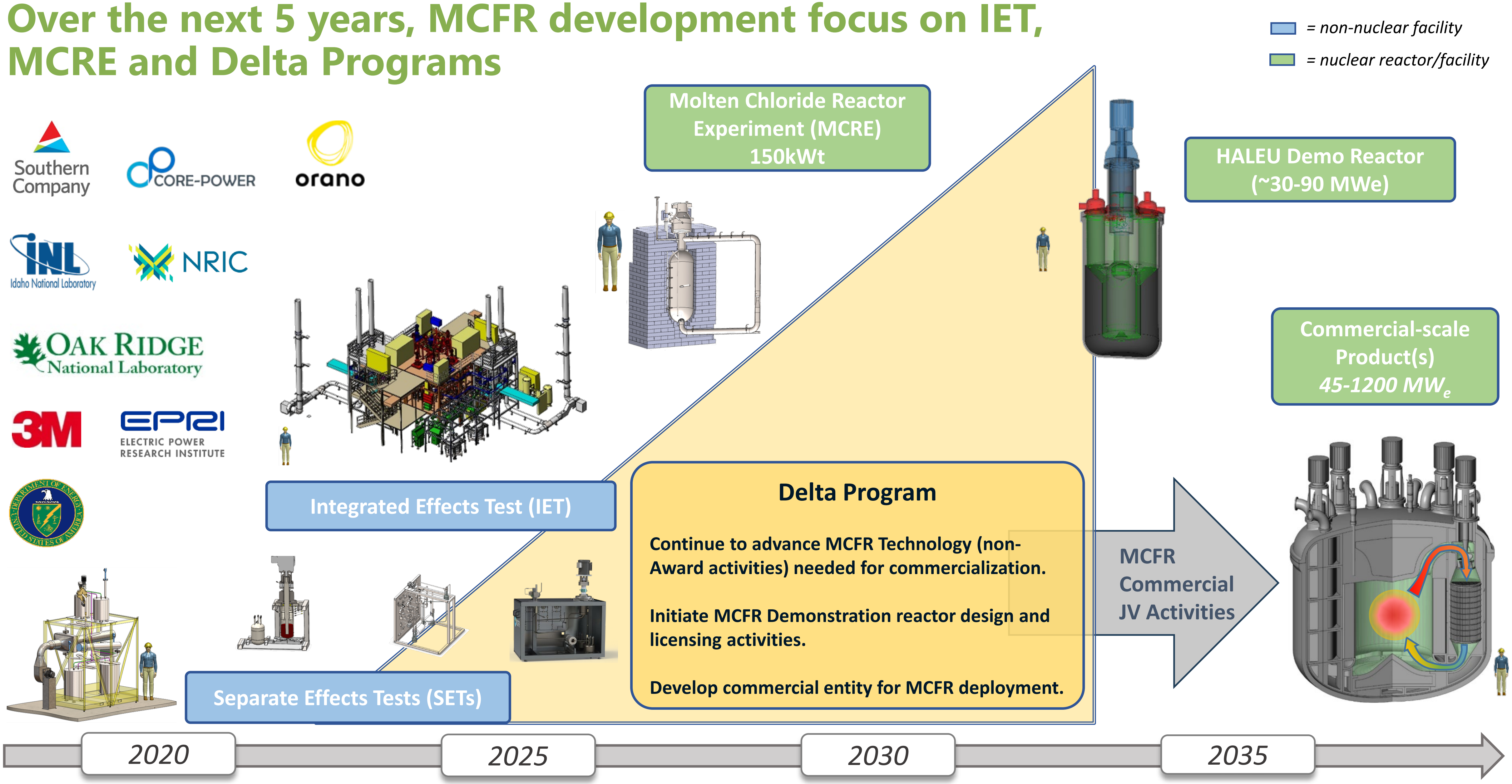
In Summary, Several Organizations Facilitate The Development Of ThorCon Fission Reactor, Including:

- ❖ Milano Multiphysics (MMP)
- ❖ Empresarios Agrupados (EA)
- ❖ PLN Engineering
- ❖ Virginia Tech
- ❖ University of California, Berkeley

Overview of TerraPower's Molten Chloride Fast Reactor (MCFR) Program

Joshua Walter
MCFR Director and Deputy Program Manager
TerraPower, LLC

Over the next 5 years, MCFR development focus on IET, MCRE and Delta Programs

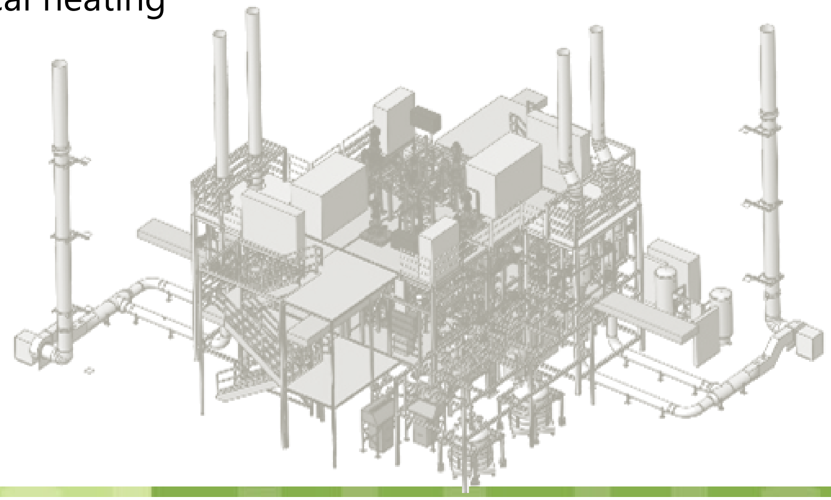


TerraPower

Two DOE programs play an important role in MCFR technology development

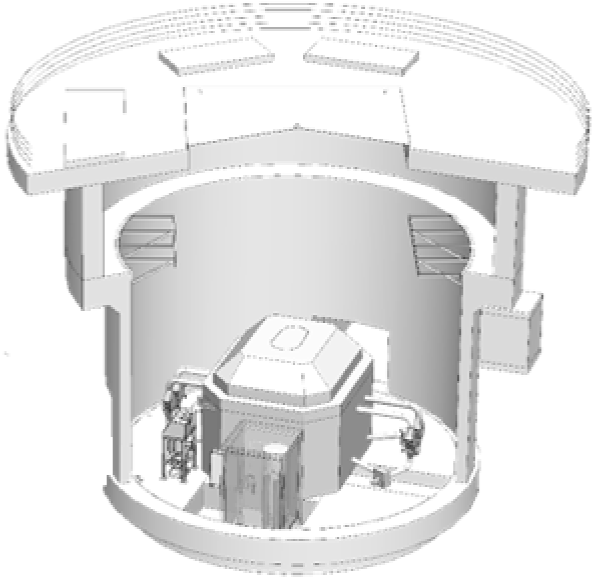
Advanced Reactor Concepts (ARC15)

- Separate Effects Tests: microloops, salt selection, isothermal and polythermal loops
- Integrated Effects Test (**IET**):
  - Government Award concluded in 2023
  - Multi-loop system; Pumped slat operations underway
  - >1 MW electrical heating
- Total project cost ~ $85M



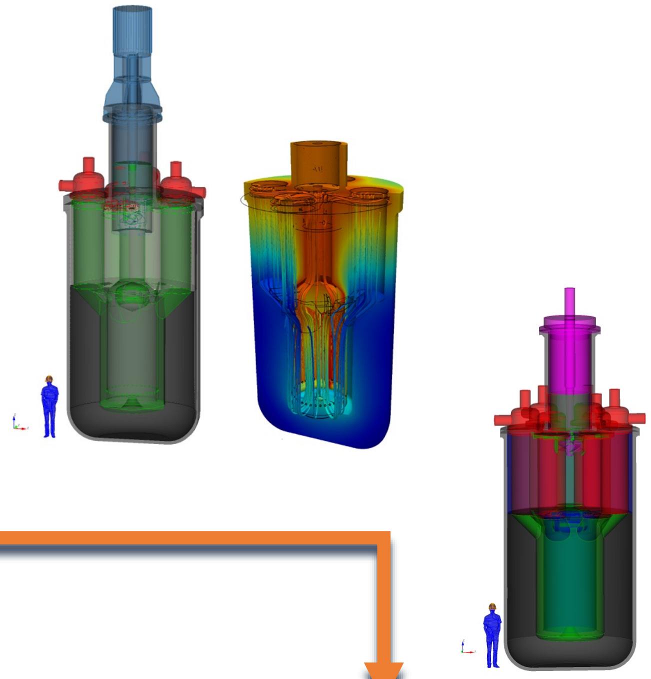
Advanced Reactor Demonstration Program (ARDP)

- Separate Effects Tests: pump test, liquid transfer system, mockup
- Molten Chloride Reactor Experiment (**MCRE**):
  - World's first fast spectrum molten salt reactor
  - Confirm key physics
  - INL sited, DOE authorized
  - Startup and Critical Ops
    - 2027-2028
- Total project cost ~ $260M



TerraPower

The Delta Program initiates effort toward MCFR commercial demonstration, MCFR-D



- MCFR-D enables multiple MCFR product offerings
  - MCFR-D targets a 2 x 90 MWth system for 180 MWth/75 MWe
    - Develop the “unit cell”, which includes a pump and heat exchanger
    - Varying numbers can serve multiple commercial products and can be coupled with the same core

MCFR-D
180 MWth/75 MWe
(2 x 90 MWth)

Maritime propulsion*

Fleet of de-rated MCFR-D plants
70 MWth/25 MWe
2 x 90 derated to 2 x 35 MWth
20 full-power-year lifetime

