INL/CON-22-69122-Revision-0

Molten Salt Reactors: Materials Challenges

September 2022

Changing the World's Energy Future

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Idaho National Laboratory

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Distinguished Research Scientist

Molten Salt Reactors

Materials Challenges

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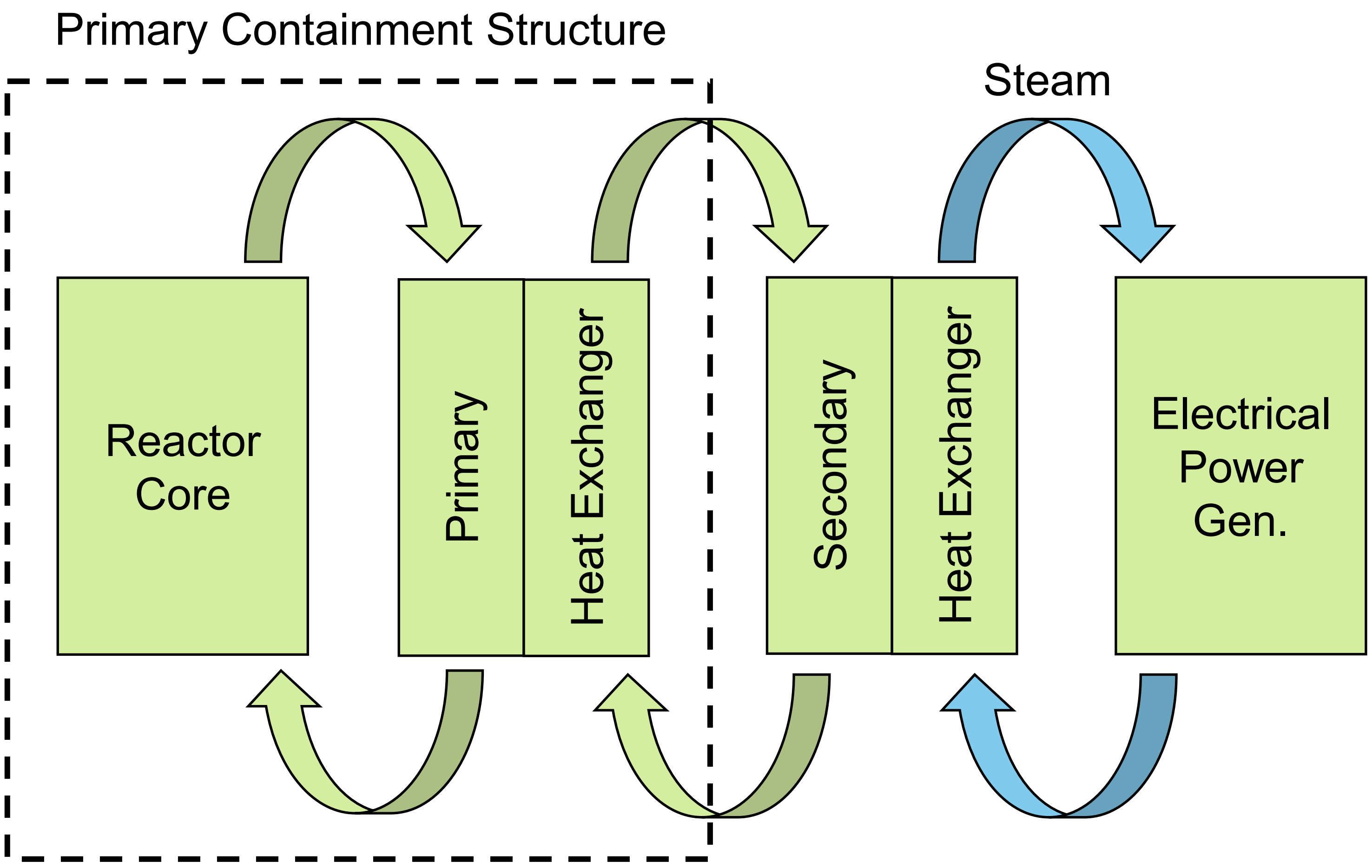
Molten Salt Reactor History

- Aircraft Reactor Experiment, November 2-12, 1954
- Molten Salt Reactor Experiment, June 1, 1965, to December 12, 1969

- Terrestrial Energy
- TerraPower
- Southern Company
- Seaborg
- Flibe Energy
- Moltex Energy
- ThorCon

Nuclear Reactors



- Primary Coolants
  - Water
  - Heavy Water
  - Gas
    - Air
    - He
    - CO_2
  - Liquid Metal
    - Pb & PbBi
    - Na & NaK
  - Molten Salt

Comparison: Salt, Sodium, Water

	ORNL Single-Fluid MSBR	Orano Super-Phenix	Westinghouse AP1000
Reactor Type	MSBR	SFBR	PWR
Status	Conceptual	Decommissioned	Operating
Thermal Power, MWt	2,250	3,000	3,415
Electrical Power, MWe	1,000	1,200	1,117
Power Efficiency, %	44.4	40.0	32.7
Liquid Coolant	Molten Fluoride Salt	Sodium	Pressurized Water
Liquid Coolant Inventory, MT	160	3,500	178
Fuel Type	Molten Fluoride Salt	Mixed Oxide	Uranium Oxide
Breeder Fuel Cycle	$^{232}Th/^{233}U$	$^{238}U/^{239}Pu$	-
Neutron Spectrum	Thermal	Fast	Thermal

References:

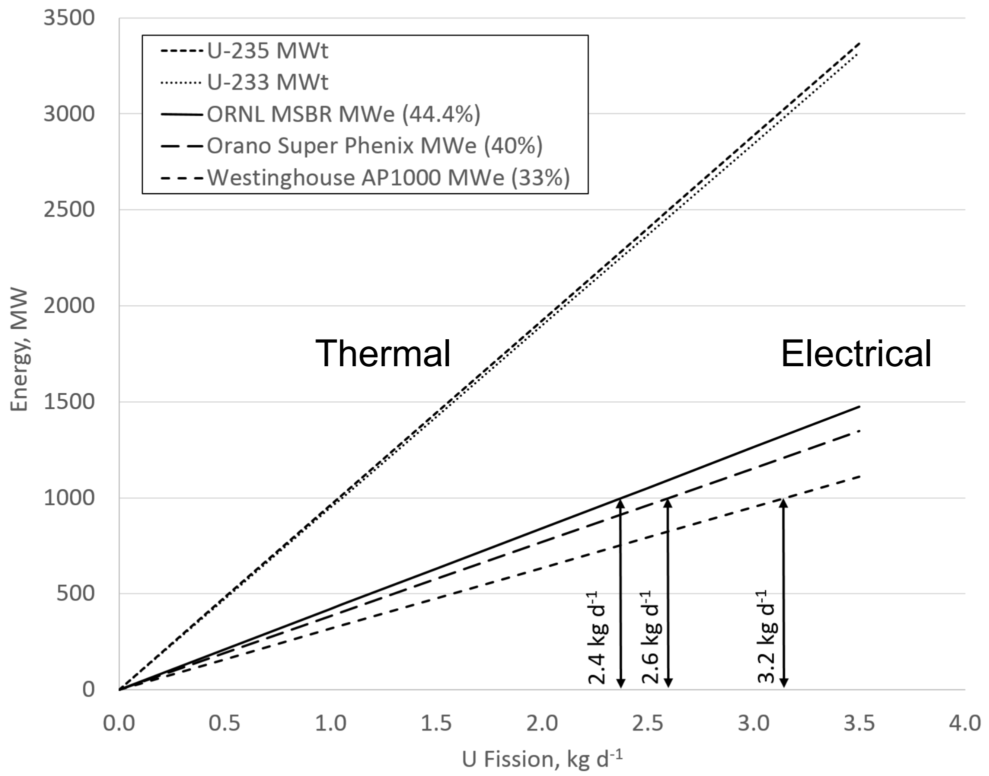
- Conceptual Design Study of a Single-Fluid Molten-Salt Breeder Reactor, ORNL-4541, Jun 1971
- Liquid Metal Cooled Reactors: Experience in Design and Operation, IAEA-TECDOC-1569, Dec 2007
- The Westinghouse AP1000 Advanced Nuclear Plant: Plant Description, Westinghouse, 2003

