"Molten salt reactors are here; we need to accelerate innovation and de-risk unknowns"

Advanced Fuels Campaign

# Advanced Fuels Campaign Fuel Salt Focus Area

Toni Karlsson (Fuel Salt Lead)

Dan Wachs (National Technical Director)

INL/CON-25-88848

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

# Nuclear Energy Executive Orders

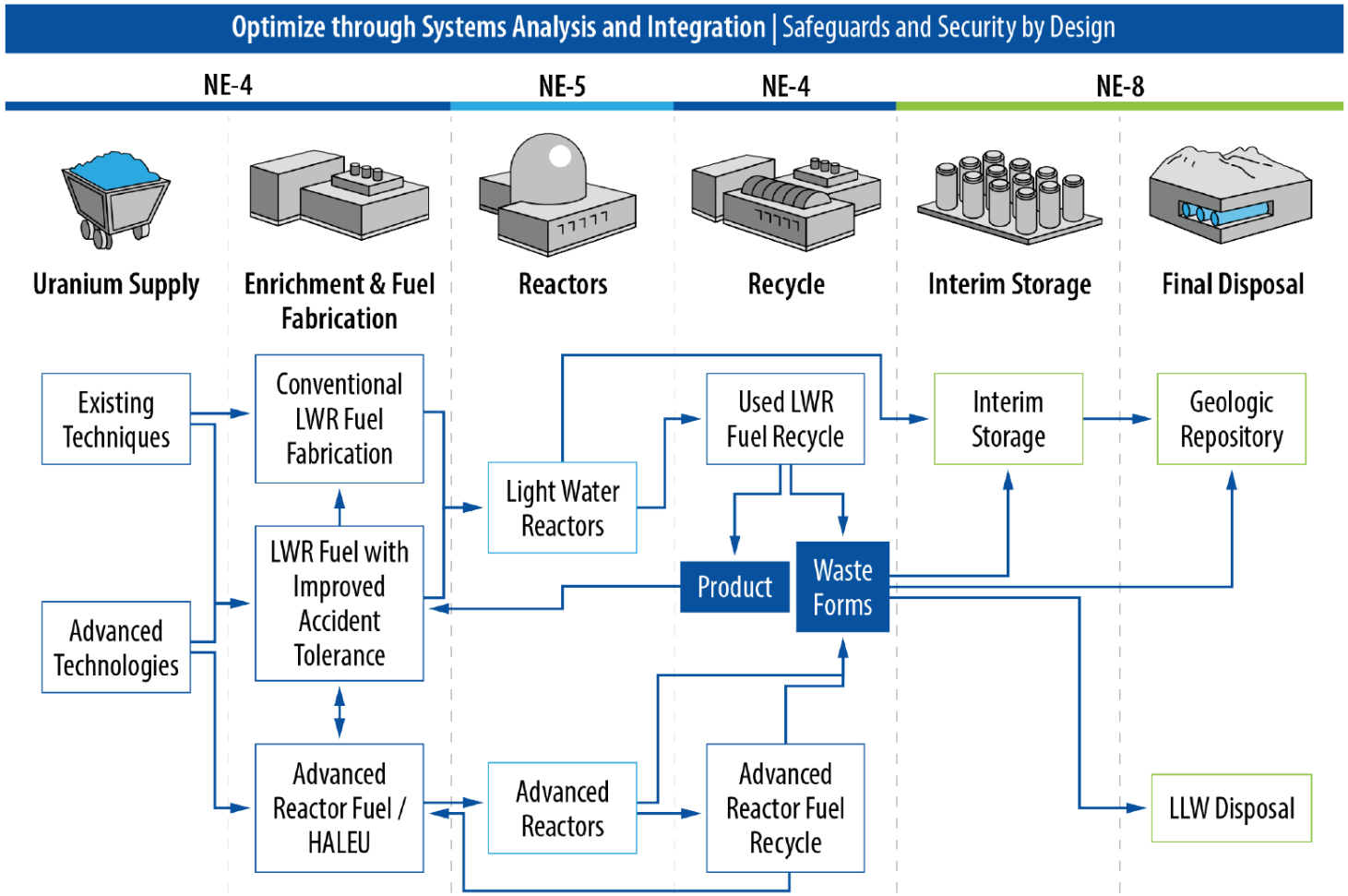
- Reinvigorate the Nuclear Industrial Base
- Reform Nuclear Reactor Testing at DOE
- Deploy Advanced Nuclear Reactor Technologies for National Security
- Reform the Nuclear Regulatory Commission

*President Donald Trump holds up a signed executive order in the Oval Office of the White House May 23, 2025 in Washington, DC. Win McNamee/Getty Images*