CORE-POWER

Off-shore power and chemical production

Fleet of MCFR-D plants
180 MWth/75 MWe
2 x 90 MWth

CORE-POWER

Transuranic Destruction

Fleet of MCFR-D plants
Fueled on Pu/TRU
4 x 90 MWth/150MWe

orano

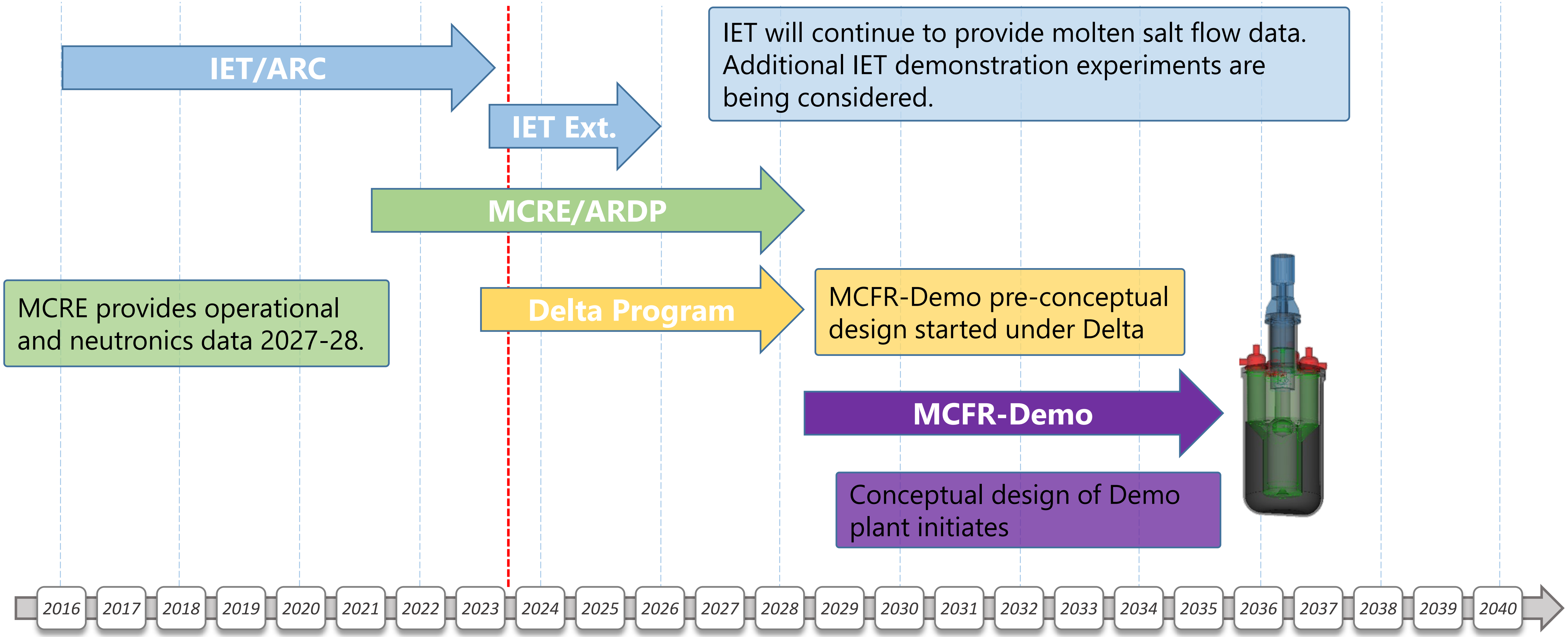
Terrestrial heat & power production

Fleet of terrestrial plants
540-720 MWth/230-310 MWe
6 x 90 or 8 x 90 MWth

Southern Company

* Domestic maritime propulsion (under Jones Act) is possible now, but international would require a shift in US stance.

The overall MCFR development program is a 20-year, $2-3B combined effort



TerraPower

TerraPower is additionally supporting broader MCFR efforts

- **Two ARPA-E awards explore oxide and metal fuel (with surrogate fission products) to chloride salts.**
  - ONWARDS project (Chloride-Based Volatility) underway and CURIE is initiating
- **TerraPower has worked with LANL on two GAIN awards**
  - **Chlorine cross-section**
  - **Neutron Dilatometry for Pu-bearing salts**
- **NEUP with University of Tennessee, University of Illinois Urbana-Champaign and ORNL**
  - **Application of MCFR to UIUC Campus.**
- **Salt characterization activities at the University of Utah.**

Uranium chloride in the gas phase (brown gas near the boat), solidified UCl_4 (dark crystals just outside of the heated zone)

