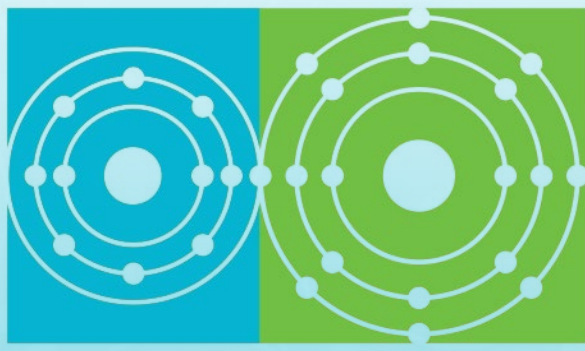
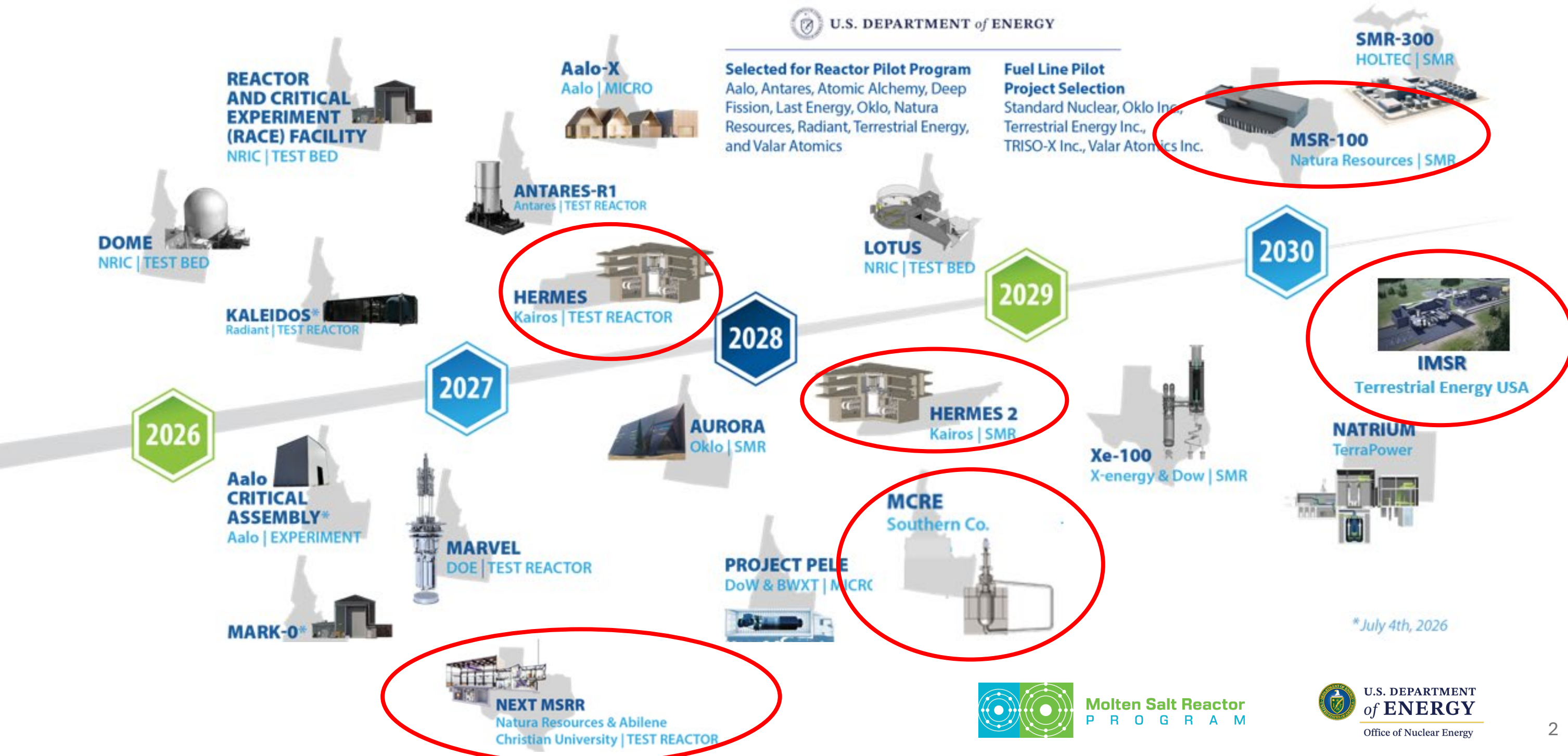