# Advanced Fuels Campaign

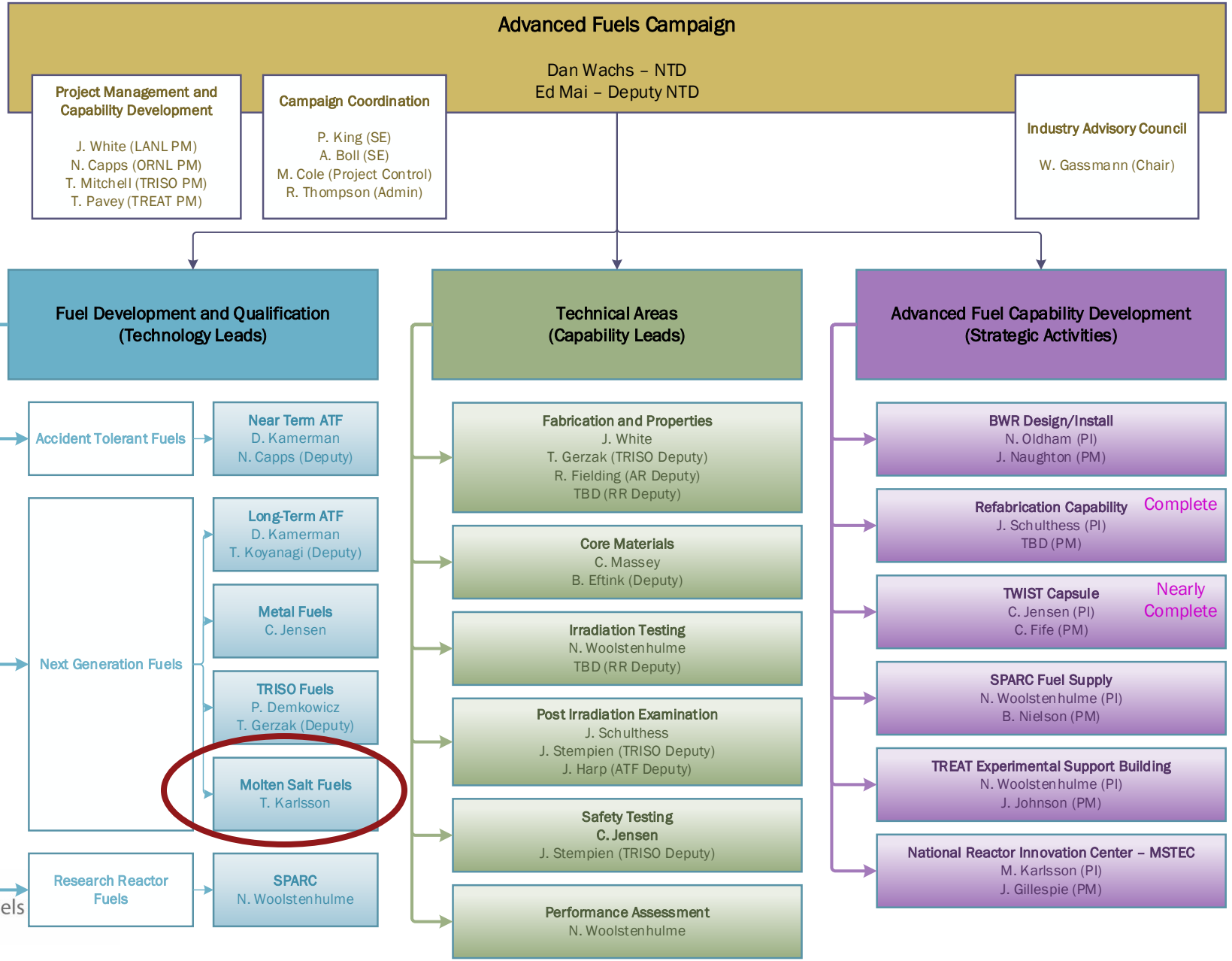
AFC is focused on the design, development, and qualification of advanced nuclear fuels and materials that can significantly improve the performance, safety, and efficiency of current and future nuclear reactors.

## "Fuel is the intersection between fuel cycle and reactor technology"

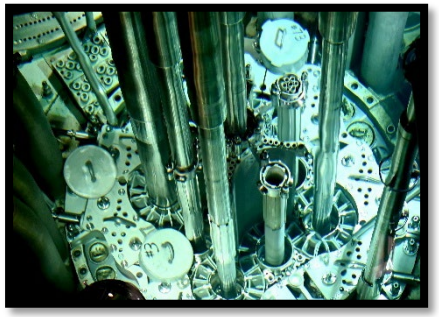



https://www.energy.gov/sites/default/files/2022-09/ne-neac-meeting-notes-august-2022.pdf

# Advanced Fuels Campaign



# Bottom Line Up Front (BLUF)



## Technical Problem

Lack of access to high purity fuel salts, irradiation performance data, and standards which inhibit qualification of liquid fuels and the advancement of molten salt reactor technologies

## BLUF

The Fuel Salt Focus Area addresses and reduces technical risks for molten salt fuels by establishing production pathways, qualification data, irradiation performance, and predictive modeling capabilities needed to support regulatory approval and commercial readiness.

## Integrated Outputs

High Purity Fuel Salts • Salt Standards • Experimental Data
Qualification Framework • Irradiation Testbeds • Fuel Performance
Validated Codes • Work Force Development • Materials Interactions

## Fuel Salt

### Stakeholders/Collaborators

- Industry, Southern Company, Natura, Saltfoss, EPRI
- DOE-NE, AMMT, ARSS, ASI, MRWFD, MSR, NEAMS Campaigns
- National Reactor Innovation Center (NRIC)
- National Laboratories – INL, ANL, ORNL, LANL
- Safeguards community
- Academia
- IAEA, NRC, KAERI

# Fuel Salt Focus Area (FSFA)

## Mission Statement

Innovate and enable technologies needed to support fuel salt research and development, focusing on emergent and future needs to derisk fuel salt utilization in advanced reactors.

## Fuel Salt Focus Area Thrusts

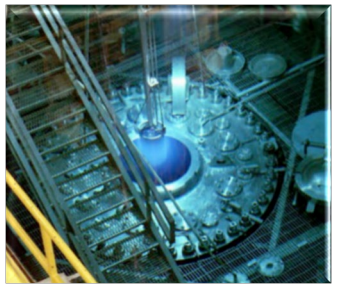
### Synthesis & Purification

Demonstrate fuel salt synthesis and purification pathways from a variety of feedstock materials while simultaneously developing a library of fuel salts

### Methods & Qualification

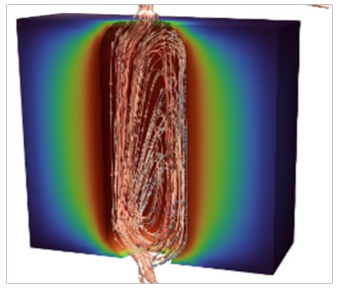
Establish a fuel salt specification/standard and develop the necessary techniques to quantify chemical requirements

### Irradiation & PIE



Develop a fuel salt irradiation and PIE program including irradiation testbeds vehicles, and instrumentation