Copenhagen Atomics
Thorium breeder reactor

copenhagen
atomics

Aslak Stubsgaard
CTO & Co-founder

The goal

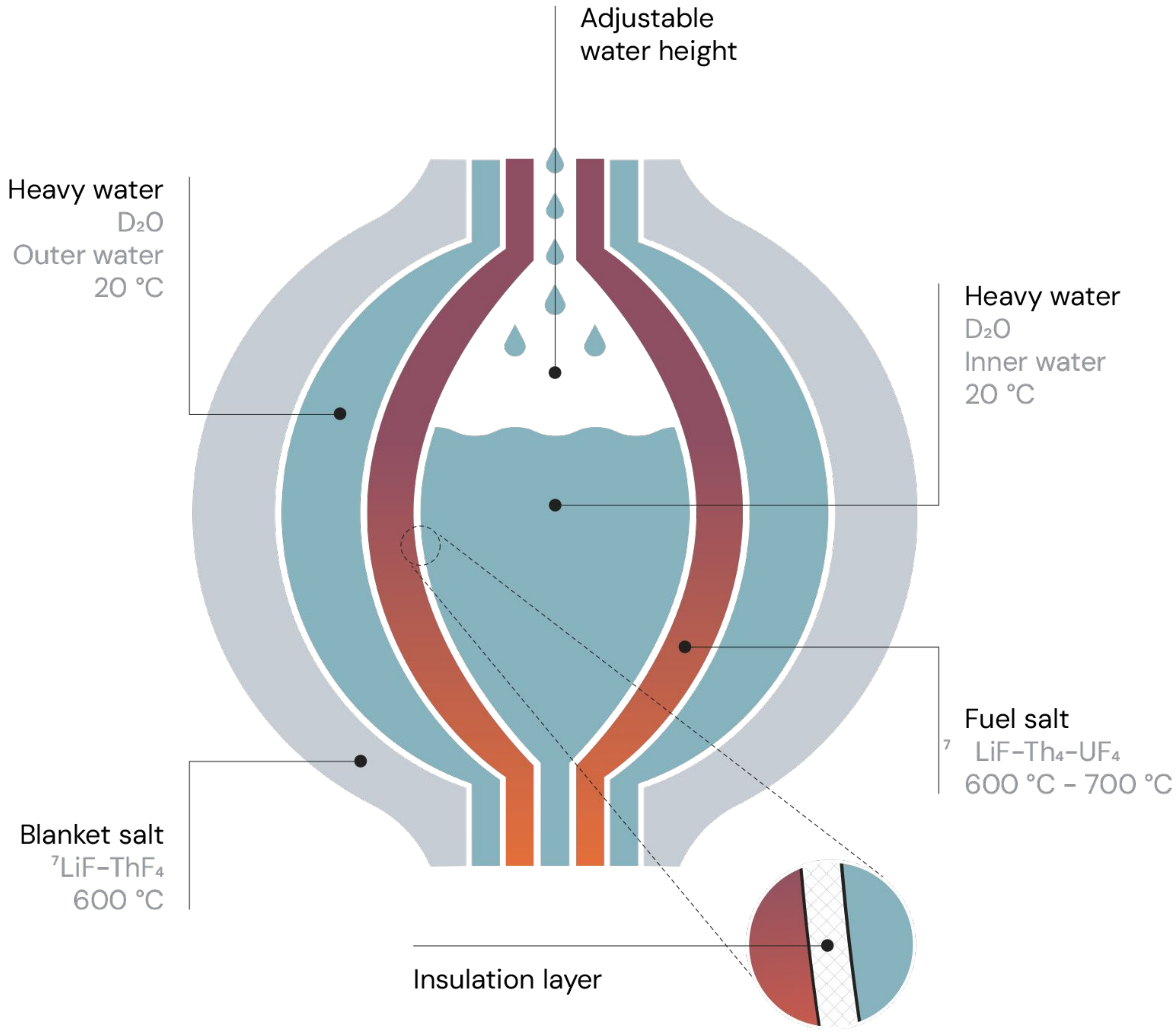
Mass manufacturing thorium reactors

copenhagen
atomics

The Onion Core®

Cross-section view

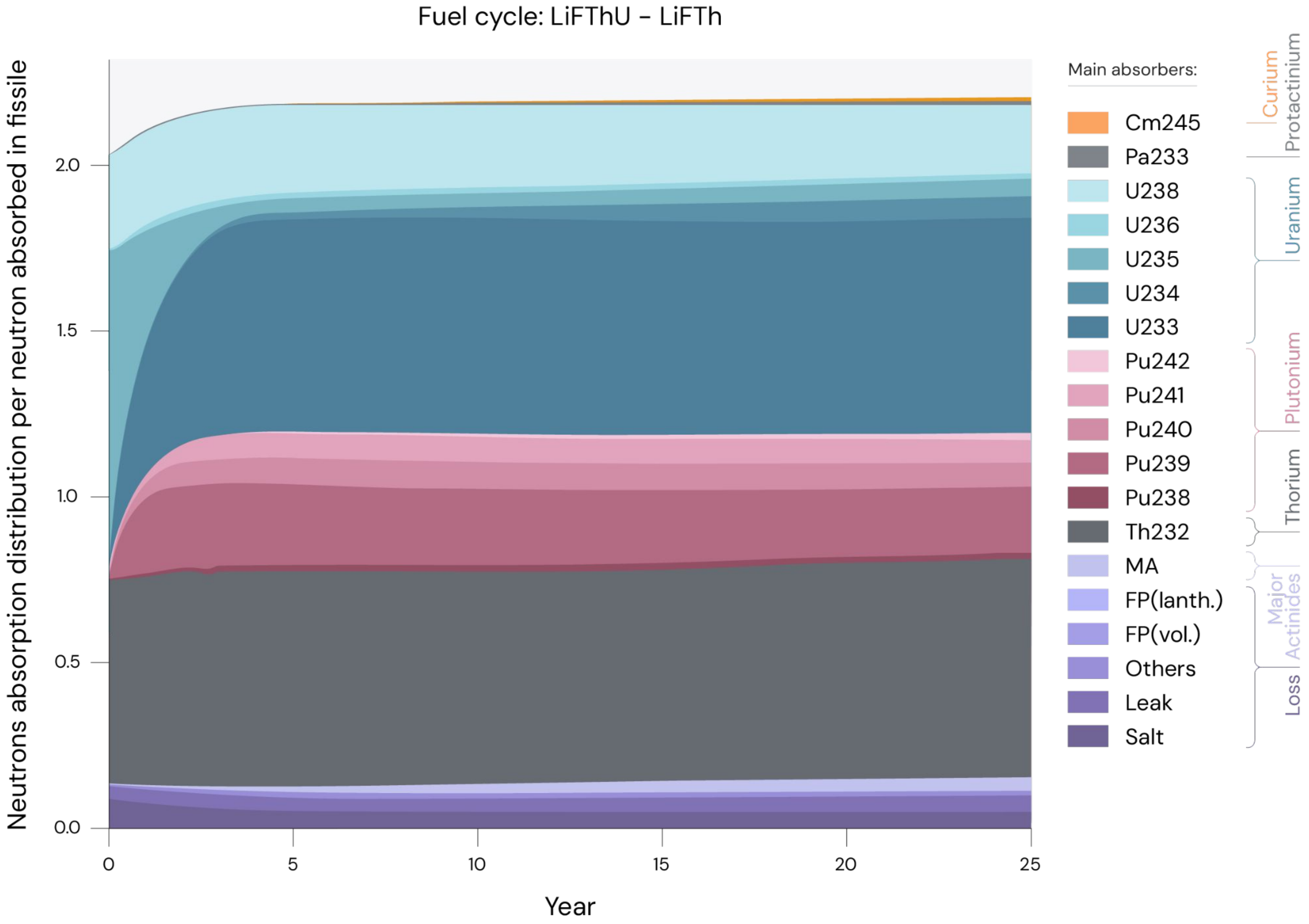
- Unpressurized room temperature heavy water moderator
- Double barrier and insulation between salt and heavy water
- segments made from metal or composite material
- Below 2% neutron leakage
- Reactivity control using heavy water level adjustment



copenhagen atomics

Reactor specs and burnup chart

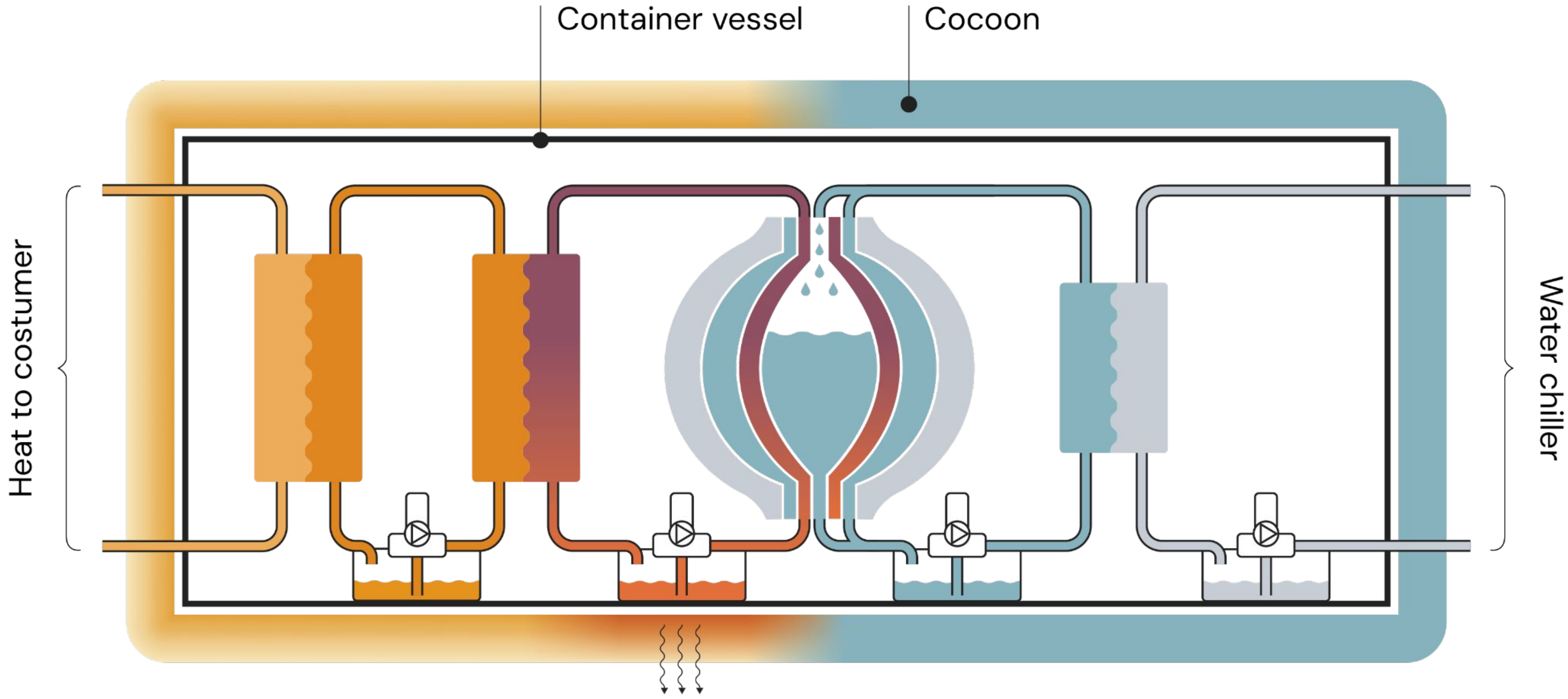
- 700L FLiTh-TRU (75-22-3 %mol) or
  FLiTh-LEU (75-3-22 %mol)
  starting fuel salt composition
- 3000L FLiTh blanket salt
- 3000L D_2O
- 5N enriched ^7Li
- Composite core structure
- Online fission product separation
- Transfer of uranium from blanket salt to fuel salt



copenhagen atomics

The Onion Core®

Loops and containment



copenhagen atomics

- 2.5GW(th) / 1GW(e) plant
- Autonomous operation
- 5 year reactor lifetime
- Salts and D_2O are reused
- Target heat price of $5/MWh(th)

copenhagen atomics

Supply chain

Lithium-7
in–house

Copenhagen Atomics will produce 5N ^{7}Li in–house and starting one ton per year production in 2024.

Thorium
with partners

Copenhagen Atomics is setting up the supply chain for thorium (ThF_4) with partners around the world.

Heavy Water
from market

Copenhagen Atomics will source heavy water from the existing capacity.

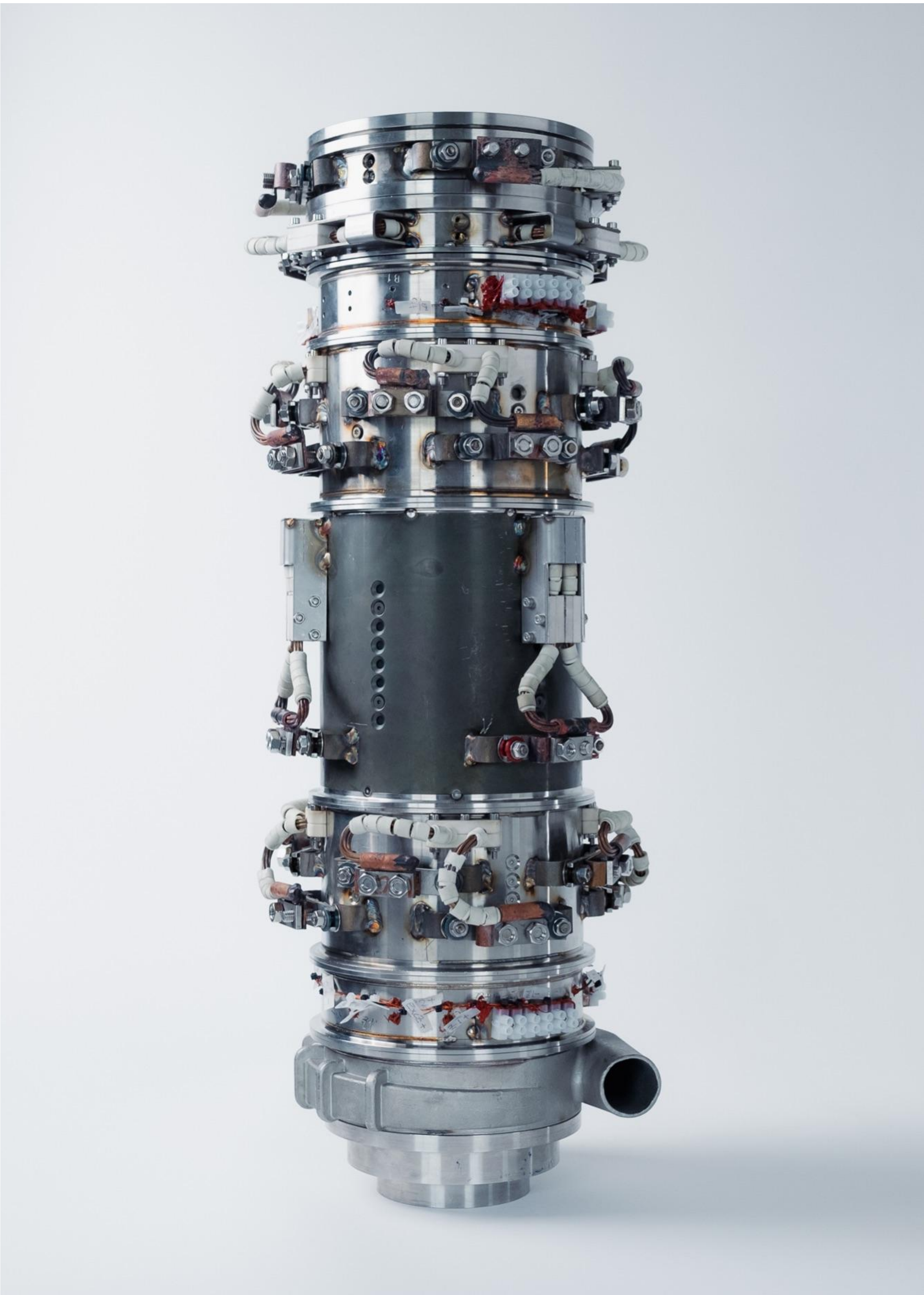
Low Enriched Uranium
from market

Copenhagen Atomics will source 5% LEU from existing capacity as UF_6 and convert to UF_4 in–house.

