INL/MIS-23-75619-Revision-0

U.S. MSR Development Programs & Supportive Efforts

November 2023

Changing the World's Energy Future

David Eugene Holcomb, Patricia Paviet

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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U.S. DEPARTMENT OF ENERGY | Office of Nuclear Energy

Molten Salt Reactor PROGRAM

U.S. MSR Development Programs & Supportive Efforts

David Holcomb & Patricia Paviet

Idaho National Laboratory and Pacific Northwest National Laboratory

GIF MSR pSSC meeting

Avignon, France – 30 Nov & 1 Dec 2023

U.S. MSR* Development Includes Government, Industry, and Regulatory Activities

- Department of Energy (DOE)-Office of Nuclear Energy (NE) activities remain focused on enabling MSR industry and building supporting infrastructure
  - Largest fraction of DOE support is via the Advanced Reactor Demonstration Program (ARDP)
- DOE-NE continues to support MSRs via multiple mechanisms
  - MSR technical campaign and regulatory development activities
  - Nuclear Energy Advanced Modeling and Simulation (NEAMS) tool development
  - Nuclear Energy University Program (NEUP), small business opportunities, Gateway for Accelerated Innovation in Nuclear (GAIN) vouchers, and direct industry awards
- Advanced Research Projects Agency (ARPA-E) reactor initiatives include MSRs
- Nuclear Regulatory Commission is developing a technology-neutral, performance-based, risk-informed regulatory framework

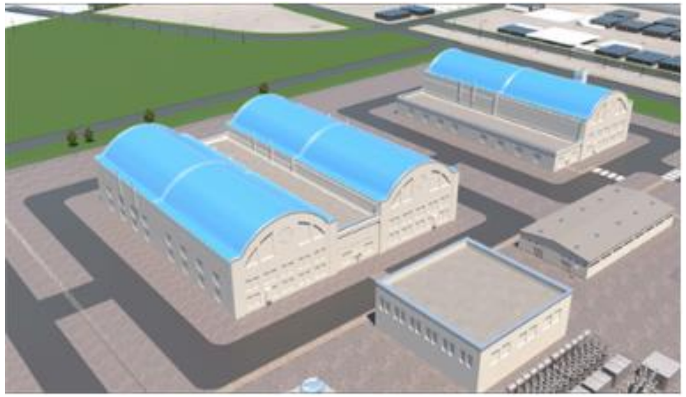
*MSR support includes both solid (aka FHRs) and liquid fueled concepts

MSR Advanced Reactor Demonstration Projects Jointly Funded by Government and Industry Continue to Progress

Kairos Power

Applied for Construction Permit for Hermes 2

https://www.nrc.gov/reactors/non-power/new-facility-licensing/hermes2-kairos.html



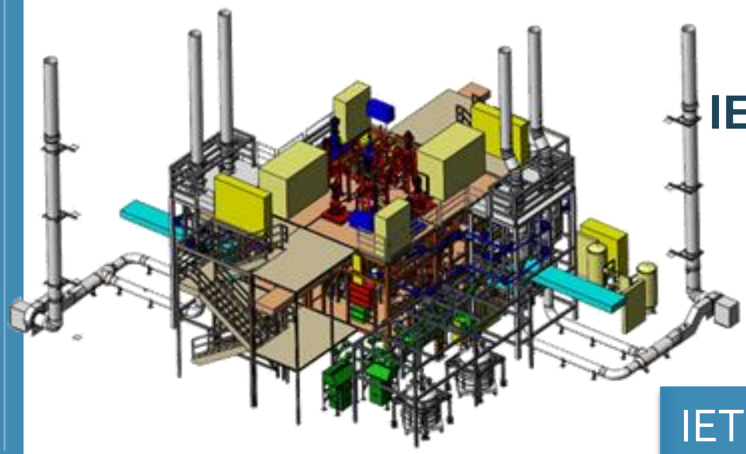
Hermes 2 next to Hermes 1

Plant Characteristic	Description
Reactor Type	Two low-power test reactors to support development of Kairos Power's fluoride salt-cooled, high-temperature reactor (KP-FHR) technology
Containment Type	Functional containment implemented principally by the high temperature TRISO particle fuel. The fuel utilizes a carbon matrix coated fuel particle, similar to that developed for high temperature gas-cooled reactors, in a pebble-based fuel element. (See SECY-18-0096 for a description of functional containment.)
Power Level	35 MW_{th} each unit
Fuel	Tri-structural Isotropic (TRISO) fuel particles embedded in a carbon matrix pebble. High Assay Low Enriched Uranium (HALEU)
Balance of Plant	Shared steam powered conversion system (Rankine Cycle)

MSR Advanced Reactor Demonstration Projects Jointly Funded by Government and Industry Continue to Progress

TerraPower | Southern Company

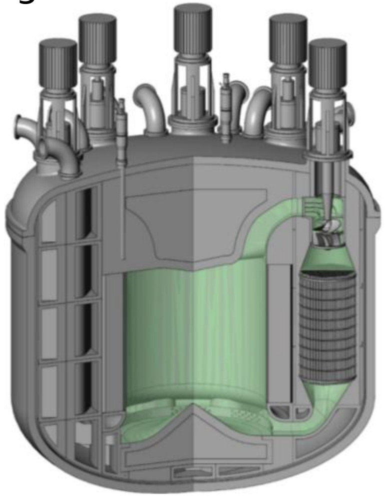
- DOE issues finding of no significant impact for the environmental assessment of MCRE – October 18th, 2023
  - https://www.energy.gov/sites/default/files/2023-10/fonsi-ea-2209-molten-chloride-reactor-2023-10.pdf
- Salt operations begun at IET – October 3rd, 2023
  - https://www.prnewswire.com/news-releases/southern-company-terrapower-and-core-power-begin-salt-operations-of-integrated-effects-test-301945913.html



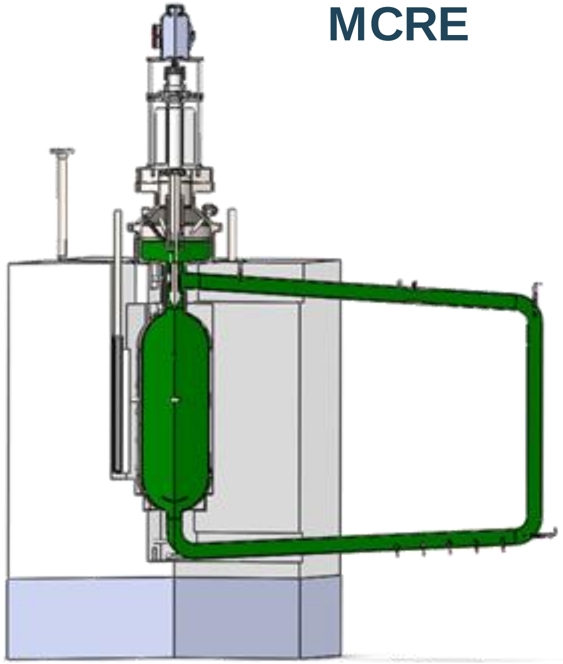
IET

IET overview video

https://www.youtube.com/watch?v=JQR_b19lZGE



MCFR



MCRE

Abilene Christian University Research Reactor Underway

Natura Resources SUSTAINABLE ENERGY

NEXTRA Nuclear Energy eXperimental Testing Research Alliance

ABILENE CHRISTIAN UNIVERSITY

- Natura Resources is sponsoring a collaboration between University of Texas at Austin, Texas A&M University, Abilene Christian University and Georgia Tech University to construct a non-power MSR at ACU
- Design is a simplified version of MSRE – operating license application anticipated in 1st quarter 2024
- Zachry Nuclear performing detailed design ZACHRY
- Science and engineering research center construction completed