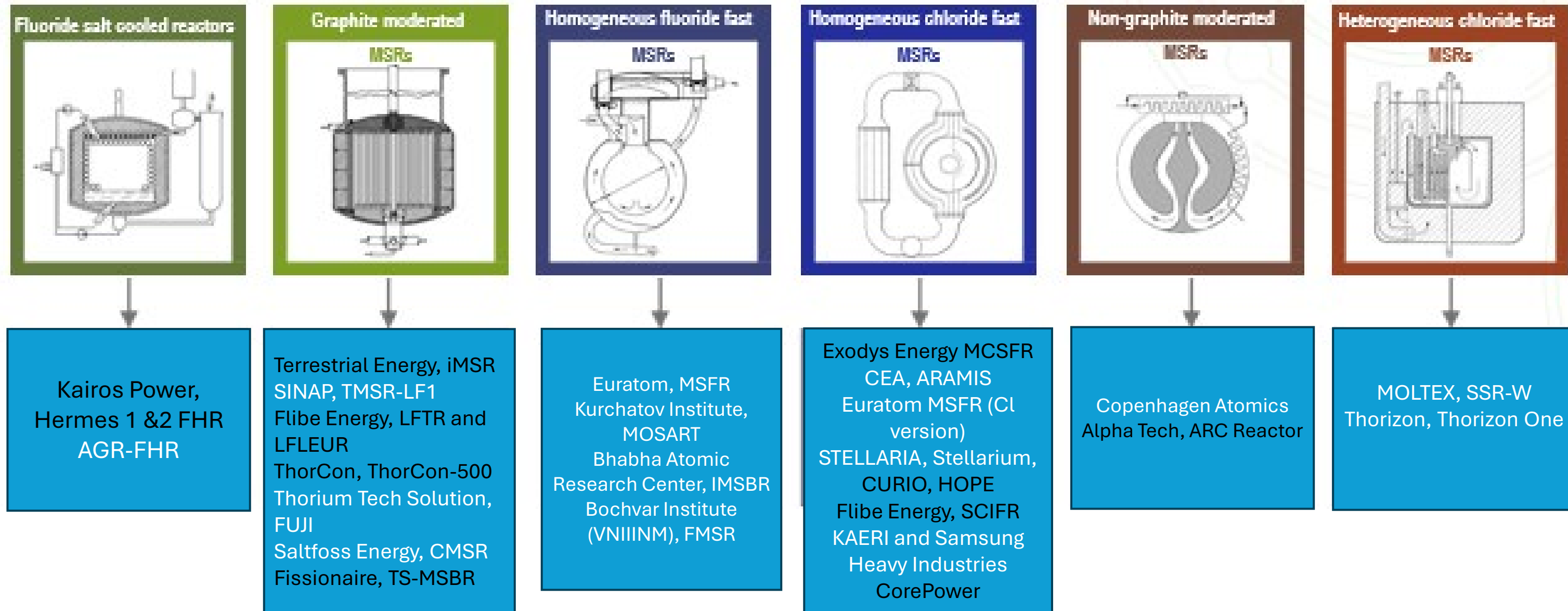
Molten Salt Reactor
P R O G R A M

Panel Session - Roadmaps

Accelerating Advanced Reactor Demonstration and Deployment in the U.S.



