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Advances in Monitoring Techniques for Molten Salt Reactor and Fuel Cycle

Prof. Sungyeol Choi

29 April 2026

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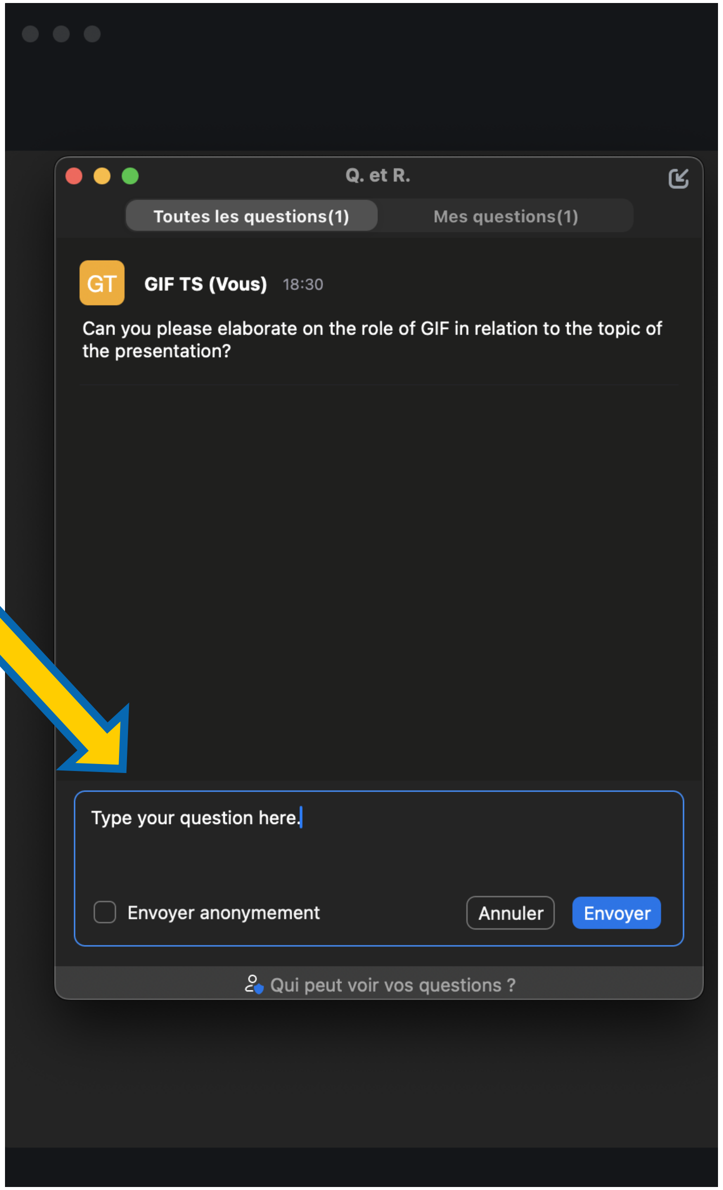

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Meet the Presenter

Dr. Sungyeol Choi is a Professor in the Department of Nuclear Engineering at Seoul National University (SNU), where he also serves as the Founding Head of the Integrated Major in Sustainable High-level Radioactive Waste Management

Prior to joining SNU, he served as a Senior Researcher at the Korea Atomic Energy Research Institute (KAERI), and a Research Fellow at Harvard University

He currently serves as Vice-Chair of the OECD/NEA Global Forum on Nuclear Education, Science, Technology and Policy

He received his Ph.D. in Nuclear Engineering in 2012 and his B.S. in Nuclear Engineering in 2008, both from Seoul National University. His research focuses on nuclear fuel cycle and used nuclear fuel management, with particular emphasis on molten salt chemistry and radioactive waste disposal

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Monitoring Techniques for Molten Salt Reactor and Fuel Cycle

- Monitoring is the continuous and systematic observation of system states during operation
  - It captures meaningful changes in real time or near real time
  - It tracks chemical, physical, and nuclear states
  - It supports safe operation, optimization, and material accountancy
- Reliable commercialization requires real-time understanding of the system state

Concentration measurement (actinide, fission&corrosion product)