### Modeling & Simulation



Utilize experimental data to validate fuel and materials performance codes for MSRs to support future use by vendors

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Argonne NATIONAL LABORATORY

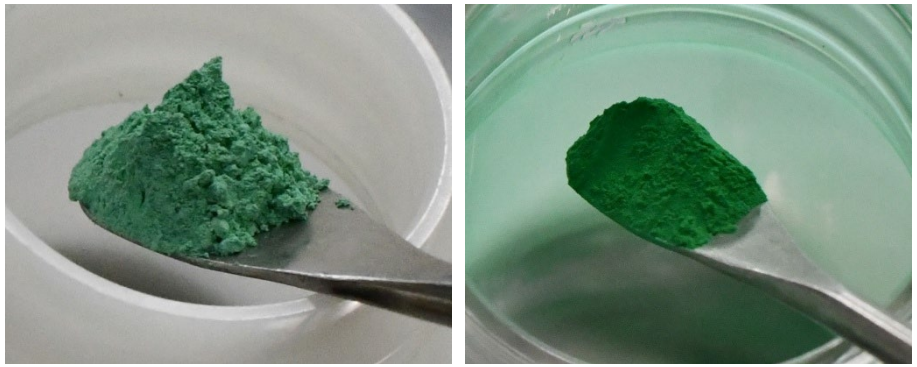
INL Idaho National Laboratory

Los Alamos NATIONAL LABORATORY

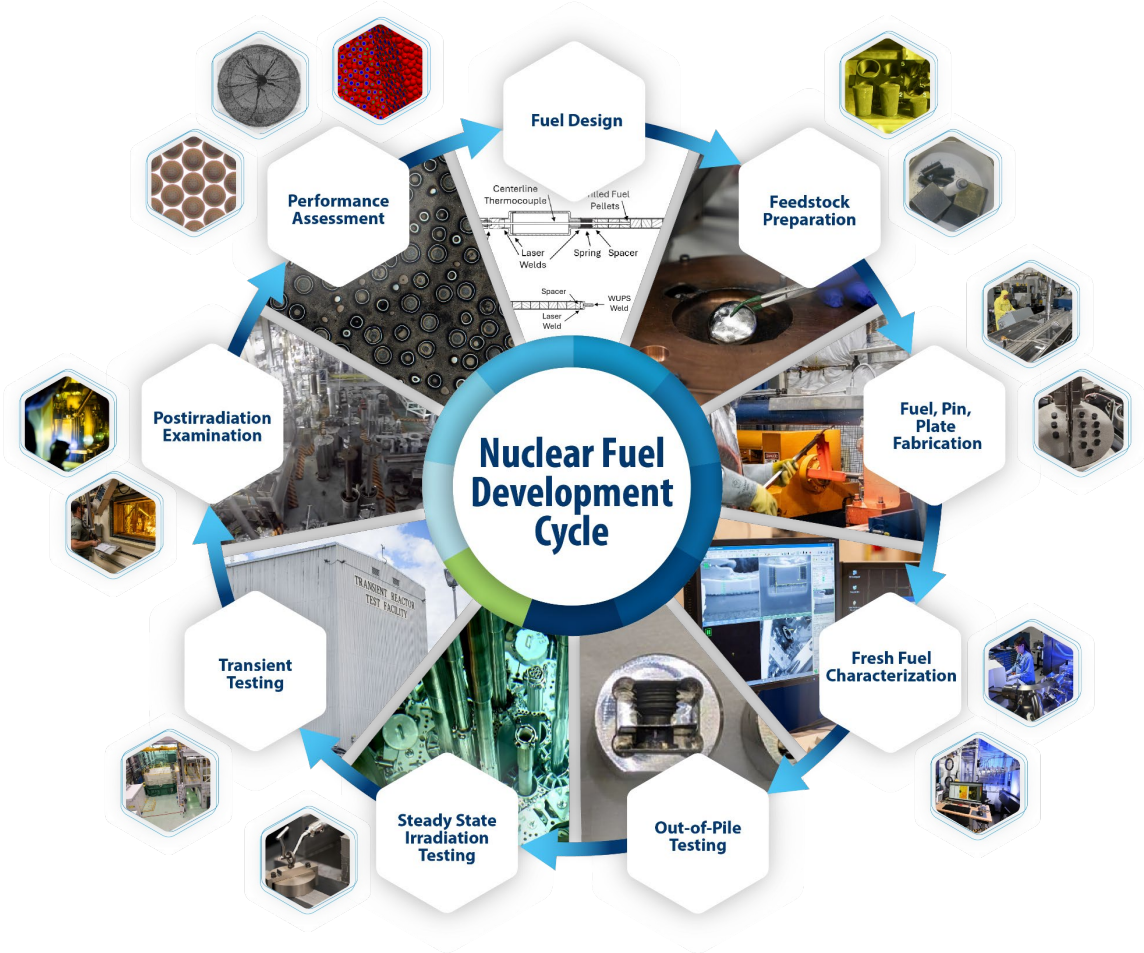
OAK RIDGE National Laboratory

# Fuel Salt Synthesis and Purification

- Why?
  - Actinide salts are not commercially available
  - Non-rad salts are often not “clean” enough
  - Fuel salt synthesis and purification is timely and costly
  - Synthesis and purification technologies selected based on starting material and product specifications
  - Material pre-treatment may be necessary
  - Need for high purity, highly characterized “Fuel Salt Library”



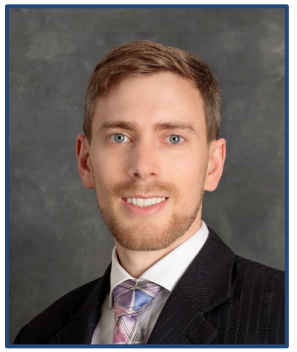
As purchased $UF_4$ with oxide impurities (left), purified $UF_4$ (right)



