Molten Salt Reactor PROGRAM

Overview of the Molten Salt Reactor Program

Dr. Patricia Paviet, National Technical Director

Annual MSR Campaign Review Meeting 22-24 April 2025

PNNL-SA-210489

Accelerating Advanced Reactors Demonstration & Deployment in the U.S.

Molten Chloride Reactor Experiment (only liquid fueled design supported under ARDP – will not produce electricity) - 150 kWth

Integrated Molten Salt Reactor (molten fluoride salt reactor; 390-MWe Generation IV UF4 (LEU) fuel in a molten fluoride salt system.

IMSR
Terrestrial Energy USA

MARVEL #53
DOE | MICRO

MCRE #55
Southern Co. & TerraPower | EXPERIMENT

HERMES 2
Kairos | SMR

Two test reactors powering common turbine generator – 20 MWe – Commercialization in the 2030s, 140MWe

SMR-160
Holtec | SMR

AURORA #56
Oklo | MICRO

PROJECT PELE #54
DoD & BWXT | MICRO

2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2035

MMR
USNC & UIUC | TEST REACTOR

Xe-100
X-energy & Dow | SMR

NATRIUM
TerraPower & GE | SMR

MCFR – Small to mid-scale
TerraPower

LOTUS
NRIC | TEST BED

DOME
NRIC | TEST BED

HERMES
Kairos | TEST REACTOR

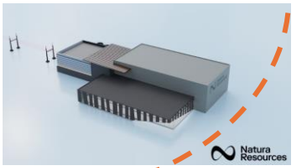
NEXT MSRR
Natura Resources & Abilene Christian University | TEST REACTOR

MSRR, Low power (up to 1 MWth, to support academic research

Kairos KP-FHR fluoride salt-cooled, TRISO pebble fueled MSR, will not produce electricity, 35 MWth

MSR-100
Natura Resources, ACU, Texas A&M, TTU, TxPWC

MSR-100, liquid fueled, fluoride salt cooled; Integrating desalination with energy production



Molten Chloride Fast Reactor (Molten Cl salt fuel serves as both the fuel and the coolant; U fuel cycle, 30-300 MWe

Kairos Power Starts Construction of Hermes Reactor

Kairos Power has started construction on one of the first advanced reactors in the United States.

July 30, 2024

wnn world nuclear news

wnn world nuclear news

& Safety · Nuclear Policies · Corporate · Urani

AIMS TO BECOME LEADER IN FIELD

search lab aims
eld

tron microreactor, is partnering with
rch and Université Paris-Saclay to
emistry which aims to be the European
uclear molten salt reactors and non-

eview for Thorizon One

nds has announced that the
r regulators are to collaborate
of its Thorizon One molten salt
eactor to streamline the pre-license applications
xpected next year.

Regulation & Safety · Wednesday, 4 September 2024

Kairos Power
30,642 followers
20h • Edited •

The Office of Nuclear Energy | U.S. Department of Energy has conditionally agreed to commit High-Assay Low-Enriched Uranium via the HALEU Availability Program for the ...more

U.S. Department of Energy Makes Conditional Commitment to Provide HALEU for Hermes Demonstration Reactor

Kairos Power

U.S. DEPARTMENT of ENERGY

wesco Innovation You Can Trust

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Terrestrial partners with EnergySolutions to suppor deployment across US

The MoU was driven by the ri interest in the SMR market, pr from data centers

December 06, 2024 By: Zachary Skidmore Hav

Terrestrial Energy, a small modular nuclear reactor (SMR) power developer, has signed a Memorandum of Understanding (MoU) with EnergySolutions to collaborate on the siting and deployment of Integrated Molten Salt Reactor (IMSR) plants at EnergySolutions-owned sites.

Denmark's Copenhagen Atomics has signed a large-scale experimental collaboration agreement with Switzerland's Paul Scherrer Institute to conduct the first critical experiment on thorium molten salt reactors in Europe.

New Nuclear · Monday, 1 July 2024

Natura Resources

NATURA MSR-100 REACTOR FACILITY

Molten Salt Reactor PROGRAM

U.S. DEPARTMENT of ENERGY
Office of Nuclear Energy

MSR Developers Status

Construction Permit Issued in December 2023 and Construction Started

Kairos Power

Hermes 1*

Construction Permit issued in September 2024

Abilene Christian University

Molten Salt Research Reactor

Construction Permit Issued in November 2024

Hermes 2*

Pre-Application Document Reviews Ongoing

TERRESTRIAL ENERGY

IMSR (Integral Molten Salt Reactor)

Other Vendors that have had Early Engagement with NRC

TerraPower

Flibe Energy

CORE POWER

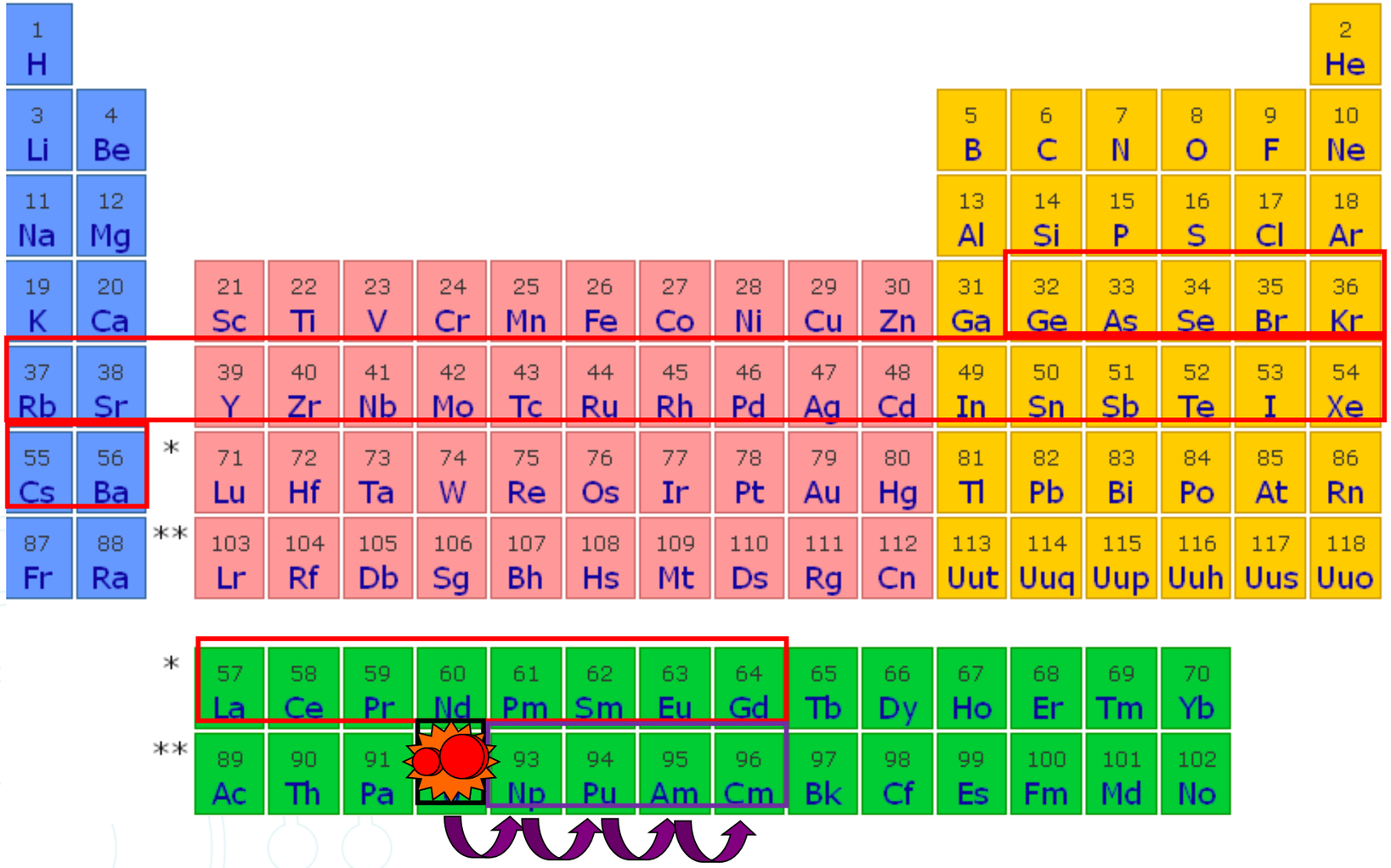
Natura Resources Sustainable Energy

*TRISO fuel

https://www.nrc.gov/reactors/new-reactors/advanced/who-were-working-with/pre-application-activities/kairos.html