Fission product removal systems

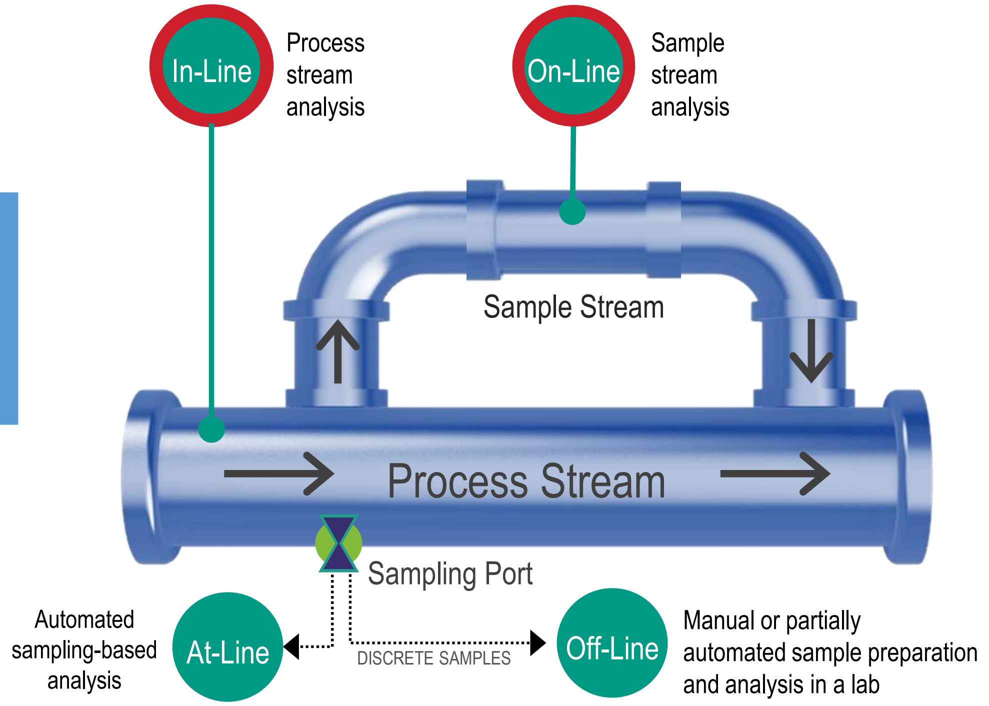
Noble metal deposition monitoring

Nuclear safeguards

Corrosion potential
Redox potential control
Controlled corrosion data

Monitoring for abnormal conditions
Autonomous and remote operation

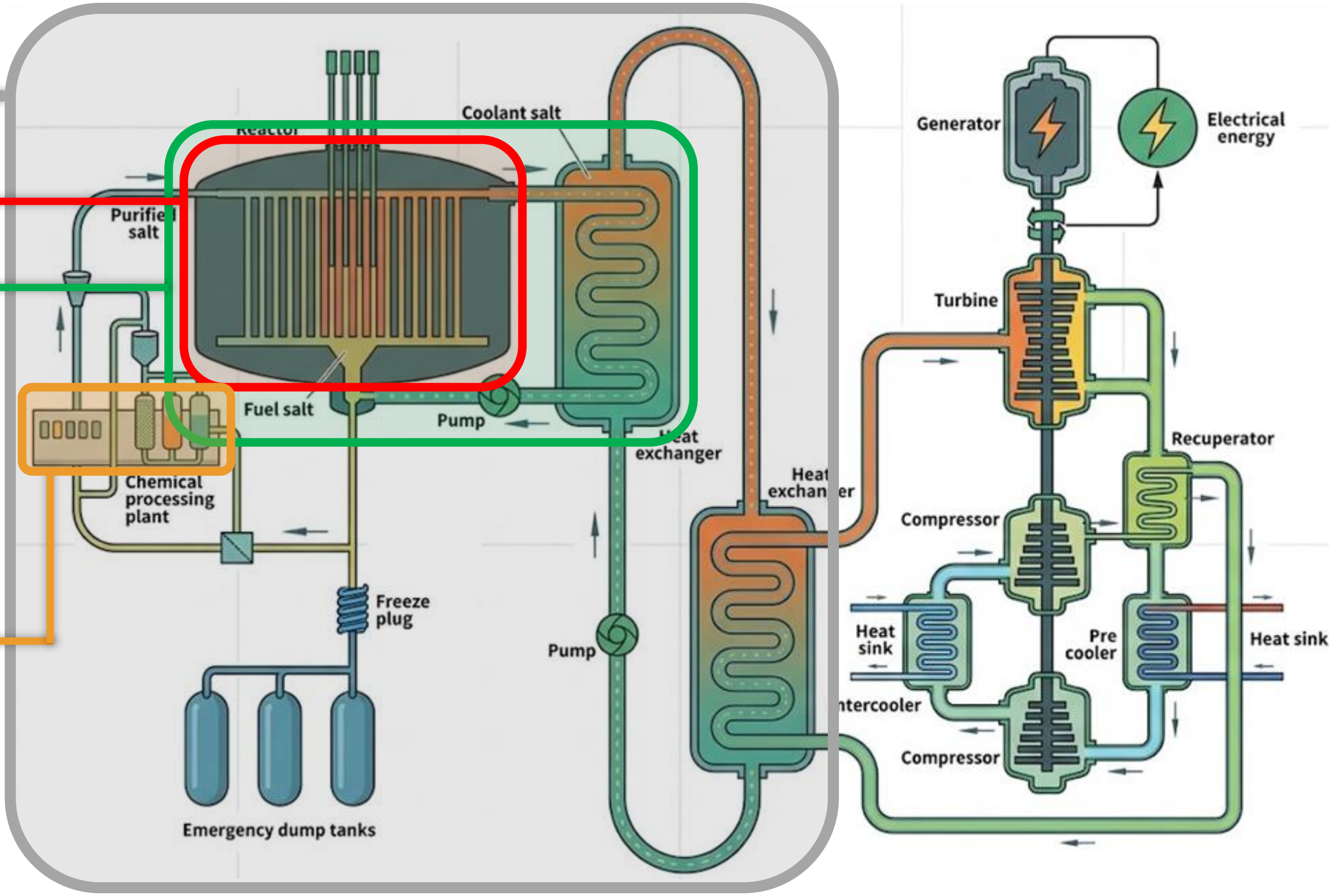
Fast data acquisition (thermochemical, electrochemical, and spectroscopic database)



Why is Monitoring Essential in Molten Salt Systems?

- Molten salt systems require dedicated monitoring approaches
  - They operate in high-temperature, radioactive, and corrosive environments making direct use of conventional instrumentation difficult
  - Their liquid-fuel nature and evolving salt chemistry introduce significant operational complexity
  - The bulk liquid form makes material accountancy more difficult
- At the same time, molten salt systems offer new opportunities
  - Online monitoring can provide information that is difficult to obtain in conventional reactors
- Monitoring supports safety, operation, safeguards, and material integrity
  - **Safety:** Enables early detection of abnormal conditions (e.g., off-gas release, thermal or chemical deviations)
  - **Operation:** Supports real-time control of salt composition, reactivity, and system performance
  - **Safeguards:** Enables continuous tracking of nuclear material in a liquid, flowing system
  - **Materials Integrity:** Monitors corrosion and degradation of structural components

Key Monitoring Parameters in Molten Salt Systems



WHOLE SYSTEM

- Temperature
- Flow rate
- Pressure
- Level
- Corrosion products
- Structural integrity

REACTOR CORE

- Neutron flux
- (Reactor power)
- (Reactivity)

PRIMARY LOOP

- Salt composition
- Redox chemistry
- Impurity ingression
- Actinides inventory
- Fission products

OFF-GAS SYSTEM

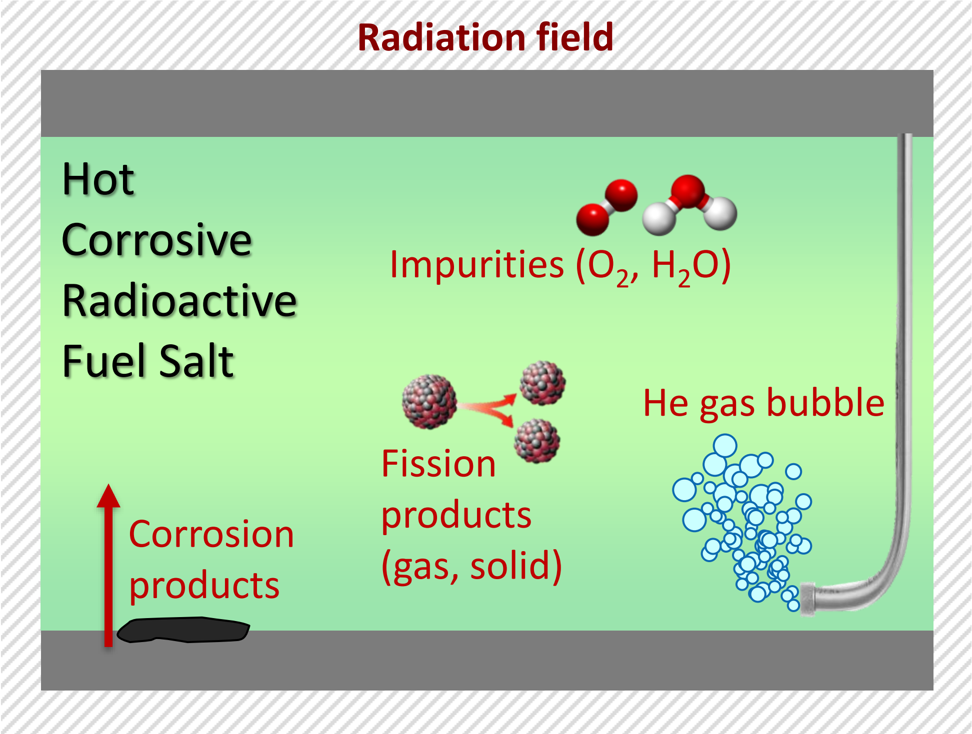
- Noble gas
- Volatile species
- Gas leak detection