Valves

copenhagen
atomics

Pumps



copenhagen
atomics

Loops

Specs

Pump
Valve
Flow meter
Pressure sensor
Salt leak sensor

Available for purchase with 1000h warranty

Upcoming

Online salt chemistry monitoring

copenhagen atomics

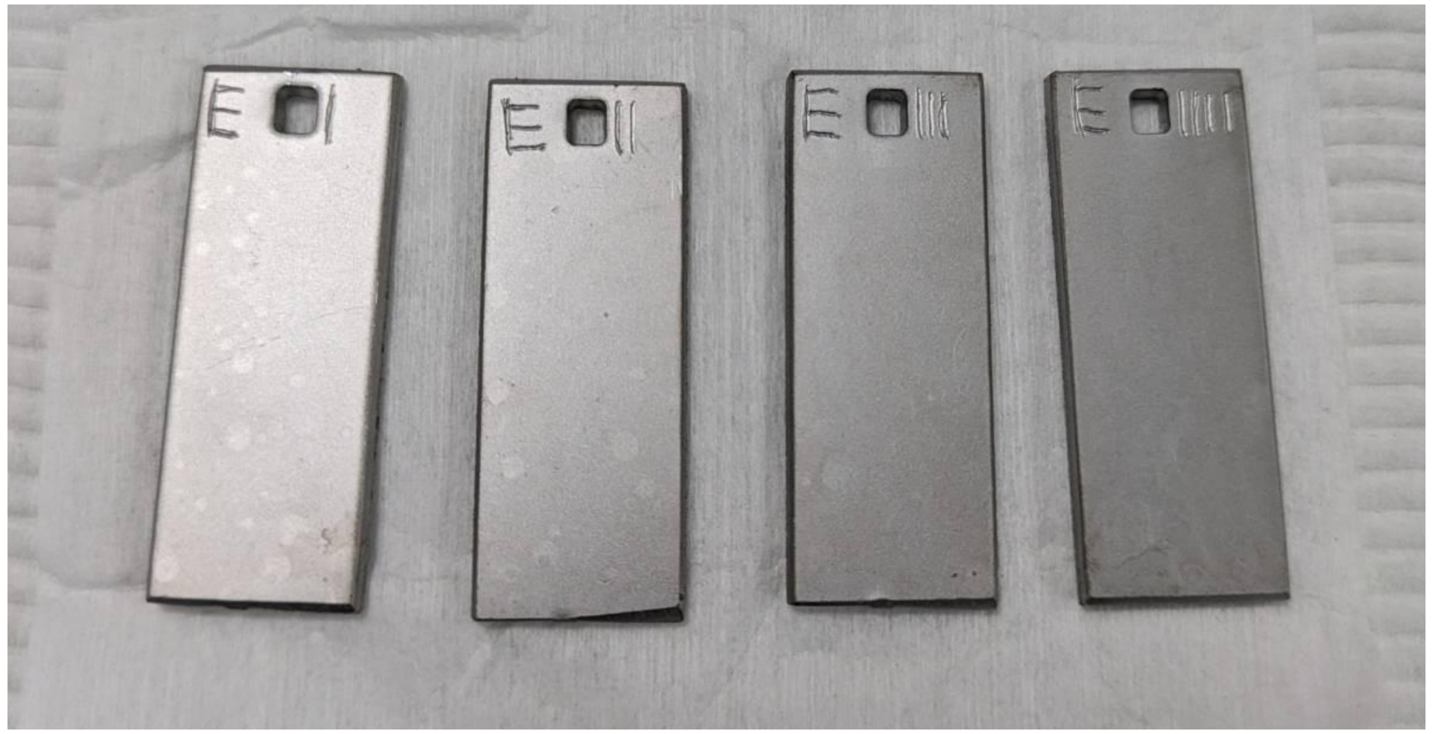
Reactor Production Facility

11.000 m^2

Copenhagen, Denmark

70+ Employees

Large-scale salt production



1000L batch size of purified FLiNaK, FLiTh, FLiThU, etc.

Purified salt specs:
<100ppm of oxide species
<500ppm of transition metal species

Available for purchase

Static corrosion study

SS316L in purified FLiTh salt
@ 700C & 3000h

1-5 μm/y corrosion rate

Non-fission water prototype

copenhagen
atomics

Non-fission FLiNaK and water prototype

Milestones towards a 1MW & 30MWd test reactor

2023	2023	2024	2024	2025	2025/ 2026
Water Prototype	FLiNaK Prototype	Fertile Salt Production FLiTh+FLiThU	Fertile Prototype	LEU Subcritical Prototype	LEU Test Reactor
Completed	Ongoing	Upcoming	Upcoming	Upcoming	Upcoming

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atomics

Kairos Power

2023 ORNL MSR Workshop

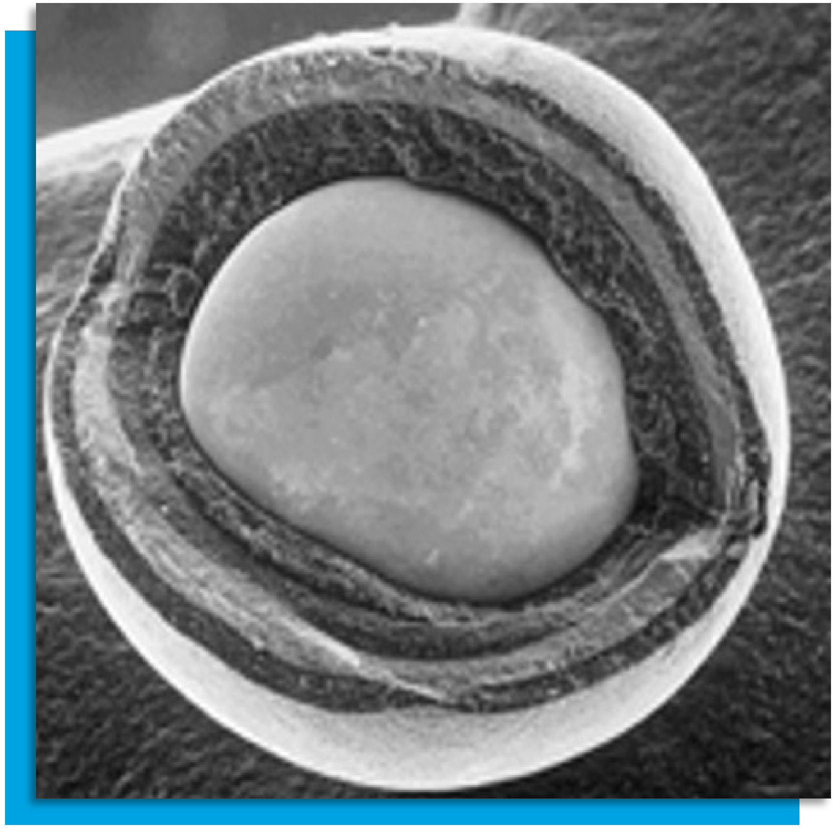
DEVELOPER'S FORUM UPDATE

Kairos Power's mission is to enable the world's transition to clean energy, with the ultimate goal of dramatically improving people's quality of life while protecting the environment.

In order to achieve this mission, we must prioritize our efforts to focus on a clean energy technology that is *affordable* and *safe*.