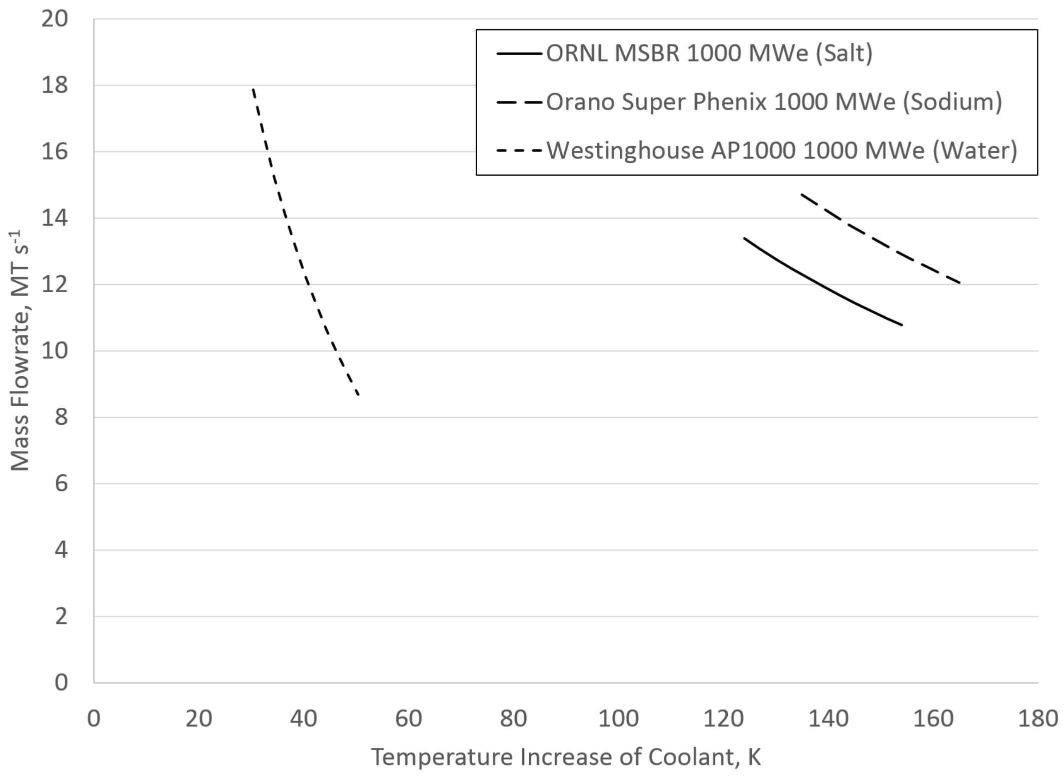
Comparison: Salt, Sodium, Water

	ORNL Single-Fluid MSBR	Orano Super-Phenix	Westinghouse AP1000
Liquid Coolant	Molten Fluoride Salt	Sodium	Pressurized Water
Liquid Coolant Inventory, MT	160	3,500	178
Inlet Temperature, °C	566	395	281
Outlet Temperature, °C	705	545	321
Increase in Temperature, °C	139	150	40
Heat Capacity, J g^{-1} K^{-1}	1.357	1.258	6.137
Density, kg L^{-1}	3.281	0.811	0.917

Takeaways: The MSBR operates at the highest temperature.
Water has the highest heat capacity.
Salt has the highest density.