Image reprocessed from “Example of a molten salt reactor scheme,” Wikipedia

Challenges in Molten Salt Monitoring Technologies

- Molten salt systems are often associated with extreme environmental constraints
  - High temperature (400–700°C)
  - Chemically aggressive molten halides
  - High radiation field
- In MSRs, system complexity even increases due to:
  - Multi-phase interaction (liquid-gas-solid)
  - Actinides transmutation
  - Fission product accumulation
  - Corrosion product accumulation
  - Impurity ingression

➔ **Conventional monitoring techniques could easily fail**



Advanced Molten Salt Monitoring Approaches

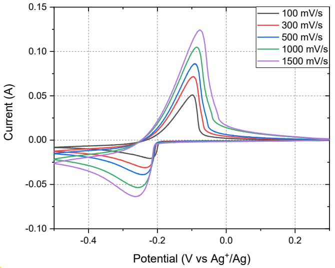
- Two advanced monitoring techniques are being actively developed worldwide to address these extreme conditions

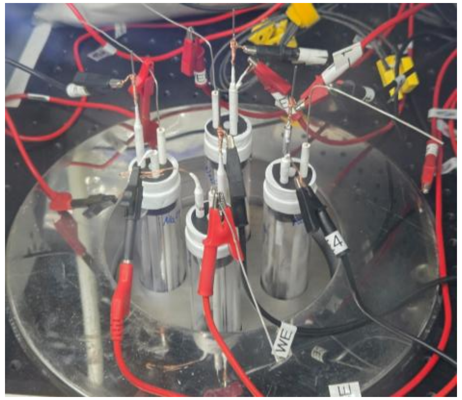
Electrochemistry-based approach

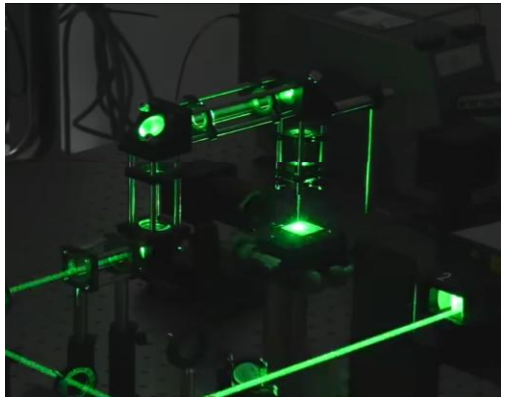
- Definition; the study of chemical processes that cause electrons to move, focusing on the relationship between electrical energy and identifiable chemical change at the interface of an electrode and an electrolyte
- As molten salts are electrolytes, they serve as conductive electrolytes that facilitate the application of electrochemical methods for characterization, monitoring, and processing

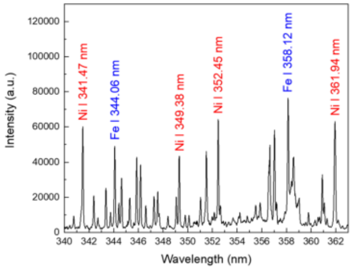
Spectroscopy-based approach

- Definition; the study of the interaction between electromagnetic radiation (i.e. light) and matter, used to analyze the absorption, emission, or scattering of light to determine the structure and composition of a substance
- As molten salts contain optically active species, they enable spectroscopic methods to identify and quantify chemical species through their electronic and vibrational signatures







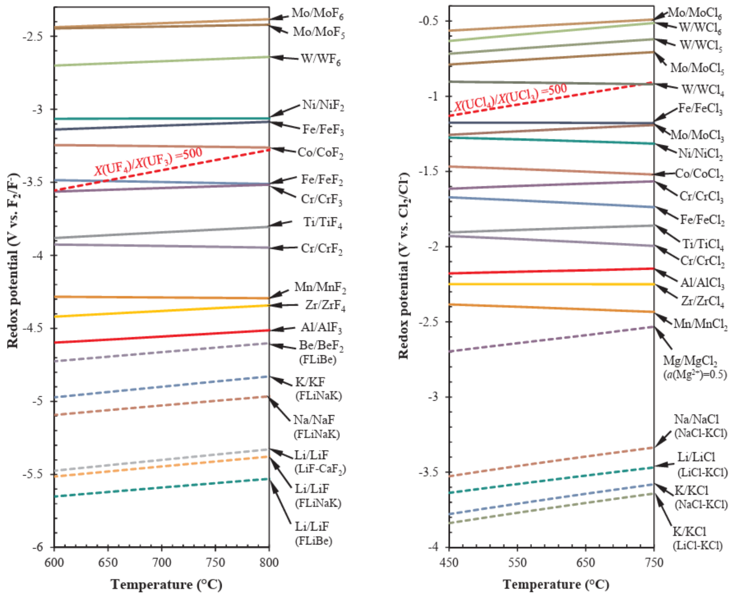


Principles of Electrochemical Monitoring Methods

- Theoretical background
  - Potentiometry
    - Measuring the potential between a working electrode and a reference electrode
    - Technique: Open circuit potential (OCP)
  - Voltammetry
    - Measuring the current when a voltage is applied to a working electrode
    - Techniques: Linear sweep voltammetry (LSV), cyclic voltammetry (CV), square wave voltammetry (SWV), etc.
- What can be monitored?
  - Redox potential of the molten salt
  - Concentration of electroactive species (corrosion products, fission products)
  - Impurities relevant to structural materials corrosion

Case 1: Redox potential monitoring

- Definition and its significance
  - The redox potential of molten salt is determined by partial pressure of chlorine or fluorine
    - $\Delta G_{X_2} \equiv RT \ln p_{X_2} \;\; (X = F, Cl)$ [1]
  - It reflects the overall oxidation-reduction state of chemical species in molten salt
    - Especially for uranium, it determines the ratio of U(Ⅳ) to U(Ⅲ), or is determined by that ratio
    - $E_{UX_4\,/UX_3} = E^0_{UX_4/UX_3} + \frac{RT}{F} \ln \frac{a_{UX_4}}{a_{UX_3}}$
  - It is related to the redox-driven corrosion
    - The corrosion behavior of structural materials can be predicted through redox potential monitoring