# Fuel Salt Synthesis and Purification

- Major Activities
  - Developing roadmaps for Cl/F salt synthesis and purification technologies
  - Implement bench-scale actinide Cl/F synthesis activities to inform scalable technologies for actinide salt production
  - Purification technologies for oxides, fission products, corrosion products, etc.
  - Develop of system for monitoring the synthesis/purification of fuel salts


Krista Hawthorne (ANL)


Jacob Yingling (INL)


Marisa Monreal (LANL)


Tony Birri (ORNL)


Possible molten salt fuel starting materials and synthesized fuel salts. (Left to right - oxidized Pu, Pu, $PuCl_3$-NaCl salt, EBR-II HALEU, $UCl_3$-NaCl)

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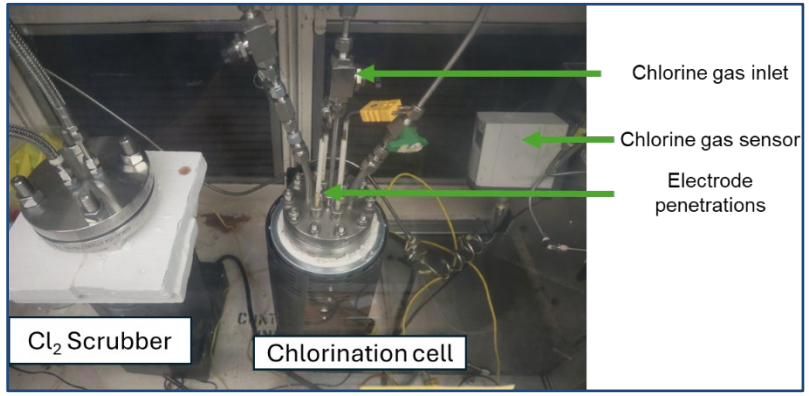
# Fuel Salt Synthesis and Purification

## *Purification Activity*




Chlorine-gas cathode to support chloride salt fuel synthesis. In-situ chlorination of metals and Zr-mediated chlorination of oxides, extend to fluoride salts

## *Example of Synthesis Salt and Facilities*

$UF_4$ in a flame-sealed ampule (left) and PluS Lab for advancing fundamental plutonium science, including plutonium halide research (right).

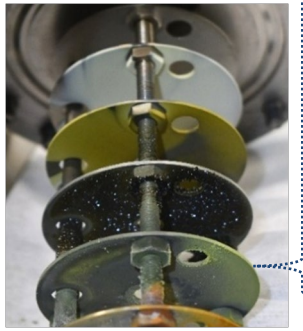
## *Example of Synthesis Salt Activities*

**First study of new halide exchange process:**

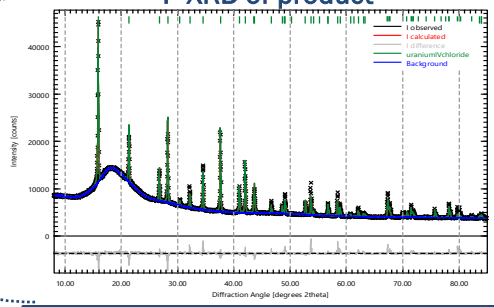
$$2MgCl_2 + UF_4 \rightarrow UCl_4 + 2MgF_2$$

heat/vacuum

**Fractional Distillation**



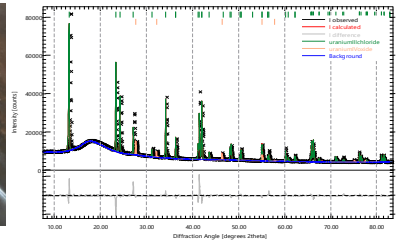
**P-XRD of product**




$$UCl_4 + Zr \rightarrow UCl_3 + ZrCl_4$$

To Zr and $Cl^{37}$ recycling process

heat/vacuum




95wt% $UCl_3$ with oxide contaminant

Mass exchange reaction between $MgCl_2$ and $UF_4$. The reaction occurs at elevated temperature and when under vacuum will volatilize $UCl_4$ which fractionally separates from contaminants. Subsequent reduction yields substantially pure $UCl_3$. Oxide contamination is likely from the untreated Zr used for the reduction.

# Fuel Salt Methodology and Qualification


- Why?
  - Proposed fuel salts for MSRs vary in neutron spectrum, enrichment, fissile isotopes, thermal properties, and composition
  - Test methods and validation needed for identification and quantification of impurities
    - What is in the salt and at what concentration?
    - When making a salt, what is pure enough?
  - Analysis of Cl/F fuel salts are not equal

Vacuum dried, “anhydrous” KF (left), vacuum dried, anhydrous KF (right)

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*Fuel salt qualification framework is a massive task that will require organization, collaboration, strategic approach, money, time, and diverse skill sets… Lets accelerate it!*

# Fuel Salt Methodology and Qualification

- Major Activities
  - Develop a roadmap outline for a fuel salt specification standard and identify gaps in elemental/isotopic analysis capabilities
  - Develop test methods for Cl/F salt chemical, mass spectroscopic, and impurity analysis
  - Engage with industry vendors and larger MSR community to define fuel salt qualification needs
  - Engage with TRISO and LWR team members to elucidate considerations and framework for fuel salt qualification
  - Development of standard specification for fuel salts, similar to LWR spec

Amber Polke (ANL)

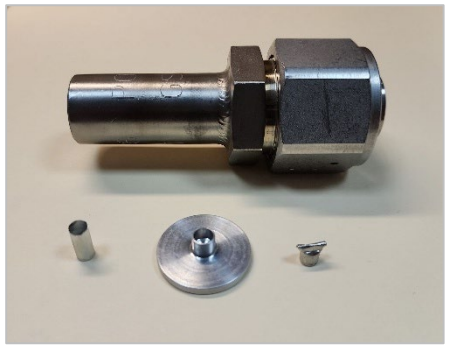
Delia Perez-Nunez (INL)