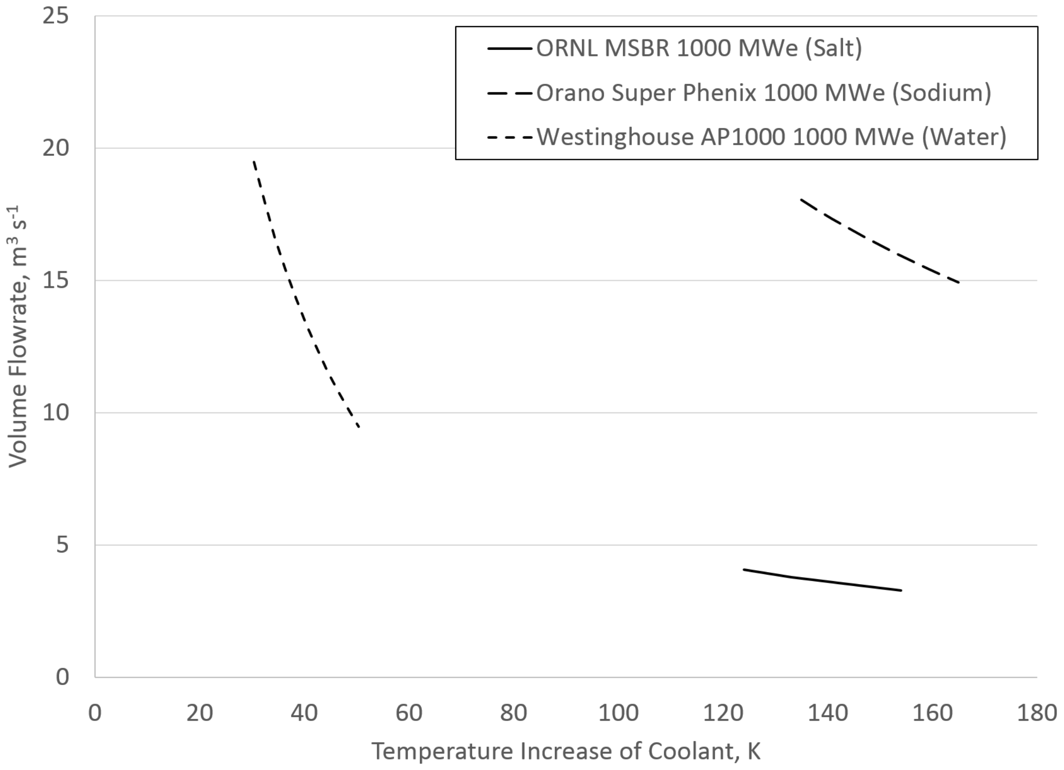
Comparison: Salt, Sodium, Water

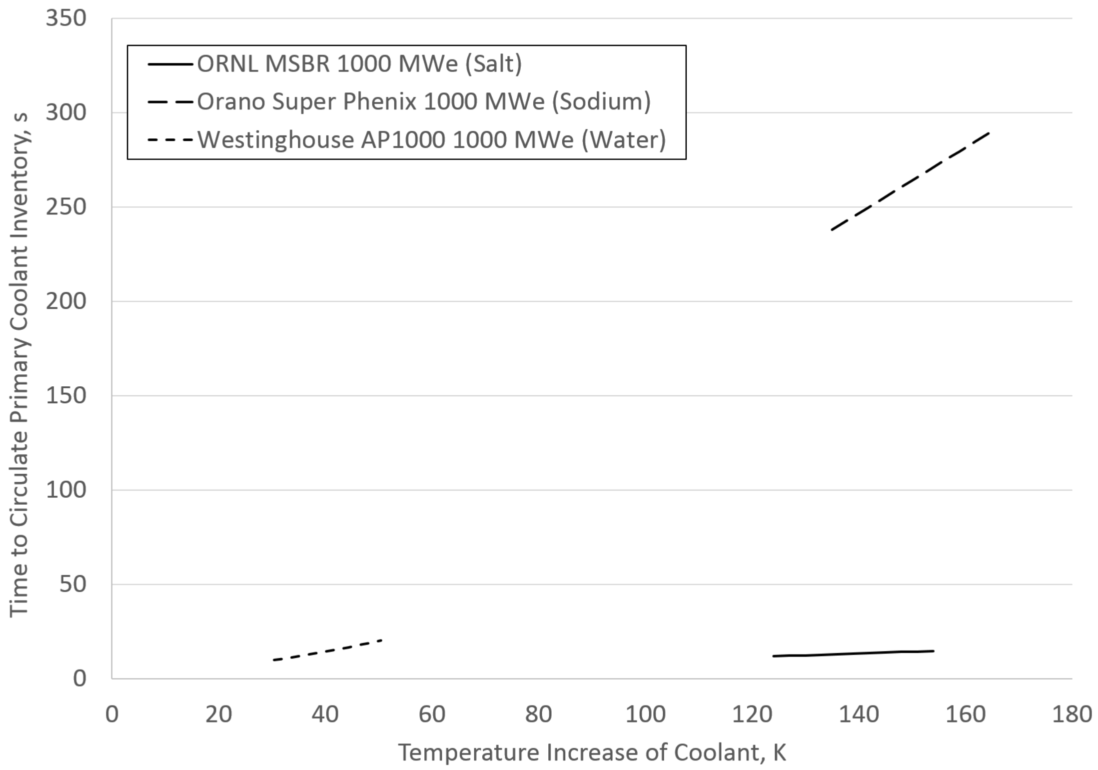




Takeaways: 1 kg d^{-1} fission is approximately 1000 MW thermal.
The mass flowrates of salt, sodium, and water are similar.

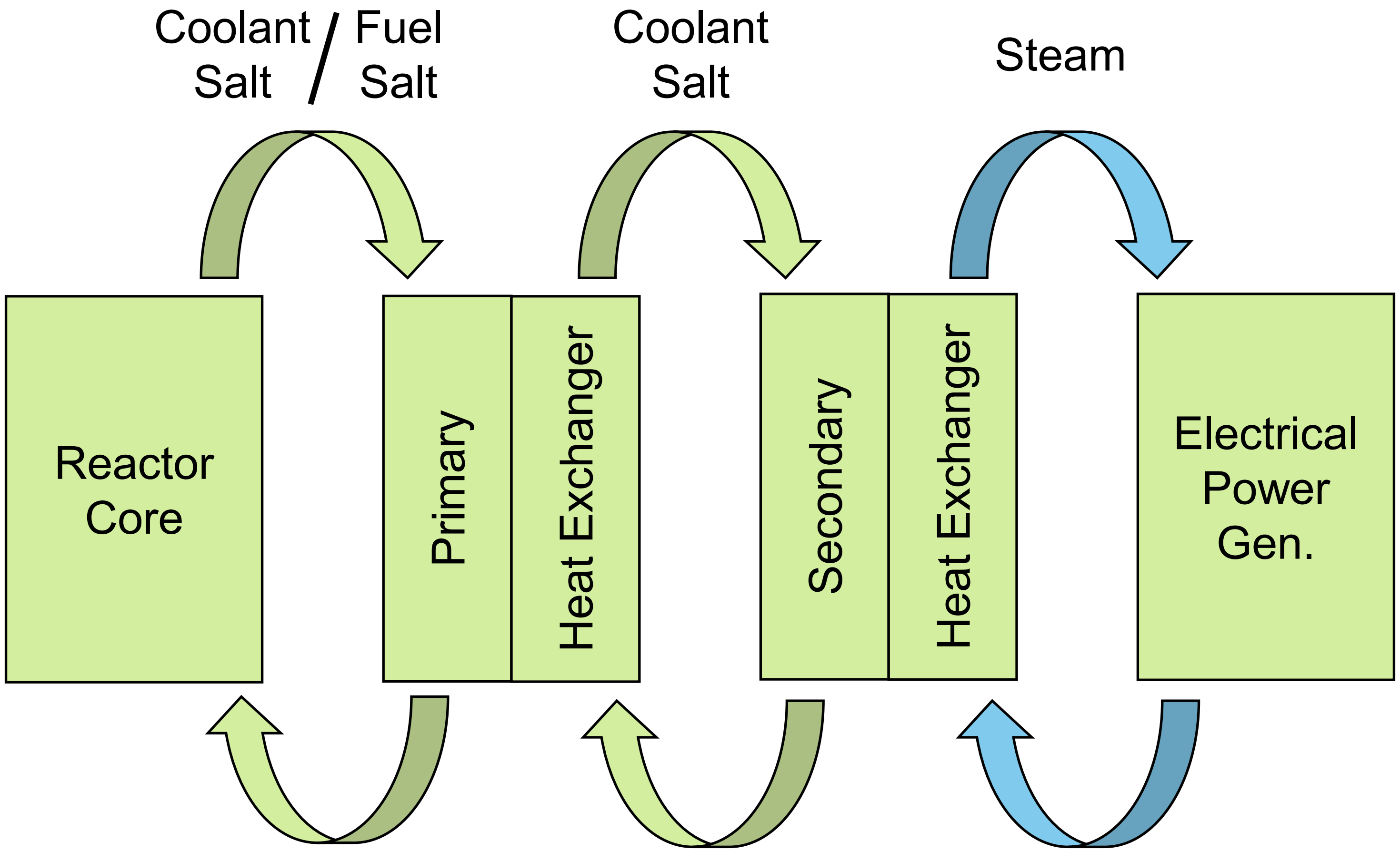
Comparison: Salt, Sodium, Water





Takeaways: The volume flowrate of salt is the lowest because its density is the highest.
The cycle times of salt and water are similar.
The SFBR has a large inventory of coolant sodium (pool-type reactor).