Fluoride Salt-Cooled High Temperature Reactor

Technology Basis



Coated Particle Fuel
TRISO

Liquid Fluoride Salt Coolant
Flibe ($2LiF-BeF_2$)

Kairos Power Testing Program

Rapid Technology Demonstration Requires
Non-Nuclear *Development and Qualification Facilities*

R RAPID LAB

Rapid Analysis, Prototyping, and Iterative Design Lab, Use of Surrogate Fluids for Iterative Testing & Component Development

S SALT LAB

Flibe Chemistry & Materials Testing, Flibe Component Development, & Salt Flow Loops

T TESTING FACILITY

Component Testing Facility

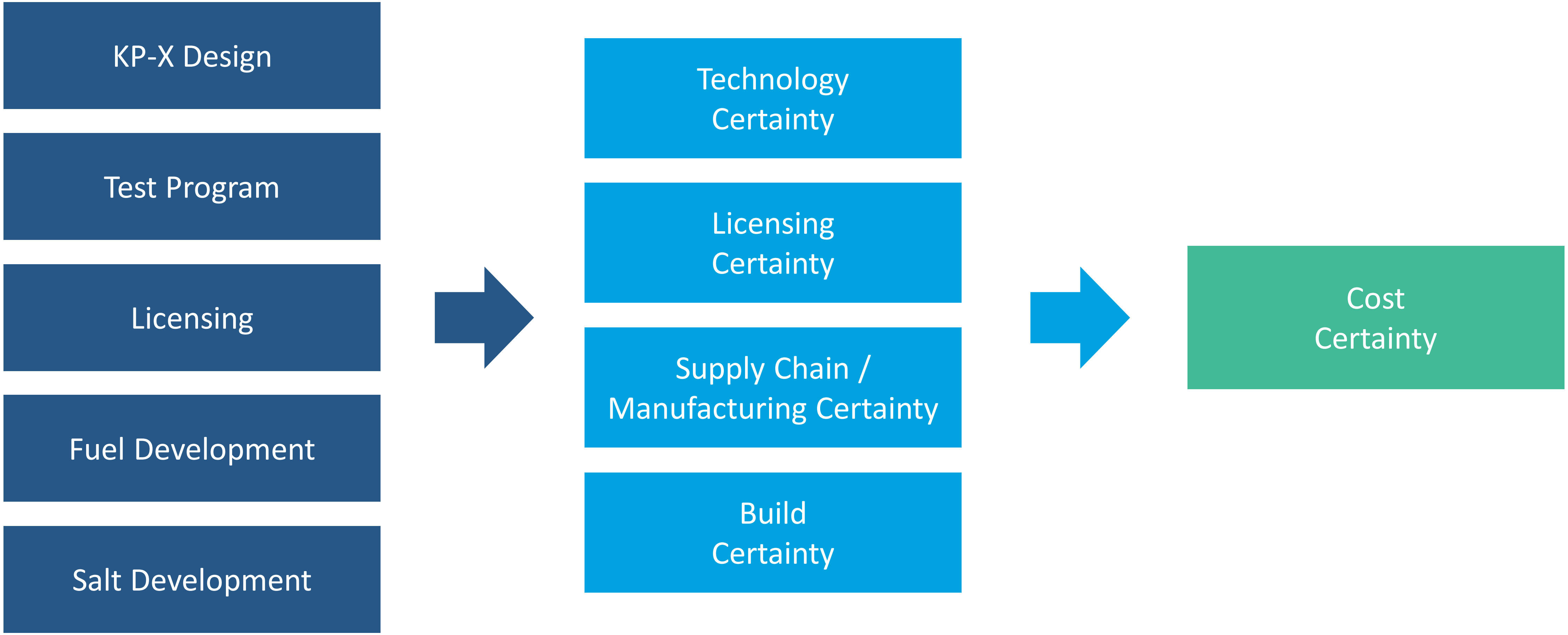
Includes Engineering Test Unit (ETU)

U USER FACILITY

User Ops & Maintenance Training Facility

Kairos Power Workstreams

Reduce risk and build cost certainty



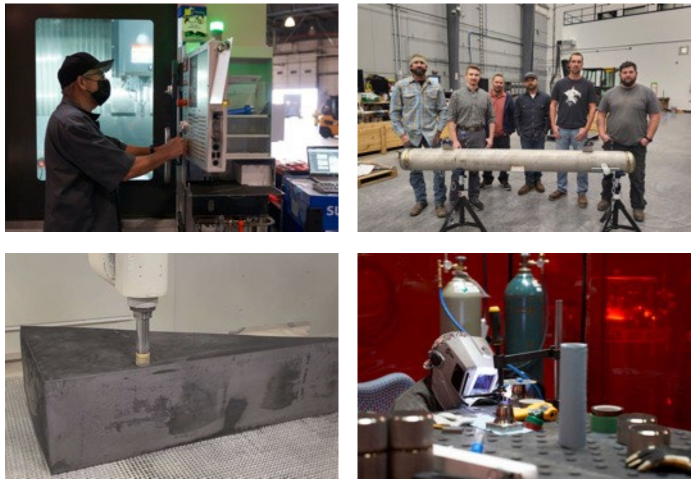
Vertical Integration

Delivering Cost Certainty

Kairos Power has made significant investments in infrastructure to de-risk the supply chain and deliver cost certainty, vertically integrating production or assembly of components and materials that are:

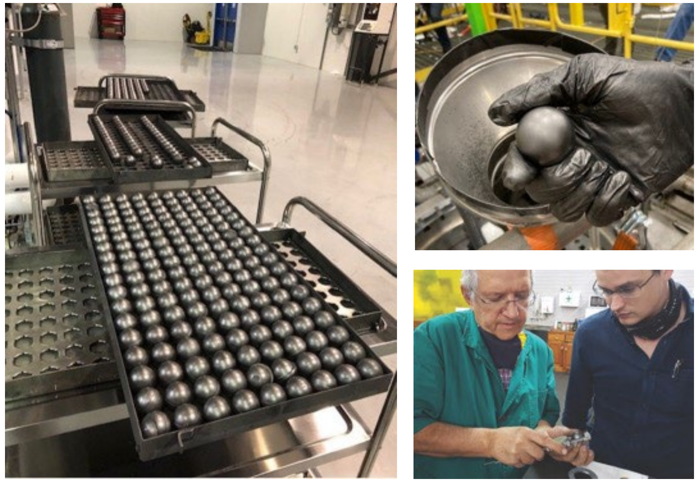
1) related to salt   2) safety-related   3) not available off-the-shelf