Cut-away showing reactor in trench

Gayle and Max Dillard Science and Engineering Research Center - completed

Rapid Gen-IV Reactor Deployment

2040	NOAK
2030	FOAK 250 MW_{th} 100 MW_e
2026	MSRR
	R&D

Images courtesy Abilene Christian University

Multiple Additional US Based MSR Activities Continue

- ThorCon has modified its design to use LEU (no thorium)
  - Significant changes to heat rejection – drain tanks to minimize temperature rise
- Metatomic awarded gain voucher to work with Savannah River National Lab (SRNL) to develop technology to convert used LWR fuel to chloride salt MSR fuel
  - https://gain.inl.gov/SiteAssets/2023VoucherAbstracts-4thRound/Abstracts/Metatomic_Abstract_23.4.pdf
- Alpha Tech Research awarded gain voucher to work with ANL to validate yttrium hydride as a moderator for MSRs
  - https://gain.inl.gov/SiteAssets/2023VoucherAbstracts-3rdRound/Abstracts/AlphaTechResearchCorp_Abstract_23-3.pdf
- Kairos Power awarded gain voucher to work with PNNL to evaluate ICP-MS to validate lithium isotopic ratios
  - https://gain.inl.gov/SiteAssets/2023VoucherAbstracts-3rdRound/Abstracts/KairosPower_Abstract_23-3.pdf
- Moltex Energy USA awared gain voucher to work with ANL to simulate salt to metal heat transfer within its fuel salt pins.
  - https://gain.inl.gov/SiteAssets/2023VoucherAbstracts-3rdRound/Abstracts/MoltexEnergy_Abstract_23-3.pdf
- DOE's industry funding opportunities program selected
  - 3M Company to receive award to develop isotope recovery process for MSRs
  - Terrestrial Energy USA to receive support for submitting pre-licensing topical reports

Revised ThorCon LEU Layout

NRC Advanced Reactor Licensing Processes Remain Under Development

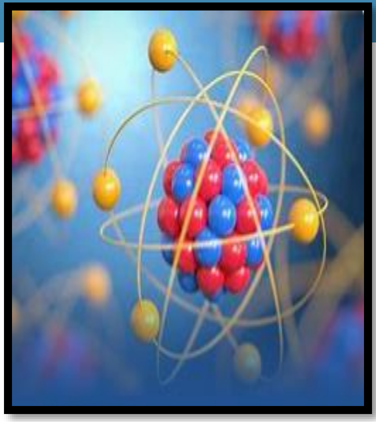
- Modern licensing framework under development
  - Technology-inclusive, performance-based, risk-informed
  - New part to the Code of Federal Regulations (10 CFR Part 53) under development
    - Two Commissioners have voted and indicated the need for substantial changes
      - Caputo - ML23199A289
      - Wright - ML23275A204

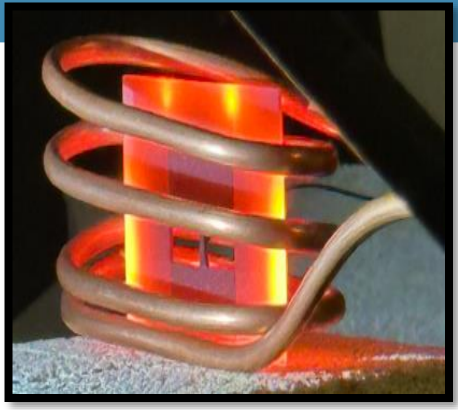
SECY	Title	SRM
23-0021	Proposed Rule: Risk-Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors (RIN 3150-AK31)	Pending
22-0072	Proposed Rule: Alternative Physical Security Requirements for Advanced Reactors (RIN 3150-AK19)	Pending
22-0052	Proposed Rule: Alignment of Licensing Processes and Lessons Learned from New Reactor Licensing (RIN 3150 AI66)	Pending
22-0001	Rulemaking: Final Rule Emergency Preparedness for Small Modular Reactors and Other New Technologies (RIN 3150-AJ68; NRC-2015-0225)	Pending
21-0098	Proposed Rule: Advanced Nuclear Reactor Generic Environmental Impact Statement (RIN 3150-AK55; NRC-2020-0101)	Pending

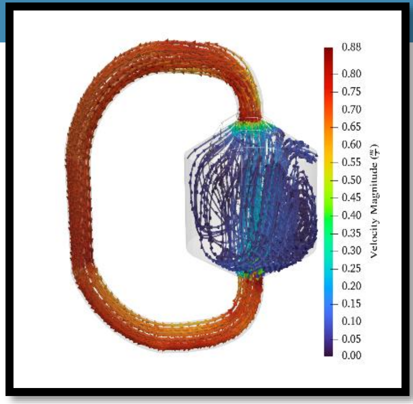
https://www.nrc.gov/reactors/new-reactors/advanced/policy-development/historical.html