Courtesy NRC

Irradiated Nuclear Fuel: Chemical Diversity



Periodic Table from : http://www.webelements.com/

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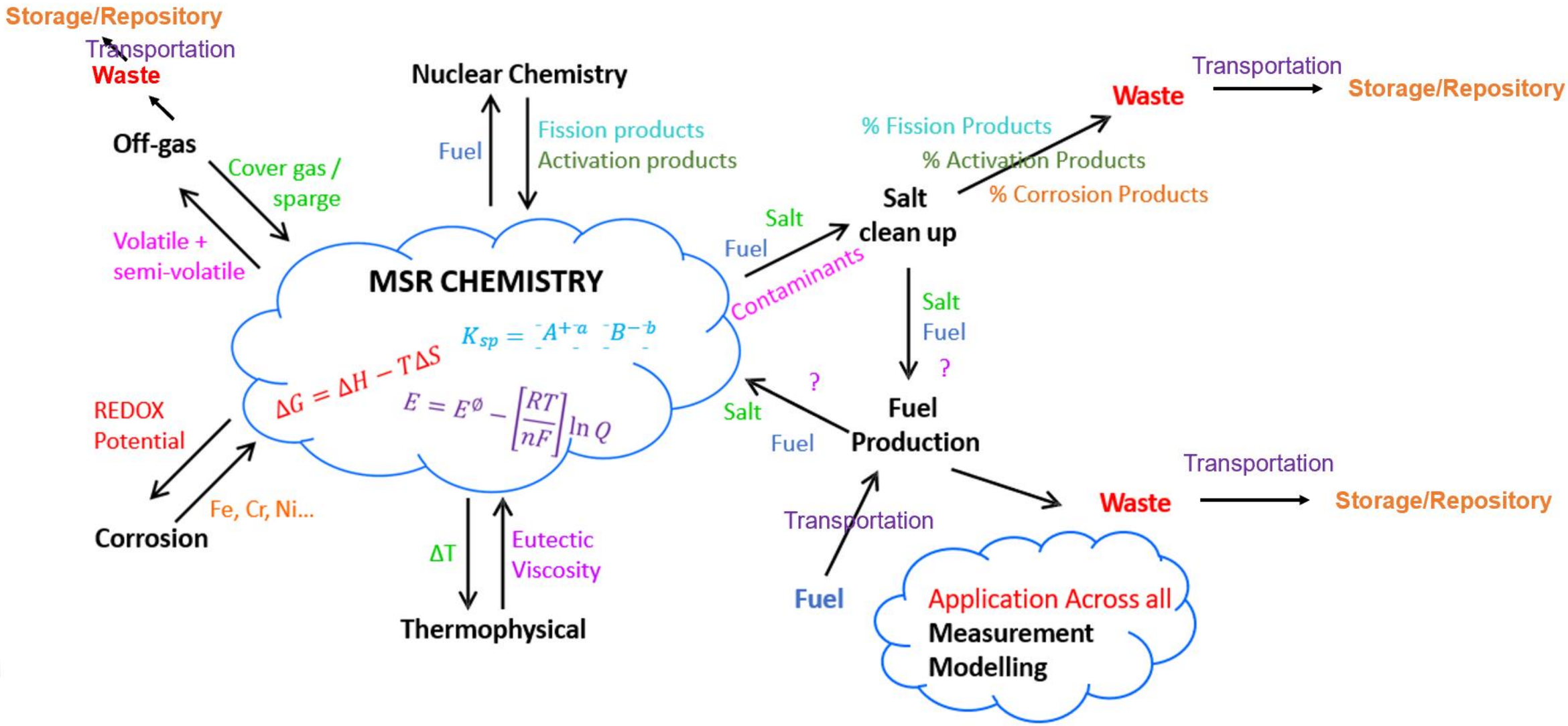
Chemistry is Everywhere in an MSR



Courtesy Mike Edmondson, NNL, UK

Challenges

Chemistry Challenges

- Gaps in thermophysical and thermochemical properties of molten salts, Actinide fluoride and chloride bearing mixtures. No irradiation studies on chloride fuel salt .

Monitoring and Chemistry Control of Molten Salts, with potential Online Purification

- Fuel Salt Processing: The online processing of liquid fuel salts to extract fission products and manage the chemistry of the salt mixture is one of the most promising aspects of MSRs. However, this area needs further investigation and demonstration to ensure reliability and efficiency.

Safety Demonstration and Regulation

- Novel Designs and Fuel Cycles: MSRs employ innovative designs and fuel cycles, necessitating thorough safety demonstrations and regulatory approval. Developing safety cases and regulatory frameworks for MSRs is a key condition for its success.

Material Challenges

- MSRs operate at high temperatures and with molten salts for which corrosion can be an issue. Finding materials that can withstand this harsh chemical environment, resist corrosion, endure high temperatures, and tolerate neutron fluxes over long periods remains a significant challenge.
- Addressing these materials challenges requires extensive research and development. This includes testing and qualifying new alloys, composites, and coatings that can meet the demanding conditions of MSR operation.

Scale-up and Commercialization

- Scaling Up Technology: Transitioning from experimental or small-scale models to full-scale commercial reactors involves significant challenges in scaling up the technology and demonstrating its economic viability at a commercial level.

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

Thermophysical and Thermochemical Properties of Molten Salts –
Experimental and Computational

TECHNOLOGY DEVELOPMENT

Off-Gas Management
Radionuclide Release Monitoring, Sensors & Instrumentation
LSTL & FASTR

NATIONAL AND INTERNATIONAL MSR SAFETY

Guidance on reasonable approaches to demonstrating safe and economic commercial prototype molten salt reactors.

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

1) MSRs can provide a substantial portion of the energy needed for the U.S. to have energy security, energy independence.
2) There is a need for an abundant energy for the foreseeable future for data centers, desalination, process heat, hydrogen production…

SALT IRRADIATION

Fuel salt irradiation and post irradiation examination capabilities
NRAD, ATR
.

MODELING & SIMULATION

NEAMS Tools & MELCOR utilized for
- Species Tracking
- Accident Scenario
- Mechanistic Source Term…

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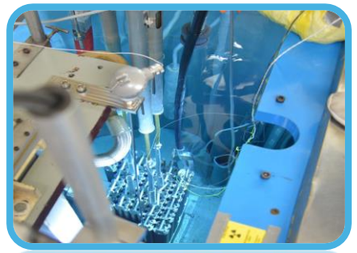
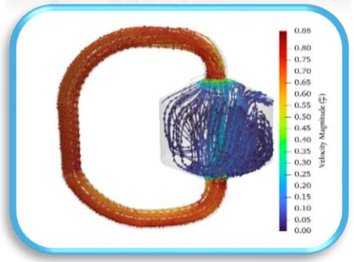
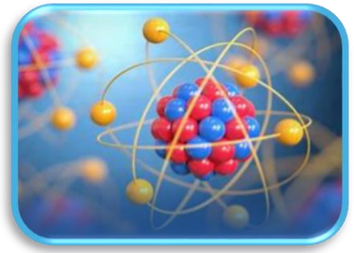
MSR RADIOISOTOPES

Developing new Technologies to separate Radioisotopes of Interest to the MSR Community.







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Goals and Charter

Identify needs short- and long-term	Gather stakeholder input Identify gaps being addressed , and assess remaining gaps Identify action and resources needed
Share information	on R&D findings and share among stakeholder Campaign review; MSR website, ORNL Annual MSR workshop
Inform and Complement	Relevant National and International Events (IAEA, NEA/OECD, GIF, Conferences, Workshops, Bootcamps…)
Input to roadmap	Develop a MSR roadmap which aligns with EPRI/NEI advanced reactor roadmap as well as ARSS and AMMT roadmaps

MSR Campaign Has Broad Objectives

SALT CHEMISTRY

Continue to develop capabilities for thermophysical properties of molten salts – Adding Vapor pressure and surface tension.
Continue development of an extensive thermal properties database (MSTDB-TP and MSTDB-TC). Workshop planned in June 2025
Data are used in multi-physics numerical codes for the simulations of the fuel salt heat and flow distribution in the reactor cavity.