KP Southwest Manufacturing Facility



In-house manufacturing of specialized components

Pebble Development Lab & TRISO Development Lab



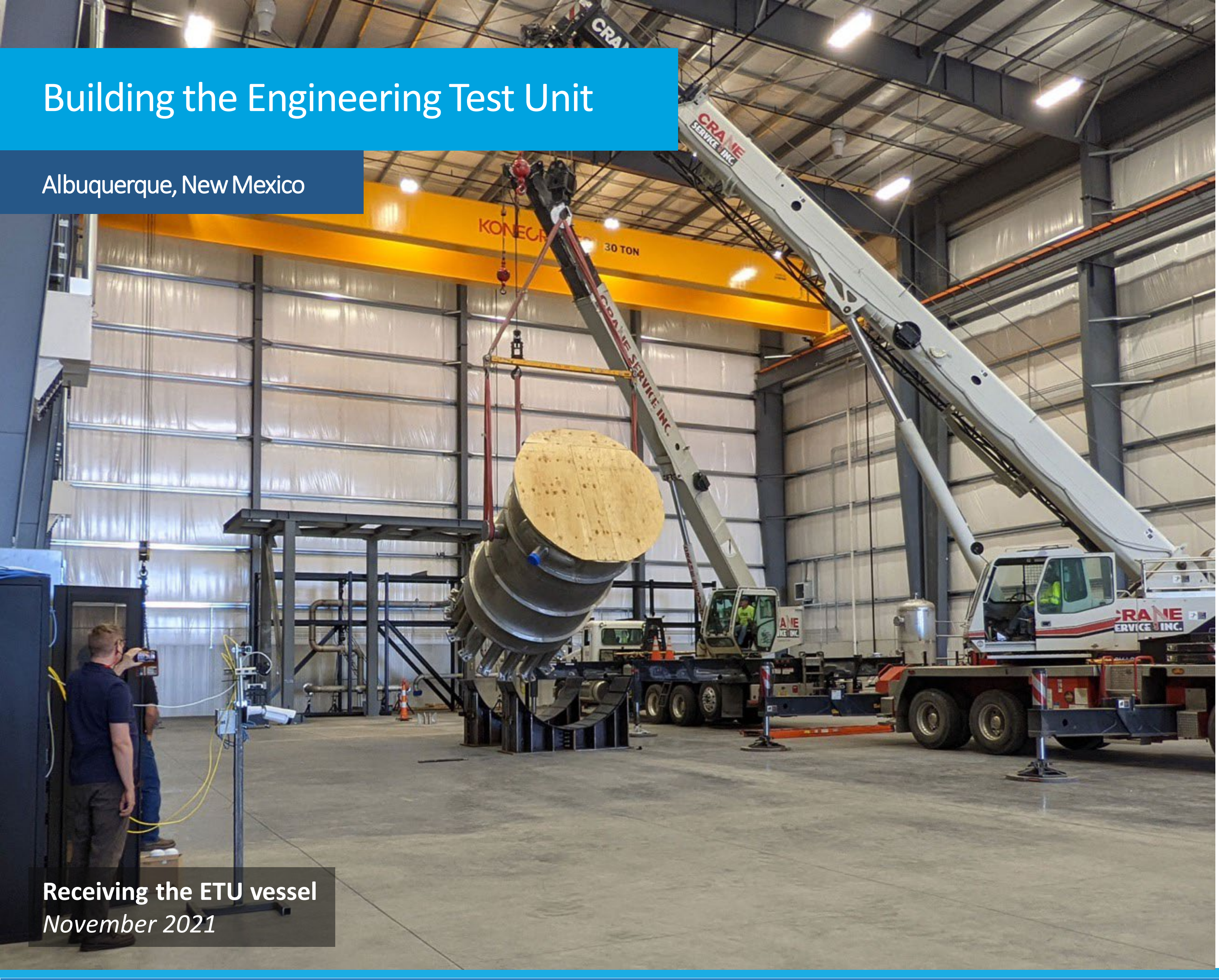
Fuel development

Molten Salt Purification Plant

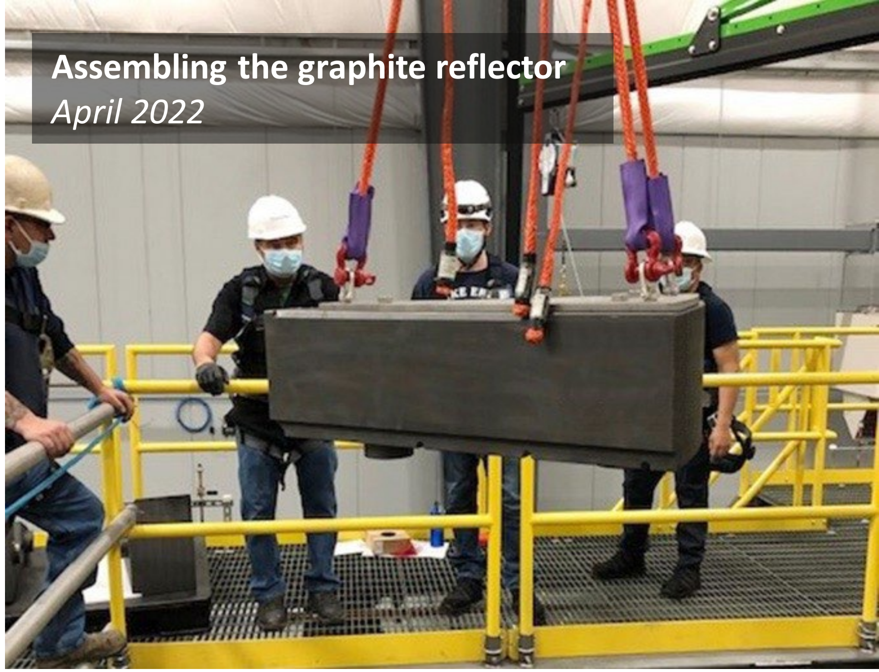
Commercial-scale Flibe production

Building the Engineering Test Unit

Albuquerque, New Mexico



Receiving the ETU vessel
November 2021



Assembling the graphite reflector
April 2022

Adding the 30,000th simulated fuel pebble
May 2022


Construction complete / hot commissioning in progress
November 2022


ETU Control Room
Albuquerque, NM


Argos Remote Control Room
Alameda, CA

Kairos Power’s Commitment to the Community

Embedded in Our Mission

Everything we do at Kairos Power is driven by our mission to **improve people’s quality of life while protecting the environment**

Our Commitment:

- Engage and support local communities
- Prioritize diversity, equity, and inclusion
- Selectively build on brownfield sites
- Deliver high energy density with low land use

1 fuel pebble = 4 tons of coal

Headquarters
Alameda, CA

KP Southwest
Albuquerque, NM

K-33 Site
Oak Ridge, TN


Kairos Power
Enabling the world's transition to clean energy
while improving people's quality of life
and protecting the environment

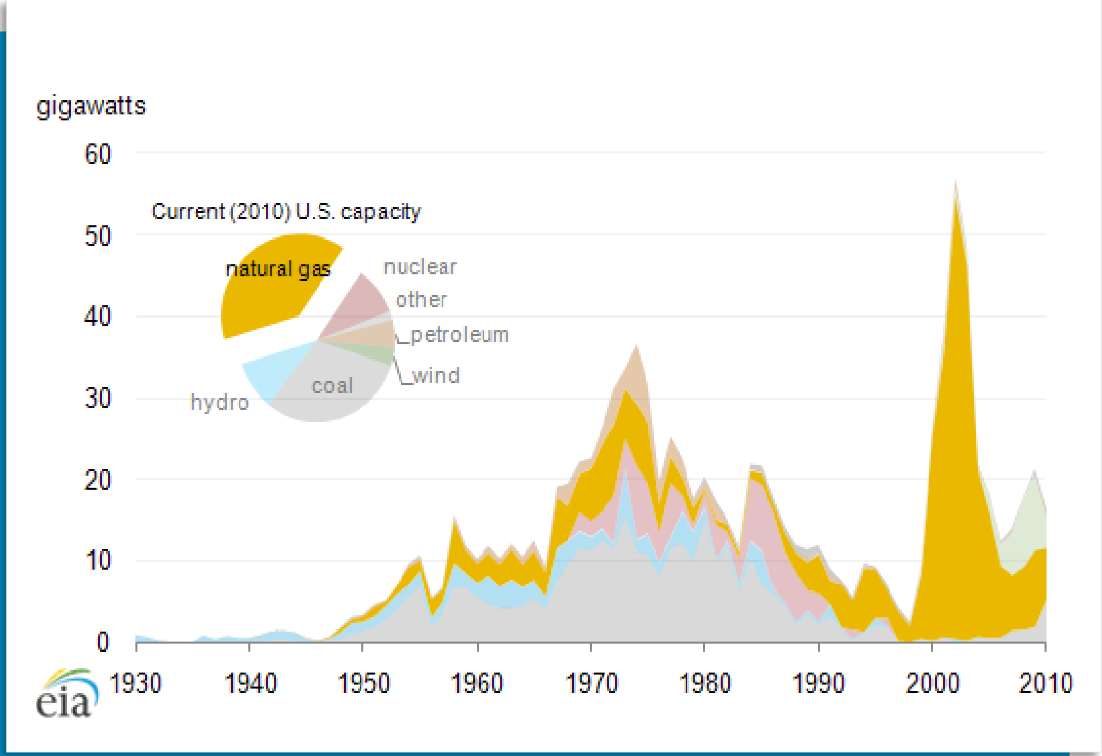
Overview of Kairos Power

- Nuclear energy engineering, design, and manufacturing company ***singularly focused*** on the commercialization of the fluoride salt-cooled high-temperature reactor (FHR)
  - Founded in 2016
  - 368 Employees (~90% Engineering Staff)
- Novel approach to nuclear development that includes iterative hardware demonstrations and in-house manufacturing to achieve disruptive cost reduction and provide true cost certainty
- Schedule driven by US demonstration by 2030 (***or earlier***) and rapid deployment ramp in 2030s
- Cost targets set to be competitive with natural gas in the US electricity market

Kairos Power Headquarters

Kairos Power Team

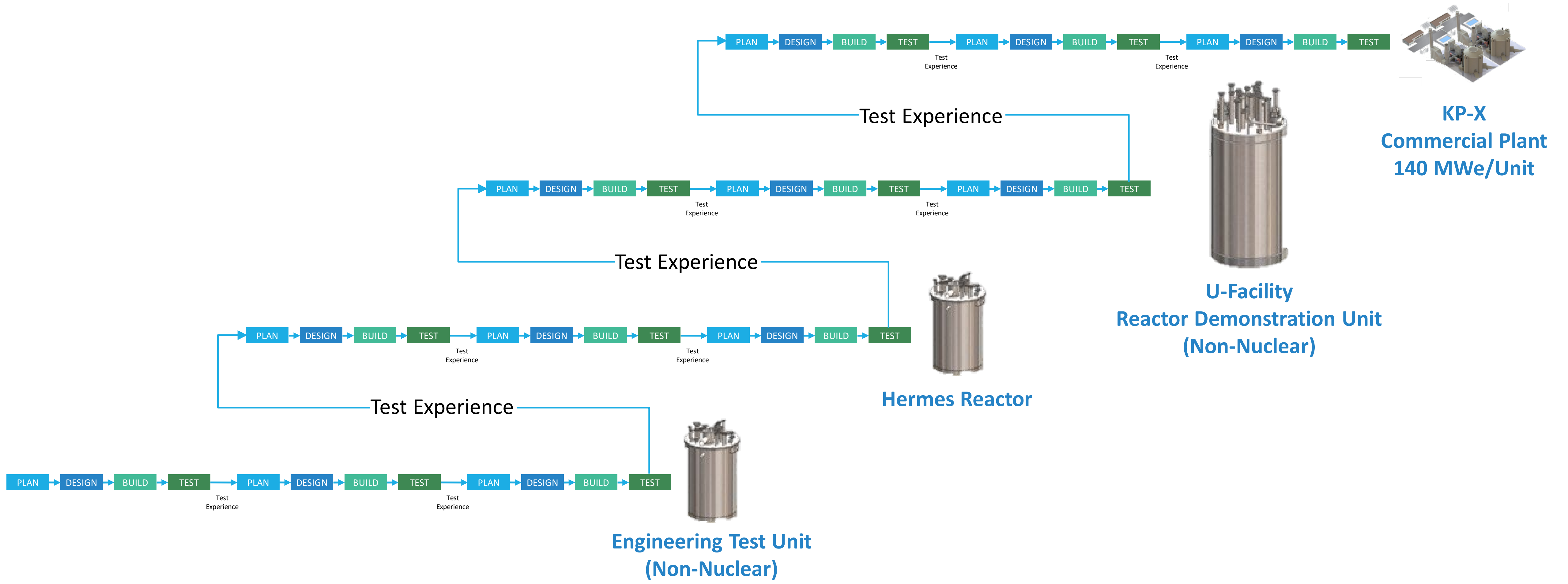
kai·ros (def.): the right or opportune moment