Designation: C776 – 17 (Reapproved 2022)

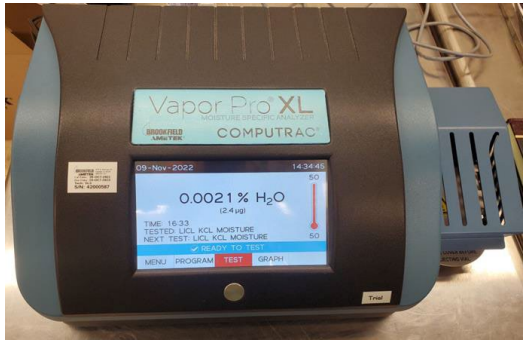
**Standard Specification for**
**Sintered Uranium Dioxide Pellets for Light Water Reactors**[1]

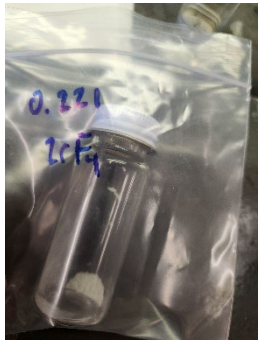
This standard is issued under the fixed designation C776; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon ($\varepsilon$) indicates an editorial change since the last revision or reapproval.

# Fuel Salt Methodology and Qualification



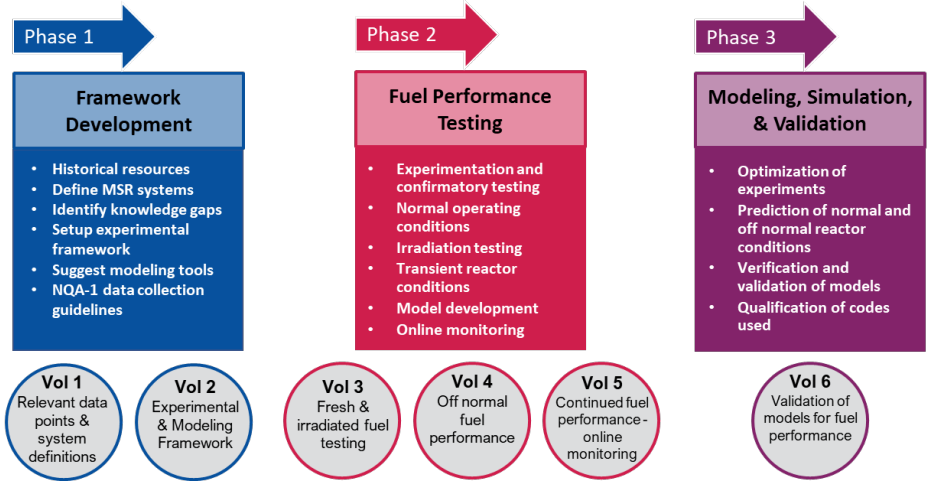




Development of a variety of tools and methodology, for low uncertainty light element analysis to determine moisture and oxygen content in Cl/F fuel salts.
(Left to right - Pure/impure $UF_4$, sample prep materials for oxygen analysis of Cl salts, light element analyzer, NaI detector, moisture analyzer, sample for moisture analysis)


Begin optimizing and updating in-line and multimodal sensors for real-time monitoring of actinide and impurity concentrations during Cl fuel salt synthesis. Multimodal Analysis (in situ Echem, Raman, DTA, densitometry)*

*Note: Multimodal monitoring system originally developed for safeguards applications under ARPA-E OPEN 2021 Project 21/CJ000/01/04




Utilizing TRISO lessons learned, develop the Molten Salt Accelerated and Integrated Licensing (MSAIL) methodology that will layout the framework and recommendations for a fuel salt qualification process following the Nuclear Quality Assurance-1 (NQA-1) standard

# Fuel Salt Irradiation & PIE

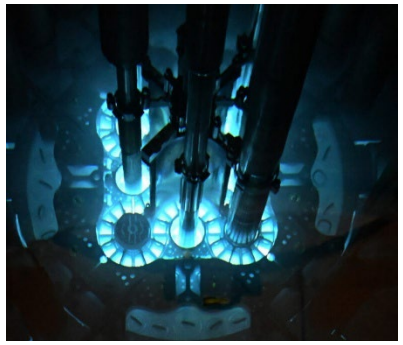
- Why?
  - Fuel salt irradiation and PIE are vital for closing technical gaps in our understanding of fuel salt behavior in MSR conditions
  - These studies show how radiation affects fuel salts, including retention of radionuclides and corrosion between salts and material samples under irradiation
  - They allow us to investigate how fission products dissolve in the salt and how that changes the salt's thermophysical properties
  - The data collected is essential for building the safety basis required to develop and license MSRs
  - Without these experiments, we risk being caught off guard by unknown issues—"we don't know what we don't know" until we actually test it
  - Detailed information on radiolysis, corrosion, and thermal properties (both solid and liquid) is needed to fully understand the behavior and safety margins of MSRs

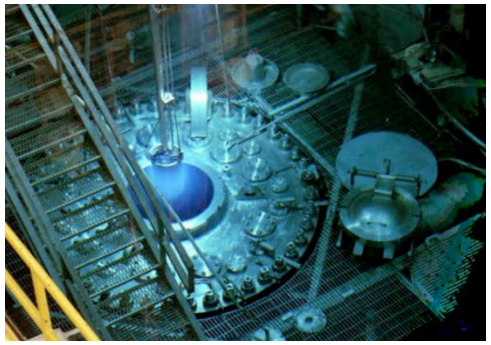
Matthew Arrowood (INL)

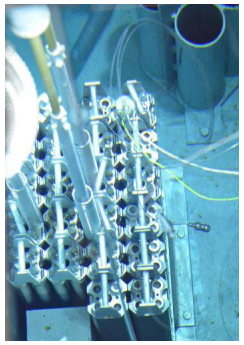
Calvin Downey (INL)