Molten Salt Reactor Concept(s) ... so many



ORNL/SPR-2020/1865

Roadmap for thermal property measurements of Molten Salt Reactor systems



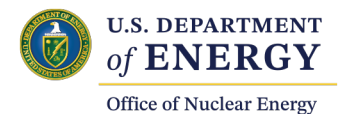
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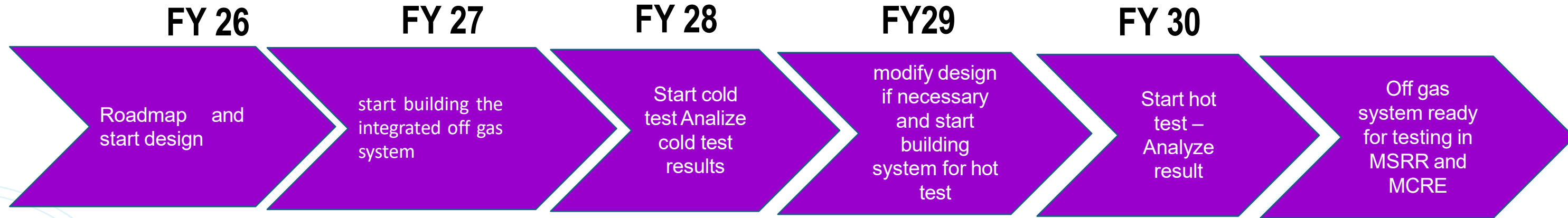
March 2021

Updating the MSR Thermal Property Measurements Roadmap

Ted Besmann
Tony Birri
Melissa Rose



Objective: Demonstration of an integrated off-gas system in 5 years.



Integrated Off-Gas System

**Hunter Andrews
Joanna McFarlane
Praveen Thallapally**

Panel Session on Thursday 23 April at 11:05 am MT



Stakeholder Engagement Priorities (GAIN)



600 18th Street North
Birmingham, AL 35203

August 25, 2020

Ms. Christine King
Director, DOE Gateway for Accelerated Innovation in Nuclear -GAIN-
Idaho National Laboratory
Idaho Falls, ID 83415

Subject: Needs related to the development and demonstration of Molten Salt Reactor Technology

Molten Salt Properties

One of the most significant challenges facing the industry is the lack of a broadly accepted, NQA1 qualified set of data characterizing various unirradiated and irradiated molten salts. Thermochemical and thermophysical properties of the salts (with and without fuel, pre- and post-irradiation, and across a wide temperature range) are necessary not only for technology developers but also for the regulatory body. Currently, a knowledge gap exists in available data and an understanding of the thermophysical, chemical, and materials properties relating to irradiated multi-component molten salt systems and reactor construction materials. Collection of historical data and establishment of new data is necessary for the design and construction of demonstration reactors, as well as licensing of future commercial MSR designs.

Ongoing experimental work occurring under the MSR National Campaign and summarized in a soon-to-be established Salt Property Database is a starting point for addressing these needs; however, this effort has not been focused on the priority needs of the industry and existing salt property characterization infrastructure within the national lab complex is insufficient to meet the needs of industry. These capabilities need to be significantly expanded in the near-term to enable demonstration of commercially competitive MSR designs.

MSRs introduce a new set of material related challenges associated with salt in contact with structural materials. In particular, the following phenomena need to be further investigated: development of tertiary creep, defect annihilation, chromium depletion mechanism, and cracking due to inward migration of fission product in alloys in contact with chlorine-based molten fuel salts. Graphite salt interaction is also an area of interest for several of the members, in particular: salt infiltration, chemical interaction with salt and fission product, irradiation stability, manufacturing process, and silicon carbide coating (effect in tritium penetration).

Progress in modern instrumentation, maintenance, and robotics for nuclear environments has been slow due to gaps in radiation-hardened electronics technology and research. Due to the harsh neutron and gamma radiation doses coupled with the elevated temperature environment, research and development for new electronics and electronic materials is essential for enabling new monitoring, control, and maintenance techniques.

Filling out the Gaps – Overall Roadmap – Melissa Rose and Kevin Robb

Materials and Advanced Manufacturing

Chemistry (Specification/purification; Thermal properties; Synthesis at tonnage scale..)