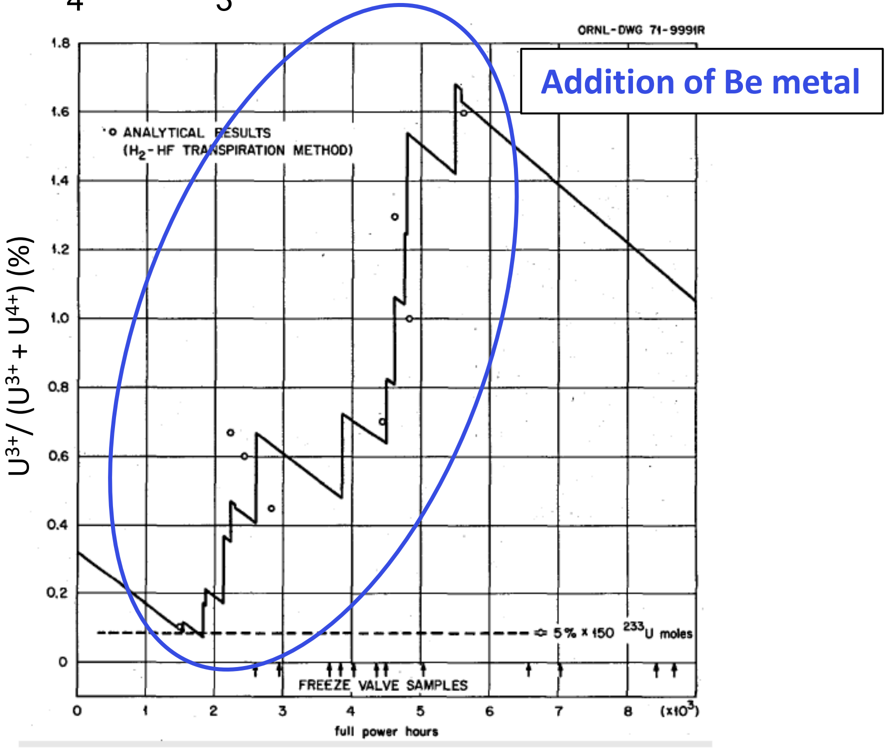


Redox potentials of various redox couples in (left) chloride and (right) fluoride [2]

[1] Olander, D., "Redox Condition in Molten Fluoride Salts Definition and Control", 2001
[2] Guo, S., et al., "Corrosion in the molten fluoride and chloride salts and materials development for nuclear applications", 2018

Case 1: Open Circuit Potential as a Redox Indicator

- Redox potential monitoring and control
  - In the MSRE, OCP value was used to estimate the ratio of U^{4+} to U^{3+}
    - The OCP was measured with platinum working electrode and Ni/NiF_2 reference electrode
  - To make a reducing environment, Be metal was added to convert UF_4 to UF_3
    - Initially the U^{4+}/U^{3+} ratio was around 250, then increased to 630 after an 1,800 hour-operation
    - The lowest value during MSRE operation was around 60
    - The Be metal produced ~600 g of UF_3 during 8-hour treatment
    - $Be + 2UF_4 = BeF_2 + 2UF_3$ (~ a rate of 600 g of UF_3 was produced)

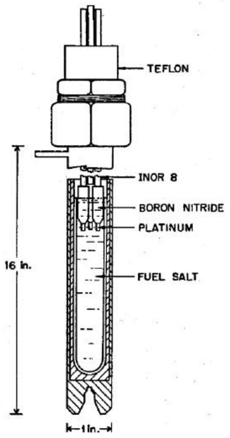


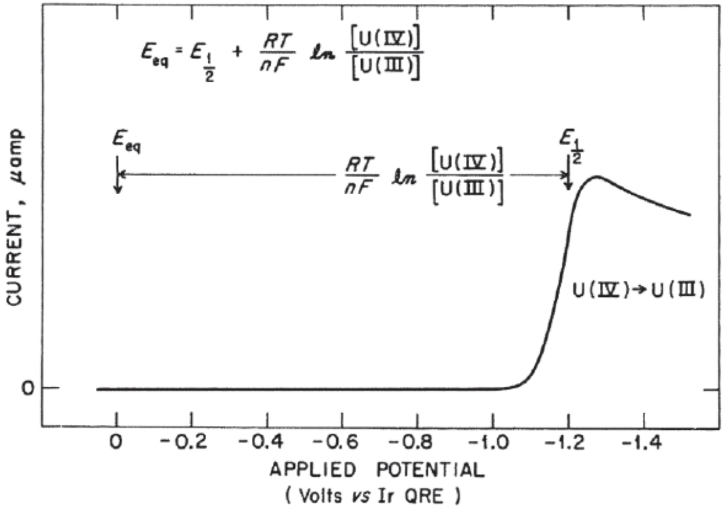
Redox changes during MSRE operation [1]

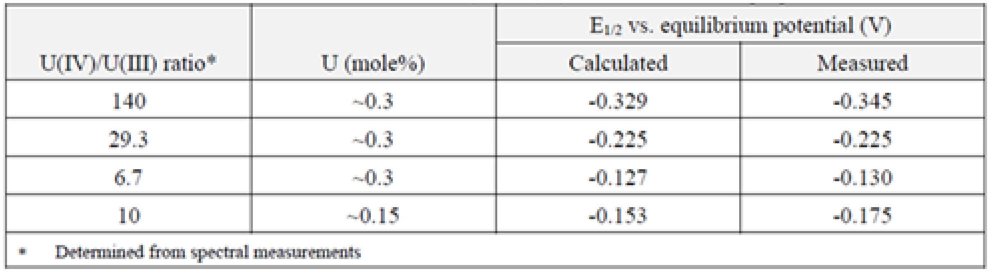
[1] Cao, G., et al., "Electrochemical Monitoring for Molten Salt Reactors: Status Review", 2025

Case 1: Linear Sweep Voltammetry as a Redox Indicator

- LSV to monitor the redox potential of molten salt
  - Along with OCP, LSV was also used to estimate the ratio of U^{4+} to U^{3+} in MSRE
    - $E_{1/2} \approx E^0\ (U(\text{IV})/U(\text{III}) = 1)$, soluble-soluble reversible reaction
    - By comparing with spectroscopy, which provides absolute values of ratio, LSV was confirmed to perform reliably







U(IV)/U(III) ratio*	U (mole%)	$E_{1/2}$ vs. equilibrium potential (V)	
		Calculated	Measured
140	~0.3	-0.329	-0.345
29.3	~0.3	-0.225	-0.225
6.7	~0.3	-0.127	-0.130
10	~0.15	-0.153	-0.175