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

IAEA International Atomic Energy Agency

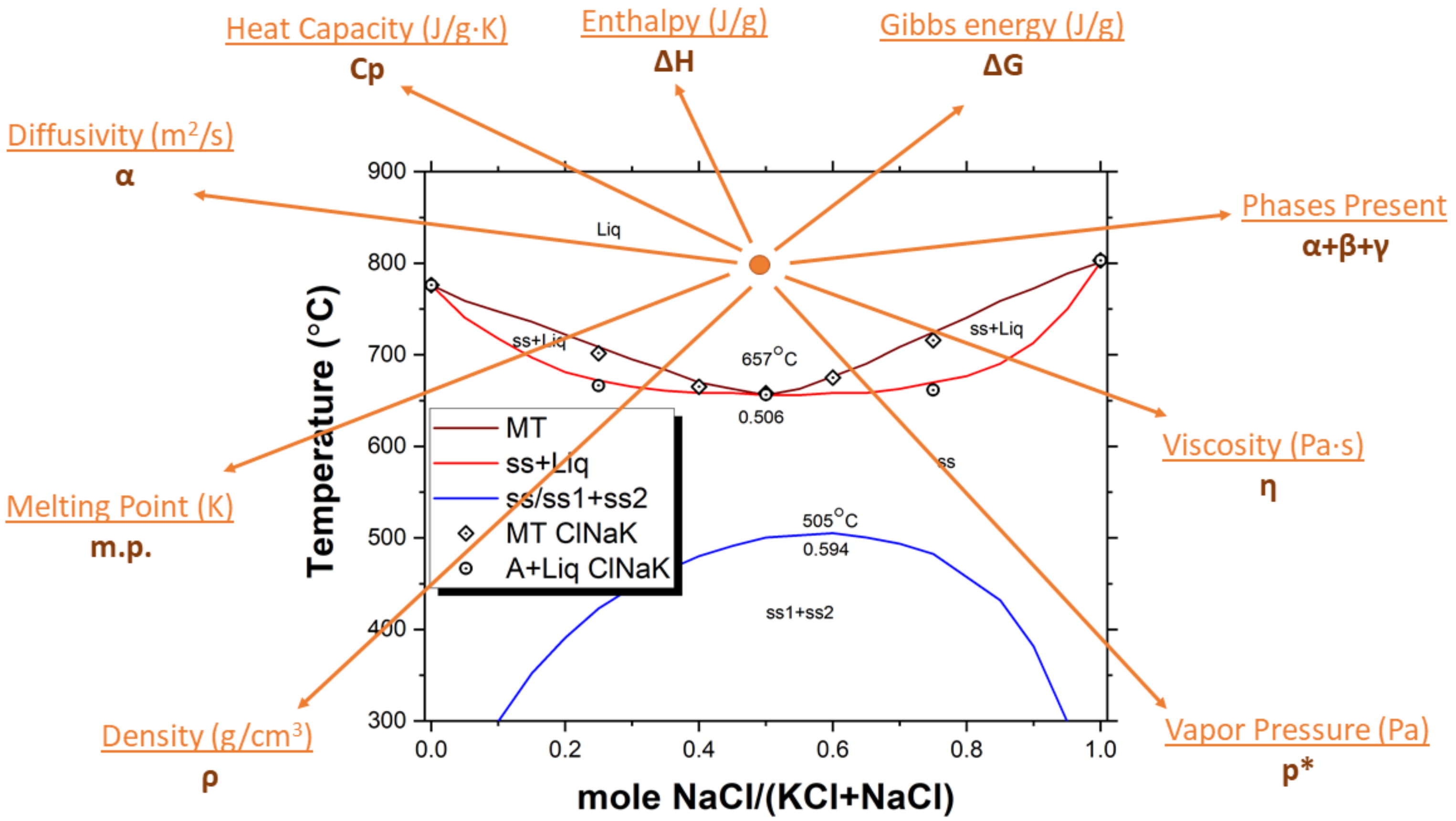
NEA Nuclear Energy Agency

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

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)

National laboratories are developing fundamental data that enables stakeholders to make informed decisions



Courtesy Jason Lonergan, PNNL

MSTDB-TP Expansion Efforts

U.S. DEPARTMENT OF ENERGY | Office of Nuclear Energy

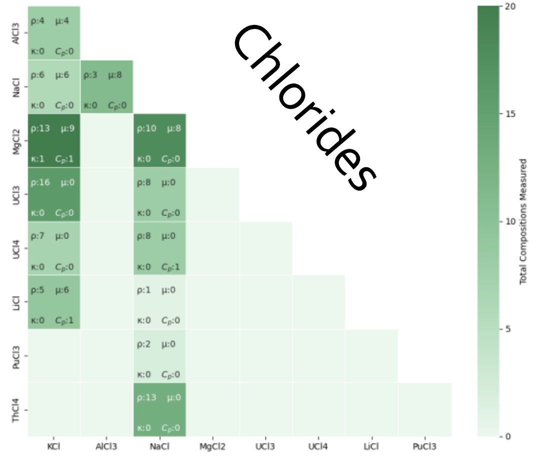
Available @ mstdb.ornl.gov

- 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 UCl_3 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

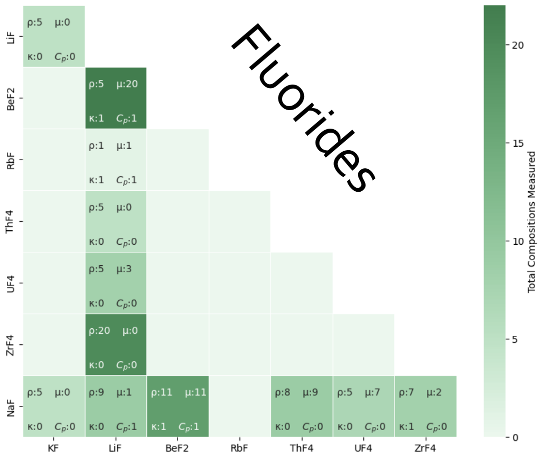
Pure:

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
- $MgCl_2-NaCl-UCl_{3,4}$
- $MgCl_2-KCl-UCl_{3,4}$

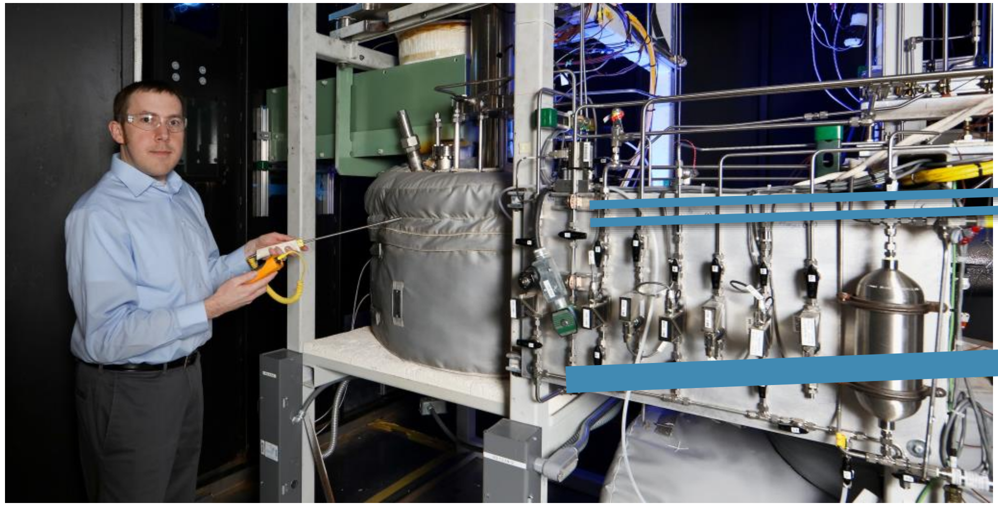
Courtesy Prof. Ted Besmann

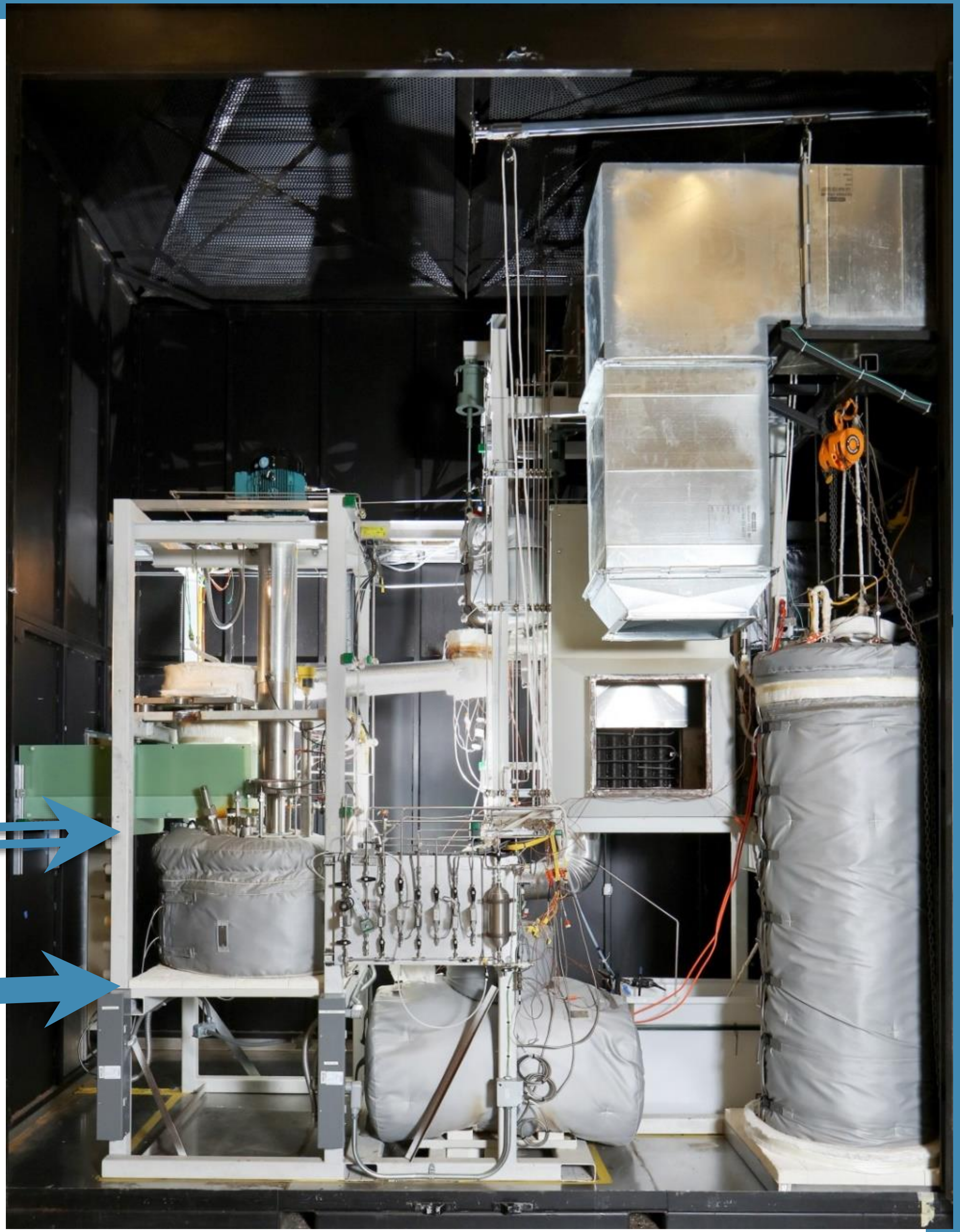
Liquid Salt Test Loops Used for Component, Materials, and Sensor Testing