Molten Salt Reactors



Takeaway: There are three categories of salt.
Primary coolant with fuel, primary coolant without fuel, and secondary coolant.

Properties of Molten Salts: Part 1

- Selection of the Molten Salt System
  - Halide Salt Systems: Fluorides and Chlorides
  - Neutronics
  - Phase Equilibrium
  - Actinide and Fission Product Solubility
  - Chemical Compatibility with Materials of Construction
- Salt Synthesis and Purification
  - Fluorination
  - Chlorination
  - Nuclear Reactor Grade = High Purity

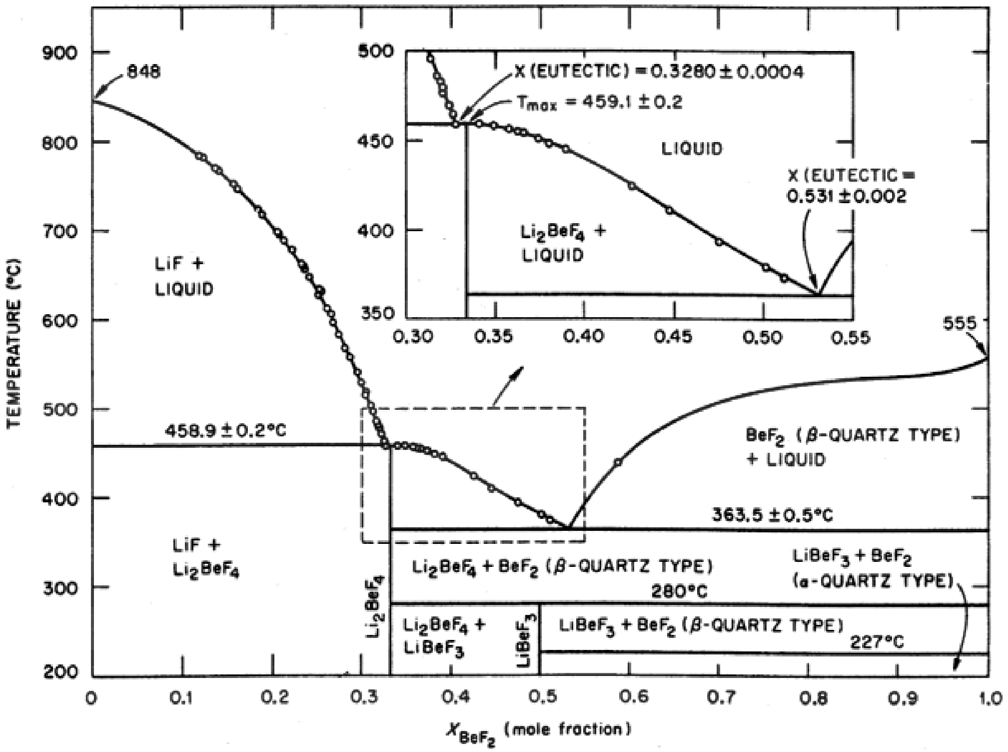
Examples: Isotopics

- Some isotopes interfere with neutronics and produce undesirable byproducts.

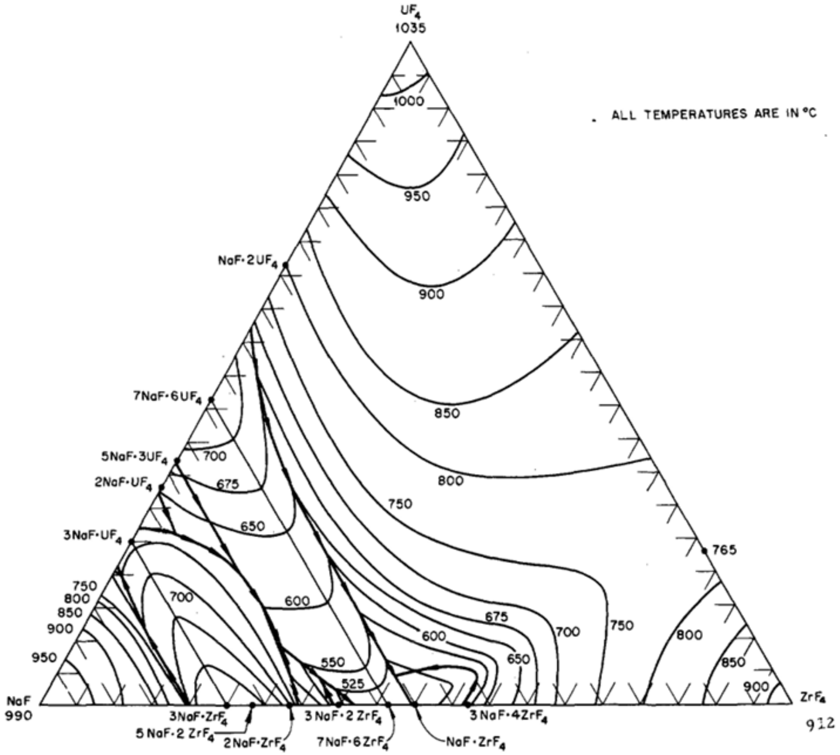
- Natural Li is 7.5 wt% ^{6}Li with balance ^{7}Li.
- ^{6}Li can fission into ^{4}He and ^{3}H.
- Li-containing salts are ^{7}Li enriched.

- Natural Cl is 75.8 wt% ^{35}Cl with balance ^{37}Cl.
- ^{35}Cl can transmutate to ^{36}Cl.
- ^{36}Cl is a long-lived radionuclide.
- Cl-containing salts are ^{37}Cl enriched.