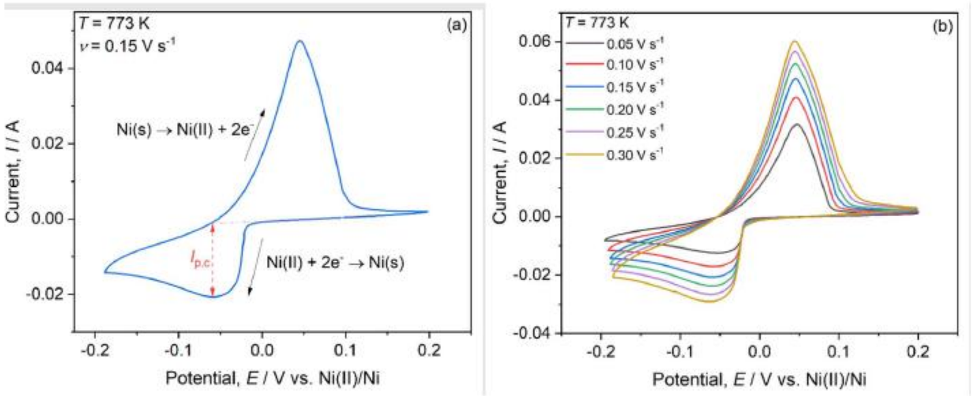
* Determined from spectral measurements

Electrochemical analysis of U(Ⅳ)/U(Ⅲ) in MSRE
(left) Electrochemical cell (center) Electrochemical analysis (right) Comparison with spectroscopy

[1] Cao, G., et al., “Electrochemical Monitoring for Molten Salt Reactors: Status Review”, 2025

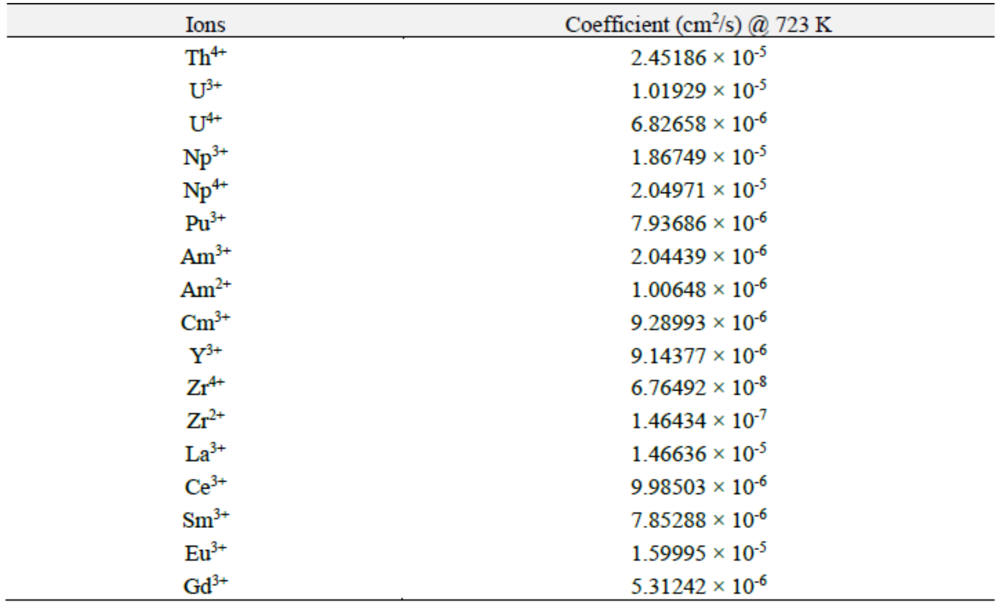
Case 2: Voltammetry for Species Identification

- CV is widely used to evaluate electrochemical properties of species in molten salts
  - Species can be identified from the peak potential, while their concentrations can be determined from the peak current
  - The diffusion coefficient is used to relate the peak current to the concentration



CV of Ni^{2+}/Ni in FLiNaK at 773 K

Summary of diffusion coefficient in LiCl-KCl at 723 K

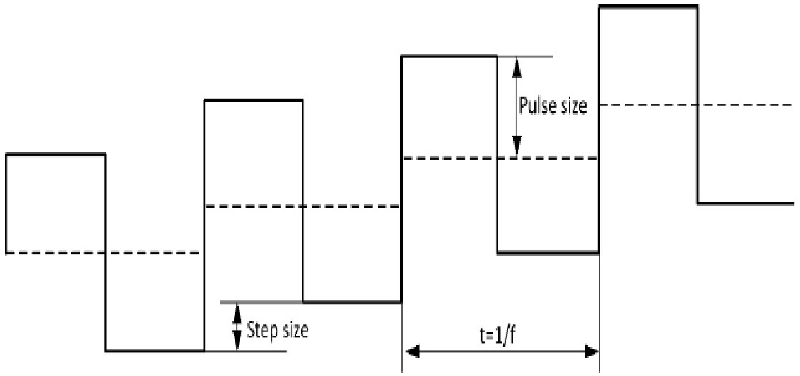


Ions	Coefficient (cm^2/s) @ 723 K
Th^{4+}	2.45186×10^{-5}
U^{3+}	1.01929×10^{-5}
U^{4+}	6.82658×10^{-6}
Np^{3+}	1.86749×10^{-5}
Np^{4+}	2.04971×10^{-5}
Pu^{3+}	7.93686×10^{-6}
Am^{3+}	2.04439×10^{-6}
Am^{2+}	1.00648×10^{-6}
Cm^{3+}	9.28993×10^{-6}
Y^{3+}	9.14377×10^{-6}
Zr^{4+}	6.76492×10^{-8}
Zr^{2+}	1.46434×10^{-7}
La^{3+}	1.46636×10^{-5}
Ce^{3+}	9.98503×10^{-6}
Sm^{3+}	7.85288×10^{-6}
Eu^{3+}	1.59995×10^{-5}
Gd^{3+}	5.31242×10^{-6}

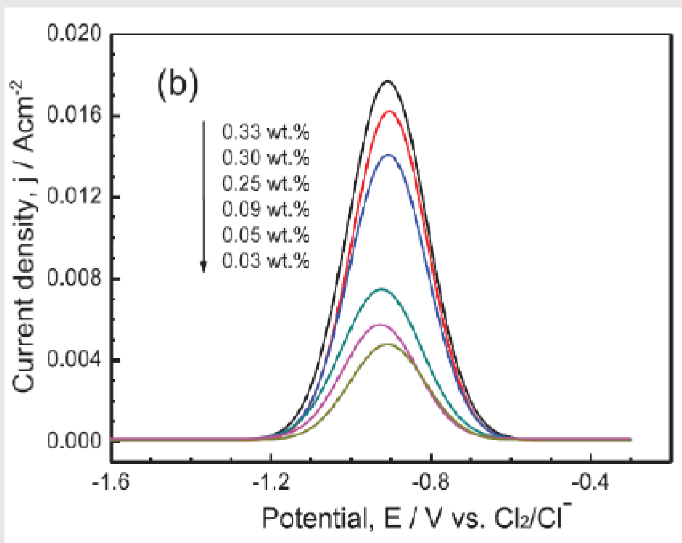
[1] Cao, G., et al., "Electrochemical Monitoring for Molten Salt Reactors: Status Review", 2025

