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

Molten Salt Reactor PROGRAM

Overview of the MSR projects with ASI Synergies

Patricia Paviet (NTD) and Janelle Eddins (Federal Manager)

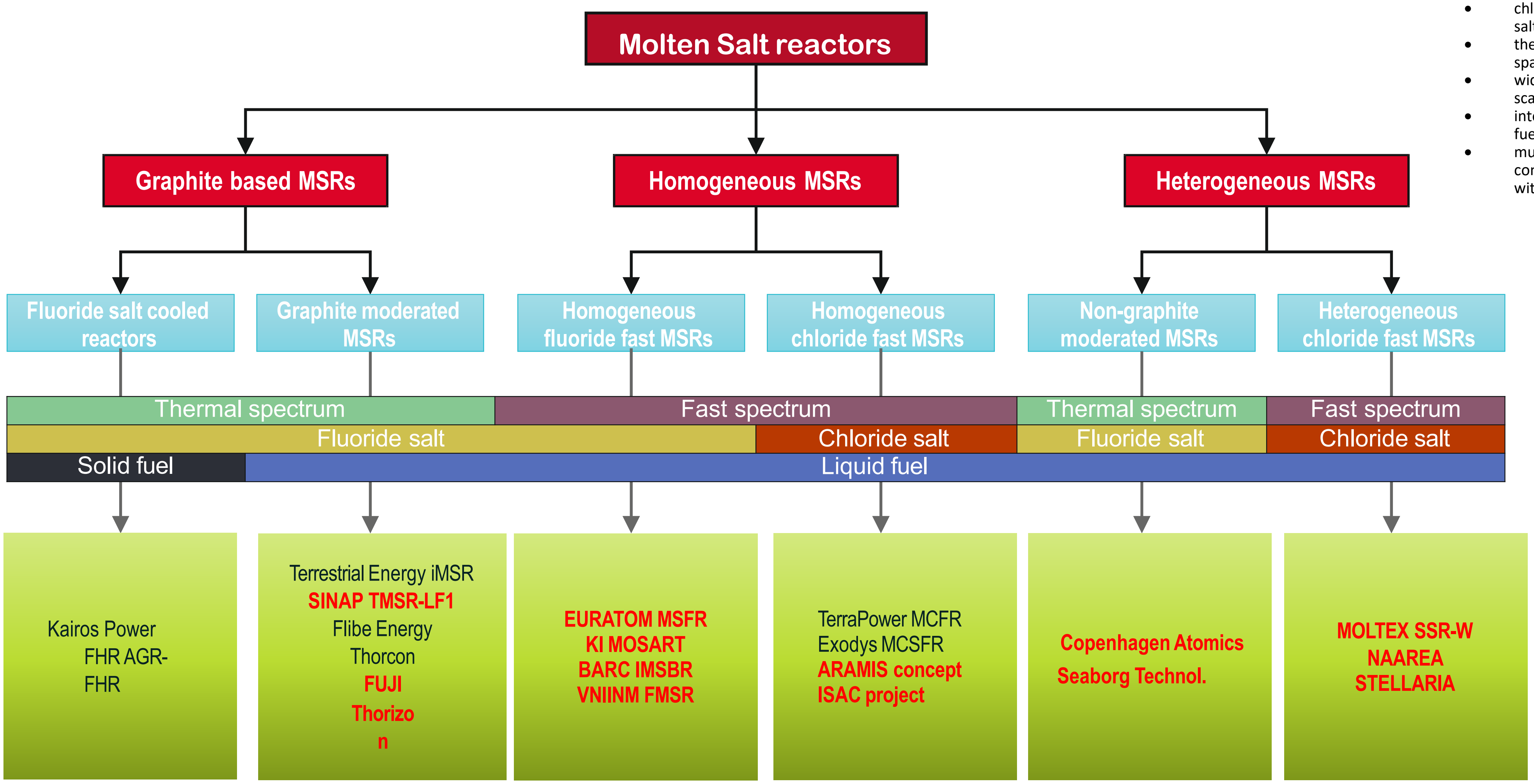
PNNL-SA-191976

Annual ASI Campaign Review Meeting- 30 October – 02 November 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

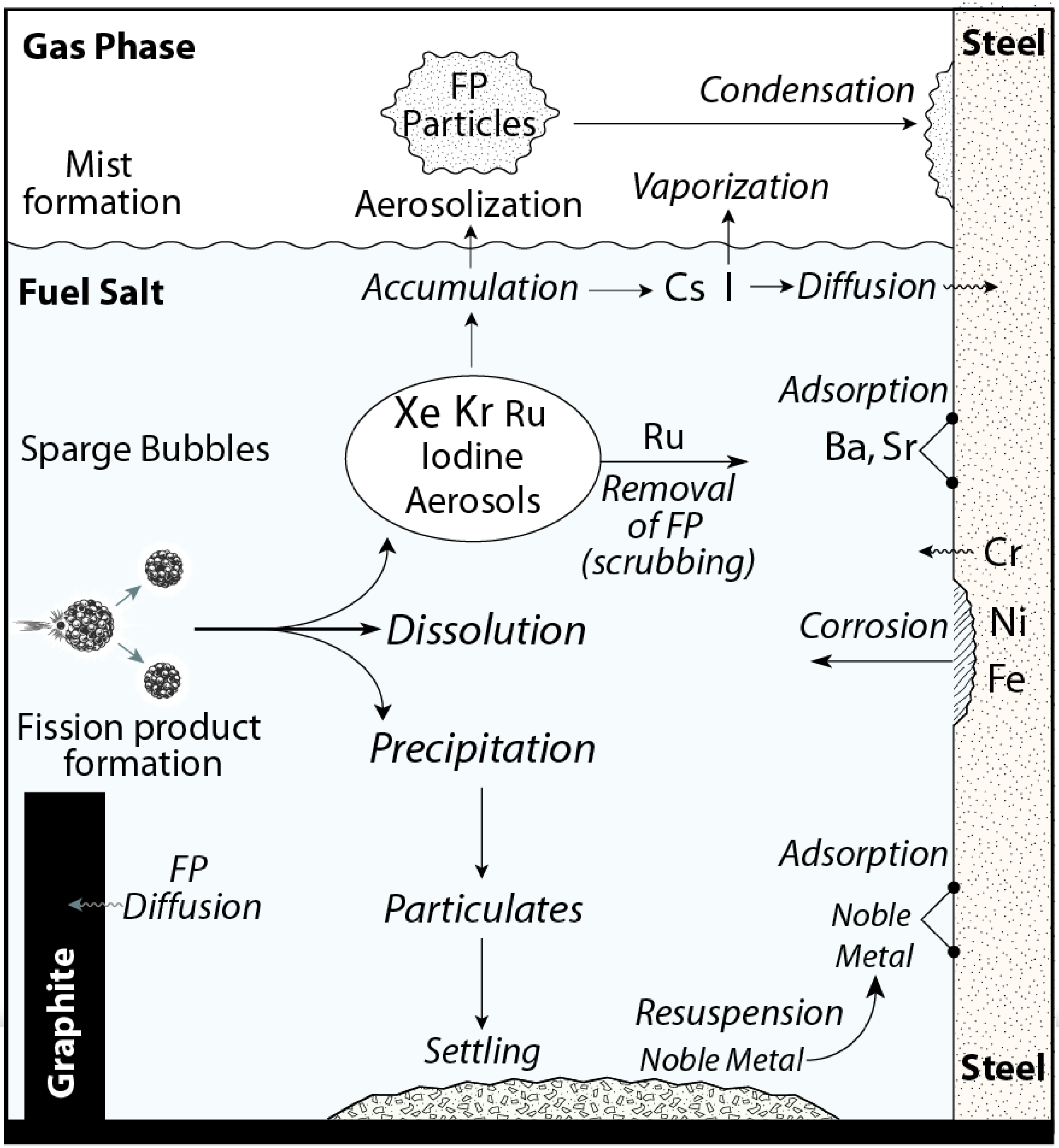
MSR – Broad Array of reactions and chemical phenomena

Comprehensive understanding and monitoring of these phenomena are needed

1. to maintain margins for radiological releases

2. to ensure adequate heat removal for reactor shutdowns

3. To maintain proper reactivity control



Jerden, J, et al. ANL/CFCT-19/4 (2019)
Courtsey N. Hoyt, presentation" FUEL SALT CHARACTERIZATION AND QUALIFICATION" 20 SEP 2023

Monitoring of Molten Salt Systems

Measurement Type	Sensor Type
Salt Composition (species concentrations)	Salt Sampler Electrochemical Raman UV Vis LIBS
Isotopics Radiation	Gamma spectroscopy Alpha spectroscopy
Isotopic Ratio	LIBS QQQ-ICPMS
Pressure	Pressure Transducer (NaK filled etc...)
Flow Rate	Thermal flow meter Ultrasonic flow meter Activation flow meter
Corrosion/Structural materials	Magnetic susceptibility Meter Ultrasound UV Vis/Raman (Cr, Fe, Ni)
Temperature	Thermocouples Fiber optics

Measurement Type	Sensor Type
Salt Redox Potential	Dynamic reference electrode Optical Spectroscopy (UV Vis, raman Thermodynamic reference electrodes)
Volume (Liquid/Level)	Tracer dilution Ultrasound Contact Depth sensor Radar
Particulate Monitoring	Electrical Resistance Tomography Ultrasonics
Off gas monitoring	Optical LIBS
Under salt viewing	Ultrasound Video
Vibrations/accelerations	accelerometers
Valve position monitoring	Position monitoring
In reactor video monitoring	Camera (CCD, CMOS…)

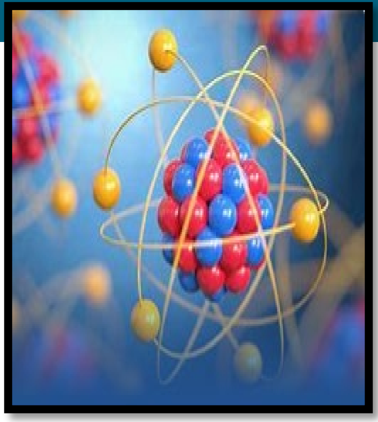
Adapted from N. Hoyt presentation, “Fuel Salt Characterization and Qualification”
MSR fuel Cycle Workshop 19-21 SEP 2023, ANL

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

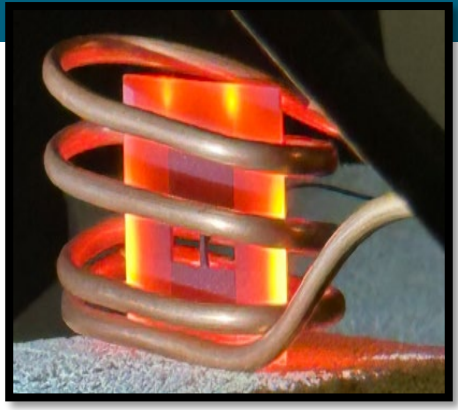


MSR Radioisotopes

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

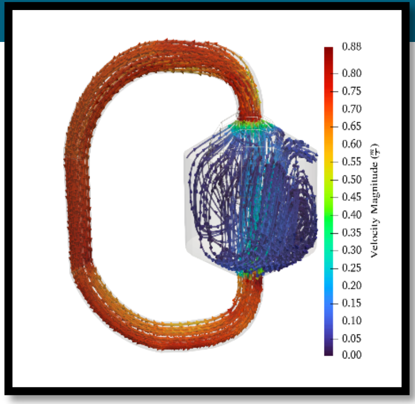
Technology Development and Demonstration – Radionuclide Release

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.