RADIONUCLIDE RELEASE

Develop and demonstrate Online Monitoring technology to meet deployment process control needs . Transition Lab Scale to FASTR
Complete construction and dry shakedown of MSTTE (Molten Salt Tritium Transport Experiment) – Start - D_2/FLiNaK campaign
Complete design of engineering-scale spill test facility at ANL
Creation of a pumped actinide loop and supporting tools to enable the development and testing of molten salt reactor technologies. (loop to be installed at ANL to enable rapid installation of new components and changeover of salts)

IRRADIATION

FY24 a sodium chloride – uranium trichloride (NaCl-UCl3) salt containing enriched uranium, was irradiated in the Neutron Radiography(NRAD) Reactor at INL.
Continue post irradiation examination (PIE) 1- neutron radiograph images, 2- precision gamma scanning (PGS), 3-. Emanation of material of construction for corrosion and salt interaction, 4- Analysis of the irradiated fuel for its chemical and isotopic composition.
Lessons learned during the first irradiation to be documented and used to guide the next design of the irradiation capsule.
Preliminary design of an improved irradiation capsule for ATR irradiation planned in FY 2027

MODELING

Deliver an initial engineering framework for species transport in MSR using NEAMS tools that includes all the main physics required for this purpose: neutronics modeling with thermal-hydraulics coupling and depletion, liquid-gas phase transfer, and species deposition and leaching in structures due to molecular and galvanic mechanisms. Start collaborative work with CEA for MSR safety.
MELCOR code analyses to evaluate/inform MSR campaign mechanistic source term for critical safety functions and generalized radionuclide species transport.

RADIO-ISOTOPES

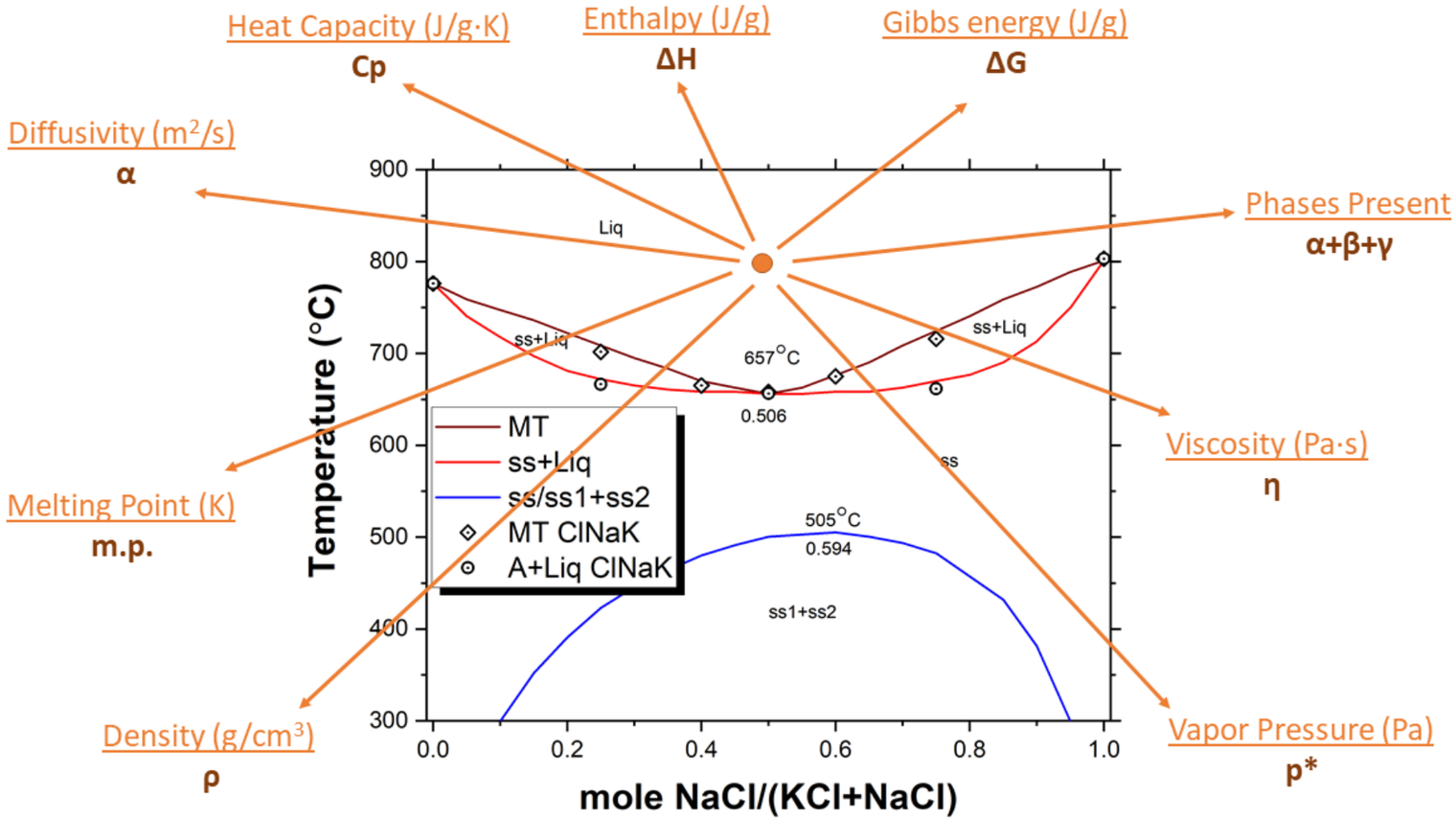
Chlorine Isotope Separations using Thermal Diffusion-
Finalizing the fabrication of the system, startup testing, production of highly enriched Cl-37 gas for use by other facilities and industrial partners.

SAFETY

Leadership on MSR safety and international cooperation in GIF MSR pSSC, GIF Safety/Safeguard activities, IAEA MSR technology, and CEA-DOE action plan on MSR Safety and development of a modern, non-proprietary evaluation model

Molten Salt Thermal Properties Determination – Experimental and Computational

- Density
- Heat Capacity
- Enthalpy of Fusion
- Viscosity
- Melting Point
- Vapor Pressure
- Thermal Conductivity
- Emissivity
- Surface Tension



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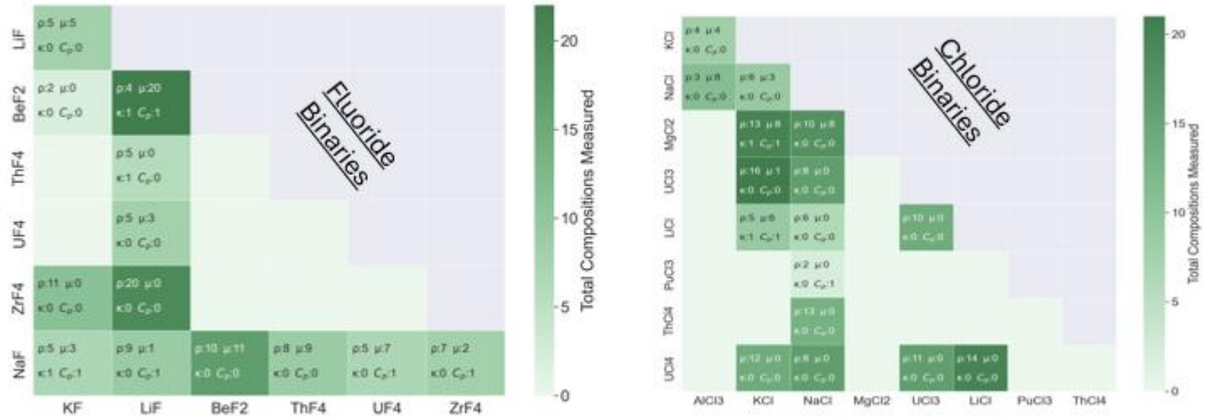
Molten Salt Thermal properties DataBase (MSTDB)