- 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 $\rightarrow$ pumped $NaCl\text{-}KCl\text{-}MgCl_2$ heated to > 600°C

Kevin Robb (robbkr@ornl.gov)

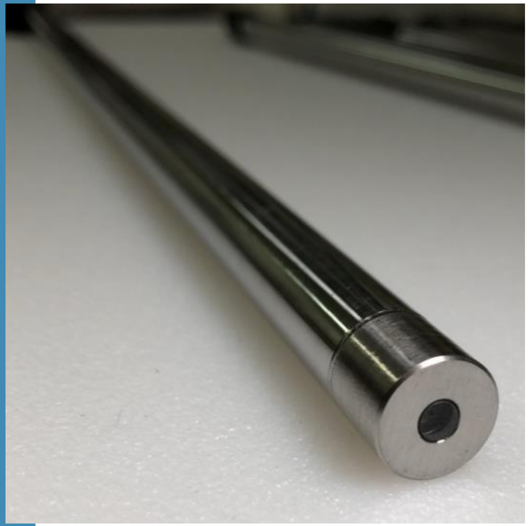
LSTL → pumped FLiNaK heated > 600°C



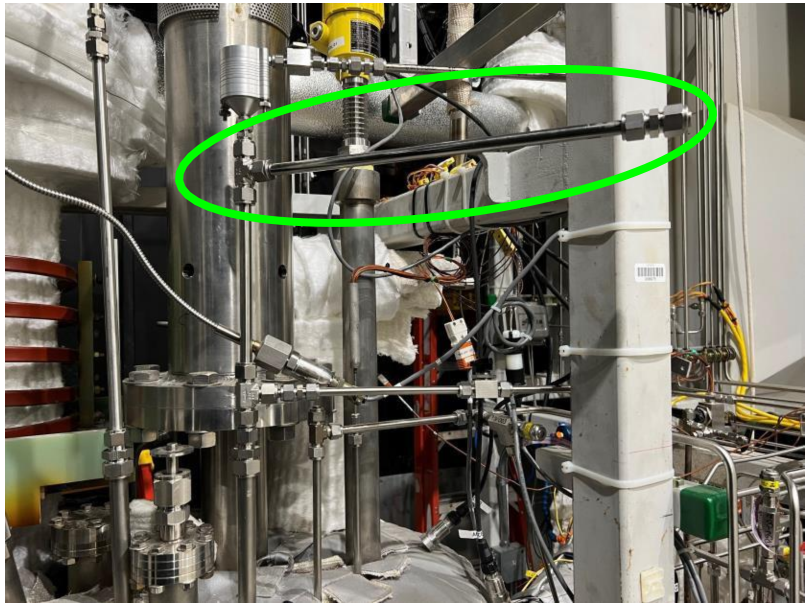


Testing Probe Materials in LSTL

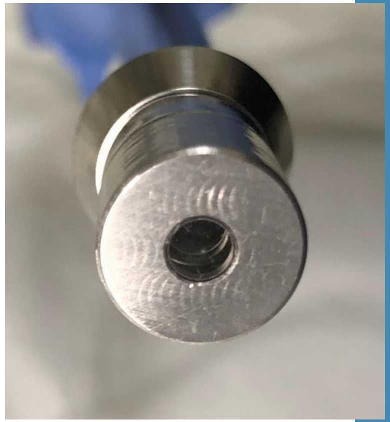
Before incorporation into salt loop

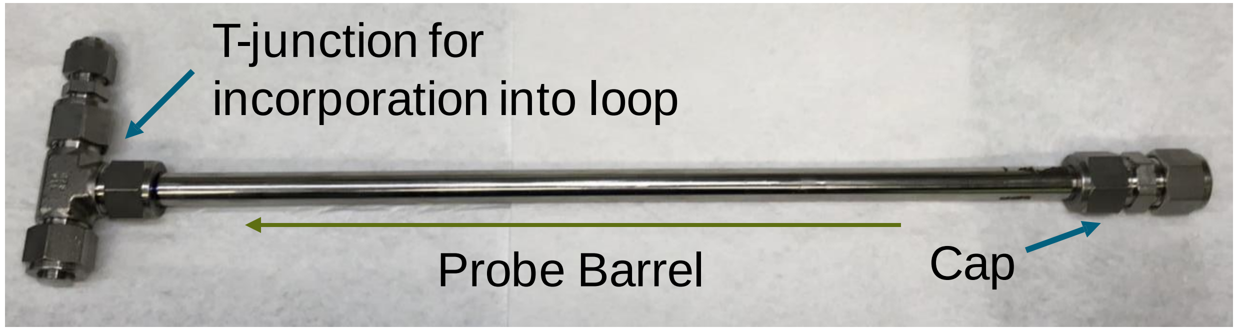


- **Salt loop testing**
  - Probe barrel swaged into loop
  - No visual degradation after testing



After incorporation into salt loop





Courtesy Amanda Lines and Sam Bryan, PNNL

INL is Converting Uranium Metal Plates to MCRE Fuel Salt

- Scaled up fuel synthesis process
  - Experiments started at 10 g U scale, then progressed to 3 kg U scale and, ultimately demonstrated 9 kg U scale
- Completed final design review of Fuel Salt Synthesis Line (FSSL)
- Placed FSSL Hardware Procurements
  - FSSL furnaces, furnace well/retort, and prototype equipment
- Performed thermophysical property measurements