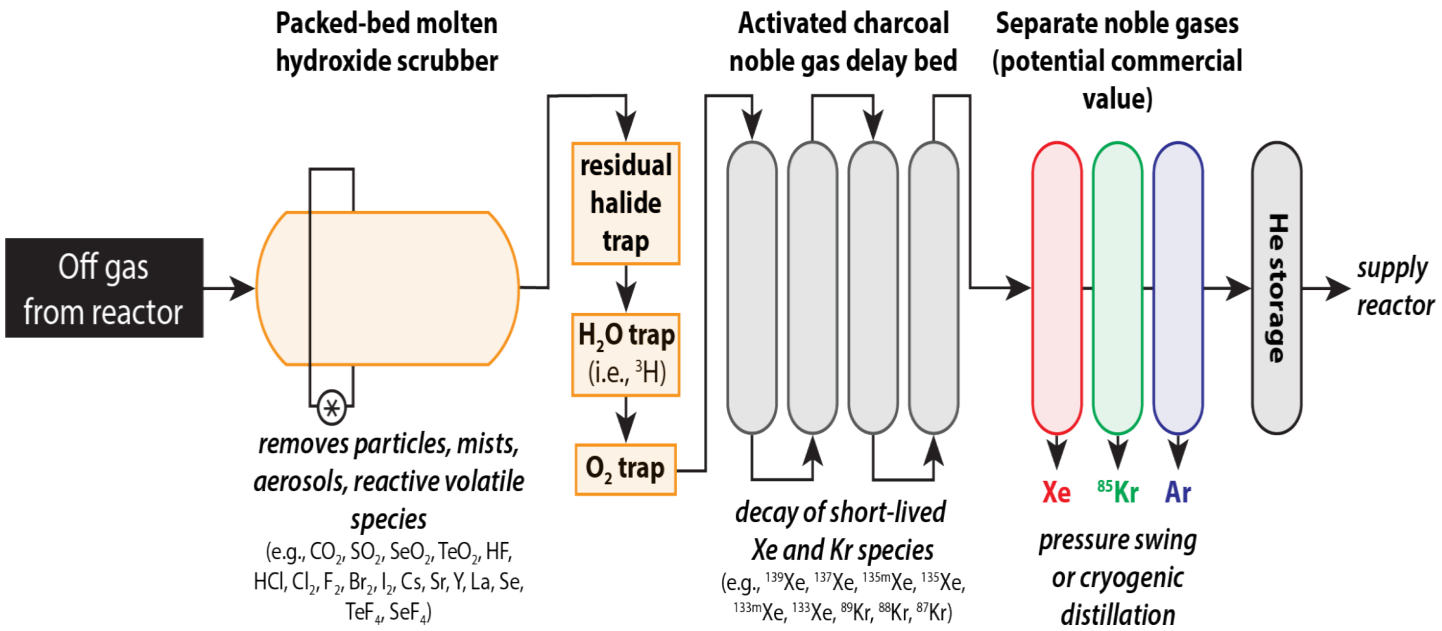
Development of Sensors for Off Gas Management and Chemistry Control

Supporting different salts:

- Chloride Salts
- Fluoride Salts
- Be-bearing Salts
- Actinides bearing salts

Building tools to support development and demonstration of off-gas treatment systems

- Informed development
- Better, faster, safer and cost effective deployment



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.

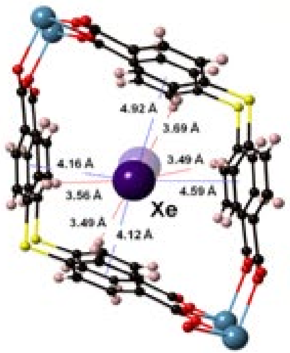
Technology Development and Demonstration

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

Component testing

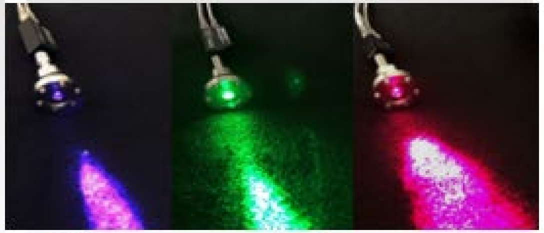
- Large Scale Test Loop

- Xe/Kr separation in MOF



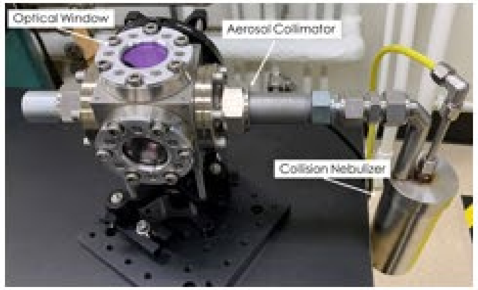
Radionuclide identification/speciation

Raman



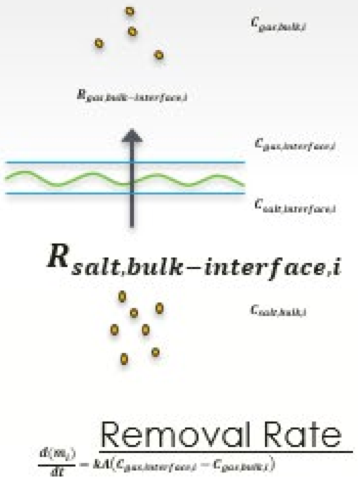
405 nm 532 nm 671

LIBS



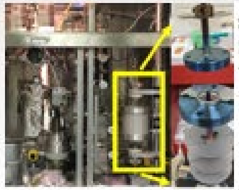
Source term modeling

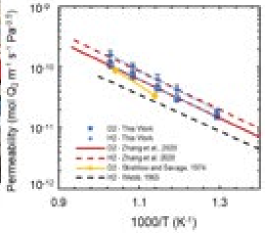
- Gas-liquid interface
- Provides source term to off-gas



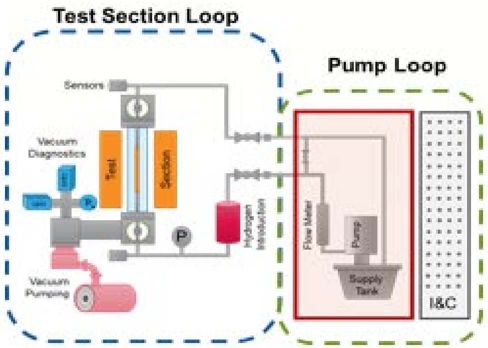
Tritium permeation

- Hydrogen isotope permeability in Hastelloy N





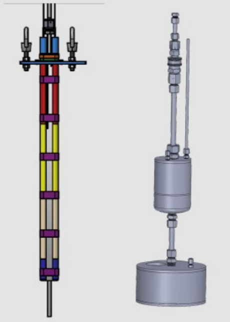
- Tritium transport salt loop



Sensors/ salt chemistry

- Salt composition
- Redox state
- Salt level

Particulate Monitoring

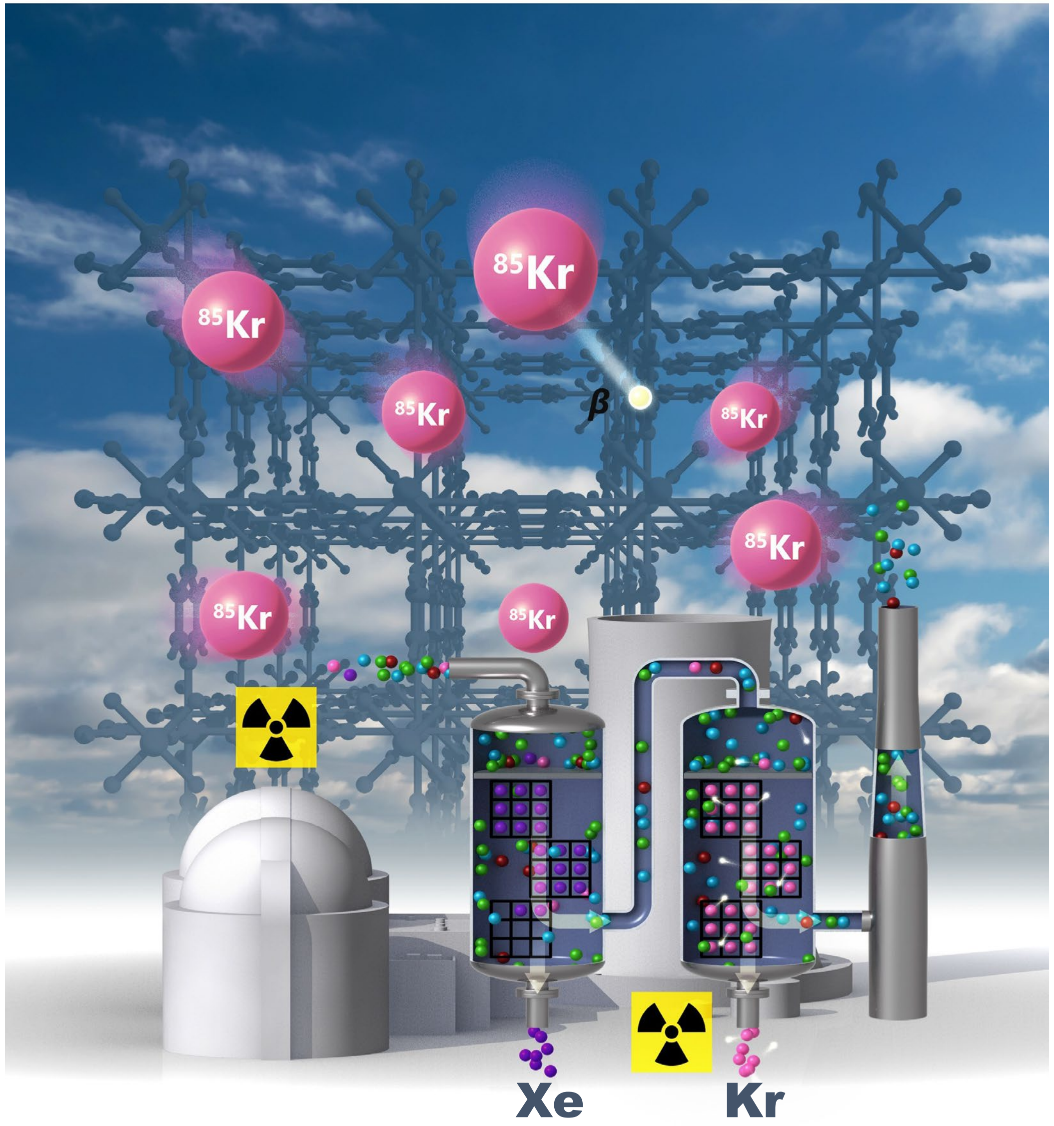


Automated Salt Sampling

Driving Factors

- **Why**
- U.S. EPA 40 CFR 190 and NRC regulation requires volatile radio nuclides (^{14}C, ^{3}H, ^{131}I, ^{133}Xe and ^{85}Kr) must be captured and sequestered
- Noble gas capture is the most difficult to capture as they are inert by definition
- Potential economic incentive if captured

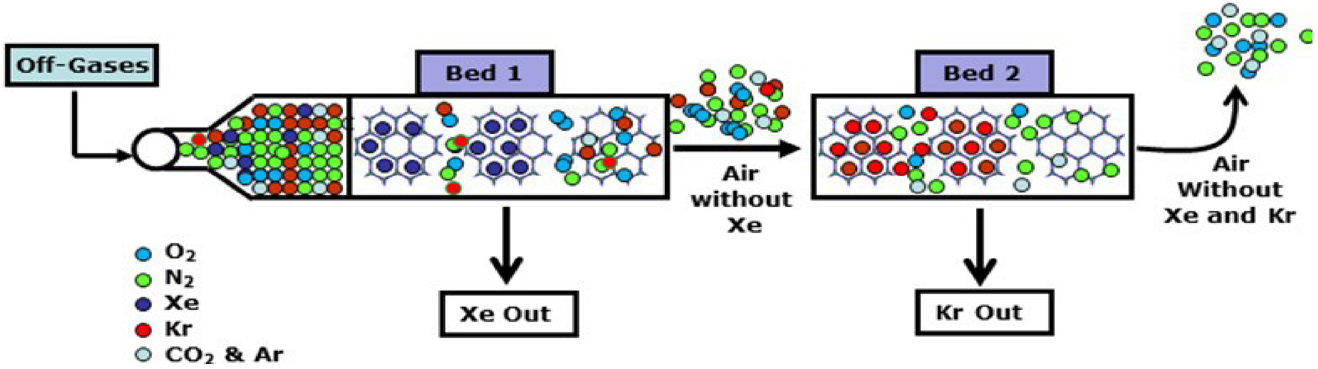
- **Major sources of emissions:**
- Regular operation of nuclear power plant
- Advanced reactors
- Reprocessing of spend nuclear fuel
- Nuclear accidents
- Medical isotope facilities



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

Two-Column Breakthrough

- **A two-bed technique to remove and separate**
  - **Bed 1 remove Xe from air**
  - **Bed 2 remove Kr**
    - ✓ **Yields air without Xe and Kr**
    - ✓ **Off-gas can be released**



Results:

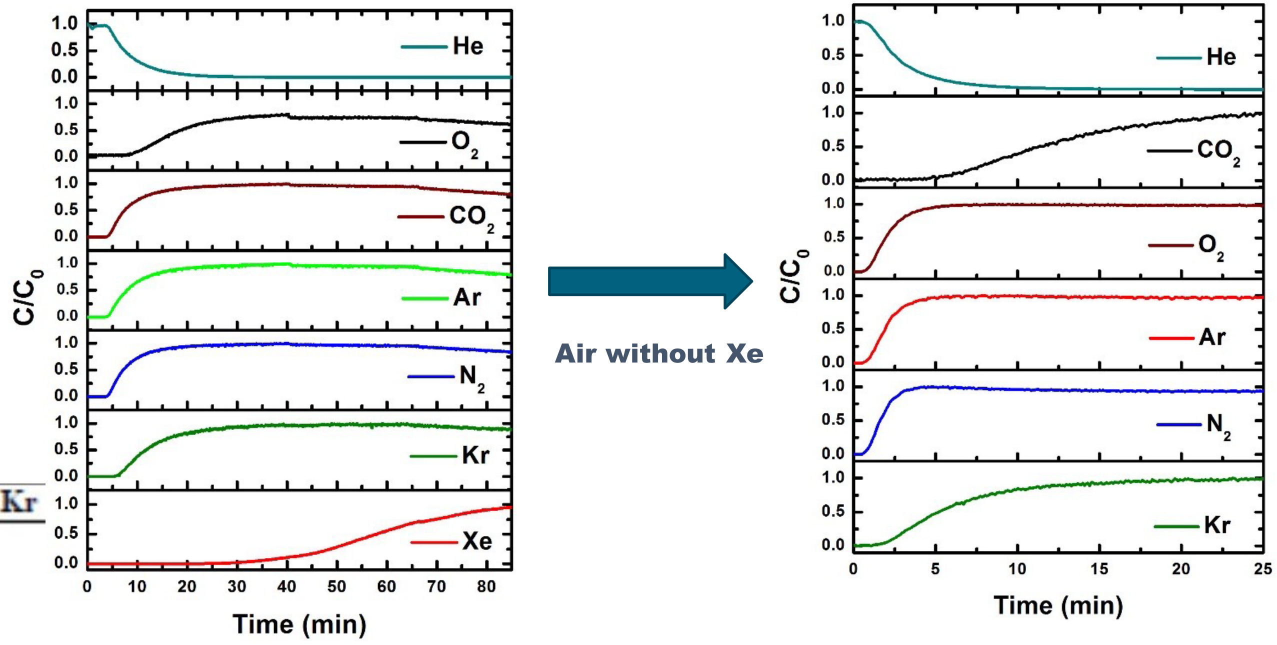
- **Bed - 1**

Gas	Breakthrough Time (min)	Capacity (mmol/kg)	Selectivity of Xe
Xe	18	16 (33.8)[a]	
Kr	1	0.11 (0.75)[a]	14
CO_2	5	1.2	3
N_2	0.08	47	209
Ar	0.08	5.28	210
O_2	0.08	12	206

[a] Capacity at equilibrium

- **Bed - 2**

Gas	Breakthrough Time (min)	Capacity (mmol/kg)	Selectivity of Kr
Kr	2.5	0.13	
CO_2	7.5	0.90	0.3
N_2	0.25	80.8	9.9
Ar	0.25	9.09	9.3
O_2	0.25	21.2	9.3

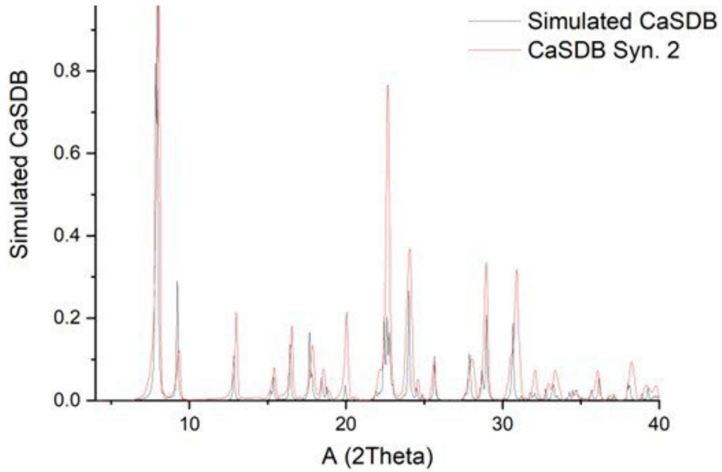


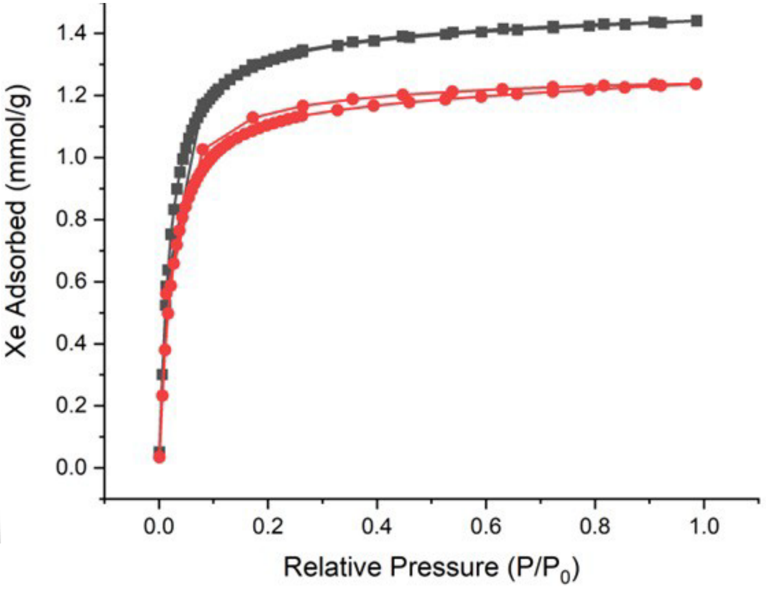
Bed 1 **Bed 2**

- Thallapally, Ali Z. Riley, BJ., Paviet, P., Matyas, J., Vienna, J., Compact and Modular Integrated Off-Gas System and Sensors.” Invention Disclosure e-IDR 18117
- 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*

MOF Synthesized at PNNL

- Identical PXRD confirmed (powder to pellet)
- No amorphous phase
- Reduced BET surface area



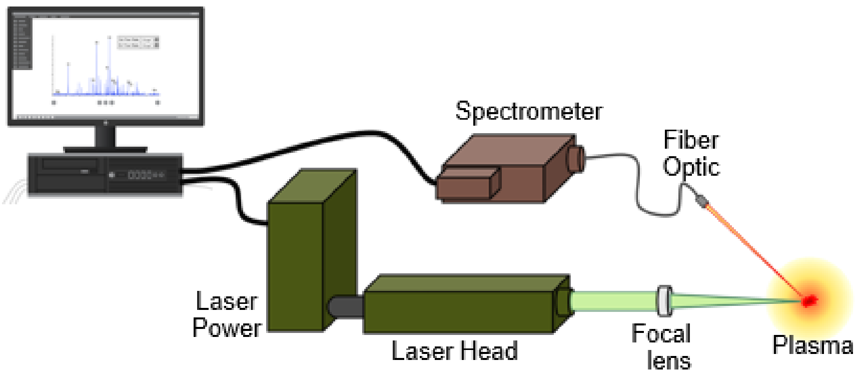


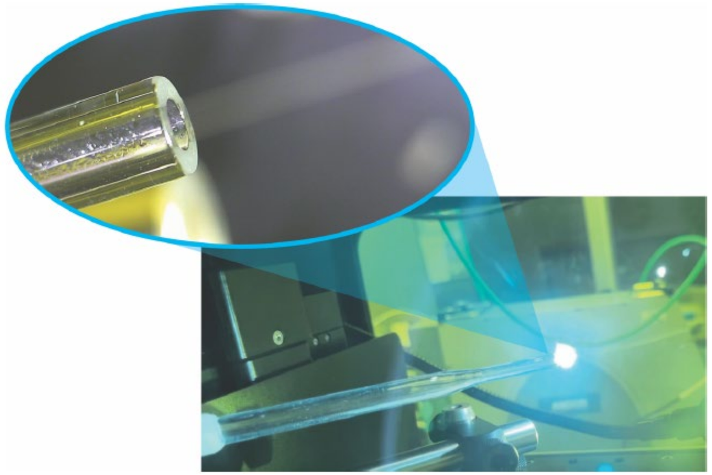
Property	Value
Pressed Pressure	2000 psi for 3 min
Size	600 – 850
BET Surface area	15 m²/g
BET Surface area, Po	120 m²/g

Courtesy Praveen Thallapally, PNNL

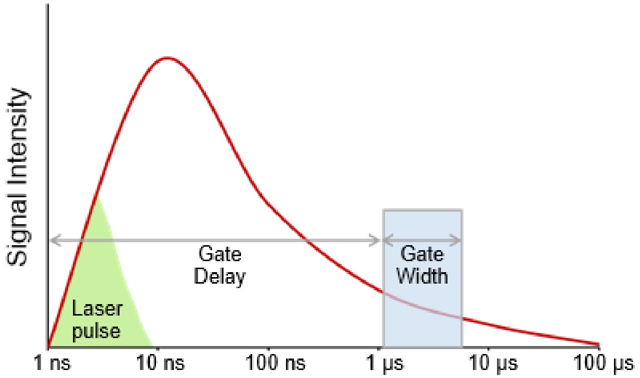
Laser-induced breakdown spectroscopy (LIBS) can provide an elemental fingerprint in real-time

A high energy density laser pulse ablates a sample to form a micro plasma at T~10,000 K

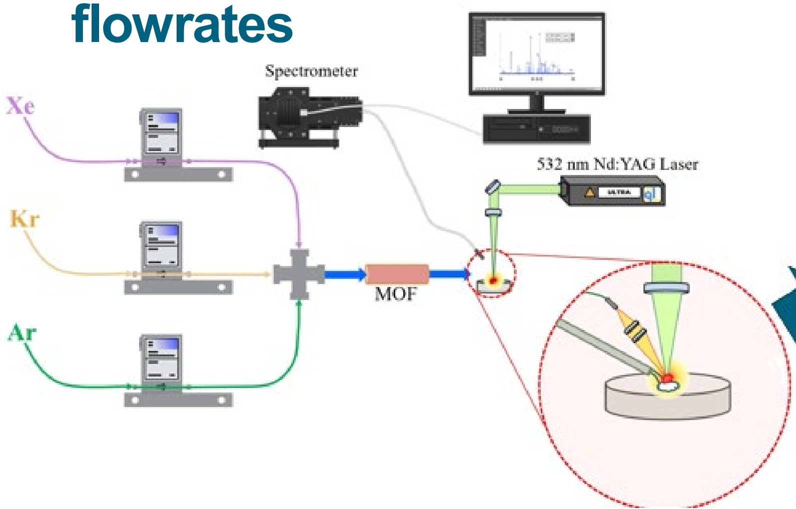


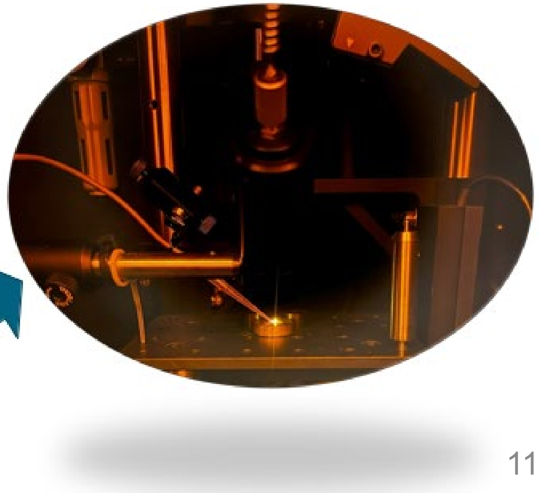


The plasma light is collected with a gated spectrometer to measure an elemental signature



New LIBS setup needed to facilitate MOF size and flowrates





Courtesy Hunter Andrews, ORNL

Conversations for deploying LIBS gas sensor on molten salt loops are ongoing

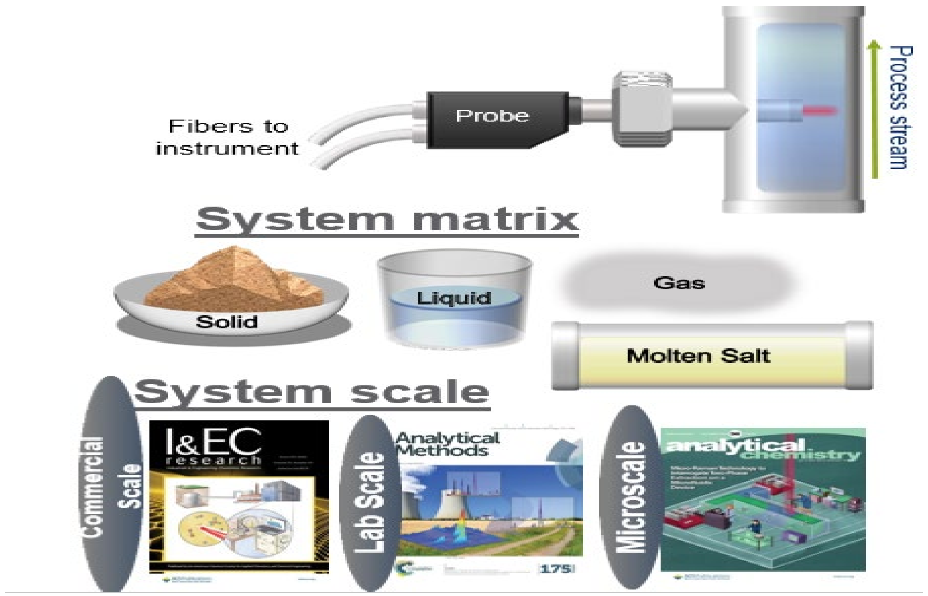
A mobile LIBS system to be coupled with various molten salt systems across the lab complex is being developed in tandem to these efforts for deployable isotopic measurements.