Sensor and Instrumentation

MSR Operations – in operando

Safety Demonstration and Regulation

Off-Gas Management

Waste

Irradiation

Heat Transfer System Hardware

Safeguard by Design

Transportation



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Proposed 2026 Updated Roadmap Contents

- Background
 - Summary of progress since 2020
 - Updated list of fuel salt systems of interest
- Thermal properties data collection methodologies: Experimental and computational
- Priority fluoride and chloride system components remaining to address
 - Fuel compositions
 - Fission product elements
 - Corrosion elements
 - Contamination (oxygen, moisture)
- Needs for addressing in-reactor fuel processing
- Needs for addressing corrosion processes
- Approaches to handling uncertainty in properties
- Path Forward and Challenges
- Appendix
 - Synergism among DOE programs

Priorities for MSD-TP and Determining Gaps

- Data gaps are apparent for fluorides and chlorides
 - Some end-members even require further characterization
 - A quality assessment rubric has been applied to existing data in MSD-TP
- Full systematic study of pseudo-binary systems including salt seeking FP/CPs will be unfruitful
 - Instead, we should continue to study effects of small, realistic additions
 - Ongoing studies at ANL/ORNL have already given some understanding of the effects
- Effect of insoluble noble metals or oxide impurities can also be studied
- Molecular dynamics data can support development of compositional characterization in MSD-TP
 - Some degree of experimental validation needed
 - These data also give insights into structure

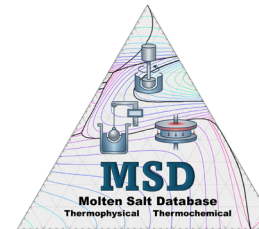


Table 5 Categories of major FPs. The soluble FPs (salt seekers) are those that are stable as halides and are expected to show some degree of solubility in the base molten salt.

Salt seekers	Noble gases	Noble metals
RE's (Nd, Ce, La, Pr)	Xe	Ru
Zr	Kr	Pd
Cs	He	Rh
Ba		Mo*
Sr		Tc*
Pu		
Cr		
Fe		
Ni		
Mo*		
Tc*		

[1] ORNL/SPR-2020/1865

[2] Nguyen et al. ACS Appl. Energy Mater. 2025, 8, 10, 6482–6491

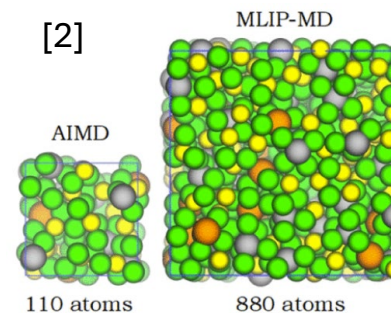
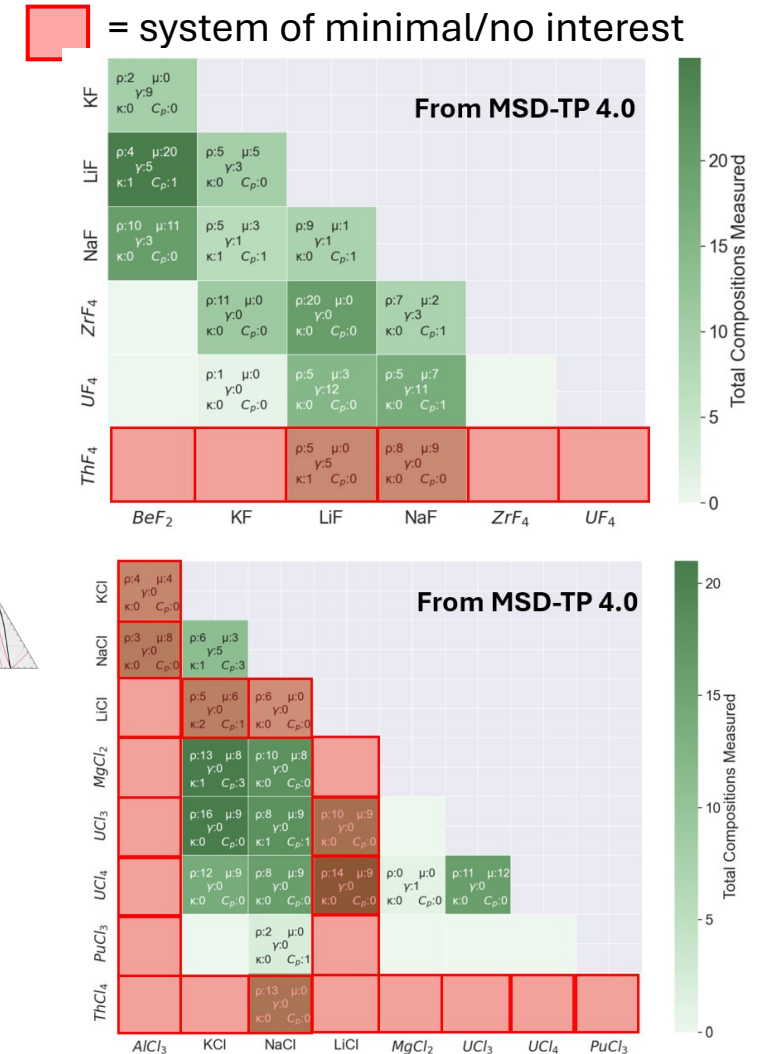