Fuel Salt Production is Key Schedule and Risk Driver for MCRE

INL Performing First Ever Chloride Fuel Salt Irradiation

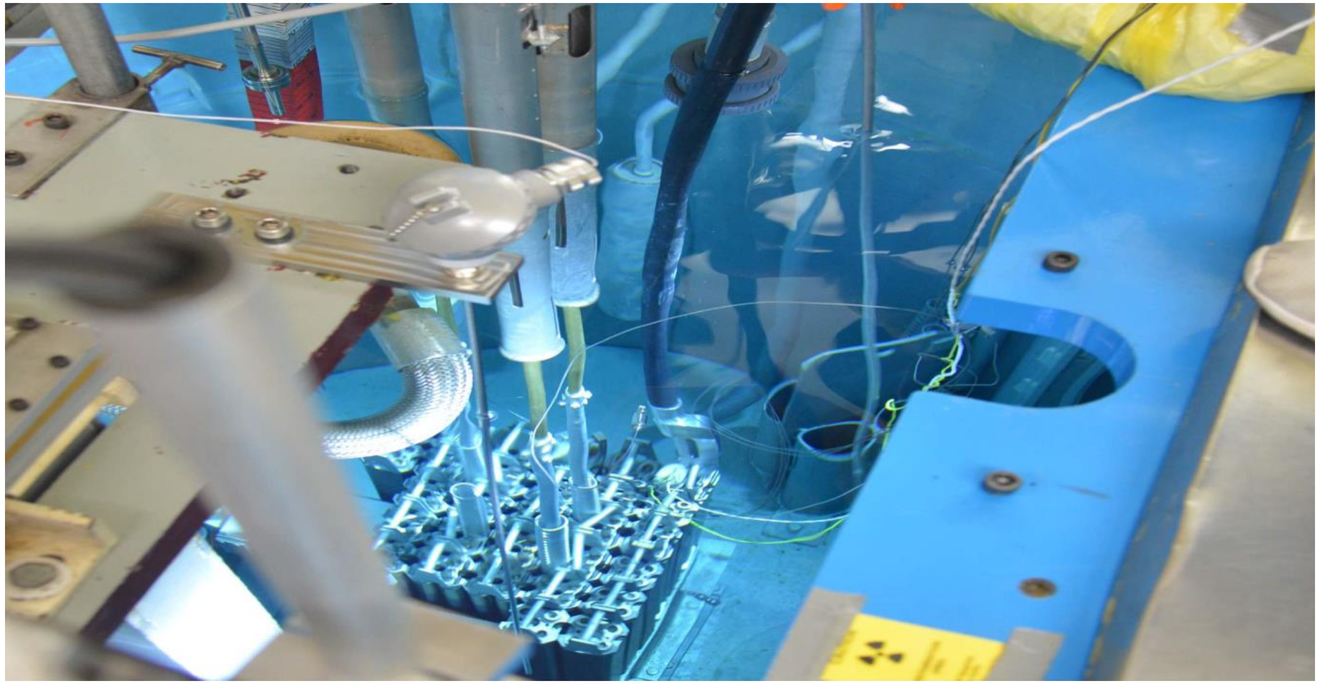
Large plenum (Argon) to reduce pressure and account for packing factor of powder salt

SS316 Radiative heat shield reduces heat loss at high temperature section of capsule

Molten salt (UCl_3-NaCl)

800W immersion heater, heated in bottom 3” section only, integrated Type-K TC

3X Type-N TCs, IN625 sheath, axially placed



NRAD reactor
Pool-type, TRIGA-fuel

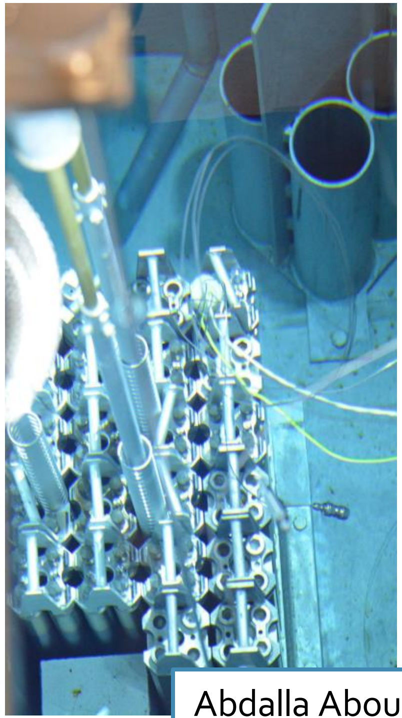
Experiment Characteristics

- Fission Heat = 20 W/cm^3
- Neutron Flux = 3.5x10^{12} n/cm^2-s
- Gamma Flux = 1.4x10^{13} γ/cm^2-s
- Salt Temperature = 525-900° C
- Salt sample: 0.66UCl3-NaCl (93wt% 235U)
- 40g, 13 cm^3

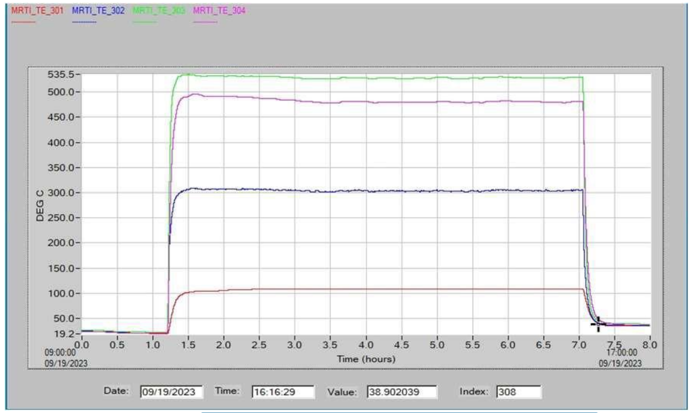
Fuel Salt Irradiation In-Progress at INL

- Irradiation commenced on 8/21
- Clocked over 100h of irradiation thus far (8h/day, 4 days/week schedule)
- Next steps: 'long-burn' irradiation initial PIE (radiography, gamma scan, and gas analysis)

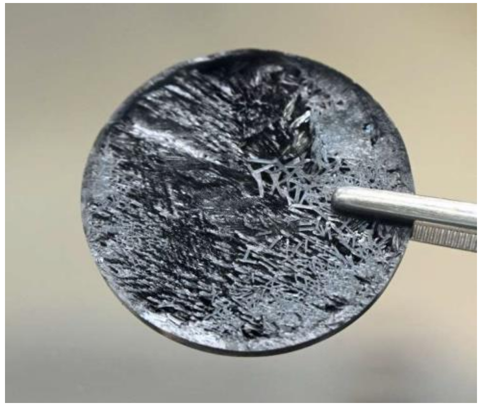
Assembly Fabrication



Insertion in-reactor



TC Readings on 09/19



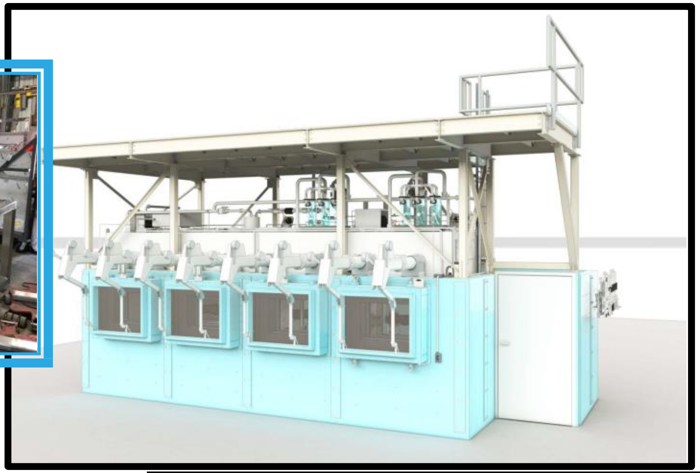
Synthesized HEU-bearing UCl_3- NaCl

Abdalla Abou Jaoude
Project lead

Molten Salt Thermophysical Examination Capability (MSTEC) in Progress at INL

- Experimental examination facility focused on high temperature chemistry
  - Half glovebox, half hot cell
  - Capability for irradiated, actinide, minor actinide, and beryllium bearing salts
  - State-of-the-art, versatile workspace
- Infrastructure to address technology gaps
  - Includes universal furnace (electrochemistry, salt synthesis), DSC, STA, TMA, rheometer, thermal hotwire, pycnometer, densitometer