Case 2: Voltammetry for Species Identification

- SWV is used to detect low concentration species in molten salt with high sensitivity
  - Compared to CV, SWV minimizes non-Faradic current enabling low detection limit
  - Several studies have applied SWV to quantify oxide concentrations in molten salts, which is crucial for corrosion monitoring and system integrity



Schematic of SWV

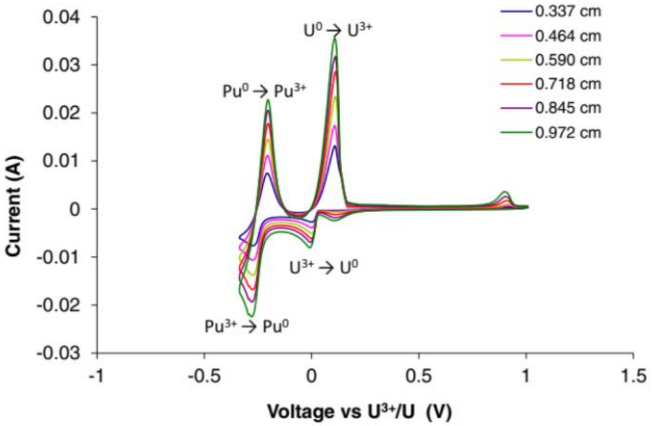


SWV of NaCl-KCl-Na_2O for various oxide contents

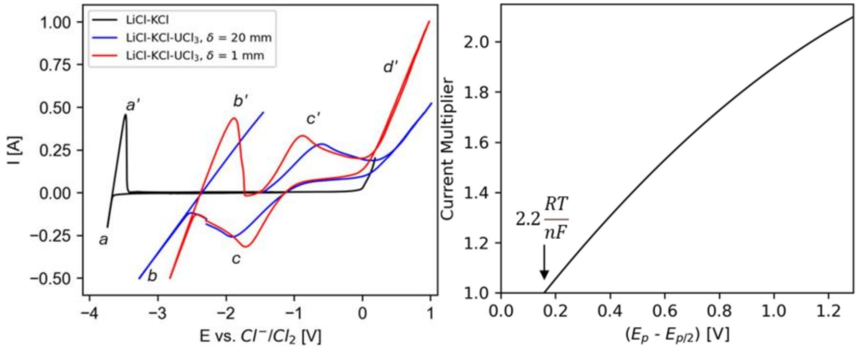
[1] Cao, G., et al., "Electrochemical Monitoring for Molten Salt Reactors: Status Review", 2025

Case 2: Electrochemical Monitoring of Actinides

- Actinides, especially U and Pu, are primary targets for monitoring
  - They affect reactor criticality and sustainability
  - They must be quantified for safeguards and material accountancy
  - In salt-fueled systems, U is often the dominant actinide and largely defines the electrochemical potential window
- High U concentration has been a persistent challenge
  - Large uncompensated resistance distorts electrochemical signals
  - Earlier studies were largely limited to the U(III)/U(0) reaction and to concentrations below practical fuel-salt levels (up to 60 wt% U)
  - Recent ANL work has proposed a current multiplier (CM) method to correct peak-current distortion at high concentration



Cyclic voltammograms obtained at different immersion depths of WE (v= 50mV/s) [1]

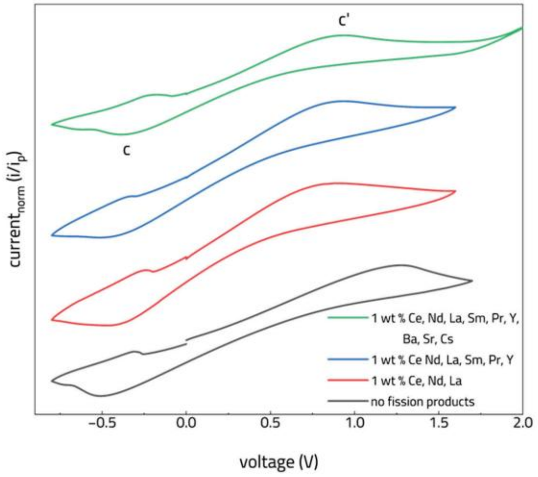


(left) Cyclic voltammograms of LiCl-KCl eutectic and LiCl-KCl-UCl_3 (right) Current multiplier (CM) as a function of the difference between the anodic peak potential and the half-peak potential, assuming a single-electron, soluble–soluble reaction at 550 °C. [2]

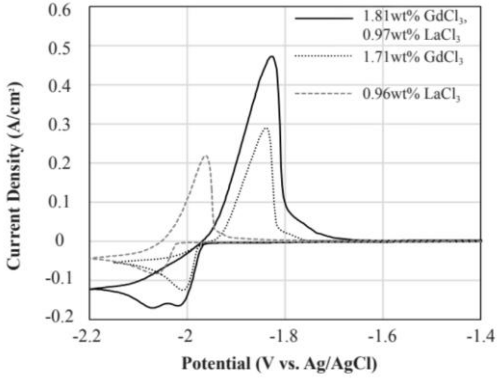
[1] Cao, G., et al., “Electrochemical Monitoring for Molten Salt Reactors: Status Review”, 2025

Case 3: Electrochemical Monitoring of Fission Products

- While some fission products are removed during operation through off-gas release or insoluble-phase separation, soluble species continue to circulate with the salt
  - Many lanthanides remain dissolved
  - Some act as neutron poisons and require quantification
  - They may also reflect reactor operation history and salt condition
- Electrochemical monitoring of fission products remains challenging
  - The accessible species are constrained by the electrochemical window, largely defined by uranium
  - Low concentration levels often require advanced electrochemical methods
  - Coupled reaction pathways (e.g. ECEC reaction) may further complicate signal interpretation



Cyclic voltammograms of LiCl-KCl-UCl with various additions of fission product surrogates. [2]