Examples: Phase Equilibrium



LiF-BeF_2



NaF-ZrF_4-UF_4

Examples: Salt Synthesis

- NaF, LiF
- BeF_2, ZrF_4
- ThF_4
- UF_4
- PuF_4

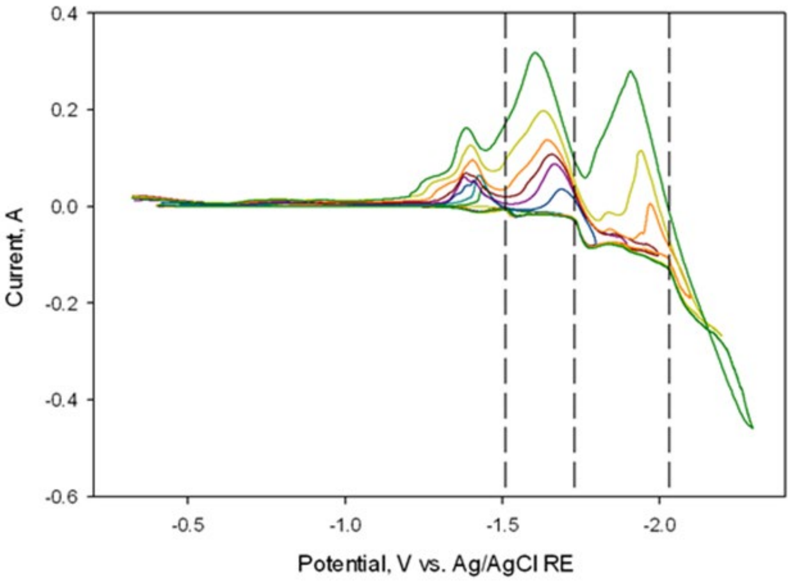
- NaCl, LiCl
- $ThCl_4$
- UCl_3, UCl_4
- $PuCl_3$

$PuCl_3$/NaCl Salt Synthesis at INL

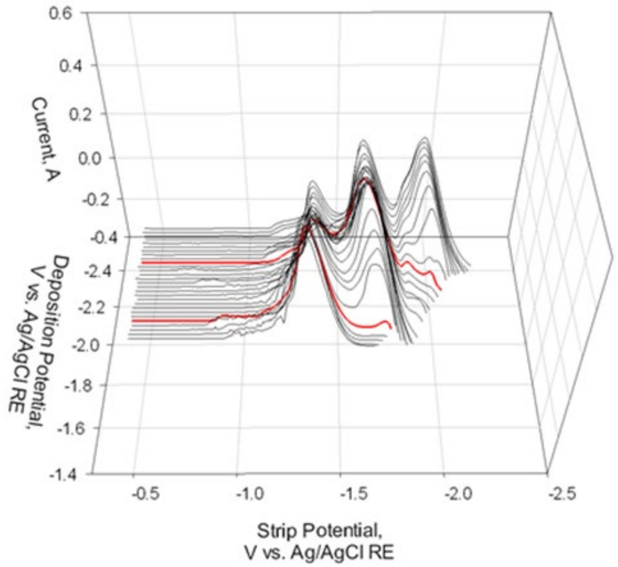
Properties of Molten Salts: Part 2

- Reduction/Oxidation (RedOx) Potential
  - Fluorine and Chlorine Chemical Potentials
  - Conceptually F_2(g) and Cl_2(g) Partial Pressures
  - Chemical Stabilities
  - Corrosion Control