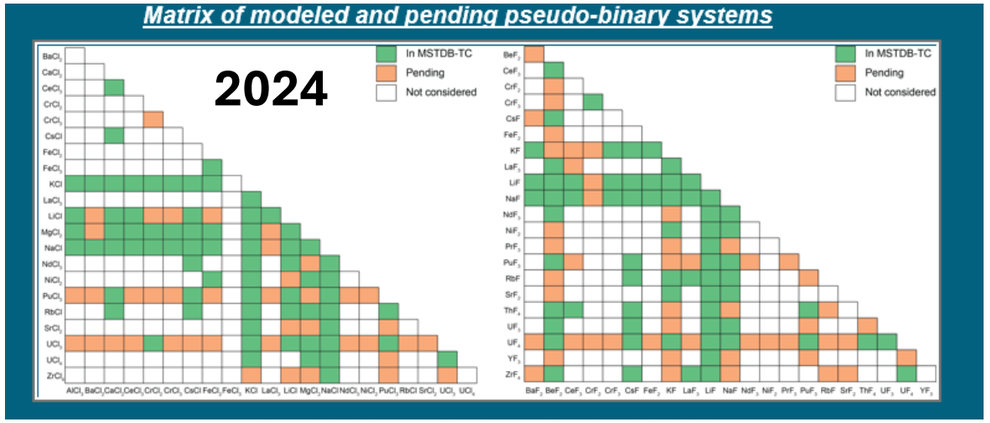
MSTDB-TP is managed by ORNL

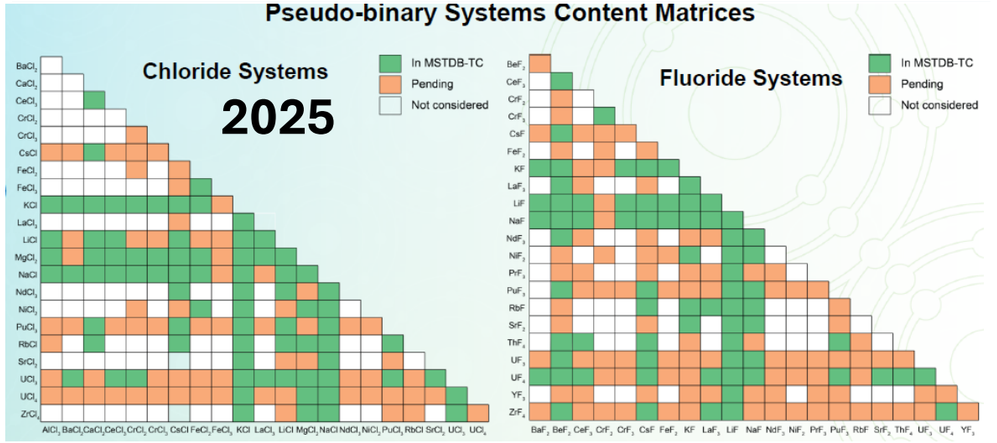
- MSTDB-TP contains empirical relations for the following properties:
  - Melting and boiling points; Density; Viscosity; Heat Capacity7; Thermal Conductivity
- As per the current version release (**3.1**) There are **820 entries (FEB 2025)** including:
  - 33 pure compounds
  - 380 pseudo-binaries
  - 395 pseudo-ternaries
  - 12 pseudo-quaternaries
- Each property entry in the database includes a margin of experimental error
  - This list is constantly expanding. The data is based on the outputs of 180+ independent experimental studies in literature.



ORNL/TM-2024/3575

MSTDB-TC is managed by U. of South Carolina



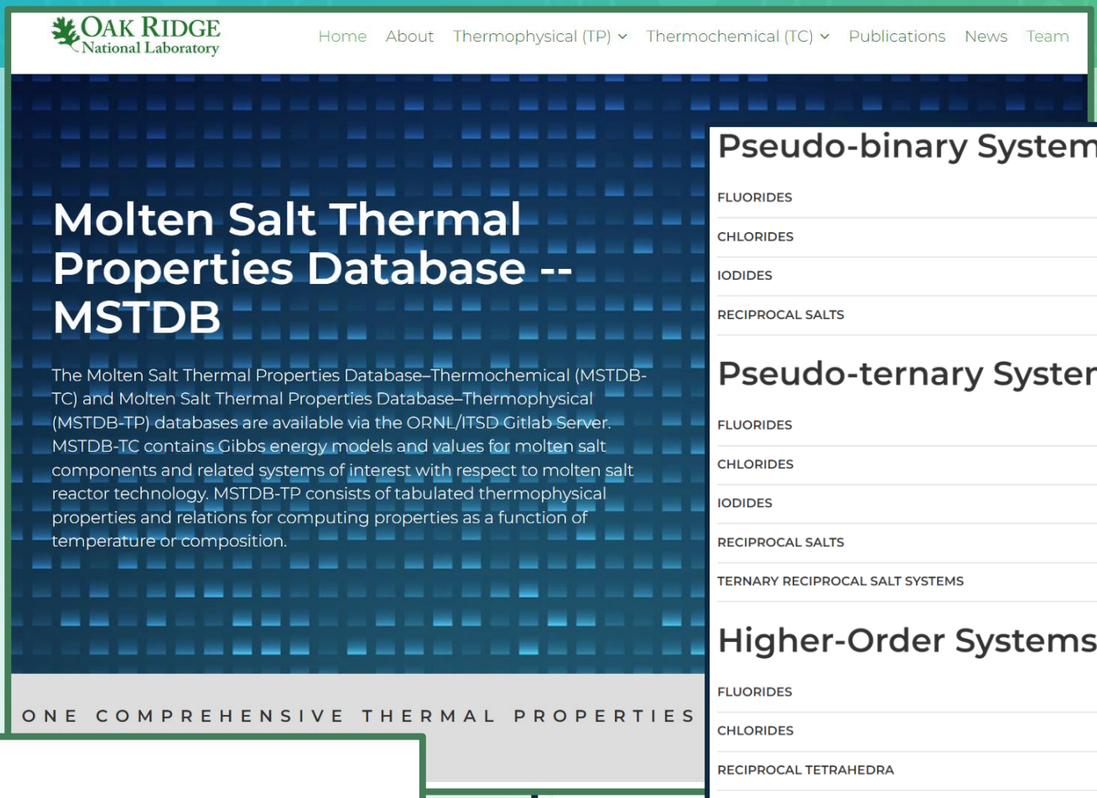


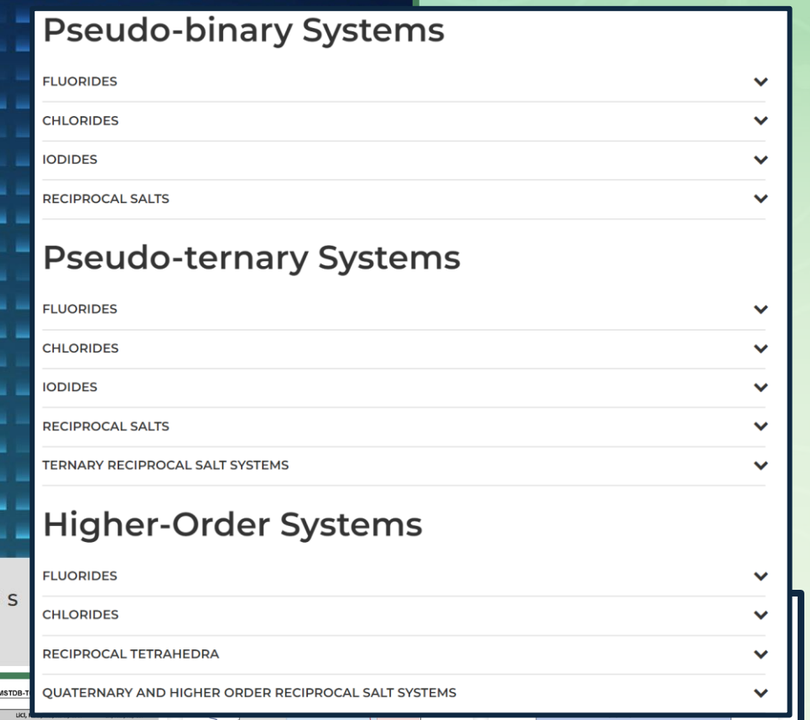
Recent release of the Molten Salt Thermal Properties Database-Thermochemical (MSTDB-TC) Ver. 4.0.