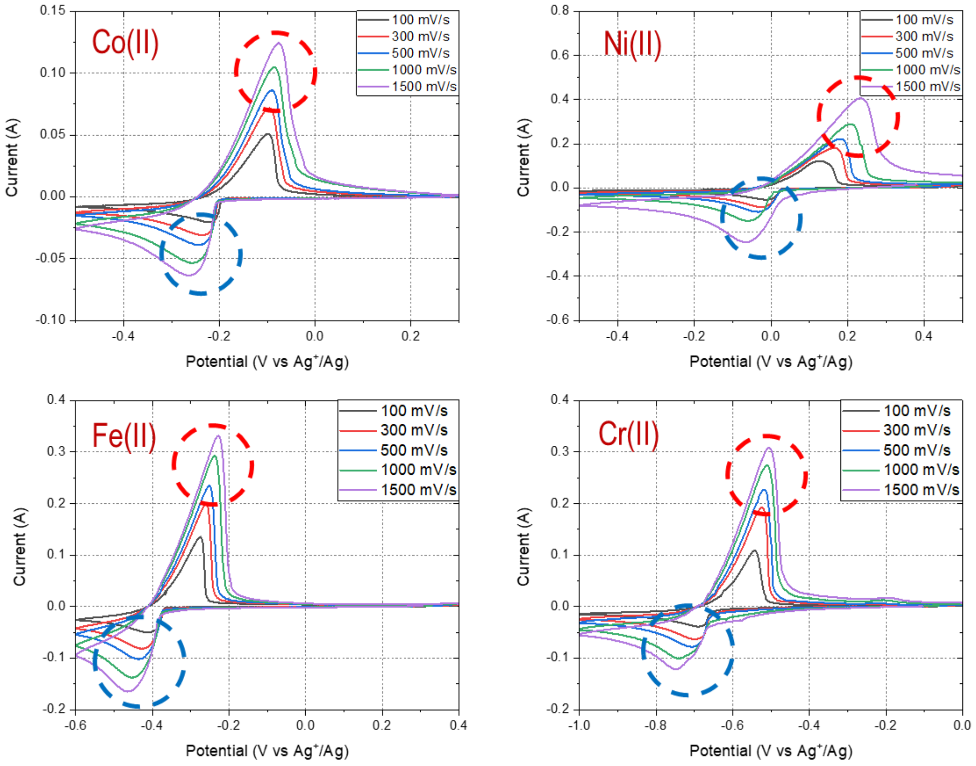


Cyclic voltammograms of LiCl-KCl with La and Gd at 100 mV/s [3]

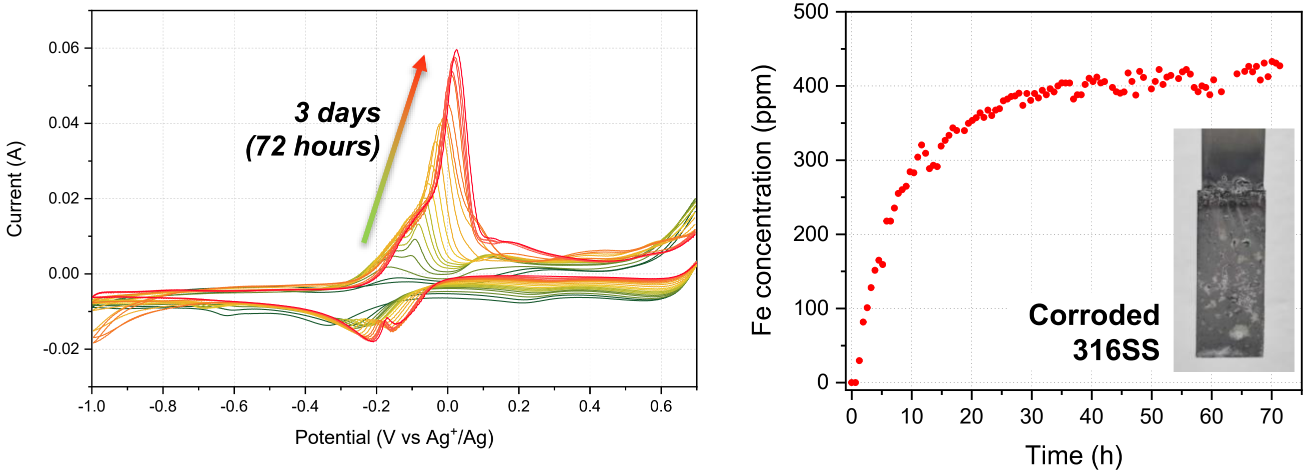
[1] Yang, W., et al., "Electrochemical Monitoring for Molten Salt Pyroprocessing of Spent Nuclear Fuel: A Review", 2024
[2] Doniger, W. H., et al., "Flow Enhanced Electrochemical Sensor Performance in Complex Salt Systems", 2025
[3] Rappleye, D., et al. "Application of Voltammetry to Measurement of Concentrations of Multiple Lanthanide Ions in Molten LiCl-KCl", 2015

Case 4: Electrochemical Monitoring of Corrosion Products

- Evaluation of thermodynamic and kinetic parameters of typical corrosion products



- Long-term in-situ monitoring of corrosion products released into 550°C NaCl-MgCl$_2$
  - 316SS produce Fe ions when corroded
  - The corresponding Fe peaks in CV were compared with ICP-OES analysis results

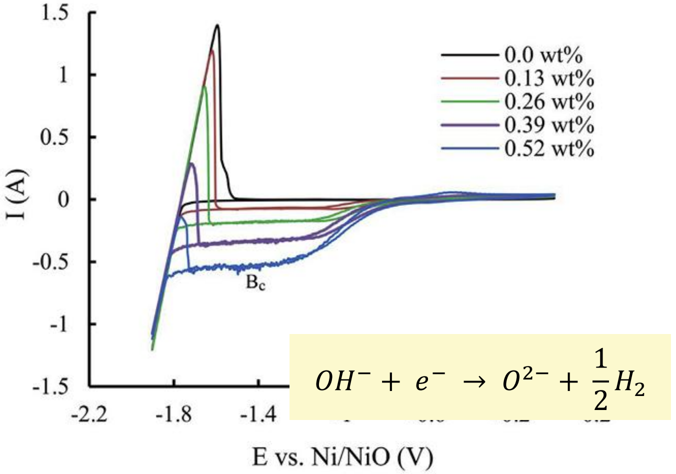


(left) Accumulated CVs of NaCl-MgCl$_2$ containing 316SS for 72 hours
(right) Concentration of Fe in the bulk salt quantified by ICP-OES

[1] Yoon, S. and Choi, S., "Spectroelectrochemical Behavior of Cr, Fe, Co, and Ni in LiCl-KCl Molten Salt for Decontaminating Radioactive Metallic Wastes", 2021
[2] Doniger, W. H., et al., "Quantitative Voltammetry Measurements of High-Concentration Actinides in Molten Chloride Fuel Salts.", 2025