The ability to monitor isotope ratios of salt species and fission products in-situ will be of high value for the MSR community and acts as a further enhancement of ongoing efforts to establish sensors for elemental and molecular monitoring tools.

Courtesy Hunter Andrews, ORNL

In- On-line Monitoring – Molecular Approach

Sensors directly in or on the process
In situ and real-time analysis of a given process or system



Optical Spectroscopy:

Provides chemical information
Highly mature technology
Simplistic integration
Versatile

Fundamental characterization

Efficient process design

Safe and cost-effective deployment

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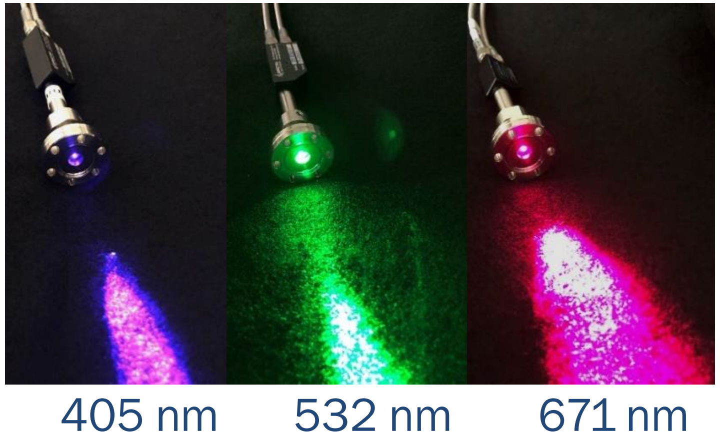
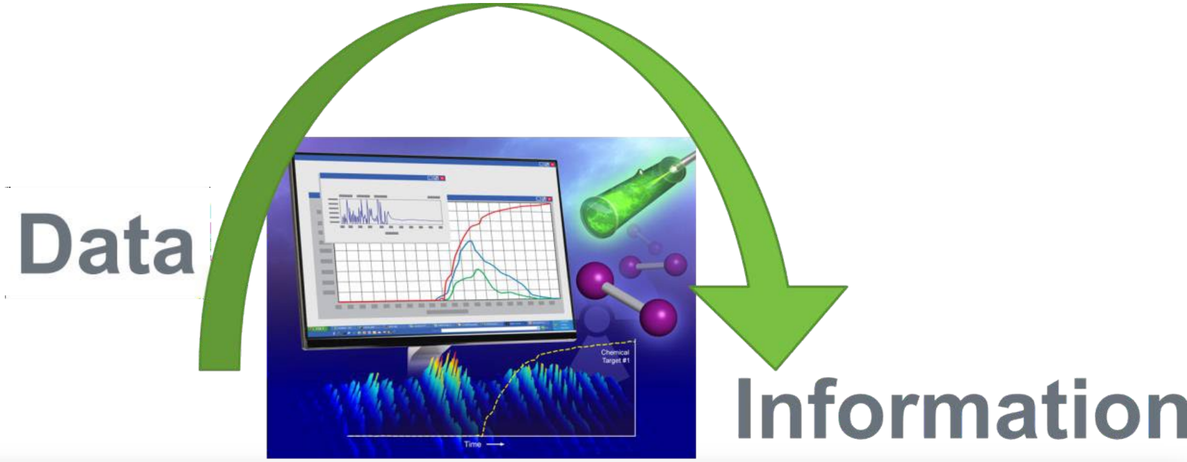
Courtesy Amanda Lines and Sam Bryan, PNNL

The Two-Pronged Challenge of Monitoring Harsh and Complex Chemical Systems

- **Probe development**
  - Overcoming COTS (commercial off the shelf) limitations to build sensors that can survive:
    - Highly corrosive systems (HF gas, molten salts)
    - High temperature systems (molten salts)
    - Radiation
- **Making smart sensors**
  - Building autonomous tool kits that can parse interfering fingerprints and accurately identify and quantify chemical targets

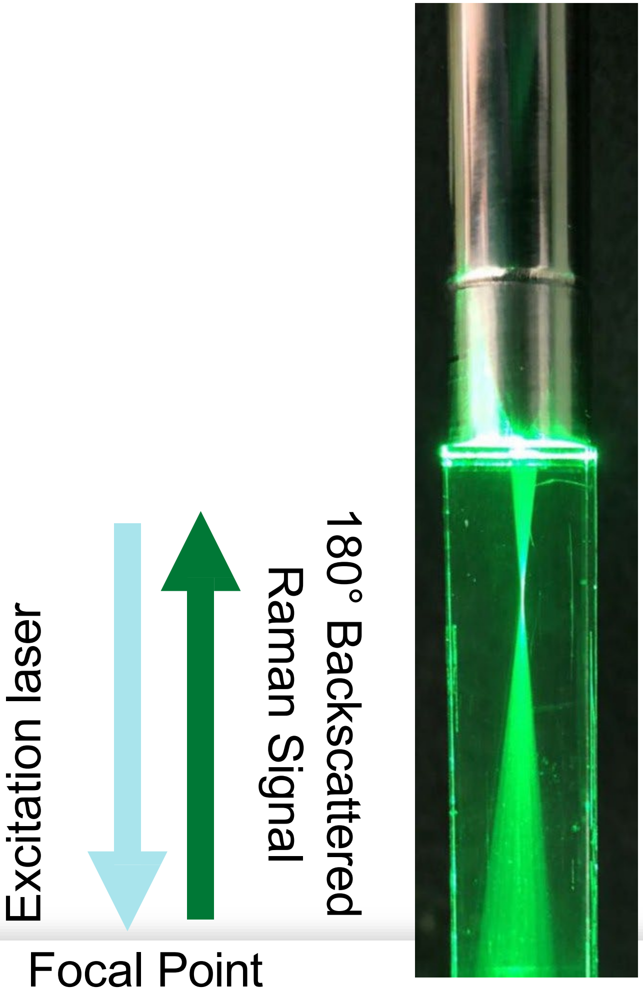


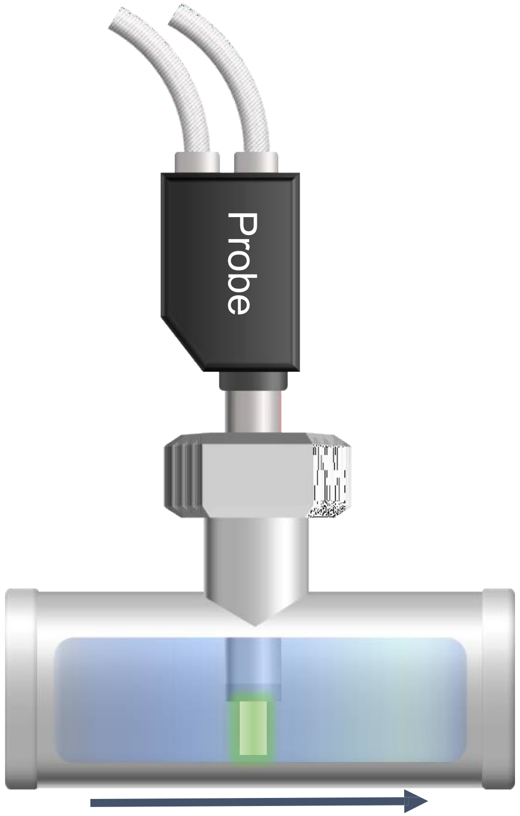


Courtesy Amanda Lines and Sam Bryan, PNNL

Probe Details

- **Utilizing Raman spectroscopy which relies on 180° backscatter**
- **Ideal for molecular, poly atomic species including several key targets in the gas phase**
- **Testing multiple probes in multiple locations**
- **Probe specs specialized for each location**

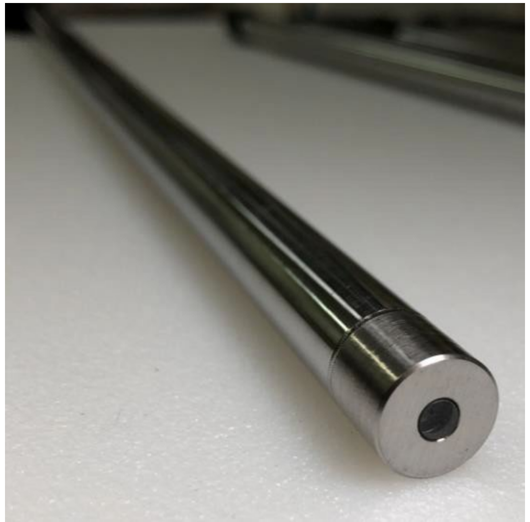




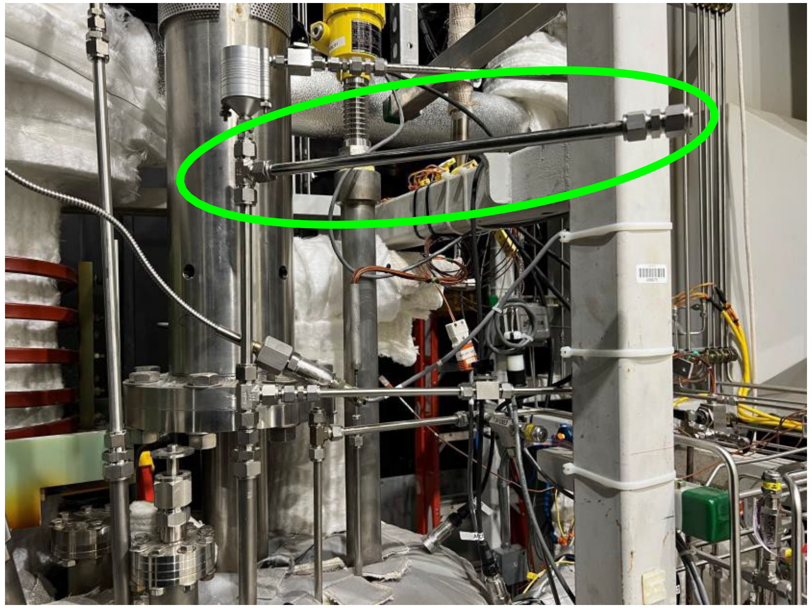
Courtesy Amanda Lines and Sam Bryan, PNNL