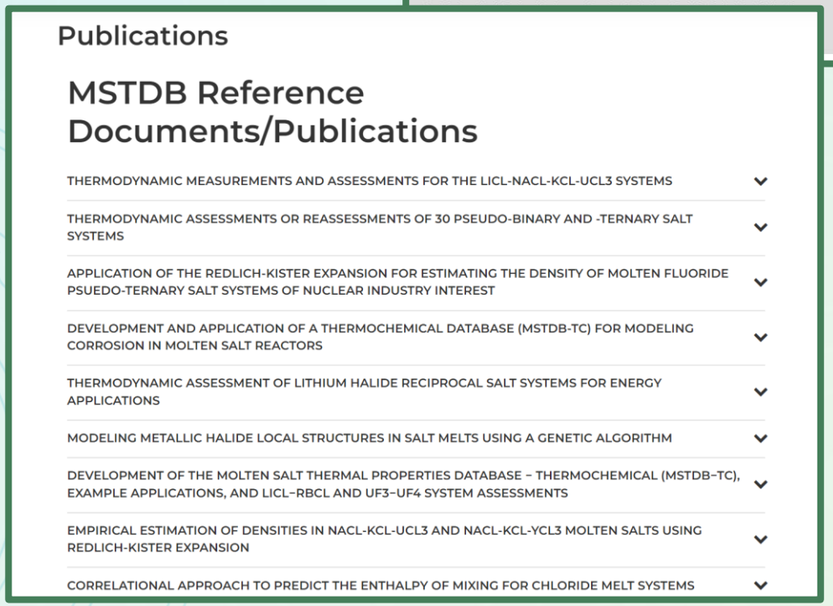
MSTDB Website

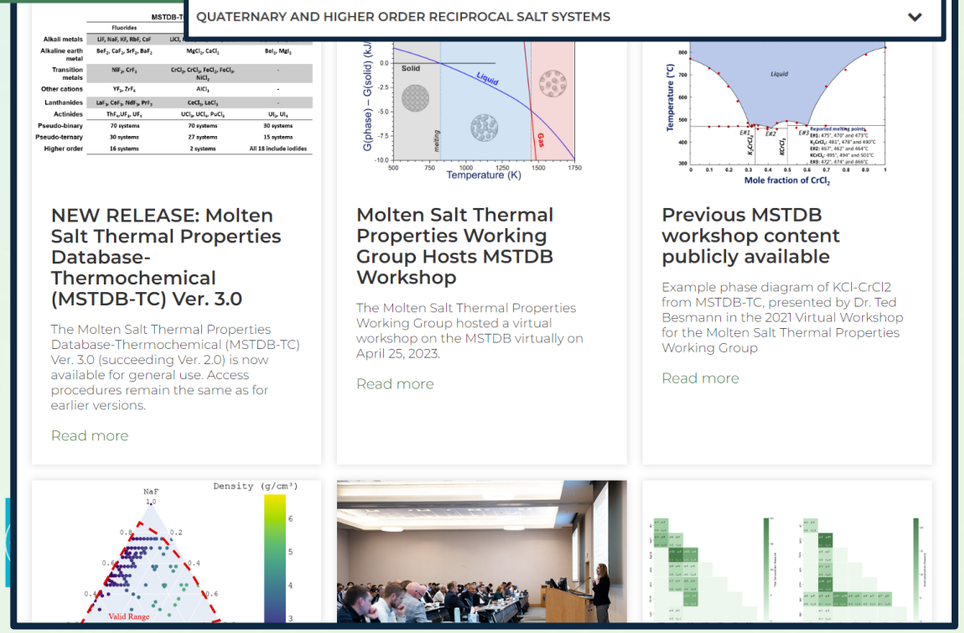
- New website to capture both MSTDB-TP and TC
  - Contains info about both arms
- Access links and instructions
- Recent News
- List of Publications and Workshop documents
- Contacts

Available @ https://mstdb.ornl.gov





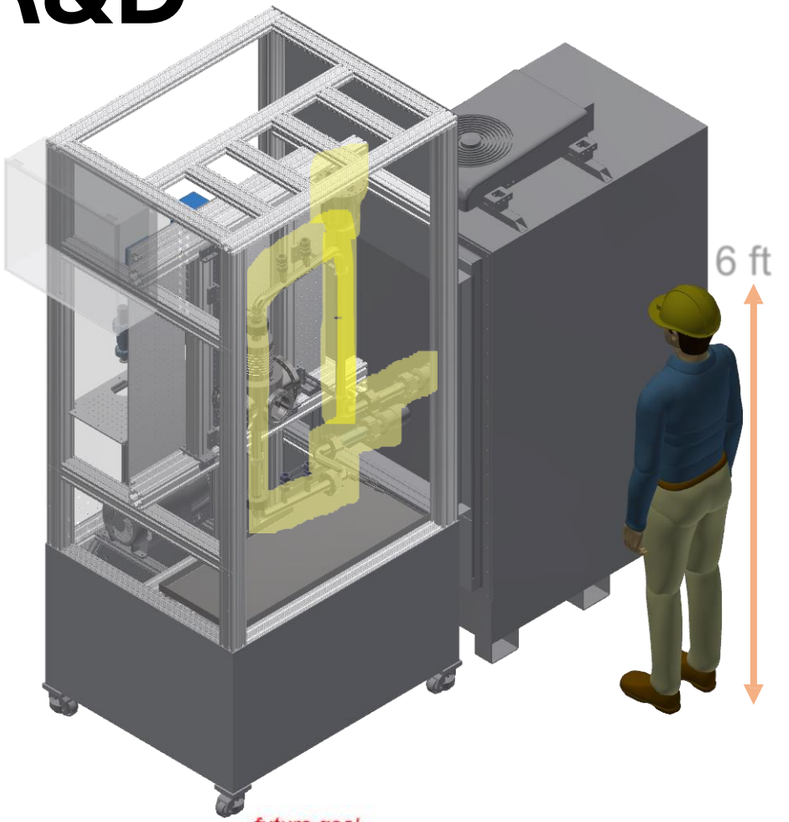




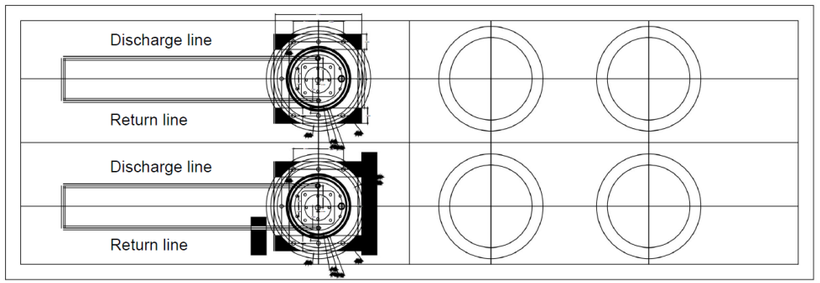
Salt Loops supporting MSR R&D

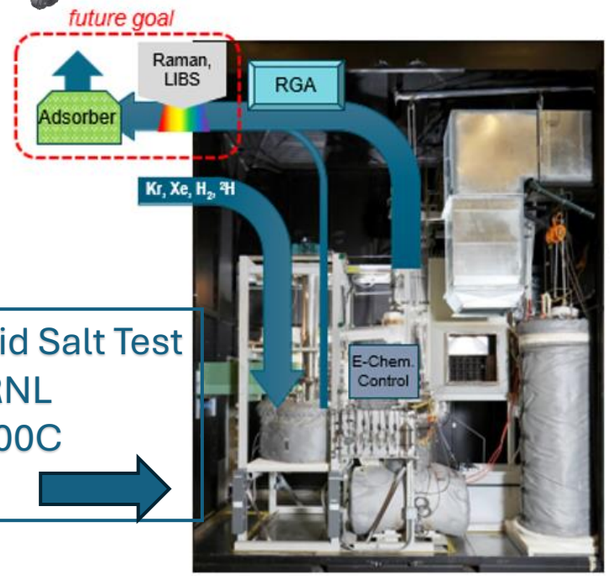
FASTR -Facility to Alleviate Salt Technology Risks – ORNL
NaCl-KCl-MgCl2
725C
154L

MSTTE – Molten Salt Tritium Transport at INL
FY 2025 Deuterium- FLiNaK salt



Actinide Salt Loop at ANL





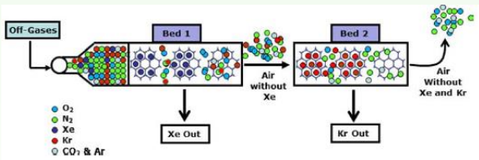
LSTL - Liquid Salt Test Loop at ORNL
FLiNaK – 700C
80L