- **Online in FY24**

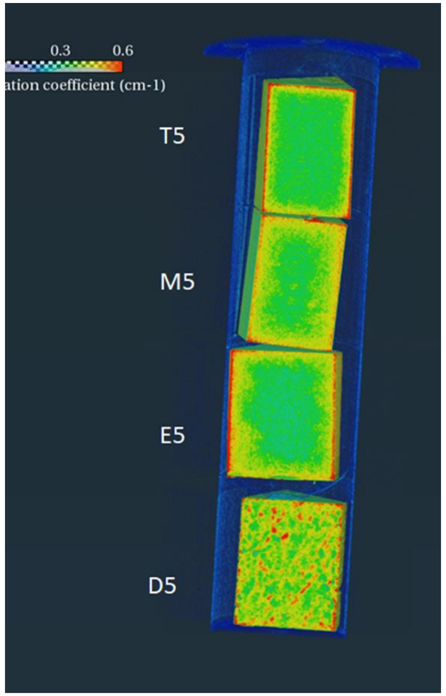


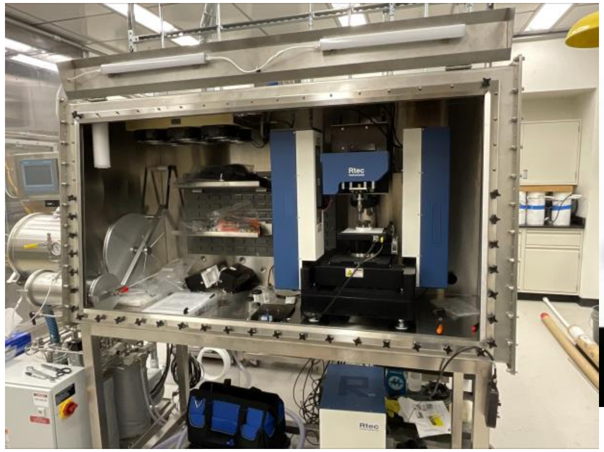
Toni Karlsson – lead scientist

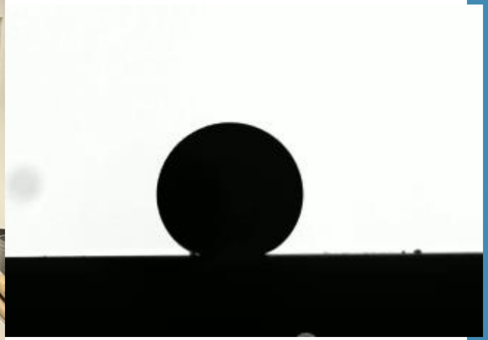
Materials – Graphite - Salt studies at ORNL

- 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.

Nidia Gallego gallegonc@ornl.gov





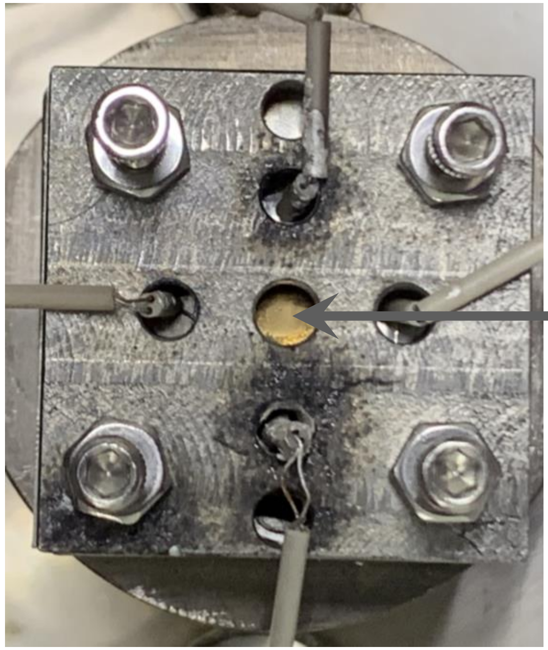


Beryllium Carbide Under Investigation as an Advanced Neutron Moderator

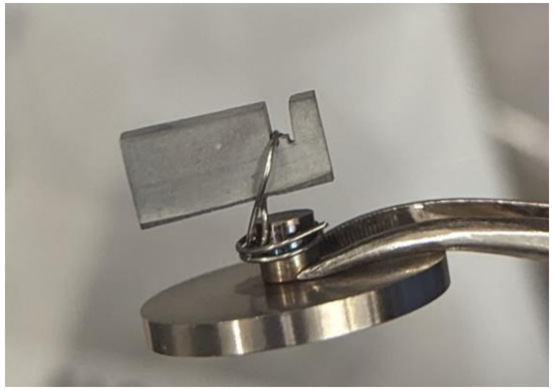
- Investigate Be_2C as a replacement moderator for graphite in MSRs
  - Fully-dense (no salt intrusion concerns unlike graphite)
  - Higher neutron moderating efficiency than graphite (less volume/mass of material)
  - Not directly compatible with uranium bearing salts

- Limited information on the effects of irradiation damage on the properties of Be_2C
  - First irradiation studies with ion irradiation damage
  - Must perform neutron irradiation

- May capture dissolved tritium as hydrocarbon gas
  - $Be_2C + 4H_2O \rightarrow 2Be(OH)_2 + CH_4$



Gold-coated Be_2C mounted on stage for carbon ion irradiation



Be_2C before (left) and after (right) high temperature thermal stability test in inert atmosphere

Anne Campbell – ORNL PI

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

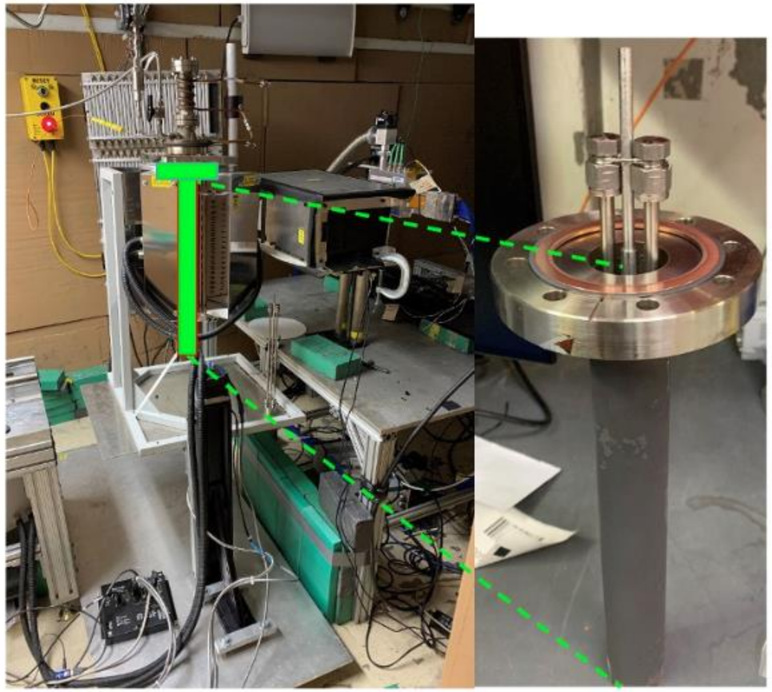
Development of standard measurement methods

- 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.