Testing Probe Materials in LSTL

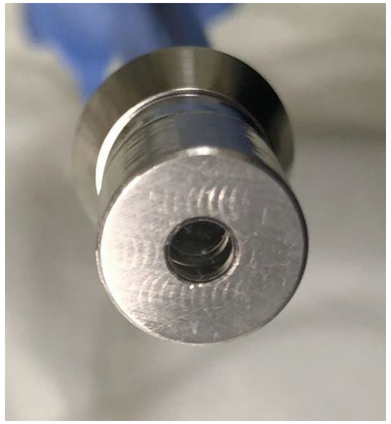
Before incorporation into salt loop

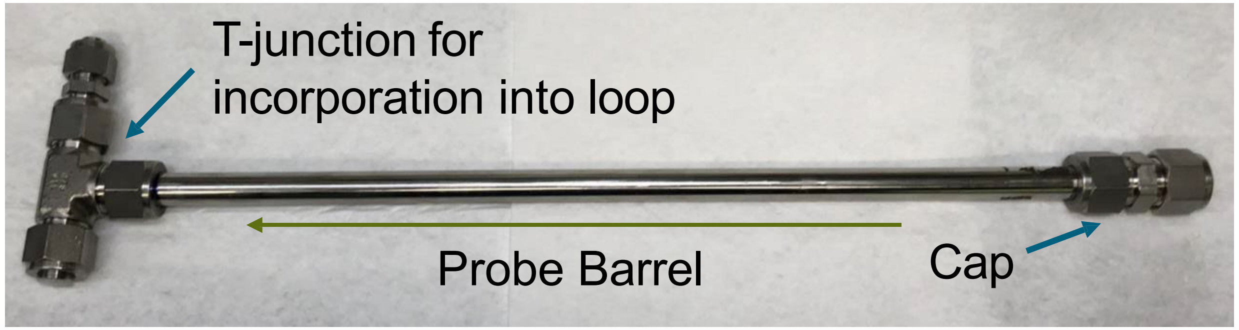


- **Salt loop testing**
  - Probe barrel swaged into loop
  - No visual degradation after testing



After incorporation into salt loop

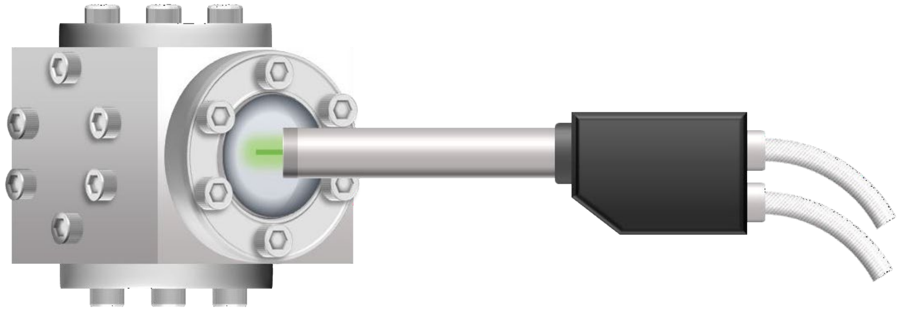


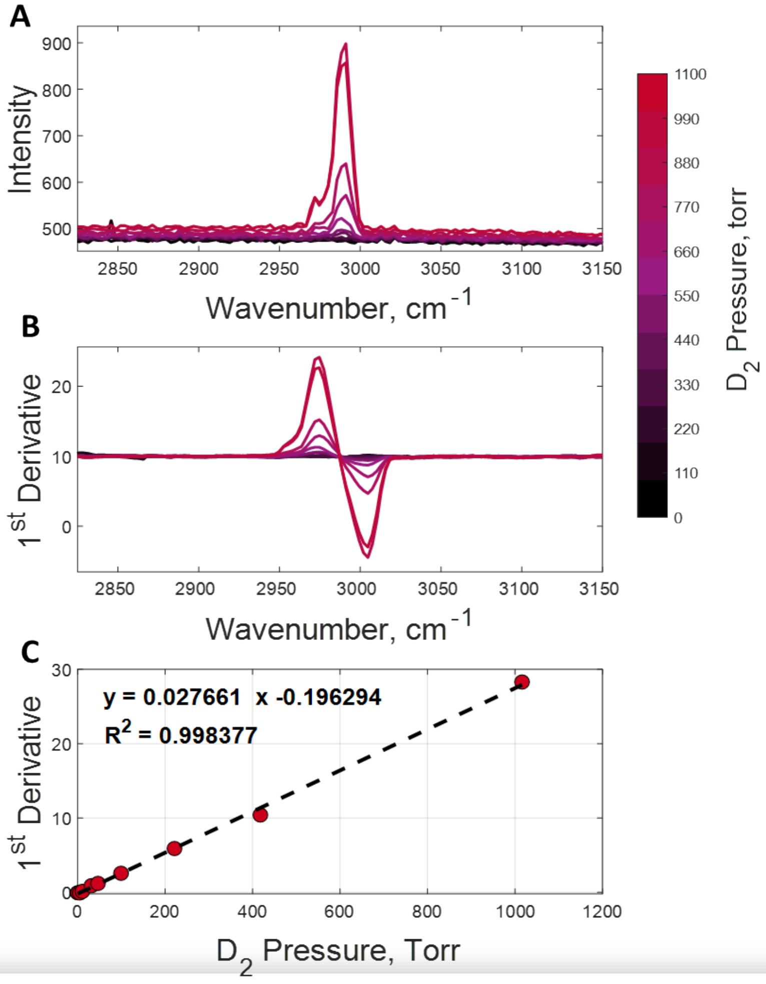


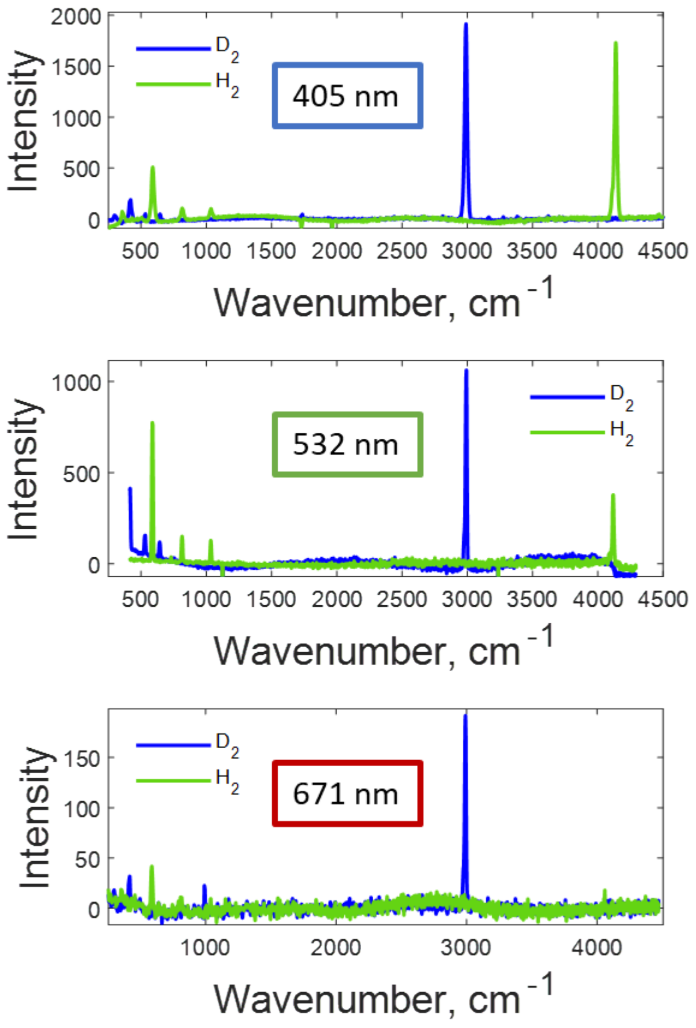
Courtesy Amanda Lines and Sam Bryan, PNNL

Building a Better Gas Cell

- Expansion to H isotopes
- Raman can identify and quantify species
- Testing the new gas cell on standards to compare limits of detection



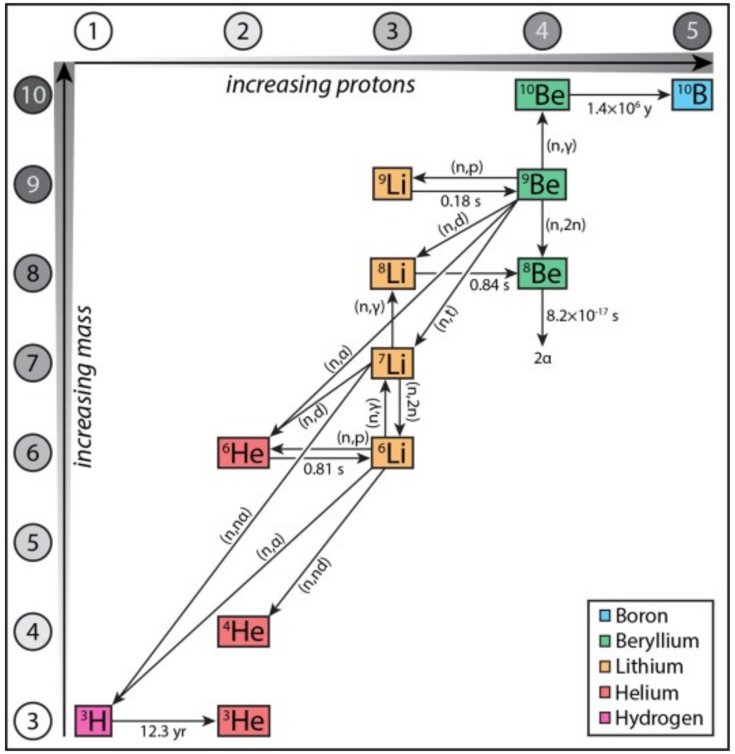




Courtesy Amanda Lines and Sam Bryan, PNNL

Tritium Generation in MSRs

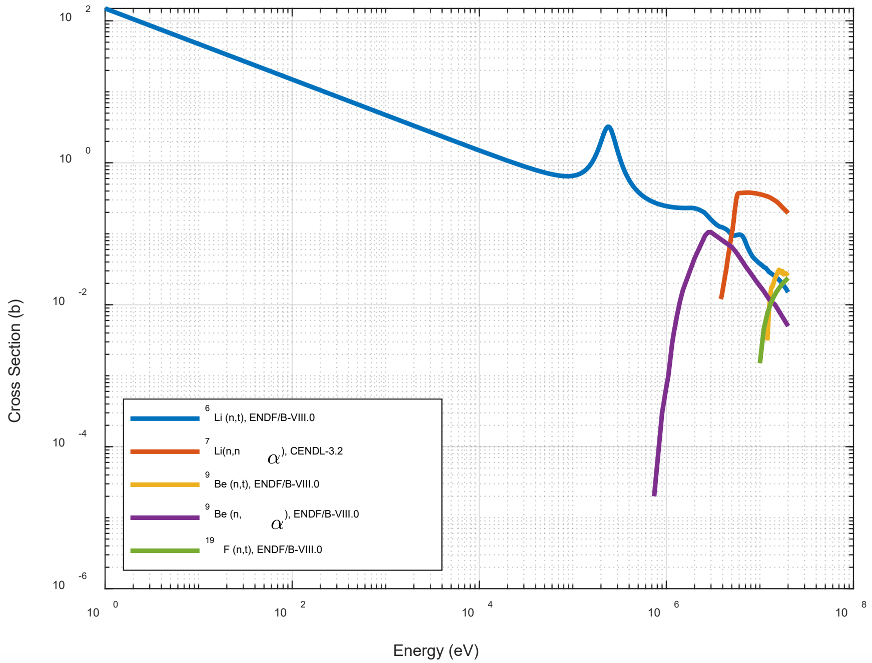
Tritium generated by neutron reactions with Li, Be, and F.



^{6}Li (7.5%) large thermal cross-section.

^{7}Li (92.5%) moderate cross-section in fast-spectrum.

^{9}Be and ^{19}F tritium in fast-spectrum.



Tritium generation rates in *fluoride* salt reactors are similar to CANDU reactors.

CANDUs produce world's supply of tritium for peaceful purposes.

Tritium is a potential valuable byproduct of MSRs.