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

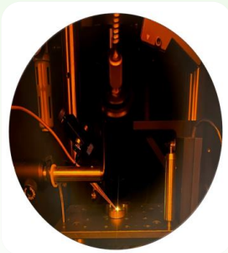


Radionuclide Identification/Speciation

Raman Spectroscopy

405 nm 532 nm 671nm

Laser Induced Breakdown Spectroscopy



Gas/Liquid Interface

Bubble Measurement

Source Term Modeling

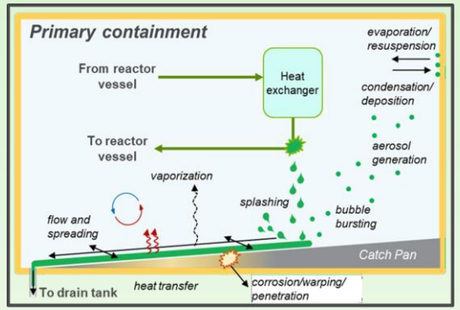
Bulk Gas	Gas Film	Liquid Film	Bulk Liquid
p_i pressure	p_i^*	c_i^*	c_i concentration

$$c_i^* = p_i H$$

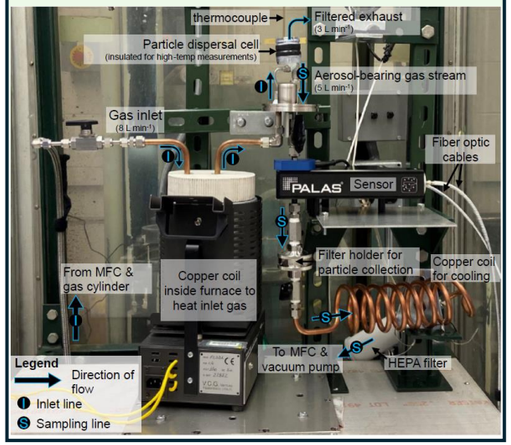
$$p_i^* = c_i / H$$

Spill Test

Engineering Scale Salt Accident Analysis Facility

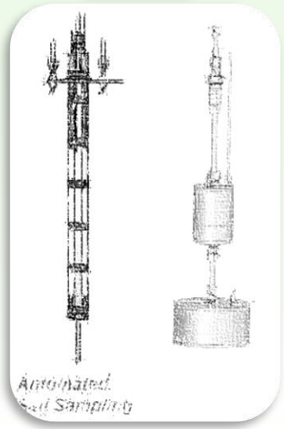


Salt Aerosol Concentration and Size Measurements



Sensors/Salt Chemistry

Salt Composition
Redox
Salt Level



Argonne NATIONAL LABORATORY · INL Idaho National Laboratory · Los Alamos NATIONAL LABORATORY · OAK RIDGE National Laboratory · Pacific Northwest NATIONAL LABORATORY

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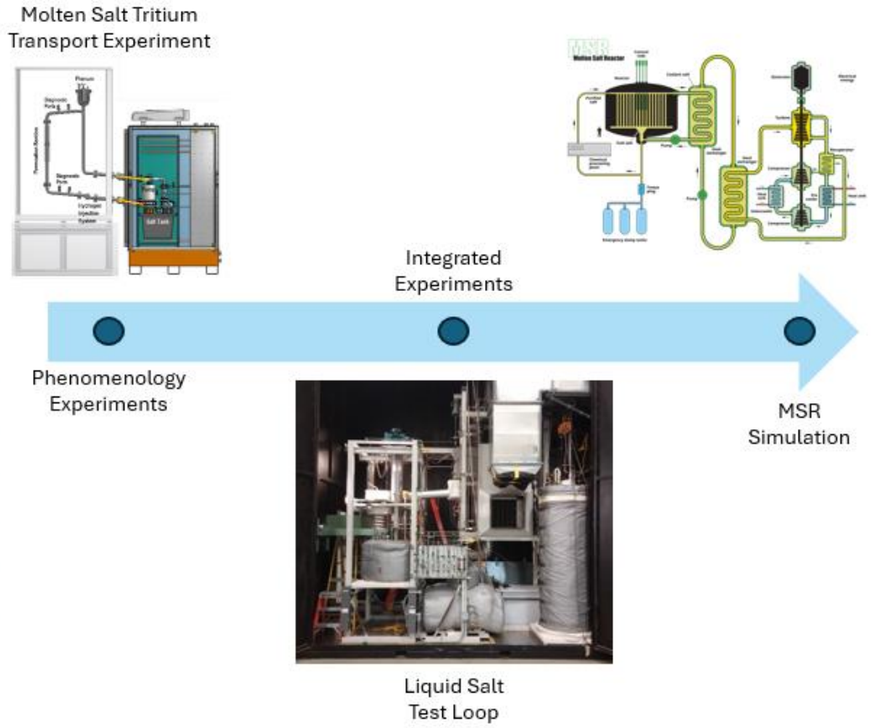
Modeling and Simulation

MELCOR: nuclear accident simulation code at SNL

Significant strides within the last few years to increase model accuracy for molten salt reactors (MSRs). It is the primary code developed for the

- Assessment and evaluation of safety for a broad range of reactor concepts, notably including MSRs.
- MSR model development has been focusing on improving chemistry and fission product transport mechanisms
- Working with MSR campaign to fill knowledge gaps

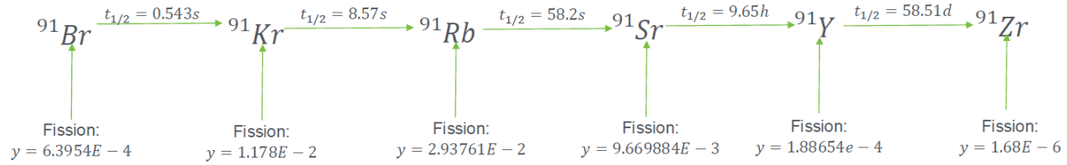


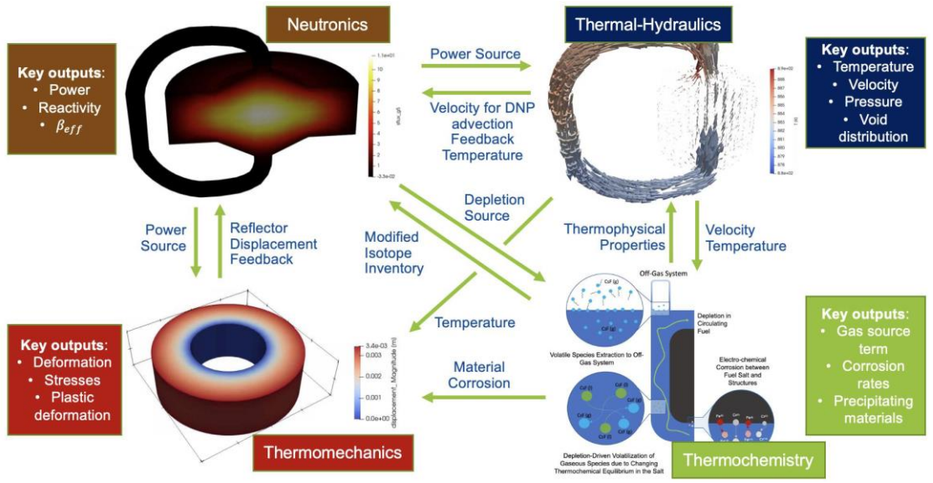
NEAMS Tools at INL

Coupling between:

- Neutronics (multi-fidelity + spatial depletion),
- Thermal-Hydraulics (coarse-mesh CFD),
- Thermomechanics (thermo-elasto-plasticity with irradiation and thermal swelling and creep),
- Thermochemistry (speciation, mass accountancy, and corrosion)

- Species tracking in MSRs
  - Tracking the depletion chain of ^{91}Br





Molten-salt Research Temperature-controlled Irradiation (MRTI) Experiment Overview & Goals (INL)