Figure 3. AIMD and MLIP-MD simulation boxes for 0.10PuCl₃. Color code: Cl (green), Na (yellow), U (gray), and Pu (orange).



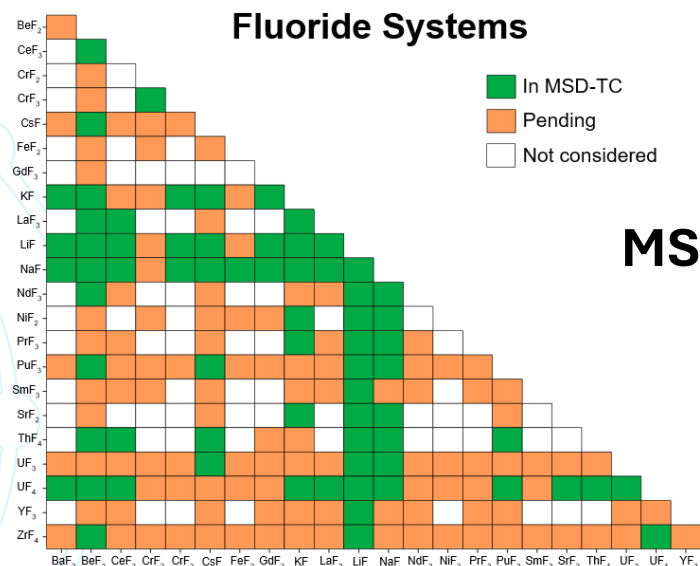
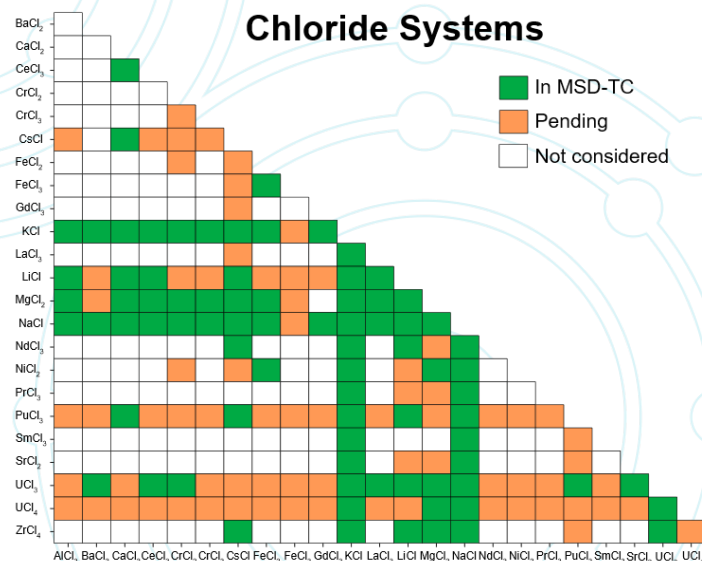
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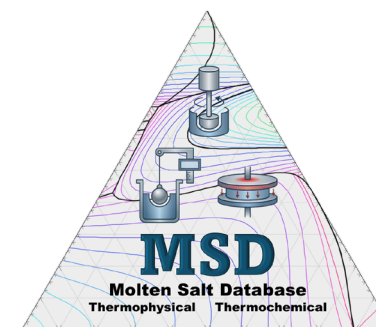
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Priorities for MSD-TC and Determining Gaps