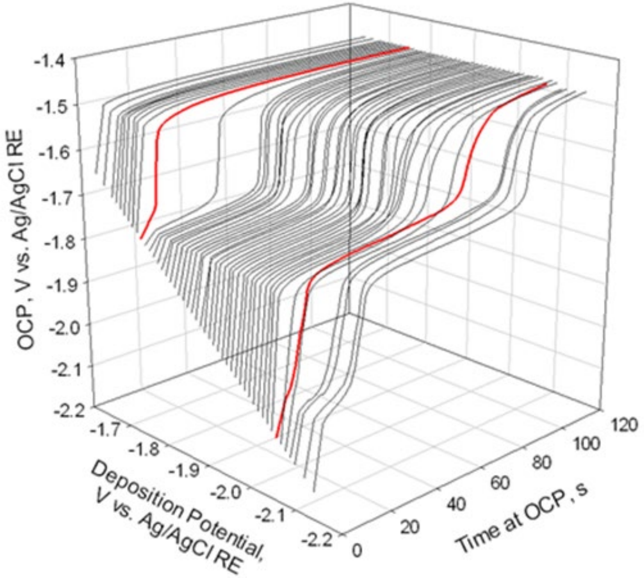
Examples: Electrochemical Measurements



Cyclic Voltammetry



Cathode Stripping

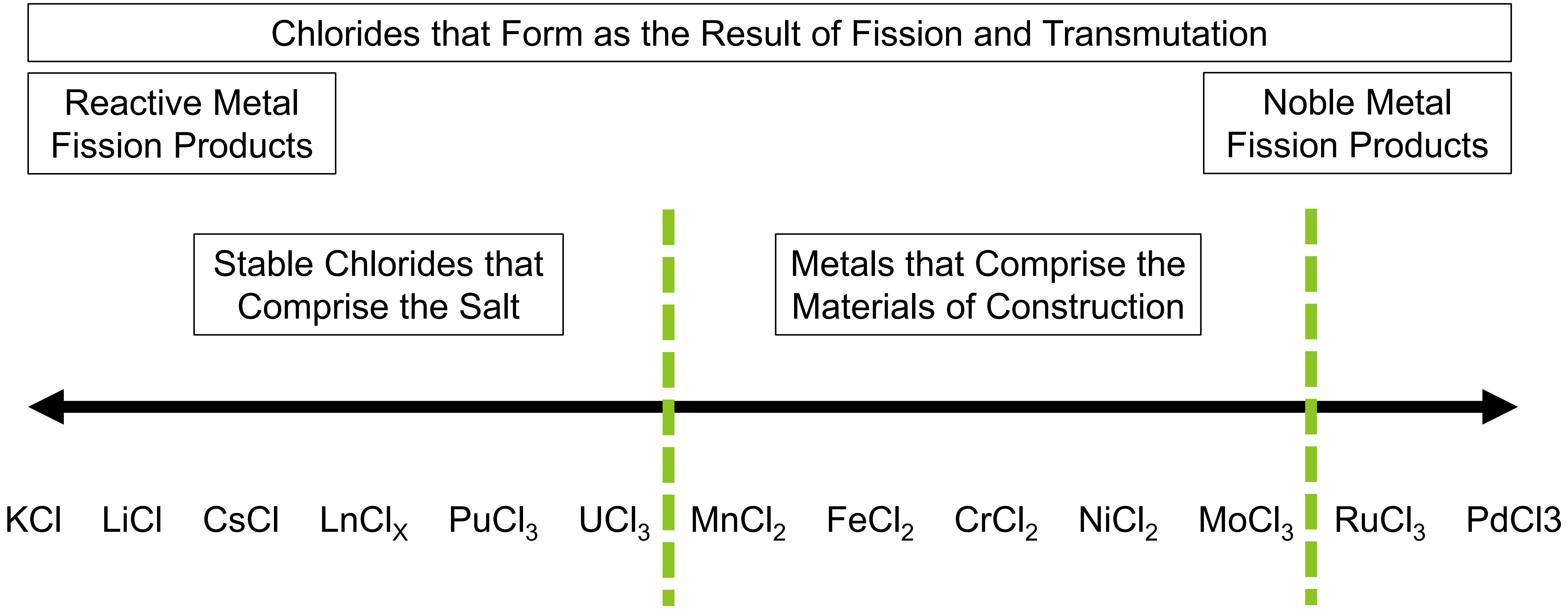


Open Circuit Potential

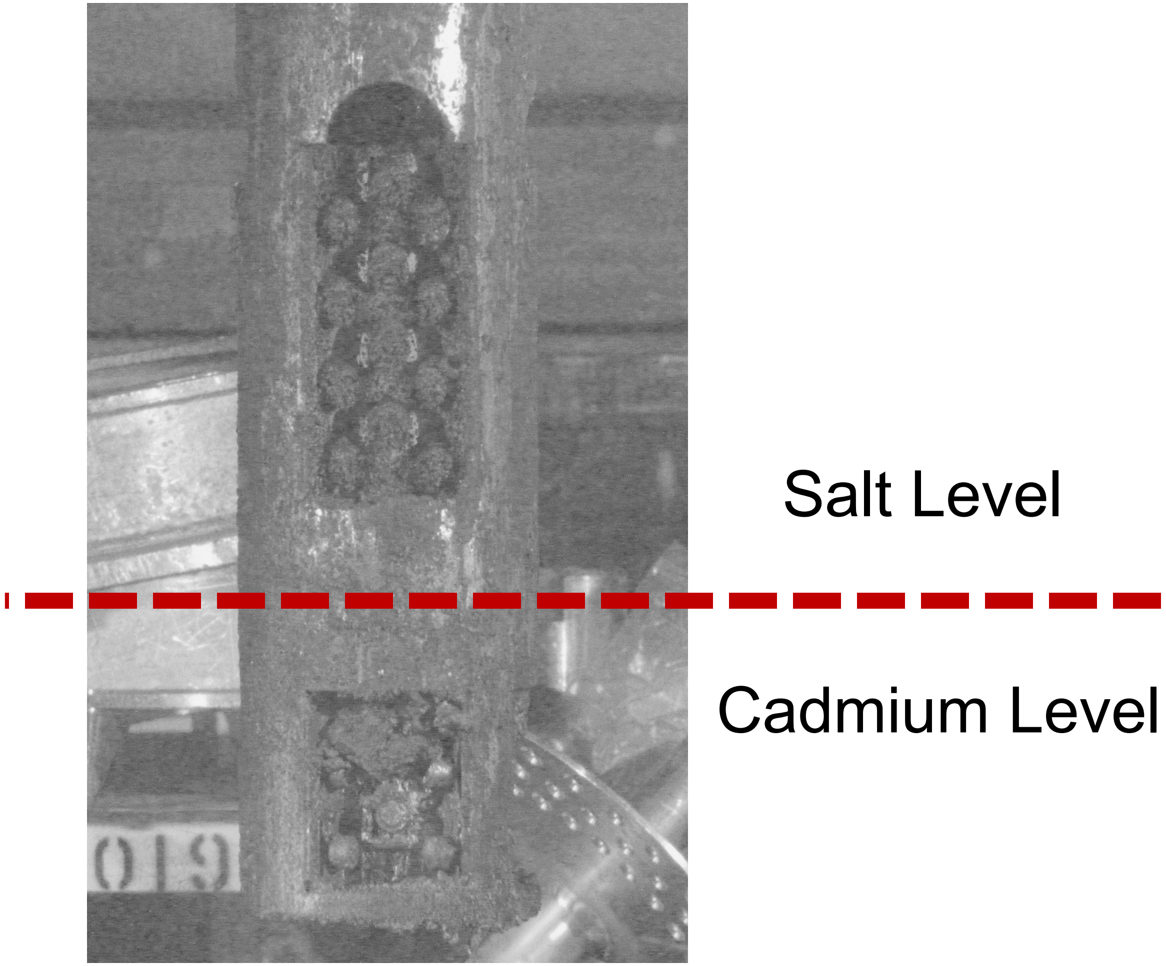
Examples: Corrosion Mechanisms

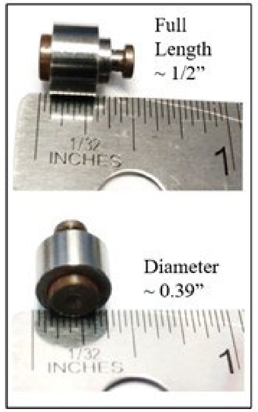
- Dissimilar Metals (Galvanic)
  - Macro-Scale
  - Micro-Scale
- Temperature Gradient
  - Molten Salt Flow Loop
- Fission Product Generation (Fuel Salts)
  - Better Part of the Periodic Table