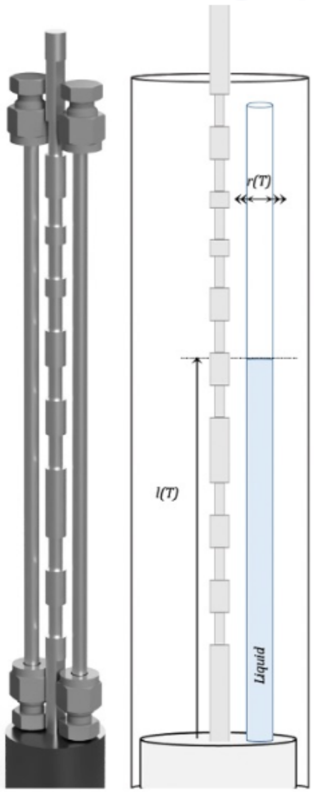
Laser Flash Analyzer for Measuring Thermal Diffusivity of Molten Salts

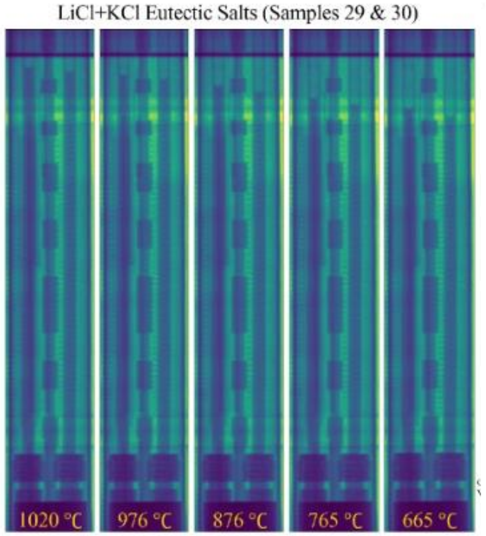
Rotational Viscometer method being standardized

Neutron Radiography Used to Determine Actinide-Bearing Molten Salt Density



LANCE neutron facility at Los Alamos National Laboratory





$PuCl_3$ + NaCl eutectic salt

Task lead
Marisa Monreal
mmonreal@lanl.gov

Los Alamos NATIONAL LABORATORY

Molten Salt Interfacial Property Measurements

- 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.

Daniel Orea oread@ornl.gov
Thien Nguyen nguyend@ornl.gov

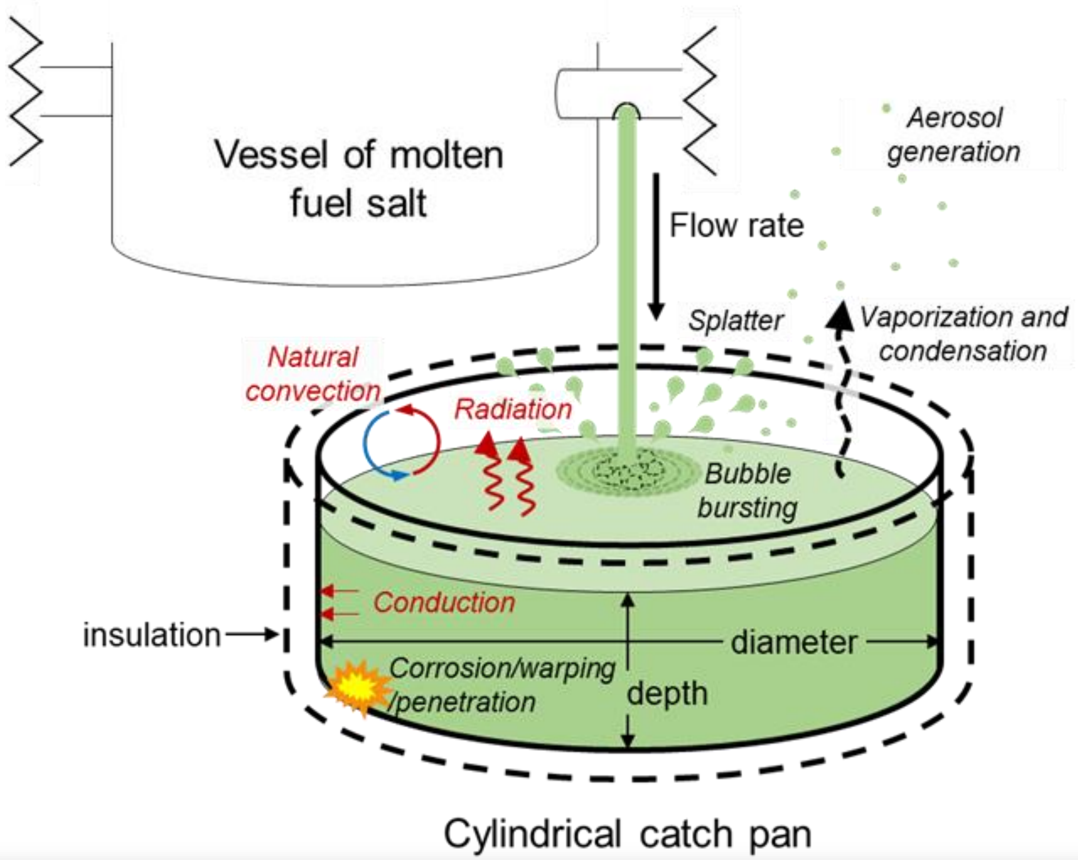
Salt Spill Tests

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

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

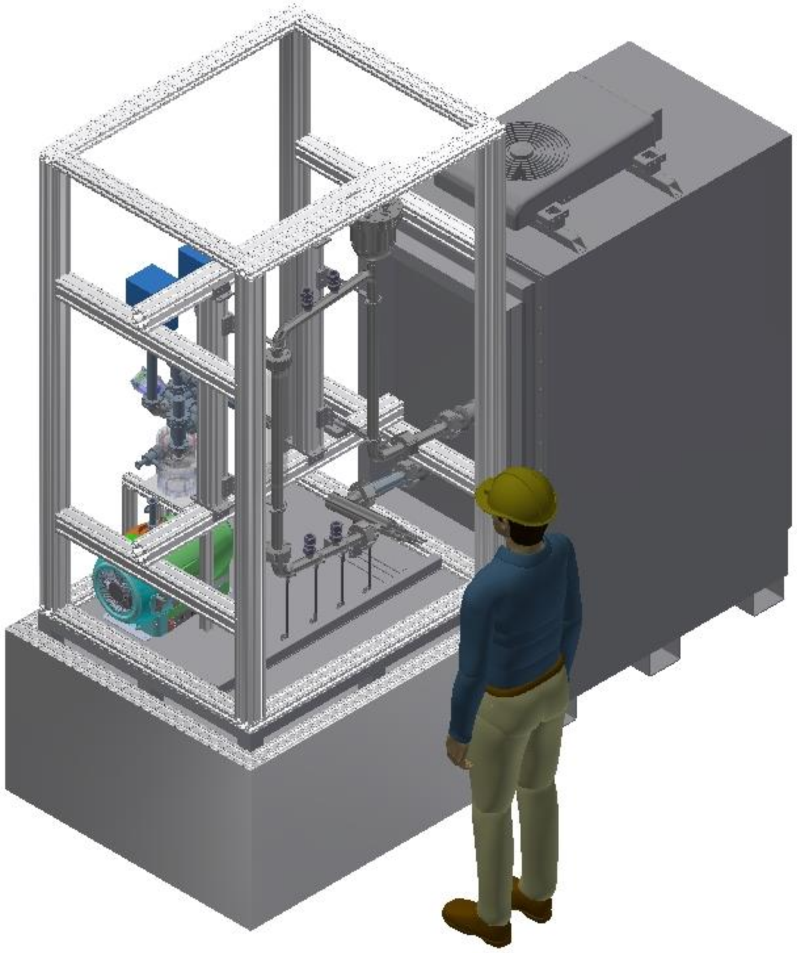


Schematic of molten salt spill scenario being simulated in laboratory-scale tests