- Chloride base salt components **NaCl, KCl, MgCl₂, and UCl₃** pseudo-binary systems with **PuCl₃**
 - Key/higher yield fission products: Zr, Nd, Ce, Sr, Cs, Ba, La, Pr, Y, Rb, Sm, Hf, Eu, Sn, Gd, Br, Cd, I
- Fluoride base salt components **LiF, NaF, KF, BeF₂, ZrF₄, and UF₄** pseudo-binary systems with **PuF₃**
 - Key/higher yield fission products: Zr, Mo, Cs, Ce, Nd, Ba, La, Sr, Te, Pr, I, Y, Sm, Rb, Nb, Sn, Eu, Cd, Se, Sb
- Common issues of
 - Corrosion products and alloy models for Cr, Ni, Fe, and Mo
 - Models for species generated with minor oxygen content
 - Models of hydrogen/tritium behavior that provide realistic speciation



MSD-TC Ver. 4.1



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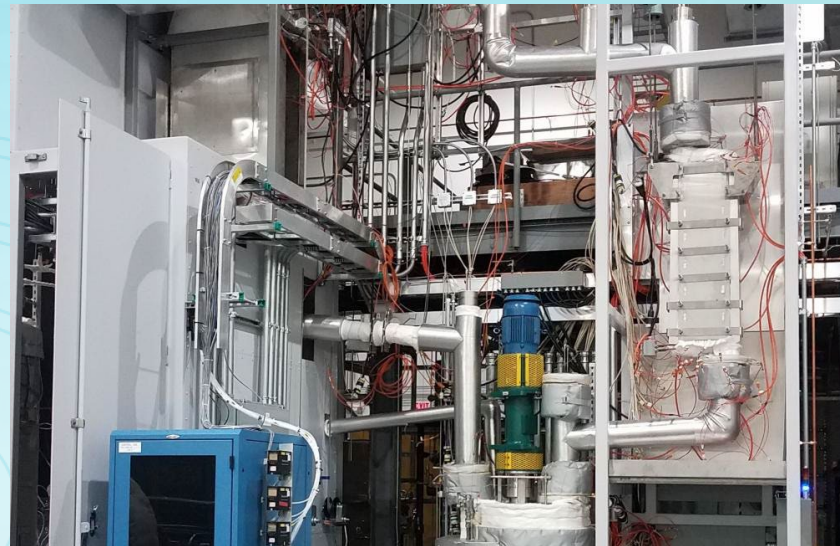
• **Uncertainty in Molten Salt Property Data**

- Large uncertainty in measured properties leads to wide design margins increasing cost
 - Minimize uncertainty by applying appropriate measurement controls
 - Quantify uncertainty inherent to measurement methods by using standard methods
- Recommendations from workshops on uncertainty in MS properties (ANL/CFCT-23/32) and fuel cycle chemistry (ANL/CFCT-23/50) will be included in the roadmap

• **Standardization of Property Measurements**

- Additional controls are required to address unique aspects of measurements of molten salts.
- A method for rotational viscosity measurements of molten salts has been prepared for standardization through ASTM-International (WK #91221)
- New standards for density by hydrostatic method and heat capacity by DSC are proposed for discussion at the June ASTM meeting.