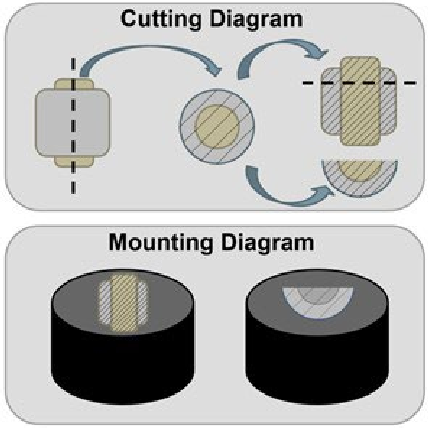
Examples: Chloride Stability Scale

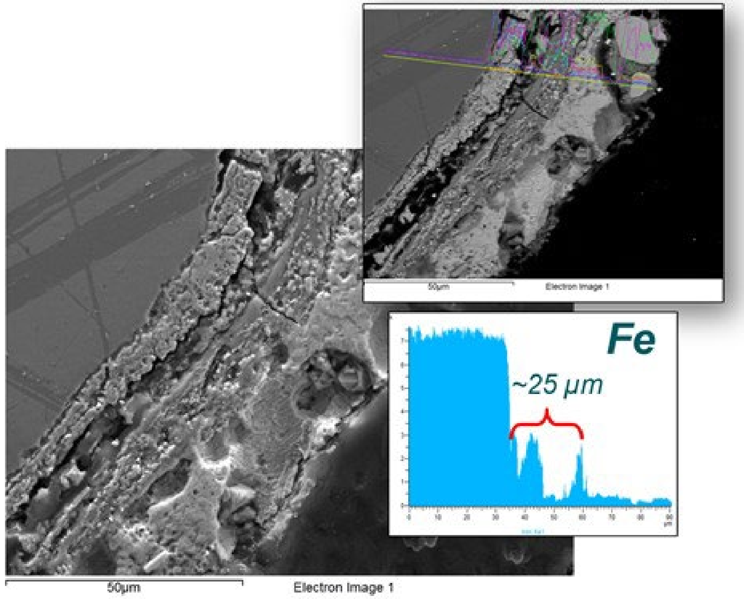


Examples: Corrosion







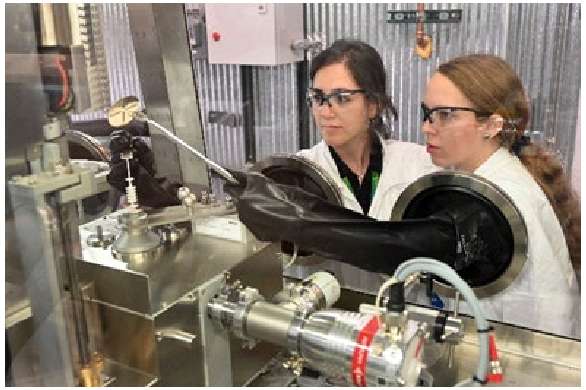


Properties of Molten Salts: Part 3

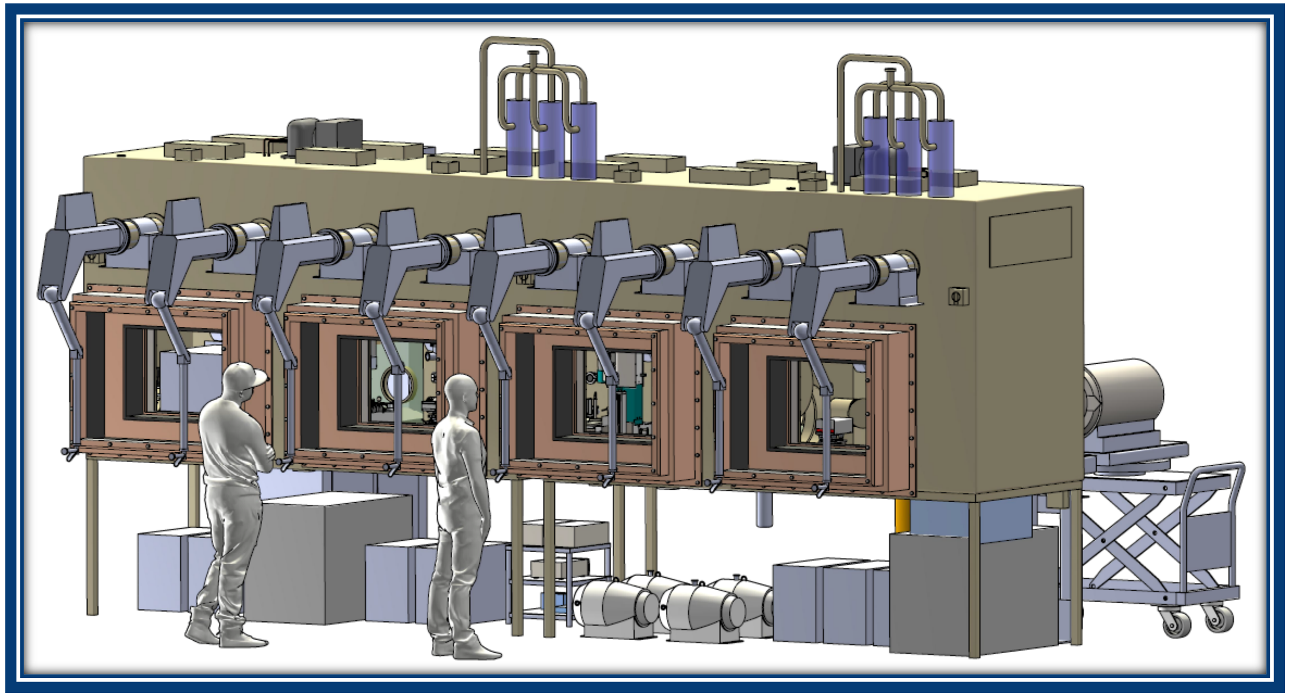
• Pycnometer	Density of Solid
• Densitometer	Density of Liquid
• Thermomechanical Analysis	Thermal Expansion
• Transient Hot-Wire	Thermal Conductivity
• Rheometer	Viscosity
• Thermogravimetric Analysis (TGA)	Mass Change
• Differential Scanning Calorimetry (DSC)	Phase Transitions
• Mass Spectroscopy (MS)	Gas Phase Analyses
• X-Ray Diffraction (XRD)	Atomic Structure
• Electron Microscopy	Phase Analysis

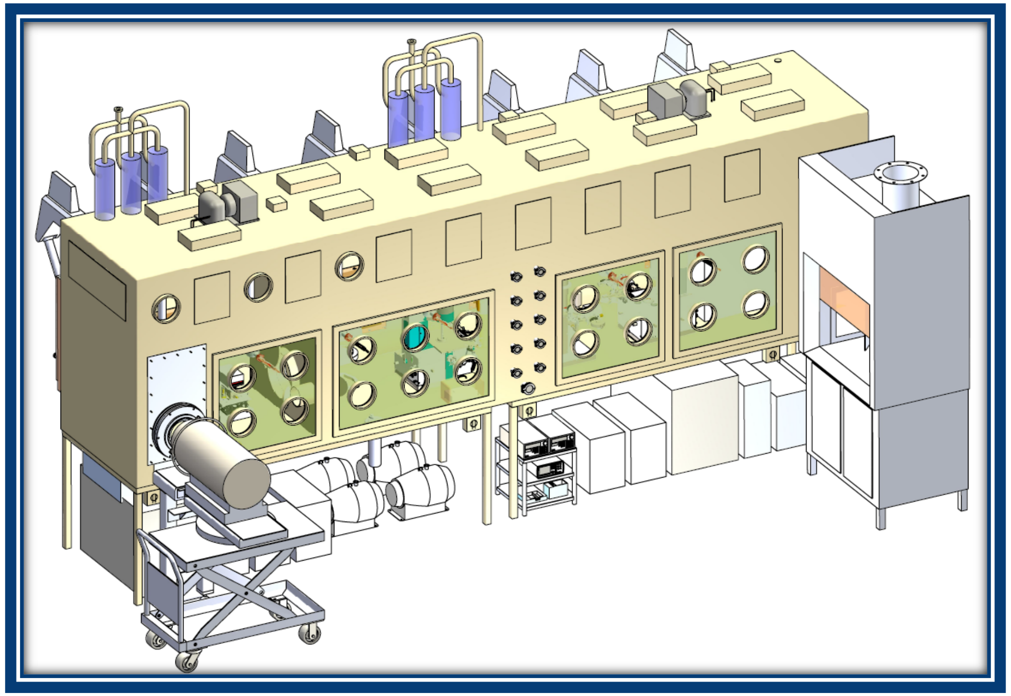
Examples: Laboratory Facilities

- Characterization equipment located inside Ar-atmosphere gloveboxes.
- Different facilities for four classes of work:
  - Non-Radiological Lab
  - Radiological Lab (work with uranium)
  - Nuclear Lab (work with transuranics)
  - Shielded Enclosures (work with irradiated materials)