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

Molten Salt Tritium Transport Experiment

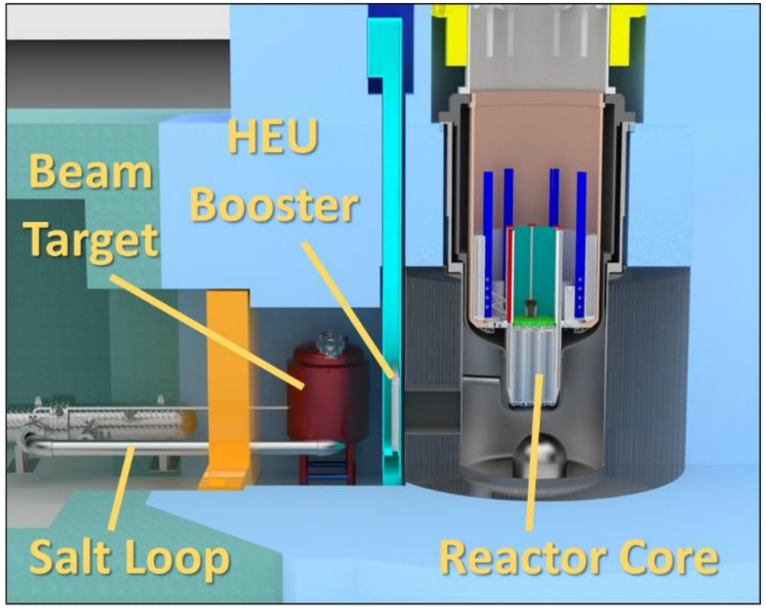
- *MSTTE is a semi-integral tritium transport experiment for flowing fluoride salt systems.*
- Location: Safety and Tritium Applied Research facility
- **Objectives:**
  - **(1) Safety code validation data.**
  - **(2) Test stand for tritium control technology.**
- *Major Equipment:*
  - **Copenhagen Atomics Salt Loop**: salt tank, pump, & flow meter
  - **External Test Section:** hydrogen injection, permeation, & plenum
- *Phased approach*
  - **Phase I:** FLiNaK and D_2
  - **Phase II:** FLiBe and D_2
  - **Phase III:** FLiBe and T_2



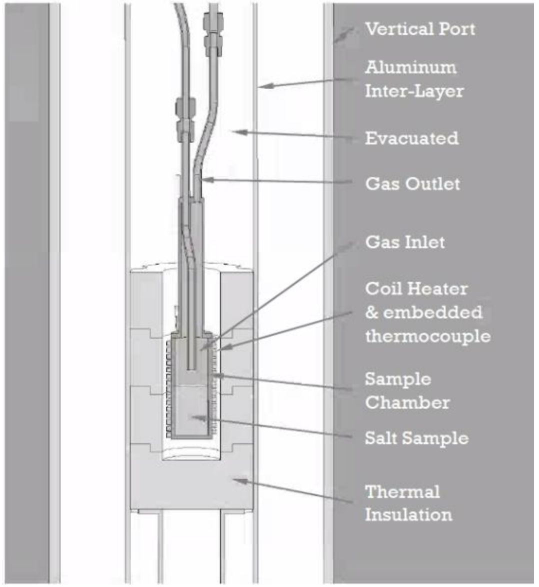
Courtesy Thomas Fuerst, INL

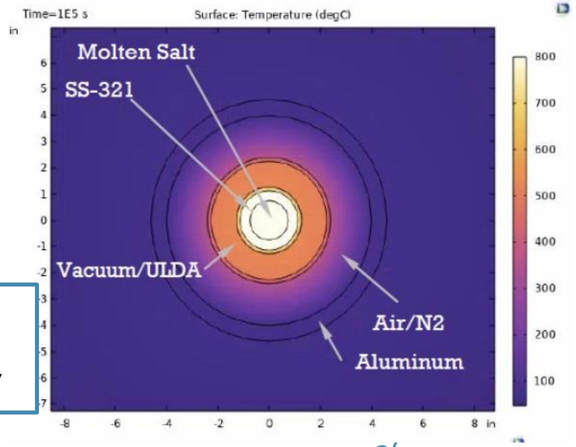
DOE-NE University Integrated Research Project - Features Multiple Salt Irradiation Facilities

- MIT led partnership with NCSU, UCB and ORNL
  - MIT developing near core loop
  - NCSU constructing a vertical tube salt irradiation facility
- Loop outside the reactor tank that partly decouples reactor neutronics from loop
- Provide an experimental test bed for chemistry control, salt cleanup, tritium control and instrumentation
- Separate tritium permeation experiment – use MITR thermal neutron beam to continuously generate tritium in flibe
  - Electrical heating complemented with nuclear
- Investigate **steady-state** tritium diffusion through metals, barrier coatings
  - Salt contact on inside surface



MIT
Reactor Loop (FLiBe)





NCSU
Vertical tube salt irradiation facility

Image courtesy of MIT & NCSU

Liquid-Fuel Molten Salt Reactor Design Safety Standard (ANS 20.2) is Undergoing Balloting

- Represents collaborative effort of staff from reactor designers, universities, national laboratories, and US and Canadian regulators
- Describes an acceptable process for risk-informing MSR designs and safety-evaluations
  - Applicable to both traditional and probabilistic safety adequacy evaluation processes
- Technical information organized into three main sections

1. Background on MSR safety and accident progression concepts that highlight differences from LWRs
2. MSR-specific design criteria translating the safety elements of the General Design Criteria (GDC) or Advanced Reactor Design Criteria (ARDC) to MSRs
   - Augmented by additional MSR specific design criteria
3. Risk-informed design process guidance that describes MSR-specific considerations for probabilistic plant safety evaluation

DOE-NE National Laboratory MSR Activities are Broadly Distributed Throughout Complex (example recent publications)

- 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).

MSR Research, Development, and Demonstration is Expanding and Diversifying in the US

- Multiple companies are pursuing deployment in the 2020s and early 2030s
- Regulator is preparing capabilities to efficiently evaluate reactor safety adequacy
- Advancement of multiple MSR supportive technologies from modeling and simulation to electrochemistry to materials science has substantially decreased the technical difficulty of implementing MSRs
- Pressing need for safe, reliable, efficient energy production driving MSR development faster than at any time in the past half century
- No MSR has yet reached the market, and no developer has openly committed the funds necessary to complete MSR development and deployment