Reactor Type	Tritium Formation Rate 1000 MWe (Ci/day) [1]
MSR	2400*
CANDU	2700
HTGR	50
PWR	2

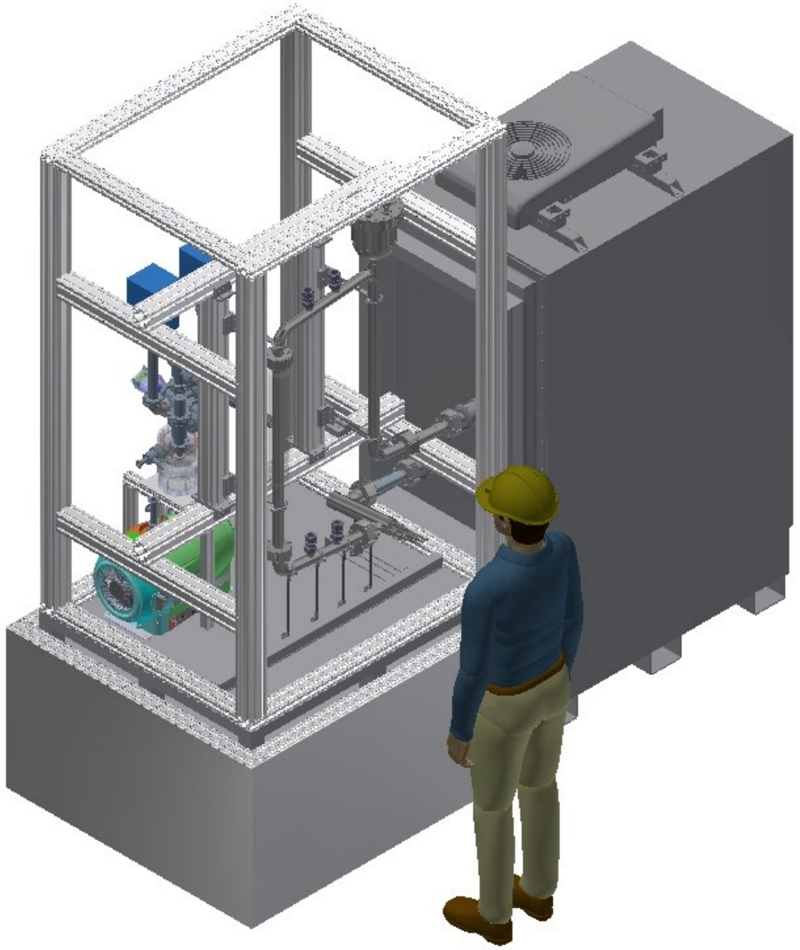
*MSBR enriched in ^{7}Li (99.992%).

Sabharwall, P.; Schmutz, H.; Stoots, C.; Griffith, G. Tritium Production and Permeation in High-Temperature Reactor Systems;, 2013. https://doi.org/10.1115/HT2013-17036.

Andrews, Hunter B., et al. "Review of molten salt reactor off-gas management considerations." Nucl. Eng. Des. 385 (2021): 111529.

Molten Salt Tritium Transport Experiment

- ***MSTTE is a semi-integral tritium transport experiment for flowing fluoride salt systems.***
- **Location: S**afety and **T**ritium **A**pplied **R**esearch 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

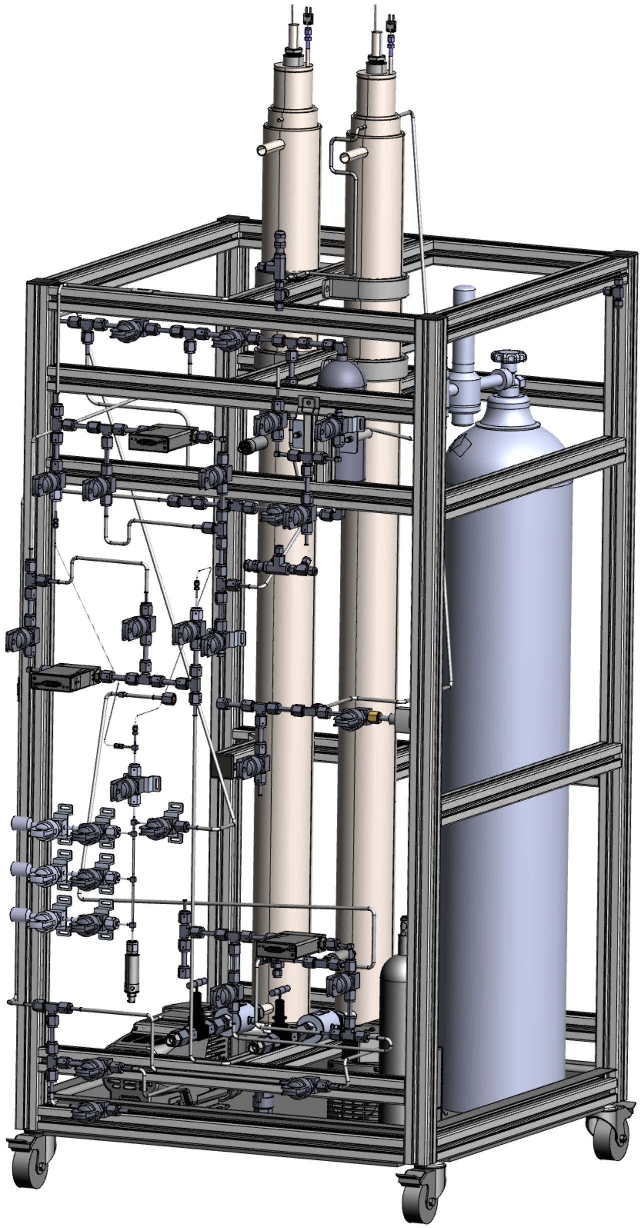
Chlorine Isotopes Separation System for Chloride MSR

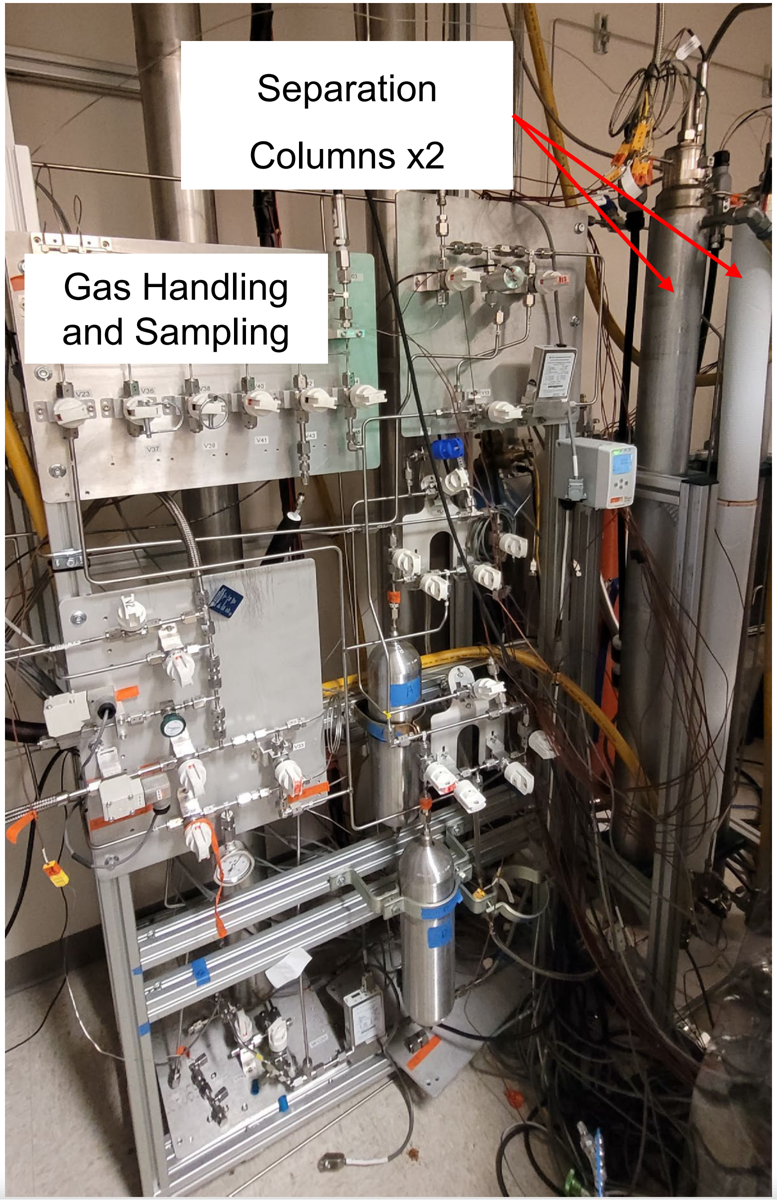
WHY

- ➢ ^{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

CAPABILITIES DEVELOPMENT at PNNL

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





Courtesy Bruce McNamara, PNNL

Online monitoring of molten salt chemistry

Argonne has demonstrated several monitoring technologies with sensors development for salt composition, redox state, salt level, etc.

Electrochemical Monitoring of Salt Composition

Windowless Optical Monitoring of Composition

Automated Salt Sampling

Particulate Monitoring

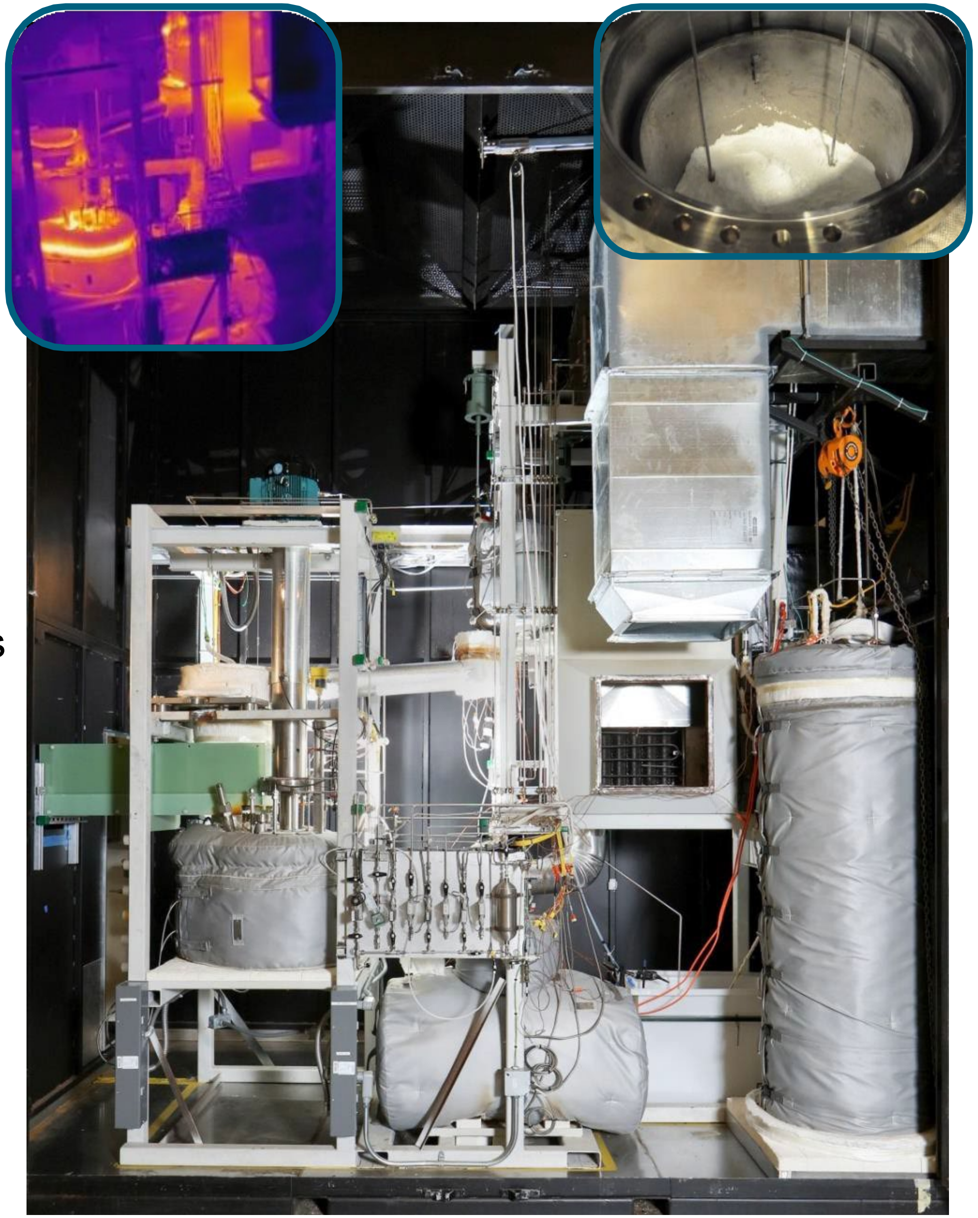
Courtesy N. Hoyt, ANL

What is the Liquid Salt Test Loop? (LSTL) at ORNL

Largest F salt loop in DOE

Salt	NaF-KF-LiF (FLiNaK)
Operating Temp.	700°C
Flow rate	≤4.5 kg/s (136 lpm)
Operating pressure	Near atmospheric
Primary Materials	Inconel 600
Loop volume	80 liters
Power	200 kW induction ~20 kW trace
Primary piping ID	2.67 cm (1.05 in.)
Initial operation	Summer 2016