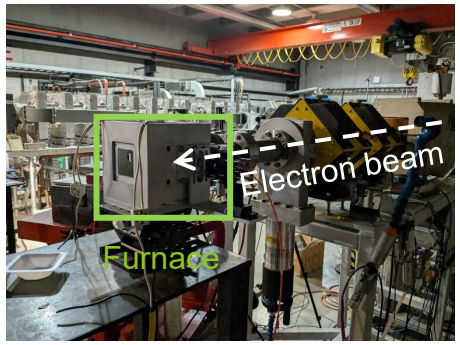
Tony Birri (ORNL)

Jacy Conrad (INL)










Pictures of ATR, HFIR, NRAD reactors, and ISU beamline (left to right)

# Fuel Salt Irradiation & PIE

## Properties Affecting Fuel Performance

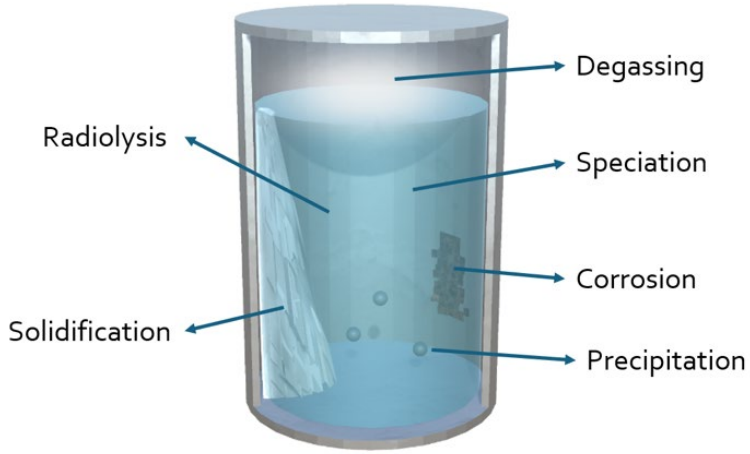
### Fuel Chemistry and Composition
- Purity of salt, i.e. moisture, oxygen, light elements
- Fissile material loading
- Fission/corrosion product concentration
- Redox buffer/control

### Materials Compatibility
- Alloy - He/H production, swelling, etc. affect corrosion
- Corrosion due to salt interaction
- Radiolysis-assisted corrosion
- Galvanic corrosion
- Thermal gradient mass transport

### Physical Properties
- Density, heat capacity, viscosity, thermal conductivity
- Change as a function of temperature
- Change as a function of impurity build up

### Chemical Stability
- Radiolysis
- Speciation
- Dose rate

### Fission Product Behavior
- Nobel metals – precipitation, plating
- Gases – solubility in salt, bubble formation
- Lanthanides – salt soluble
- Active metals (Grp I/II) – fate (solubility in fuel) depends on redox chemistry




Simplified schematic of molten salt fuel in a static reactor environment

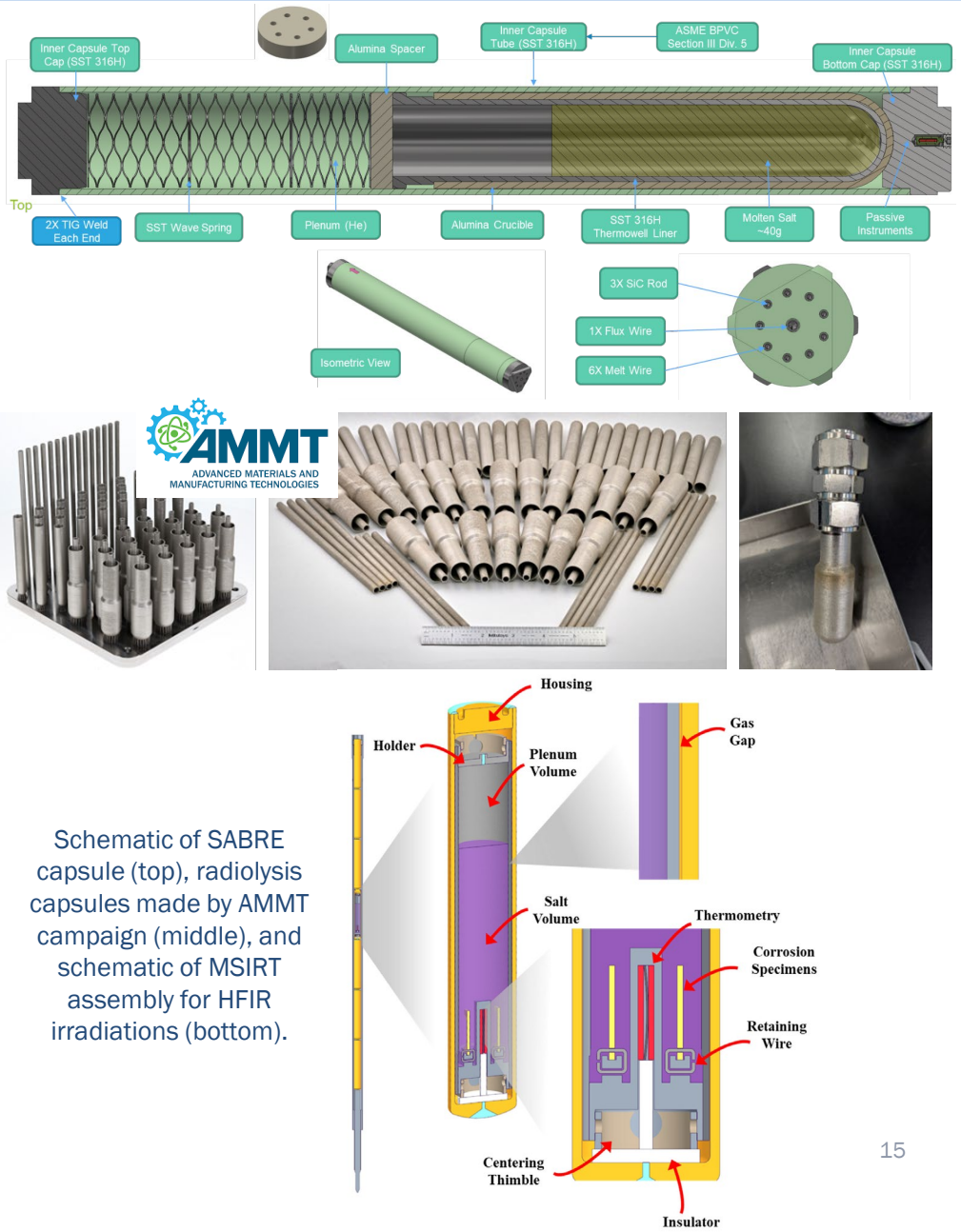
Do other fuel types have this level of interdependencies of properties affecting fuel performance?