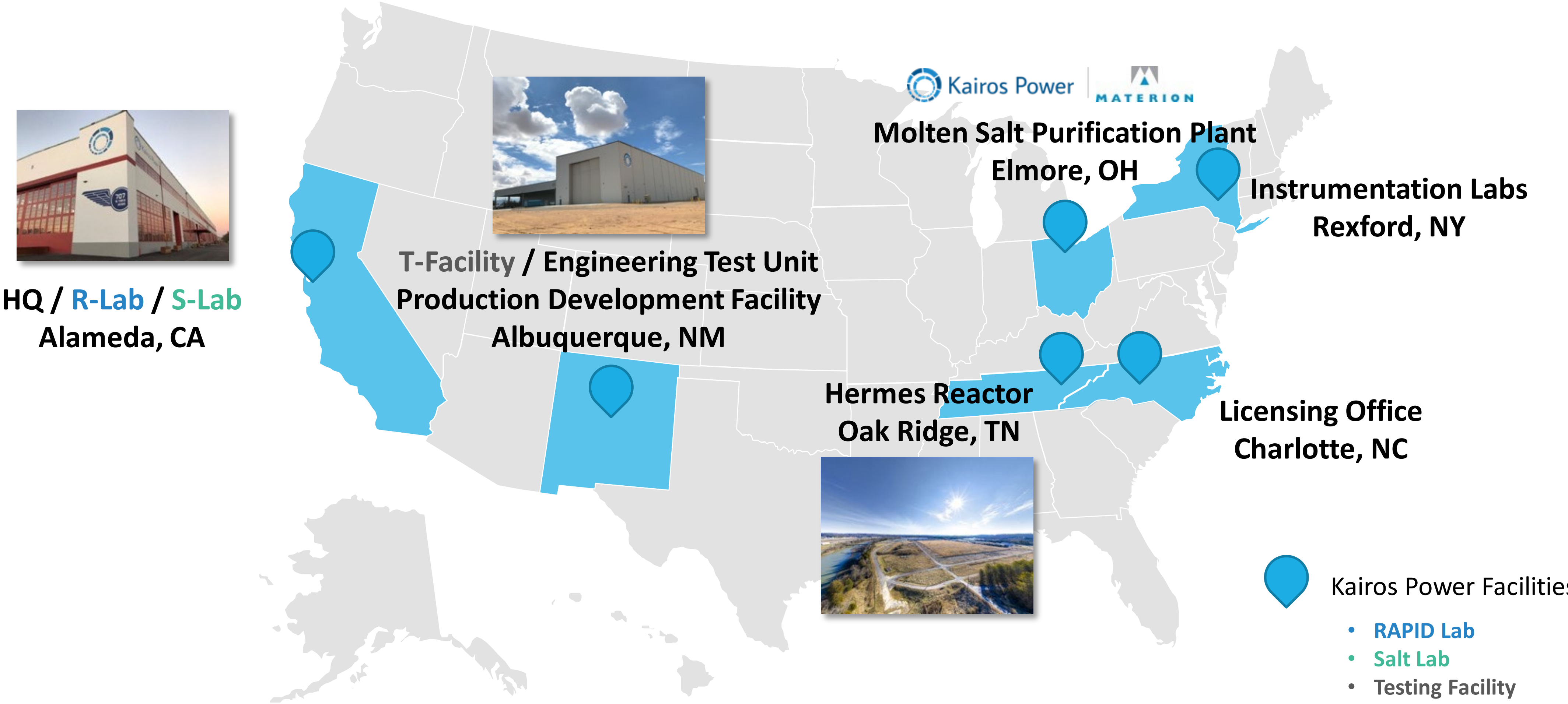
U.S. Electricity Generation by Initial Year of Operation and Fuel Type

Kairos Power Path to Commercialization

Successive Large-Scale Integrated Demonstrations



Kairos Power Locations and Infrastructure



Kairos Power Facilities

- RAPID Lab
- Salt Lab
- Testing Facility

Hermes Demonstration Reactor

Heritage Center K-33 Site / Oak Ridge, TN


Natura
Resources
SUSTAINABLE ENERGY

We don’t need more climate promises.

We don’t need more paper reactors.

We need **PERFORMANCE.**

Since 2020 Natura Resources has brought a West Texas oil & gas mentality to the advanced reactor industry. Our unique approach to advanced reactor development has quickly elevated us to a leadership position in the industry.

This mentality requires a cost-effective and efficient approach to everything we do:

- Lean Executive Team
- University Sponsored Research
- Continuous Research, Development & Experimentation
- Advanced Research Reactor Demonstration Unit

Project Milestones & Development

PRE-PROJECT & EARLY ENGAGEMENT

NATURA RESOURCES MSR PROJECT

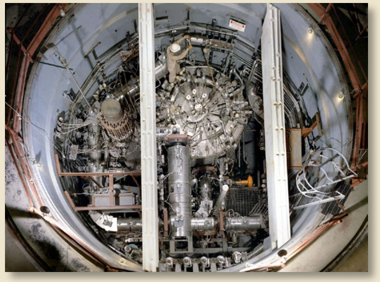
Oak Ridge National Laboratory

NEXT

Natura Resources SUSTAINABLE ENERGY

1954-1969
MSR HISTORY

- (Nov 1954) Aircraft Reactor Experiment (ARE) at Oak Ridge National Laboratory (ORNL) is the first reactor to demonstrate the feasibility of molten-salt fuel.
- (1964) Molten Salt Reactor Experiment (MSRE) is constructed at ORNL.
- (June 1965) MSRE goes critical utilizing uranium-235.
- (Oct. 1968) MSRE goes critical utilizing uranium-233.



2016 - 2019
EARLY ENGAGEMENT

- (2016) Nuclear Energy eXperimental Testing (NEXT) Lab established at Abilene Christian University (ACU).
- (2017) **Douglass Robison** commits **$3.2M** gift to the NEXT Lab to support molten salt research.
- (Dec. 2018) **Secretary of Energy, Rick Perry,** sends representatives from the **Department of Energy (DOE) Office of Nuclear Energy (NE)** to visit NEXT Lab at ACU.
- (Jan. 2019) Robison and ACU representatives visit the DOE in **Washington D.C.**
- (Nov. 2019) **DOE** encourages the development of a **Molten Salt Research Reactor (MSRR)** at ACU and provides **Programmatic Letter of Support.**

2020 – 2021
PROJECT INITIATION

- (2020) **Natura Resources** is established to develop the MSRR at ACU and commercialize MSR technology.
- (Feb. 2020) Natura enters into **$30.5M of Sponsored Research Agreements** (SRAs) with four universities:
  - Abilene Christian University
  - The University of Texas at Austin
  - Texas A&M University
  - Georgia Institute of Technology
- (Sep. 2021) Natura Resources and Research Alliance receive **Resolutions of Support** from the **Texas Senate** and **Texas House of Representatives**.

2022-2024
RAPID PROJECT DEVELOPMENT

- (March 2022) Groundbreaking takes place for the **Advanced Research Reactor Demonstration Site** for the Natura Resources 1MW_{th} system, the Science and Engineering Research Center (SERC) at ACU.
- (Aug. 2022) **Construction Permit (CP)** application is submitted to and docketed for formal review by the **Nuclear Regulatory Commission** with anticipated May 2024 approval.
- (Oct. 2022) **Teledyne Brown Engineering** completes Front End Engineering & Design (FEED) of MSRR.
- (July 2023) **Zachry Nuclear Engineering (ZNE) is** contracted to complete **Detailed Design Engineering (DDE)** of the first Natura MSR system.
- (Sep. 2023) **Advanced Research Reactor Demonstration Site** at ACU opens (SERC).

Natura Resources Team

NATURA EXECUTIVE TEAM

Douglass Robison

Founder, President

Douglass Robison is the founder and President of Natura Resources. Throughout his career in the energy sector, Douglass has been at the forefront of leading-edge technologies in his role as Partner, Co-founder, President and Executive Chair of ExL Petroleum, a Permian-based oil and gas exploration and production company, and now as the founder and President of Natura Resources. In 2004 he was appointed by former Texas Gov. Rick Perry to serve on the Texas Energy Planning Council and co-chaired the Energy Supply Committee during which time his committee identified the importance of nuclear energy in our energy future. Natura Resources is a natural fit for his deep-seated interest in advanced energy technologies.

Andrew Harmon
VP of Operations & Business Development

Jordan Robison, PE
VP of Engineering & Program Management

Ray Ferguson, CPA
VP of Finance

UNIVERSITY PARTNERS

- **PhDs:** 25+
- **Staff:** 45+
- **Grad Students:** 45+
- **Undergrad Students:** 170+

ACU ABILENE CHRISTIAN UNIVERSITY

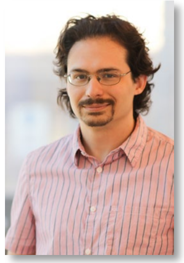
TEXAS The University of Texas at Austin

TEXAS A&M UNIVERSITY

Georgia Tech

NATURA SENIOR TECHNOLOGY DEVELOPMENT TEAM

Jack Shoemate, PE
Chief Engineer

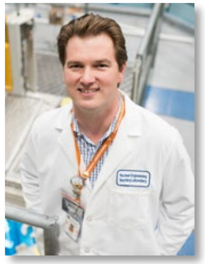


Dr. Jonathan Scherr
Sr. Nuclear Engineer

Dr. Steve Biegalski
Reactor Design

Ben Beasley
Licensing

Dr. Rusty Towell
Reactor Design



Dr. Derek Haas
Reactor Design

Dr. Pavel Tsvetkov
Reactor Physics

Dr. Kevin Clarno
Reactor Physics

Dr. Mark Kimber
Thermohydraulics

Brazos Fitch
Nuclear Engineer

Natura Resources SUSTAINABLE ENERGY

State of Texas

Texas Advanced Nuclear Reactor Working Group

GOVERNOR GREG ABBOTT

August 16, 2023

Kathleen Jackson, P.E.
Interim Chair, Public Utility Commission of Texas
1701 North Congress Avenue, 7th Floor
Austin, Texas 78711

Dear Ms. Jackson:

As our state grows, so must our electric power generation. To maximize power grid reliability, the Public Utility Commission of Texas (PUCT) should consider all forms of dispatchable power, including nuclear energy. In particular, the PUCT should evaluate advanced nuclear reactors to determine if they can provide safe, reliable, and affordable power to our grid.

I instruct the PUCT to establish a working group to study and plan for the use of advanced nuclear reactors in Texas. This working group should focus on understanding the state's role in deploying and using advanced nuclear reactors; consider all potential financial incentives available; determine nuclear-specific changes needed in the Electric Reliability Council of Texas (ERCOT) market; identify any federal or state regulatory impediments to development; and identify how the state can streamline and accelerate permitting for the building of advanced nuclear reactors in Texas. The working group should also engage Texas supply chain manufacturers to foster homegrown development of this technology in our state.