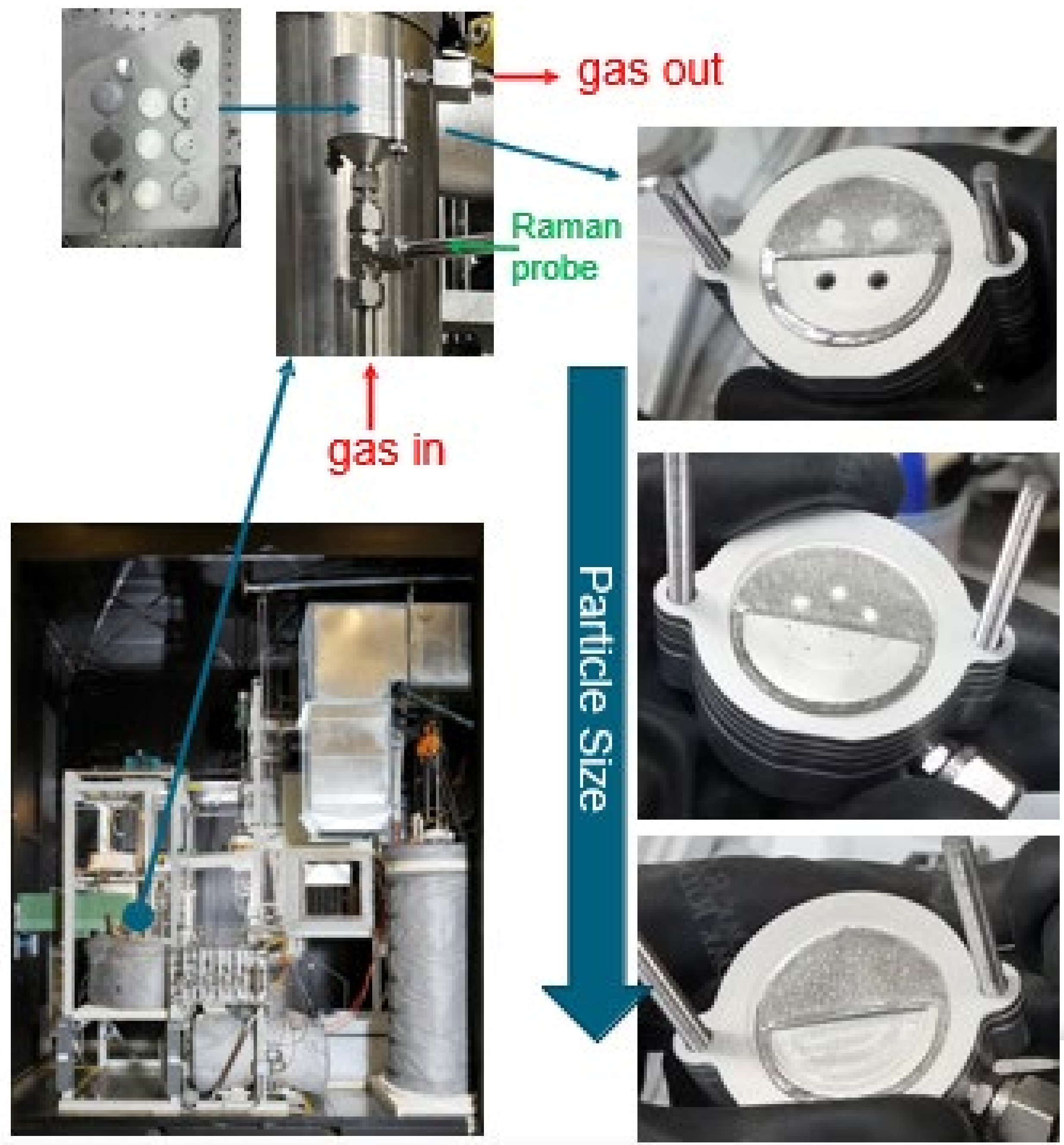
- Integral environment for testing and demonstration of technologies
- Large batch (165 kg) purification system to prepare/refresh salt
- Appreciable power and I&C
- Was and still is state-of-the-art



Courtesy Robb, ORNL

LSTL FY23 Accomplishment

- **Restarted LSTL in Nov 2022 yielding initial experimental data on:**
  - PNNL Raman probe exposure
  - ANL E-Chem sensors operation
  - ORNL gas-space particle capture
  - New test section performance
    - 4 pump speeds, 4 hours, 600°C operation
- **Input into modelling:**
  - ORNL SAM model (*separate pres.)*
  - SNL MELCOR model (*separate pres.)*



Courtesy Kevin Robb, ORNL

2nd round of testing

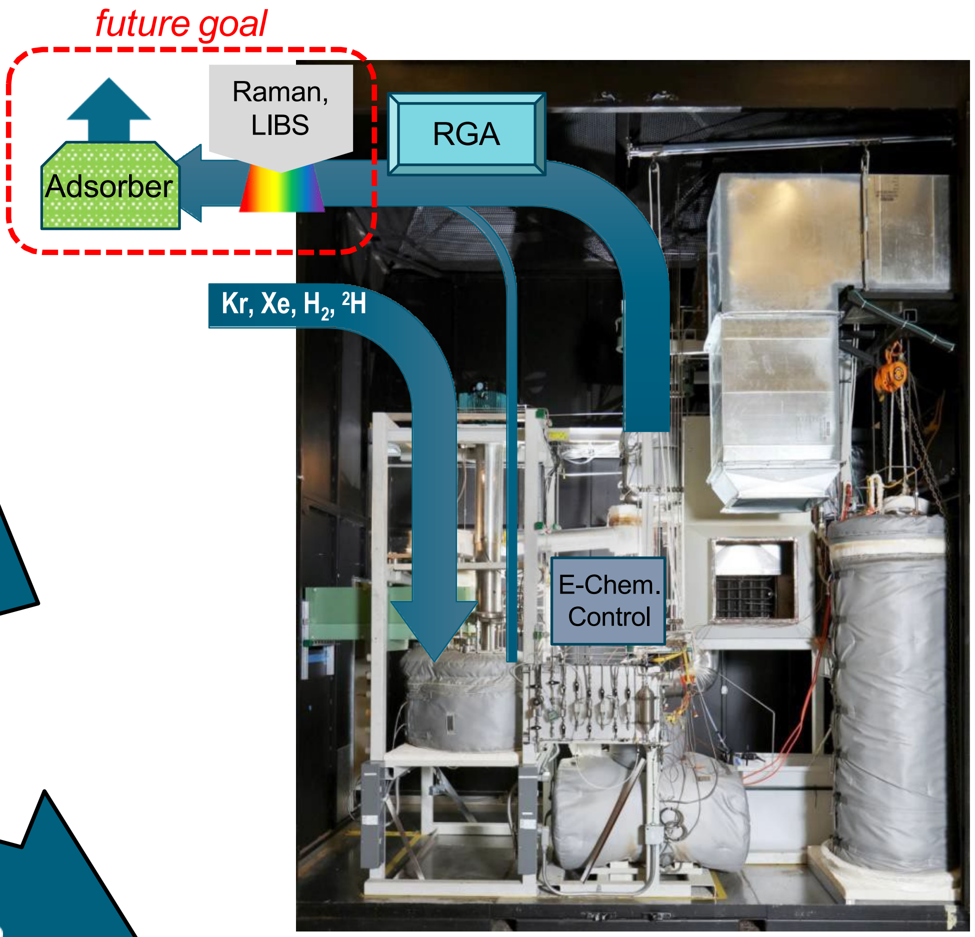
- PNNL Raman probe exposure
- ANL E-Chem sensors operation
- ORNL gas-space particle capture
- Thermal hydraulic system performance

1st round of testing

- Specie transport test
    - He, 4% H_2, and Kr injection
    - Monitoring of off-gas
- NEUP Virginia Tech: flow meter
- Small business: system PLC monitor

MSTDB-TC for test planning

Data output for specie transport code



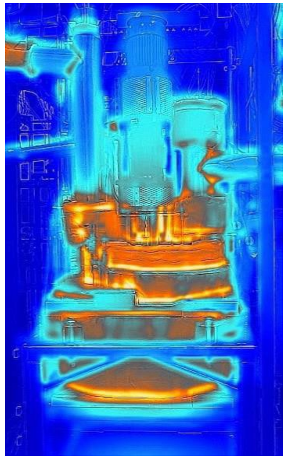
Courtesy Robb, ORNL

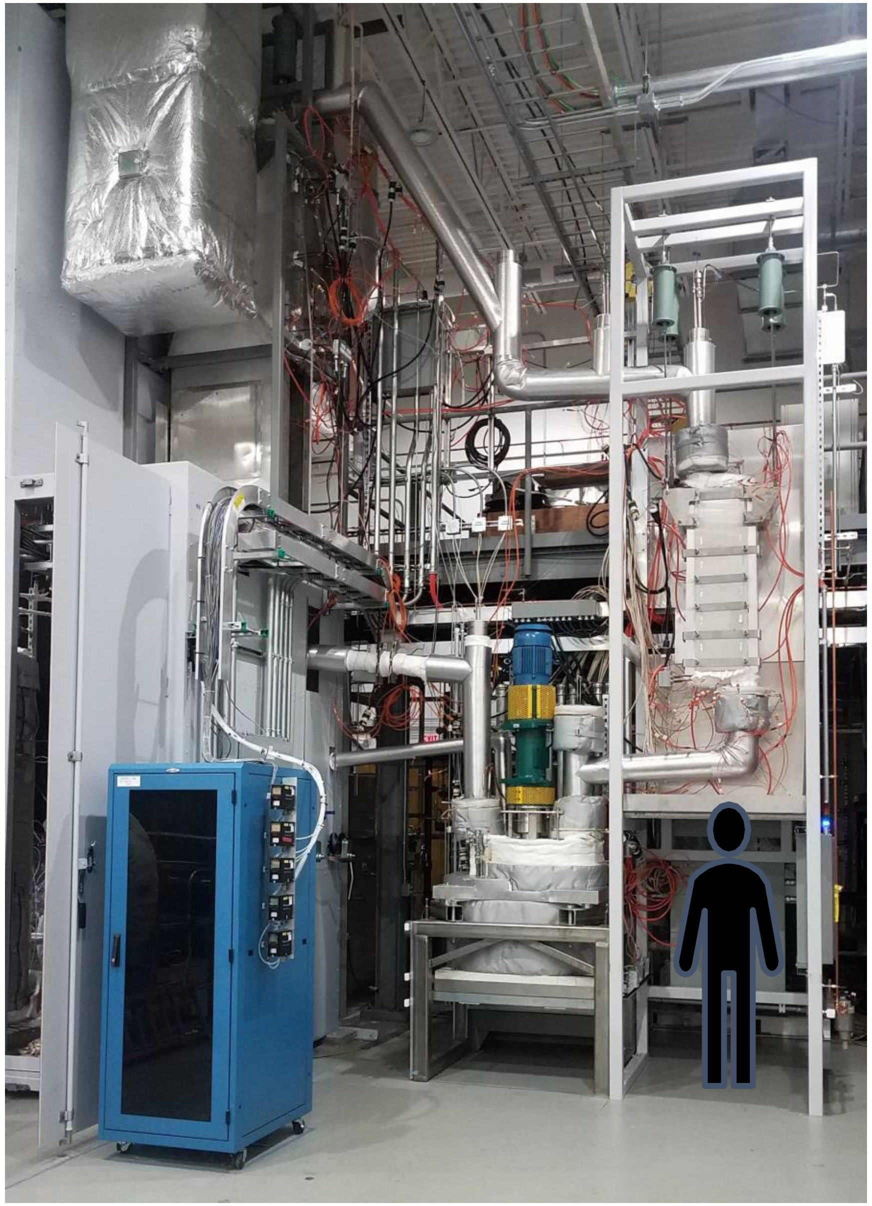
Facility to Alleviate Salt Technology Risks (FASTR)

Largest Cl salt loop in DOE

Salt	NaCl-KCl-$MgCl_2$
Operating Temp.	725°C
Flow rate	≤7.0 kg/s (228 lpm)
Operating pressure	Near atmospheric
Primary Materials	C-276 & Inconel 600
Loop volume	154 liters
Power	400 kW Main Heater ~71 kW trace
Primary piping ID	5.20 cm (2.05 in.)
Initial operation	December 2023

Compared to LSTL, FASTR is:
- 2x higher capacity pump
- 2x larger salt volume
- 2x larger pipe
- 2x thermocouples
- 2x main heating capacity
- 3x trace heating capacity
- 4x number of salt flanges





Development support by DOE-EERE SETO CPS 33875

Robb, Kevin, and Kappes, Ethan. *Facility to Alleviate Salt Technology Risks (FASTR): Commissioning Update.* United States: ORNL/TM-2023/2846, 2023. Web. doi:10.2172/1960689.
Robb, Kevin, Kappes, Ethan, and Mulligan, Padhraic L. *Facility to Alleviate Salt Technology Risks (FASTR): Design Report.* United States: ORNL/TM-2022/2803, 2022. Web. doi:10.2172/1906574.