An integrated off-gas system will be developed and demonstrated by FY30



FY26
Develop
roadmap

FY27
Construct
integrated
off-gas
system

FY28
Perform cold
testing on
salt loop

FY29
Modify
design
based on
cold tests

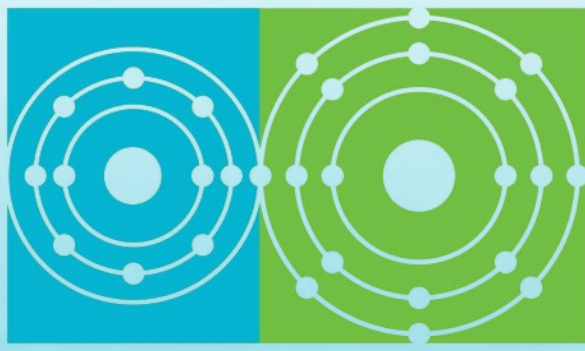
FY30
Start
radiological
tests



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MSR Program -2026 Roadmap

An update and a look forward

MSR Roadmap Goals

- Develop a technology development roadmap to facilitate near-term commercial deployment of molten salt reactors (MSRs).
- Provide a clear set of technology development tasks that will reduce the risk for private sector investment in and deployment of MSRs.
- Outline tasks to demonstrate safety adequacy to lower the regulatory and cost barriers to deployment.
- Provide mechanisms to incorporate MSR stakeholder community input.

Roadmap Topics

- Salt (*including fuel salt*)
- Materials
- Chemistry
- Reactor physics
- Salt-circuit hardware
- Sensors and instrumentation
- Off-gas management
- Modeling and simulation
- Operations and maintenance
- Safeguards and security
- Licensing and safety

Roadmap Process

- Draft topics
- Seek early industry perspective feedback (*see next slides*)
- Draft roadmap
- Collect feedback from stakeholders
- Finalize roadmap report (*living document*)

Industry Perspectives – R&D needs and technological gaps

- MSR developers are being surveyed to gather industry perspectives on short and long-term R&D needs to support the MSR industry.
- The following categories of needs are being specifically discussed:
 - Fuel chemistry and qualification
 - Materials – qualification, compatibility and lifetime
 - Safegaurds – technology, NRC acceptance and validation
 - Fuel treatment – purification, chemistry control, fuel cycle
 - Validation data (irradiation studies)

Fuel Chemistry and Qualification

An Industry Perspective

- Cross-validation of property data by multiple labs, including independent third-party labs is needed
- Specific interests in measurements of Be, Th, and Pu containing salts, as well as non-fuel bearing salt mixtures (secondary and tertiary salts)
- Emphasis that qualification will require bounding property values established by beginning and end of life salt compositions
 - Impact of corrosion products, fission products on heat transfer properties

Materials R&D Needs

An Industry Perspective

- Graphite interactions with salt, including actinide bearing salts to determine degradation mechanisms and rates of salt facing components, holdup of salts, and behavior under irradiation.
- Suggestions to utilize third party testing houses, and organizations like EPRI to spread the workload.
- Need a fast neutron facility for testing high temperature creep and fatigue under fast spectrum conditions
- Not all developers plan to only utilize ASME code qualified materials.

Safeguards R&D Needs

An Industry Perspective

- Understand limitations around obtaining representative salt samples for accounting.
- Lack of certainty around accounting method for Pu-containing fuels – will real-time quantification of Pu in liquid fuel be required?
- Must establish confidence in NDA techniques including ex-core neutron detection, electrochemistry and external to pipe flow measurements.
- Explore use of advanced robotics or automation for in-service inspection
- Characterize uncertainties in reactor physics codes and holdup quantification

Fuel Treatment R&D Needs

An Industry Perspective

- MSRs are not currently included in fuel cycle simulations
- On-site processing for fuel chemistry control should be studied
 - Adjustment of redox with buffer species (e.g. Be)
 - Removal of corrosion and environmental contaminants and particulate
 - Refueling with fresh actinide-bearing salts
 - Removal of fission products
- Some developers plan for purification and reuse of their actinide-bearing salts

Validation Data Needs

An Industry Perspective

- Concern about the ability to generate NQA-1 simulation data needed to provide NRC confidence.
- High-quality property data is needed before modeling can be completed to then undergo validation.
- Suggestion to use AI for streamlining licensing, authorization and construction planning.

Industry Perspectives

The survey is ongoing, if you are an MSR developer, or salt supplier and would like your perspective included please reach out to:

- Melissa Rose (Marose@anl.gov)
- Kevin Robb (robbkr@ornl.gov)

To schedule a time for discussion.