The working group should include and coordinate with stakeholders with applicable experience, relevant state agencies and institutions of higher education, appropriate federal agencies, and current and potential future market participants in order to best understand how Texas can encourage the timely implementation of advanced nuclear reactors. Further, I direct the working group to identify any federal incentives available for the state and stakeholders to access and utilize. Additionally, the working group should coordinate with ERCOT to begin solving the technical challenges of incorporating advanced nuclear energy into the ERCOT grid.

Foundational to these charges is the safety of Texas communities, and it is critical that this report address advanced nuclear reactor safety. Finally, I charge the working group to submit a plan and recommendations to my office by December 1, 2024, outlining how Texas will become the national leader in using advanced nuclear energy.

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PUBLIC UTILITY COMMISSION

Public Utility Commission of Texas
1701 N. Congress, P.O. Box 13326, Austin, TX 78711-3326

Press Release
Oct. 10, 2023

Contact: Ellie Breed
Media@PUC.Texas.Gov

Texas Advanced Nuclear Reactor Working Group Named

FAQs Added to PUCT Nuclear Working Group Webpage

Austin, Texas - The members of the Public Utility Commission of Texas' (PUCT) Texas Advanced Nuclear Reactor Working Group were announced today. The working group was established Aug. 16, 2023, at the direction of Governor Greg Abbott and operates under the leadership of PUCT Commissioner Jimmy Glotfelty.

"These experts are leaders in nuclear energy, business, and academia and will be instrumental as we chart a path forward for advanced nuclear technology in Texas," Glotfelty said. "The diversity and depth of their expertise will help us deliver a comprehensive and actionable plan to make our state the leader in nuclear energy. I thank each of them for their willingness to participate and serve the interests of Texas consumers."

The members of the Texas Advanced Nuclear Reactor Working Group, along with Commissioner Glotfelty, are:

Dillon Allen, Senior Manager of Advanced Nuclear Development, Entergy
Chrissy Borskey, Senior Executive Director, Government Affairs and Policy, GE Vernova/GE Hitachi
Bret Colby, Principal, Nuclear Oversight, CPS Energy
Ryan Duncan, Director of Government Relations, Last Energy
Derek Haas, Associate Professor of Mechanical Engineering, University of Texas at Austin
Maynard Holt, CEO, Veriten
Mike Kotara, President, Zachry Sustainability Solutions
Stephanie Matthews, Executive Vice President, Texas Association of Business
Sean McDeavitt, Associate Vice Chancellor, National Laboratories Office, Texas A&M University
Andy Meyers, Ft. Bend County Commissioner
Andy Nguyen, Director of Wholesale Market Development, Constellation
Preeti Patel, Associate Commercial Director, Dow
Benjamin Reinke, Vice President of Global Business Development, X-Energy
Doug Robison, CEO, Natura
Clayton Scott, Executive Vice President of Business Development, Pearl/NuScale
Jim Stanway, Senior Strategist, Samsung
Pablo Vegas, CEO, Electric Reliability Council of Texas

Natura Resources SUSTAINABLE ENERGY

MSRR Development

Natura Resources
SUSTAINABLE ENERGY

ZACHRY

TELEDYNE
BROWN ENGINEERING

ACU
ABILENE CHRISTIAN UNIVERSITY

TEXAS
The University of Texas at Austin

ATM
TEXAS A&M UNIVERSITY

Georgia Tech

Demonstration Reactor Facility

Science & Engineering Research Center (SERC)

The MSRR will be deployed in a multi-use research facility on the campus of Abilene Christian University (ACU). Groundbreaking took place in March 2022 and the facility was completed in August 2023.

The SERC, completed in August 2023, is the only current advanced reactor demonstration facility in the U.S.

March 2022

August 2022

September 2022

August 2023

Natura Resources Technology Development

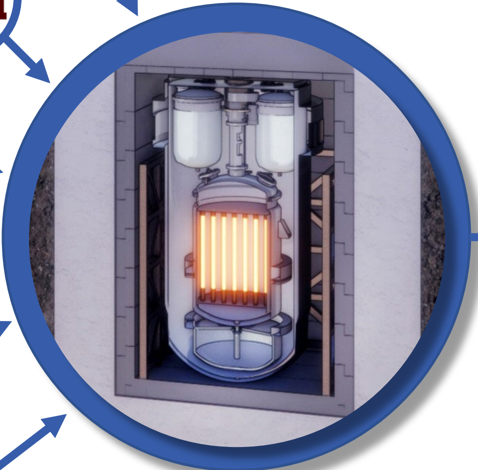
Natura Resources has taken a unique path to developing and deploying MSR technology that **reduces costs, schedule and regulatory risk**. We are on track via the MSRR demonstration reactor to **deploy the first GEN-IV advanced reactor in the U.S.**, and then begin **rapidly deploying commercial LF-MSRs at scale, to meet the world's energy needs.**

University Sponsored Research
Developing the technologies and performing analysis to support MSRs

Industry Expertise
Delivering complex projects on-time and on-budget

ZACHRY

TELEDYNE BROWN ENGINEERING
Everywhereyoulook™



Demonstration Reactor - 1 MW_{th}
Molten Salt Research Reactor (MSRR)
at Abilene Christian University (ACU)

FOAK Commercial Deployment
Successful FOAK deployment is made possible through the data, knowledge, and experience gained through the deployment of the MSRR.

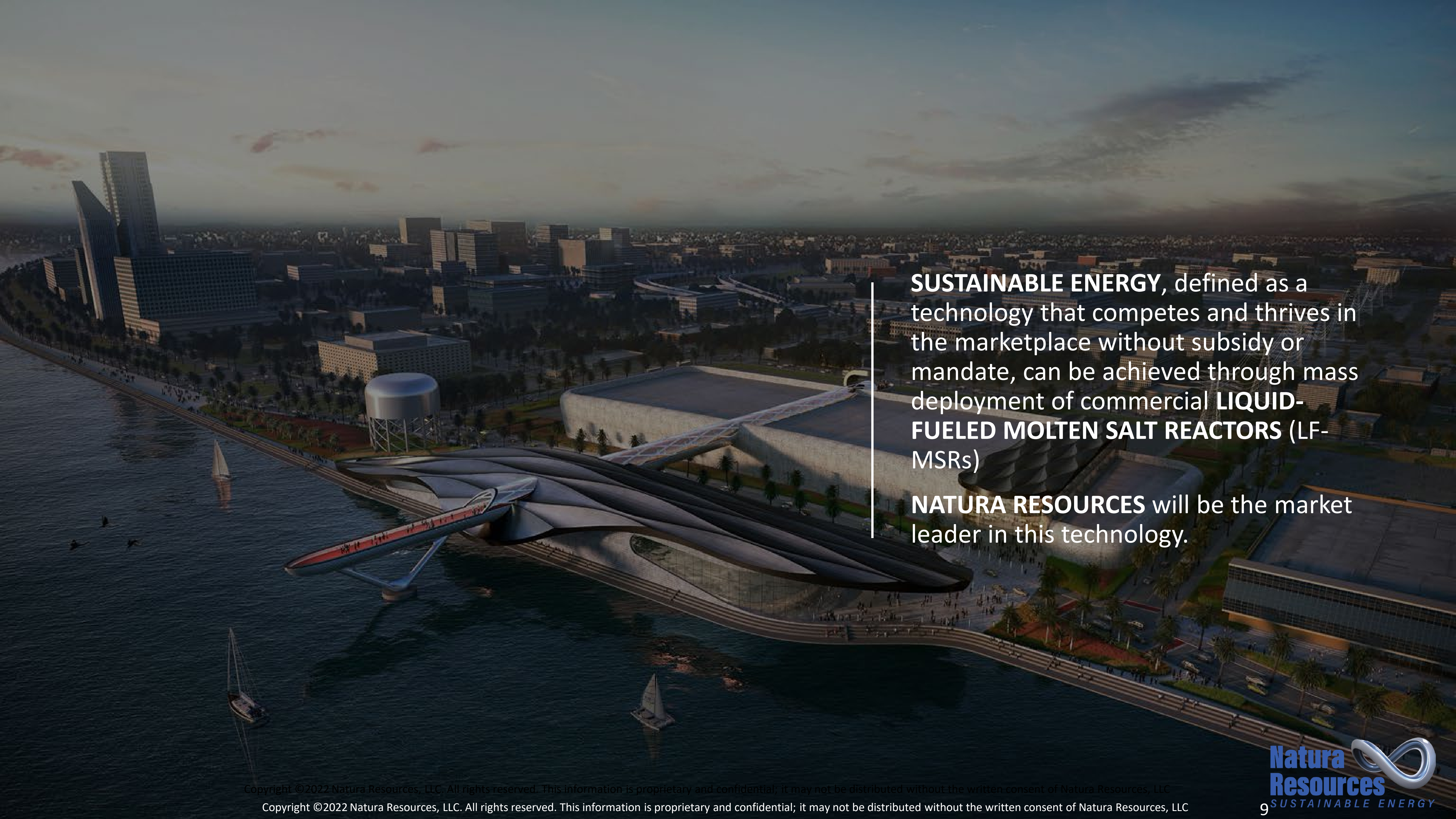
MSR - 250 MW_{th} (100 MW_e)
First-of-a-Kind (FOAK)
GEN-IV reactor deployment

Rapid Deployment
Designed for assembly line manufacturing, the LF-MSR will be rapidly deployed at scale to meet the world's energy needs

MSR - 250 MW_{th} (100 MW_e)
Nth-of-a-Kind (NOAK)
Rapid GEN-IV Reactor Deployment

R&D / MSRR	FOAK	NOAK
2026	2030	2040

Natura Resources SUSTAINABLE ENERGY



SUSTAINABLE ENERGY, defined as a technology that competes and thrives in the marketplace without subsidy or mandate, can be achieved through mass deployment of commercial **LIQUID-FUELED MOLTEN SALT REACTORS** (LF-MSRs)

NATURA RESOURCES will be the market leader in this technology.

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