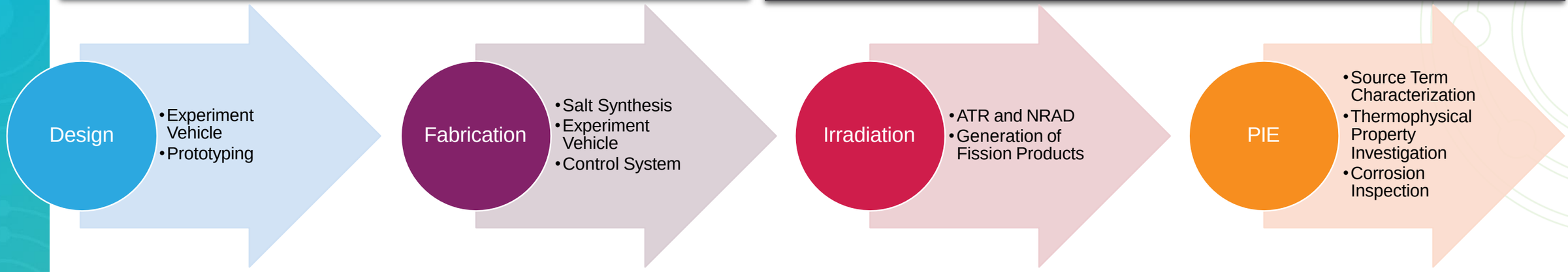
Establishment of a domestic neutron irradiation capability for fissile material-bearing salts at INL for Molten Salt Reactor (MSR) R&D.

Executing Research in Three Primary Areas

1. Radioactive Source Term Quantification
2. Thermophysical Property Evolution
3. Salt-facing Materials Corrosion

Mission Realization

Utilize the Neutron Radiography Reactor (NRAD) to irradiate molten fissile material-bearing chloride salt with salt-facing materials relevant to MSR development



Increased interest and request for fuel salt irradiations and PIE from international vendors and several DOE programs. – Planning for next FYs at ATR and NRAD with MSR, AMMT, ARSS programs as well as NNSA – Off gas analysis to be performed at PNNL

Idaho National Laboratory

Molten Salt Reactor PROGRAM

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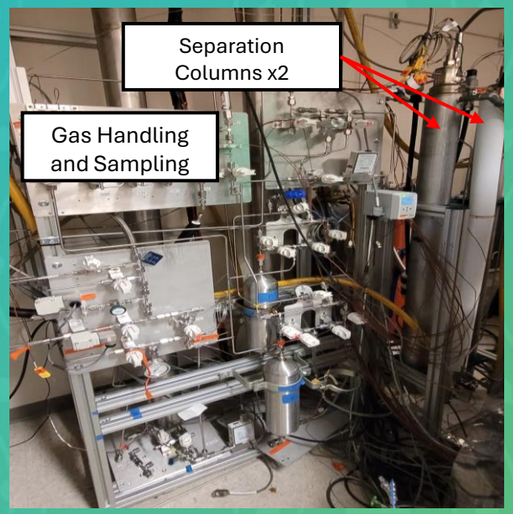
Courtesy Abdalla Jaoude and Toni Karlsson, INL

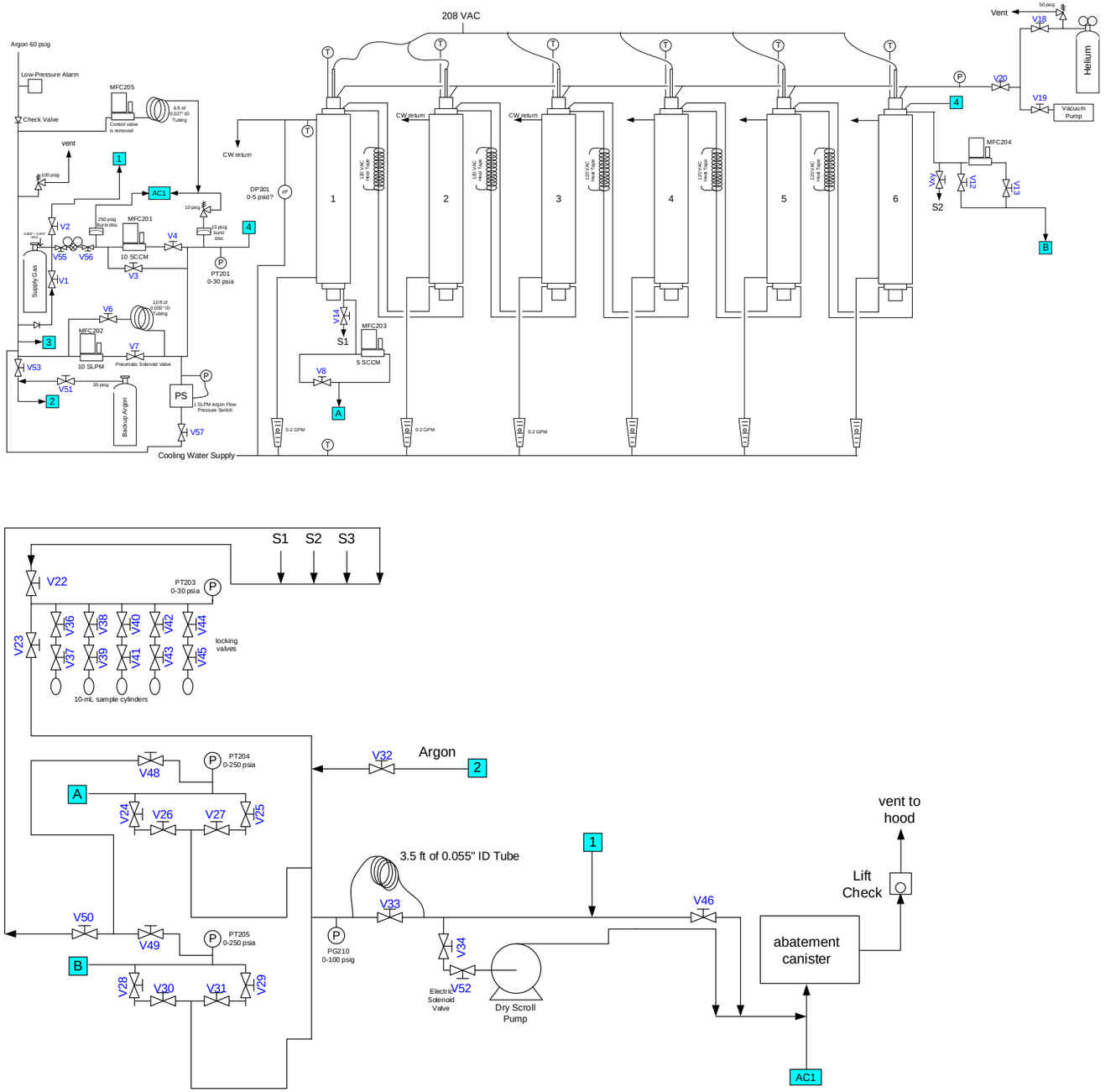
Chlorine Isotope Separation System for Chloride MSR

- Thermal diffusion isotope separation system for enrichment of ^{37}Cl.
- 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 which will complicate waste form and final disposal
- Neutron irradiation of ^{35}Cl (n, p) ^{35}S - ^{35}S is more corrosive than Fe, Cr, Ni