This is not unmanageable! We must prioritize what topics alter fuel performance the most and target our efforts there!

# Fuel Salt Irradiation and PIE

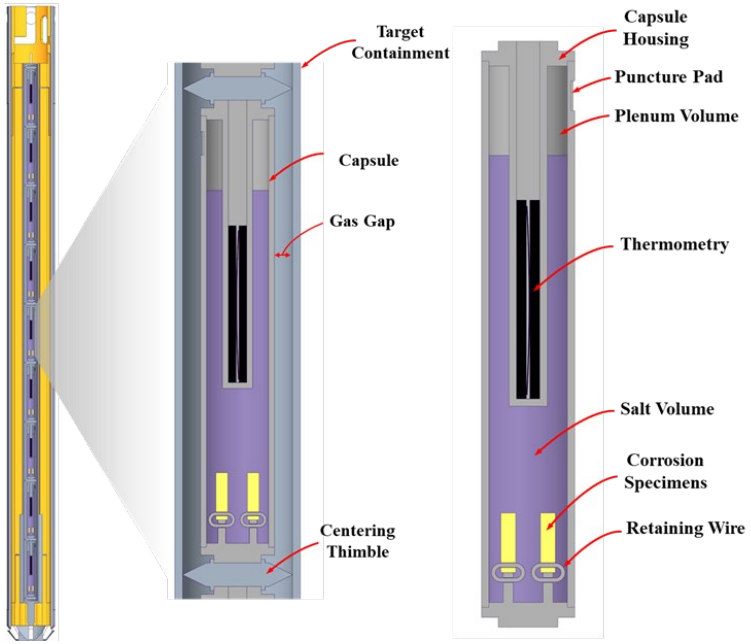
- Major Activities
  - Decouple and quantify effects of molten salt fuel performance
    - Material of construction
    - Salt radiolysis
    - Corrosion
    - Fission products
  - Out-of-pile corrosion experiments
    - To inform irradiation safety
    - Distinguish between irradiation effect and “normal” effect
  - Establish irradiation and PIE testbeds
    - SABRE – Fuel performance (ATR)
    - MSIRT – Material performance (HFIR)
    - MAVERIC – Online monitoring (NRAD)
    - Radiolysis – Chemistry of salt in high gamma field, gas products (ISU beamline)

SABRE - Salt and Actinide Burnup in a Reactor Environment
MSIRT - Molten Salt Irradiation Research Testbed
MAVERIC - Molten-salt Versatile Reactor Irradiation Capsule



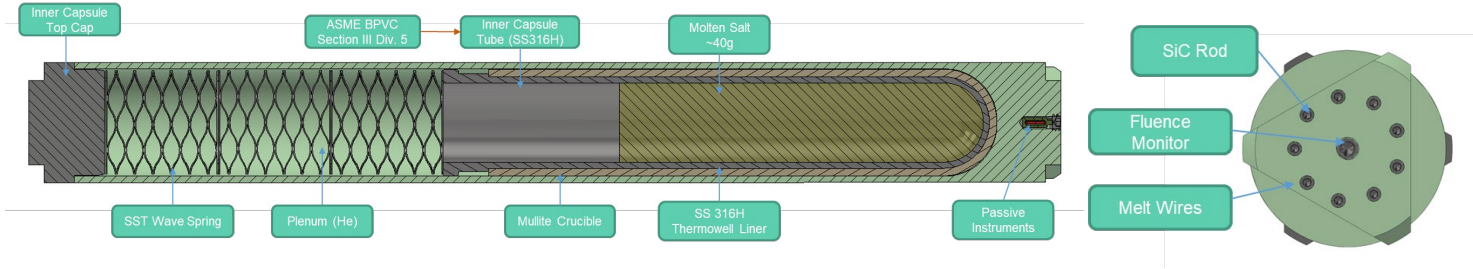

Schematic of SABRE capsule (top), radiolysis capsules made by AMMT campaign (middle), and schematic of MSIRT assembly for HFIR irradiations (bottom).

# Fuel Salt Irradiation and PIE




HFIR irradiation capsule design will allow for mechanistic insights into irradiated salt chemistry and accelerate the co-development and qualification of fuel salts and structural alloys. Irradiation-corrosion testing of Cl/F molten salts (non-fueled or surrogate-fueled systems) first then fuel salts

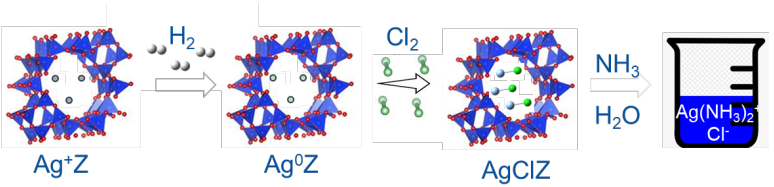
KAERI naarea SALTFOSS




Nearly complete preliminary design for non-instrumented fuel salt capsule to be used in ATR. Fuel salt fabrication will and capsule assembly in FY26/27. In reactor FY27/28, 4 cycles