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Courtesy Kevin Robb, ORNL

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

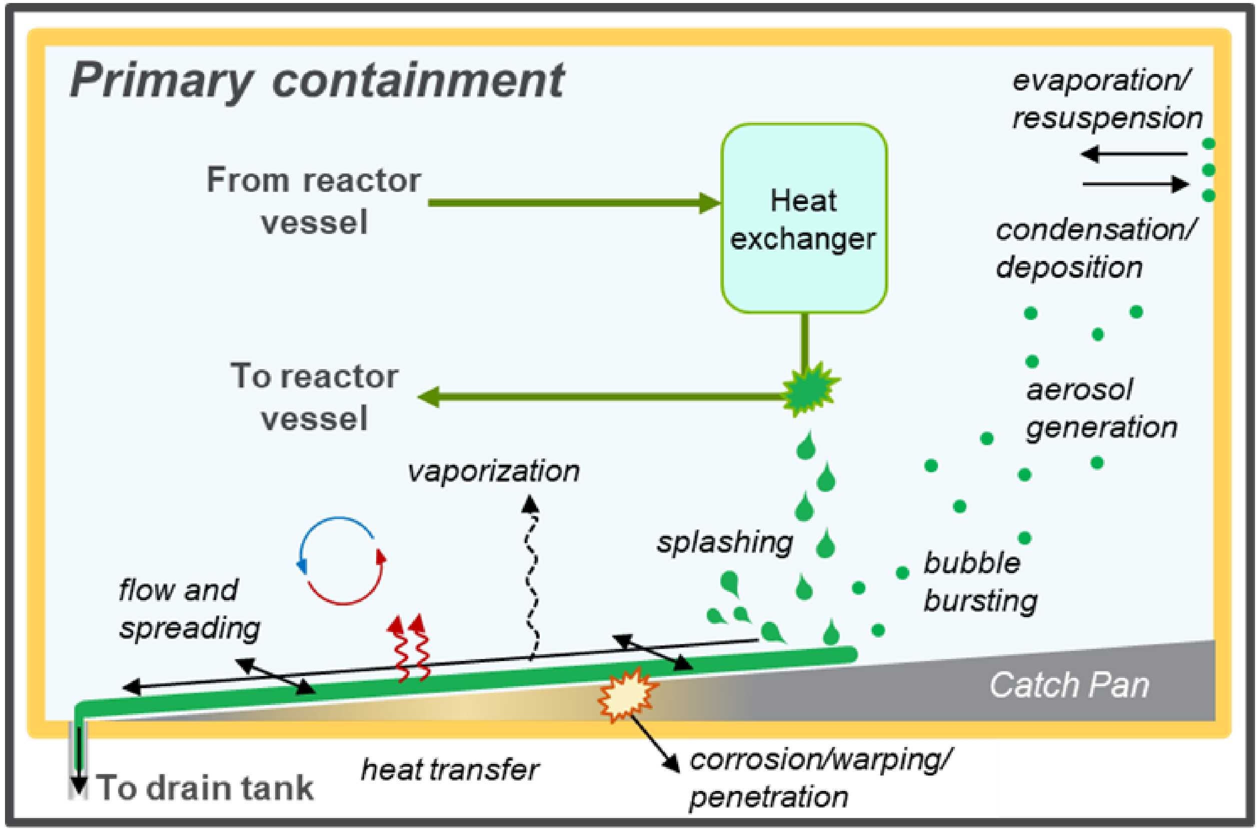
- Warping and corrosion

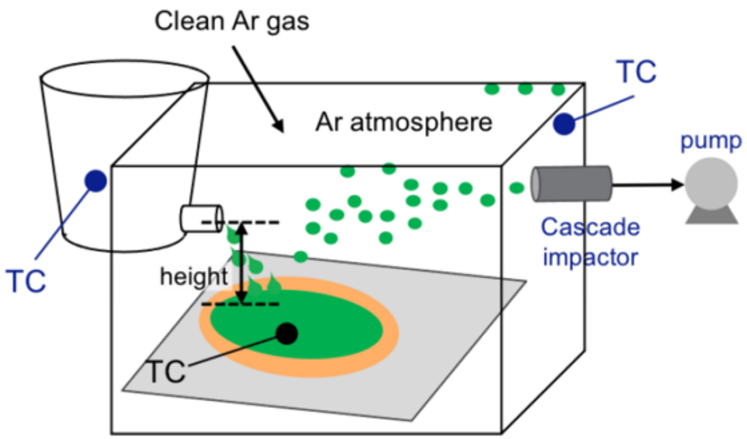
Vaporization and condensation

Aerosol and splatter formation

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

For MSR: salt spilling onto primary containment floor





Courtesy Sara Thomas, ANL

New MSR Program Website

Information on:

MSTDB

MSR Campaign Review Meeting

Publications/Reports

GIF webinars

Molten Salt Reactor PROGRAM

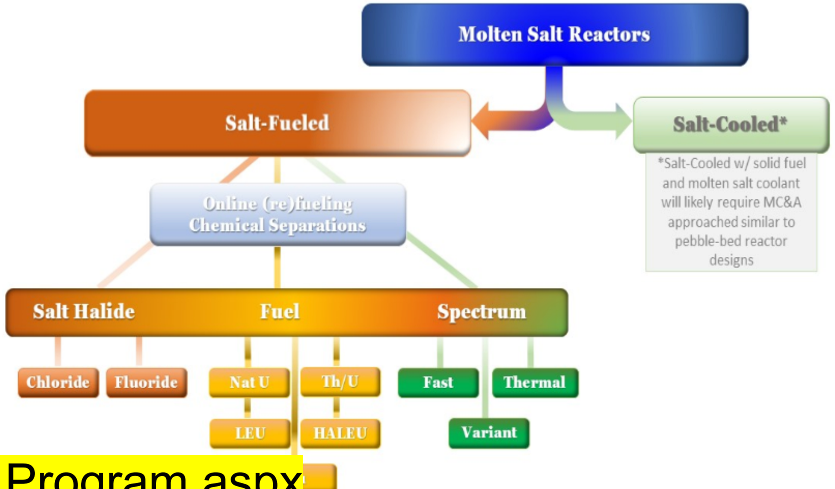
The DOE-NE MSR program serves as the hub for addressing the technology challenges for MSRs to enter the commercial market.

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

1) MSRs can provide a substantial portion of the energy needed for the US to achieve net zero carbon emissions by 2050 and

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.



FY2022 Integrated Research Projects Awards

- Reduction, Mitigation, and Disposal Strategies for the Graphite Waste of High Tempe
- Bridging the gap between experiments and modeling to improve design of molten s

NRL Projects Awarded CINR FY22 Funding

- Integrated Effects of Irradiation and Flibe Salt on Fuel Pebble and Structural Graphite Reactors

FY 2022 CINR MSR AWARDS

- A Molten Salt Community Framework for Predictive Modeling of Critical Characterist
- Understanding the Interfacial Structure of the Molten Chloride Salts by in-situ Electro Soft X-ray Scattering (RSoXS)
- Nuclear Material Accountancy During Disposal and Reprocessing of Molten Salt Reac
- Optical Basicity Determination of MoltenFluoride Salts and its Influence on Structural

FY22 SciDAC Award

- Los Alamos National Laboratory to lead study of molten-salt nuclear reactor material

MSR Annual Campaign Review

- May 2-4, 2023
- 2022
- 2021

MSR Course

Molten Salt Thermal Properties Database (MSTDB)

- University of South Carolina - College of Engineering and Computing -- MSTDB
- Oak Ridge National Laboratory -- MSTDB

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
- Walker et al., “Application of NEAMS Multiphysics Framework for Species Tracking in Molten Salt Reactors”, INL/RPT-23-74376, (2023).

Conclusions

Monitoring and characterization of the fuel salts are crucial to ensure fuel salts meet their qualification requirements. The exact form that the required monitoring approaches will be dependent on many vendor-specific factors.

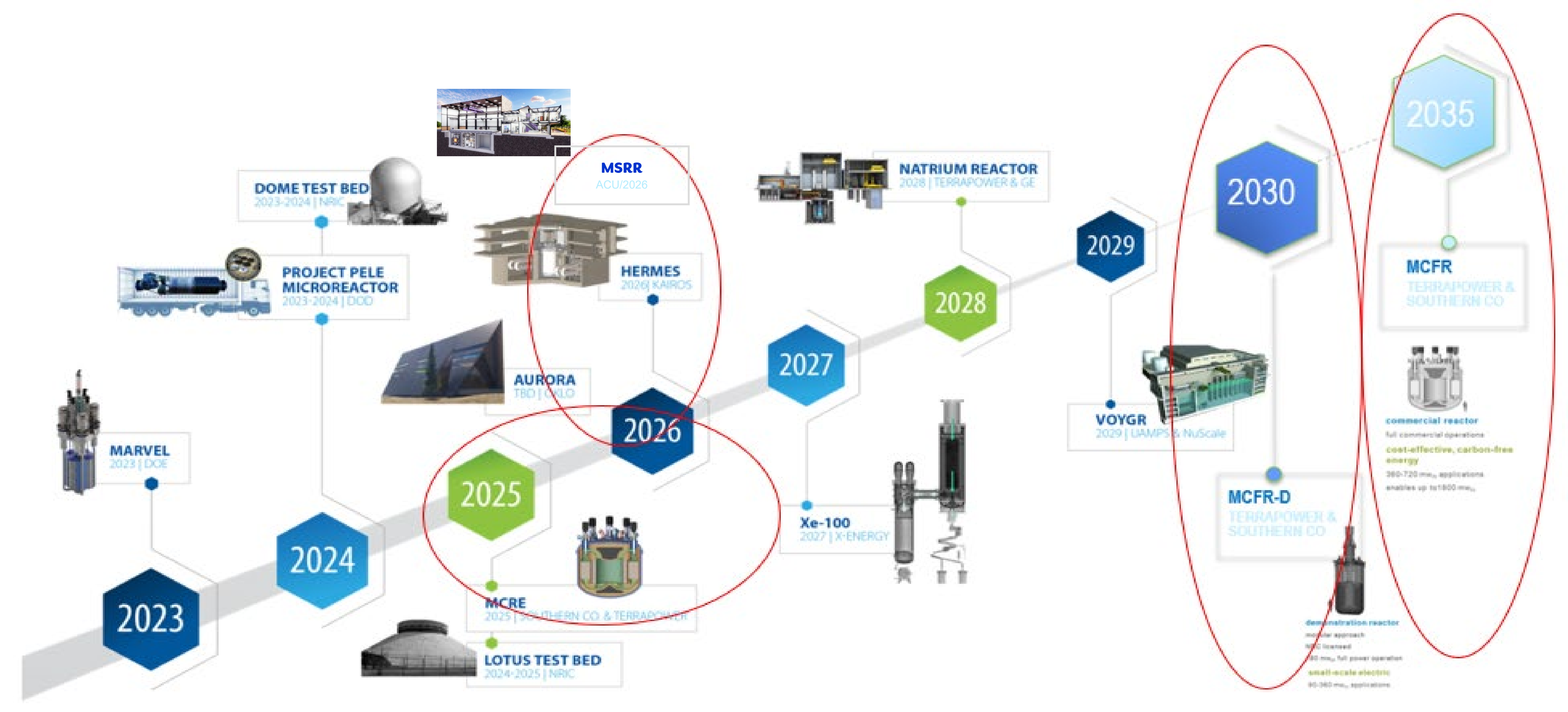
- **On-line monitoring is a powerful tool that can support:**
  - More efficient design and testing of chemical processes (e.g. off-gas treatment)
  - Informed transitions during scale up
  - Safer, optimized, and affordable deployment of processes
- **Optical based sensors can provide complex chemical information**
  - National Labs are collaborating to build comprehensive tool kits

- **Full demo of monitoring within ORNL salt loops, ACU, MCRE…**

Conclusions (2)

Many questions remain

- Where will monitoring need to be done?
- Will online monitoring (akin to chemistry monitoring in LWRs) be formally included as a fuel qualification requirement?
- How accurate will the monitoring tools need to be to ensure the salt is kept in a qualified range? How wide can the qualified range be for attributes such as salt composition?
- Can we drive down detection limits and will this increase the usefulness of the various techniques?



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

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ENERGY
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Thank you

Patricia.Paviet@pnnl.gov

509-372-5983