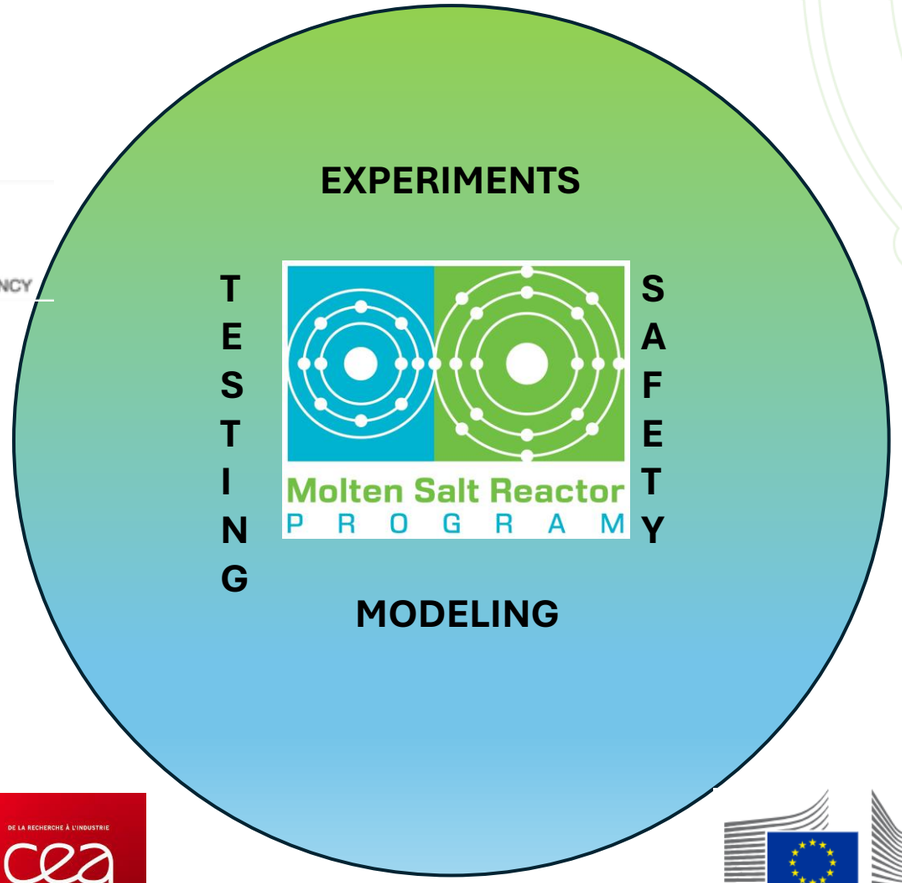


HCl Columns Flow diagram

Courtesy B. McNamara, PNNL

International Engagement

GIF MSR pSSC
13-15 MAY 2025 at Abilene Christian University, TX



CREAMM: CRitical EvAluation of fuel Management during and after MSR Operation - Kick off meeting on 13 FEB 2025; in-person meeting on 28-30 APR 2025 in Paris

Joint IAEA–GIF Workshop on the Safety of Non-Water Cooled Reactors 30 JUN-04 JUL 2025

IAEA Workshop - Molten Salt Reactors Fuels: Recent Development and Future Challenges 21-25 JUL 2025

IAEA/NEA/EC-JRC joint workshop on Molten Salt Reactor (MSR) fuel cycle taxonomy and related terminology which will take place between 3-7 NOV 2025 at the IAEA, Vienna, Austria

DOE/CEA Action Plan Safety of MSR

Molten Salt Reactor: Putting Science into Standards March 2024

MSR Campaign Website:

https://gain.inl.gov/doe-molten-salt-reactor-program/

The breadth of the MSR design space presents a substantial challenge to the completeness and broad applicability of any technology development planning activity. Dozens of design concepts are currently in some state of development, nearly all have been introduced in the past decade, and it is not currently possible to reasonably evaluate which designs will eventually be successful. Nevertheless, MSRs have common characteristics and many technology development issues are broadly applicable to most MSRs

MSR Annual Campaign Review

- April 22-24, 2025
- April 16-18, 2024
- May 2-4, 2023
- April 26-27, 2022
- June 17, 2021

MSR Course

Contacts

Federal Manager (Acting)

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Announcements

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Molten Salt Reactor Reports

CHEMISTRY

Search

Title	Link	Report Number	Year	# of Pages
Synthesis and Thermophysical Property Determination of NaCl-PuCl3 Salts	Link	INL/RPT-22-69181	2022	34
Engineering-Scale Batch Purification of Ternary MgCl2-KCl-NaCl Salt Using Thermal and Magnesium Contact Treatment	Link	ORNL/TM-2022/2554	2022	31
An Overview of the Molten Salt Thermal Properties Database□Thermophysical, Version 2.1.1 (MSTDB-TP v.2.1.1)	Link	ORNL/TM-2023/2955	2023	25
FY23 Progress Report on Viscosity and Thermal Conductivity Measurements of Molten Salts	Link	ORNL/TM-2023/3048	2023	31
Experimental Plan for Synthesis of an Americium- and Plutonium-Containing Salt	Link	INL/RPT-24-80052	2024	18

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Thank you
Teresa Krynicki, INL

2025 Molten Salts Thermal Properties Working Group Virtual Workshop - *Effect of Oxygen, Hydrogen, and Moisture on Molten Salt Behavior*

10AM to 3PM EDT, 3-4 JUN, 2025 – Information and Link at MSTDB.ornl.gov

Save the date
Annual MSR Workshop, Knoxville, TN - 18-20 NOV 2025

Next MSR Campaign Review in New Mexico, hosted by LANL and SNL – April 2026

GIF WEBINARS : https://www.gen-4.org/resources/webinars

Webinar #9 https://www.gen-4.org/resources/webinars/education-and-training-series-9-molten-salt-reactors-msr
Webinar #8 https://www.gen-4.org/resources/webinars/education-and-training-series-8-fluoride-salt-cooled-high-temperature-reactors
Webinar #35 https://www.gen-4.org/resources/webinars/education-and-training-series-35-czech-experimental-program-msr-technology
Webinar #42 https://www.gen-4.org/resources/webinars/education-and-training-series-42-comparison-16-reactors-neutronic-performance
Webinar #44 https://www.gen-4.org/resources/webinars/education-and-training-series-44-molten-salt-reactor-safety-evaluation-us
Webinar #73 https://www.gen-4.org/resources/webinars/education-and-training-series-73-molten-salt-reactors-taxonomy-and-fuel-cycle
Webinar #88 https://www.gen-4.org/resources/webinars/education-and-training-series-88-multiphysics-depletion-chemical-analyses-molten
Webinar #97 https://www.gen-4.org/resources/webinars/education-and-training-series-97-overview-and-update-msr-activities-within-gif

Molten Salt Reactor PROGRAM

U.S. DEPARTMENT of ENERGY
Office of Nuclear Energy

Thank You

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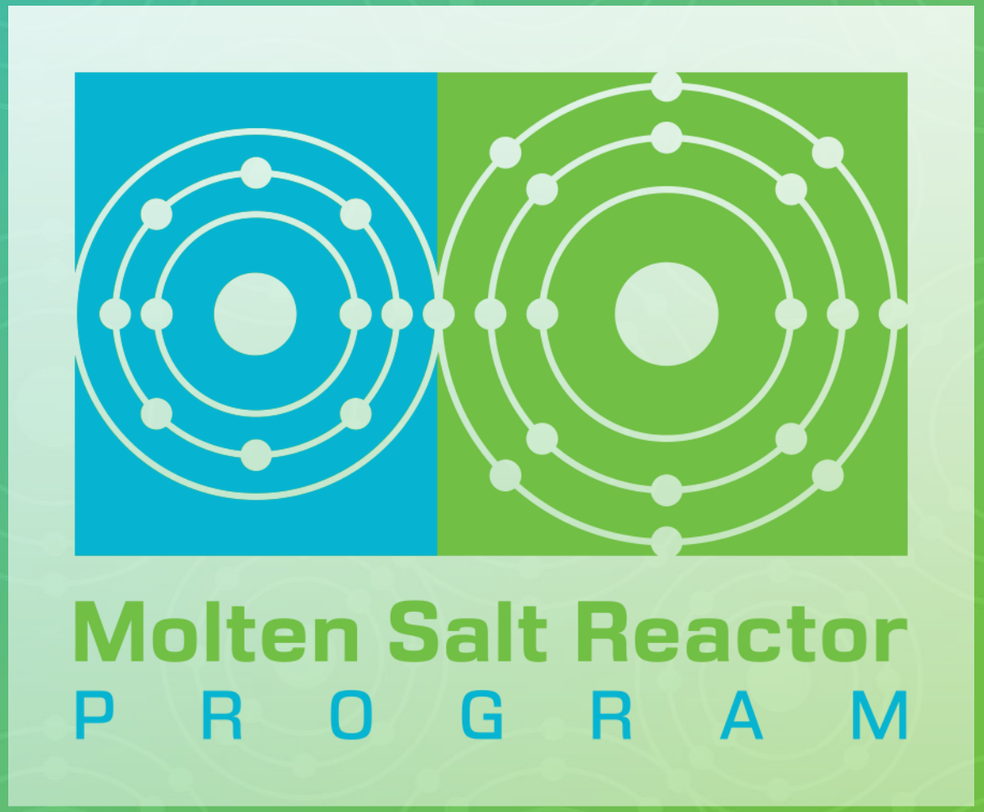

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