AMMT ADVANCED MATERIALS AND MANUFACTURING TECHNOLOGIES

**Off-Gas Capture in Silver Zeolites**

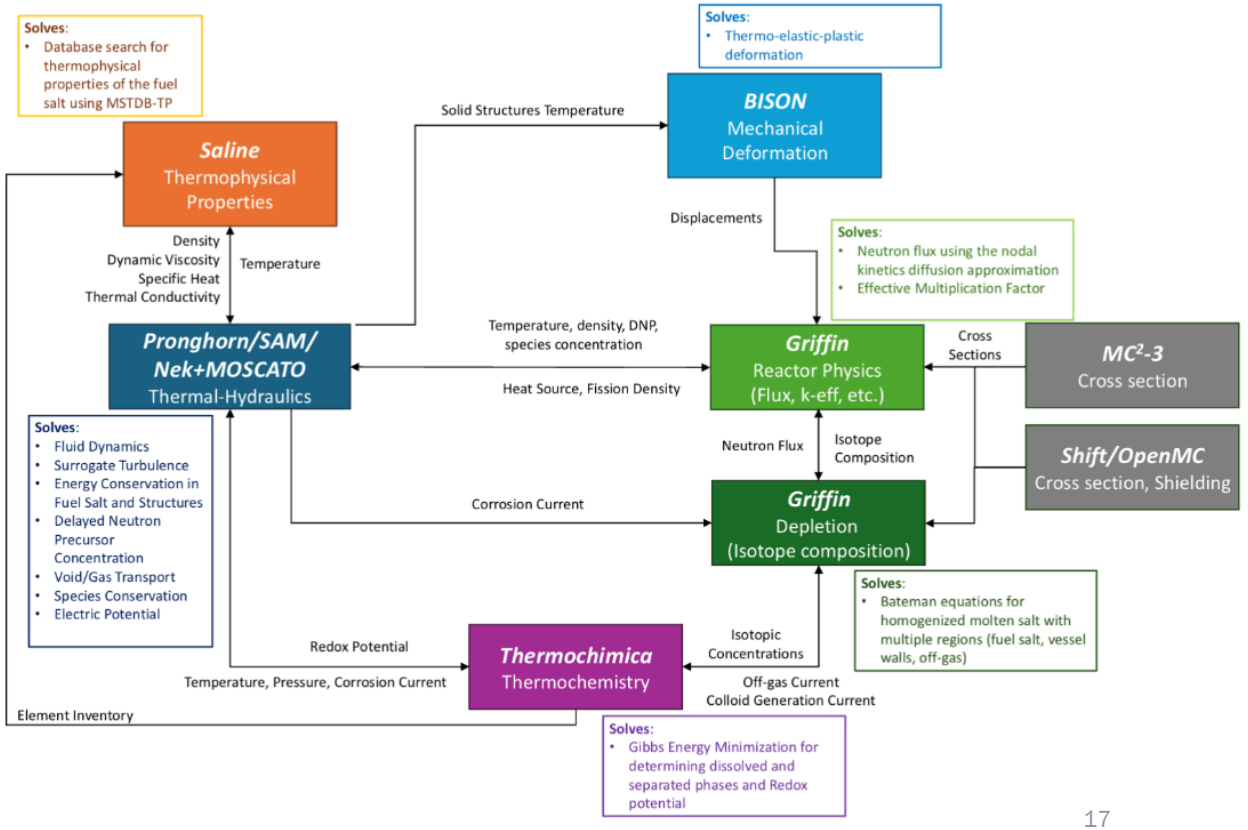



Data on the radiolysis of salts during irradiation or long-term storage is limited but necessary for irradiation experiments. Developing setup for Cl/F salts using custom 3D printed 316H SS capsules (AMMT, ORNL) and gas capture media

# Modeling and Simulation

- Validated engineering framework for species tracking in fuel salts to supporting irradiation experiments
- This work aims to develop a high-fidelity species transport model for the SABRE experiment to support validation in four key areas
  - **Neutronics and Depletion** – comparing calculated isotopic inventories with experimental data.
  - **Thermal-Hydraulics** – validating heat exchange and temperature predictions against irradiation temperature measurements.
  - **Species Transport** – comparing model predictions with isotopic profiles from axial cuts of the fuel and containment basket.
  - **Corrosion and Off-Gassing** – evaluating model predictions against observed corrosion and gas release in the irradiation capsule.

Mauricio Tano | Ramiro Freile | Parikshit Bajpai | Chaitanya Bhave



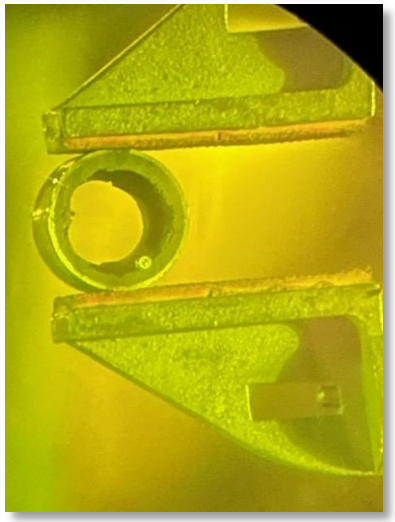

Multiphysics framework to be tested and validated

# Fuel Salt Focus Area (FSFA)

- Lots of areas for AFC to engage!
  - DOE Campaigns
  - Industry
  - NEUP/Universities
  - Vendors/Supply Chain
  - International Collaborations

- Call to Action – Please get in touch if you have questions, input, thoughts, etc.
  - Toni Karlsson, Fuel Salt Lead - Toni.Karlsson@inl.gov
  - Dan Wachs, NTD - Dan.Wachs@inl.gov
  - Contact any team member

- Fuel Salt Deep Dive Meeting
  - July 14th – 16th 2026 (virtual)

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