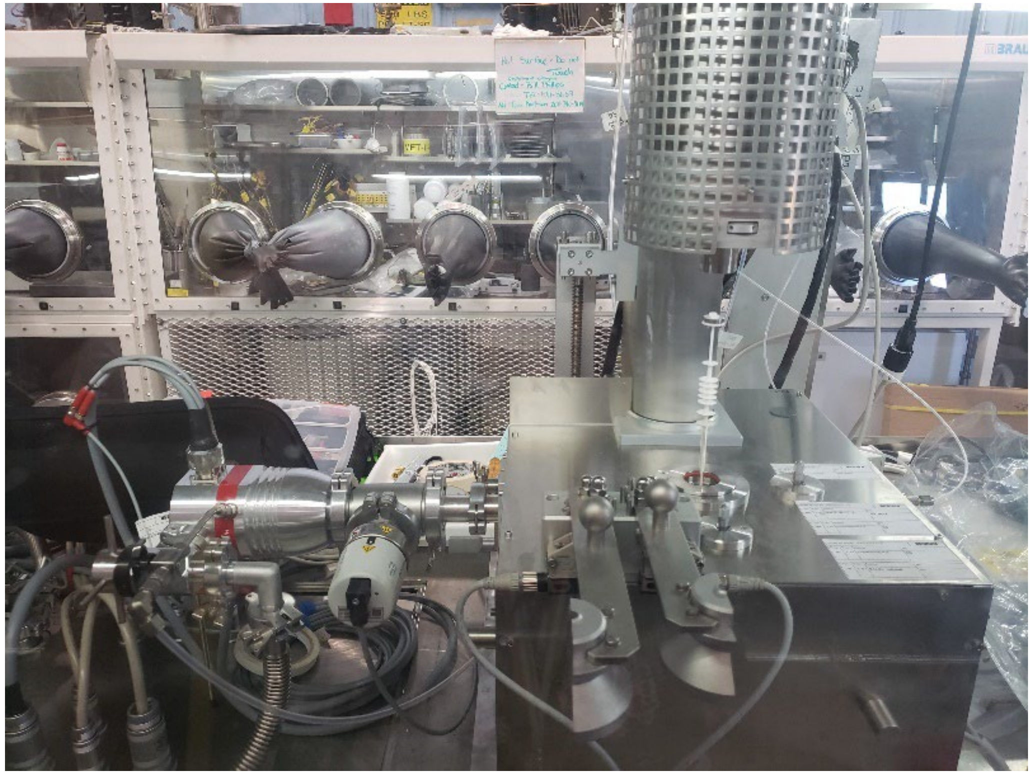


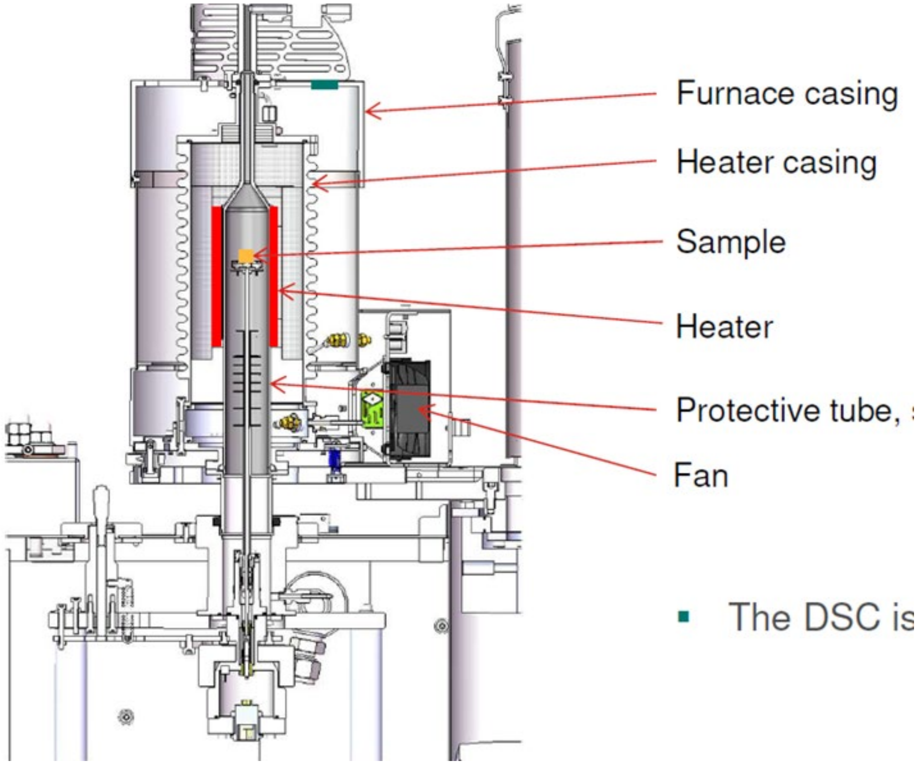
Examples: Laboratory Facilities



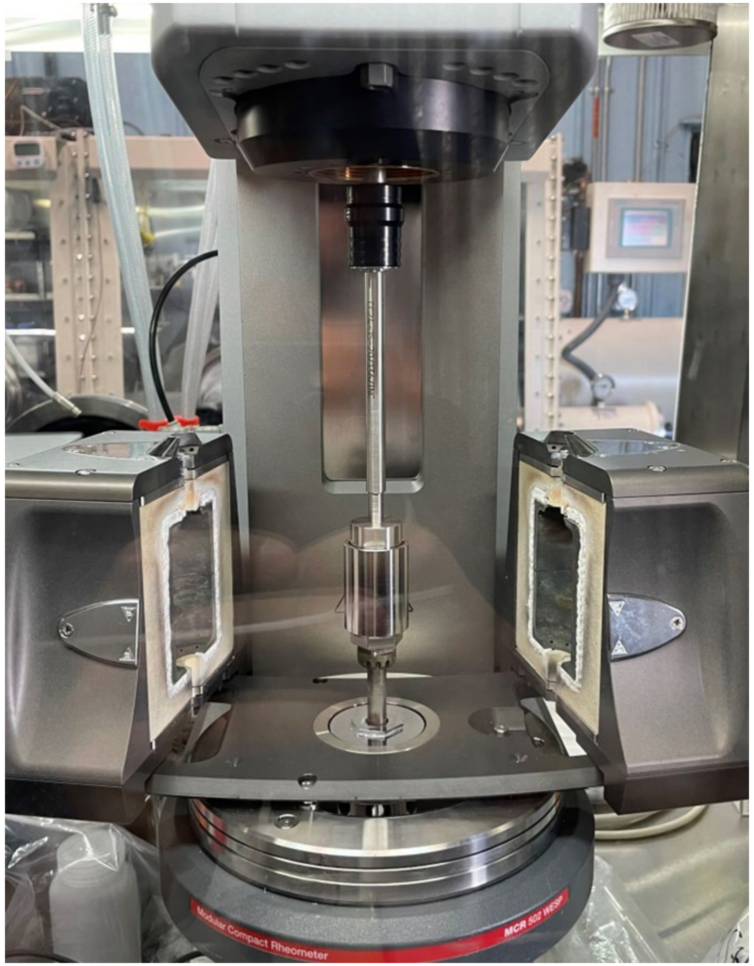


Examples: TGA / DSC





Examples: Rheometer



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