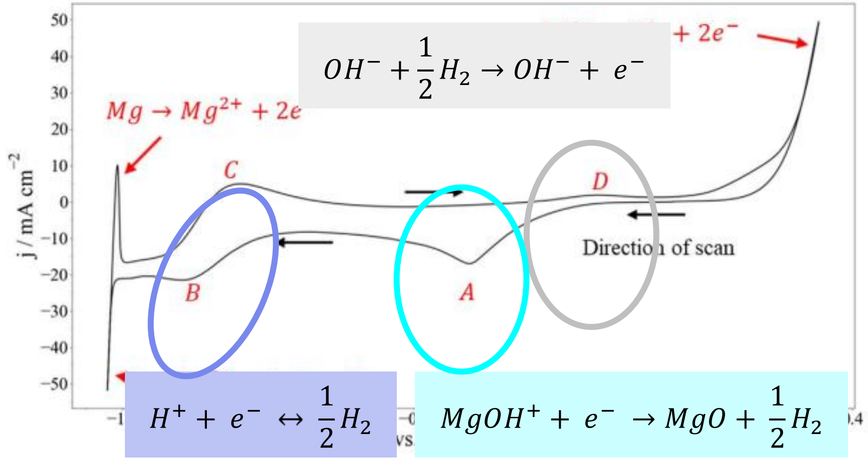
Case 5: Electrochemical Monitoring of Impurities

- When moisture interacts with molten salts, several reactions can occur [1]
  - $H_2O + 2X^- = O^{2-} + 2HX$
  - $H_2O + X^- = OH^- + HX$
  - $OH^- + X^- = O^{2-} + HX$
  - $xM + yH_2O = M_xO_y + yH_2$
- There have been attempts to detect moisture-induced ions or byproducts
  - In LiCl molten salt, the baseline shift was observed
  - In molten salts containing MgCl the reduction of MgOHCl was typically observed.



$OH^- + e^- \rightarrow O^{2-} + \frac{1}{2}H_2$

CV of LiCl varying LiOH concentration [2]



$OH^- + \frac{1}{2}H_2 \rightarrow OH^- + e^-$

$H^+ + e^- \leftrightarrow \frac{1}{2}H_2$

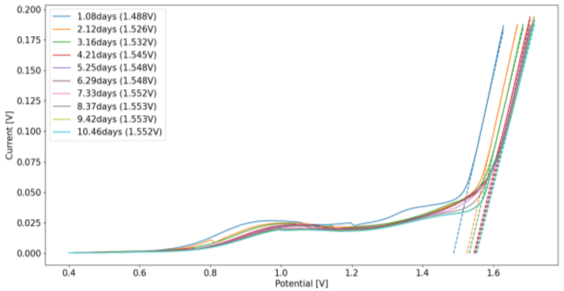
$MgOH^+ + e^- \rightarrow MgO + \frac{1}{2}H_2$

CV of NaCl-KCl-$MgCl_2$ [3]

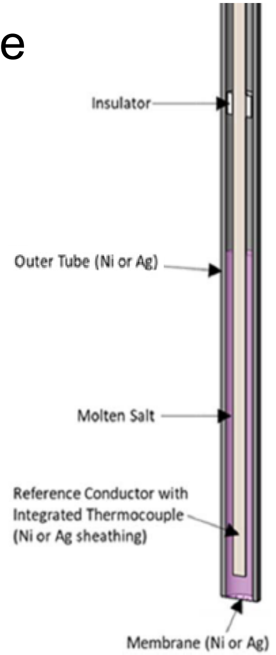
[1] Schneider, A., et al., “Mechanistic study of moisture corrosion of FeCr alloys in molten salts by ab-initio molecular dynamics simulations”, 2024
[2] Gonzalez, M., et al., “Identification, measurement, and mitigation of key impurities in LiCl-Li_2O used for direct electrolytic reduction of UO_2”, 2018
[3] Witteman, L., et al., “Continuous Purification of Molten Chloride Salt: Electrochemical Behavior of MgOHCl Reduction”, 2023

Reference electrode

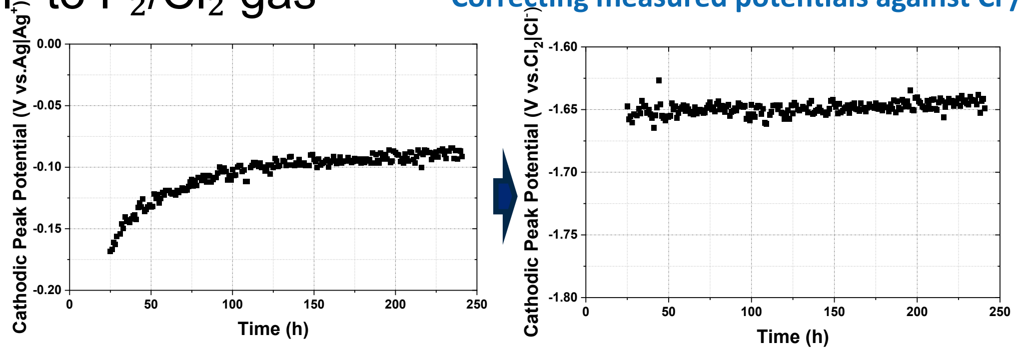
- Although monitoring electrochemical potential via OCP or voltametric methods is a simple approach, development of a long-term stable reference electrode (RE) remains challenging
  - The most problem lies in the container, which should be porous to enable ion conductivity but is difficult to operate under high-temperature and high-radiation conditions
  - The long-term operation of graphite and boron nitride containers for reference salts, which are typically used in fluoride salts, has not been verified [1]
    - The RE with boron nitride container was stable up to 12 days
  - Recently, there have been attempts to use metal containers, but further improvements are still needed [2]
  - Also, correcting measured potentials against the well-defined oxidation potential of F^-/Cl^- to F_2/Cl_2 gas
    - Bypassing long-term RE degradation



Correcting measured potentials against Cl^-/Cl_2



Reference electrode using metal membrane [2]



Stable cathodic peak potential of Fe^{2+}/Fe secured over 250 h via LSV of $Cl_2|Cl^-$

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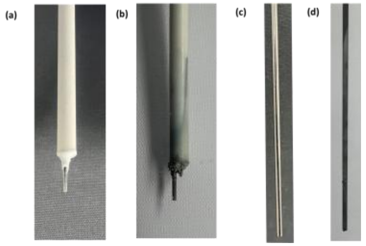
[1] Holcomb, D. E., "Instrumentation Framework for Molten Salt Reactors", 2018

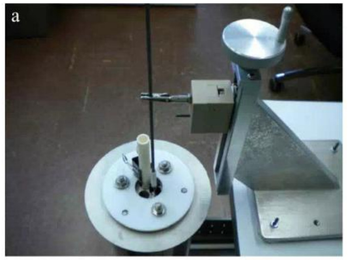
[2] Newton, M., et al., "Stability of a Ni/NiF_2 Reference Electrode with a Metallic Membrane for Use in Molten Fluoride Salts", 2024

Working Electrode Area

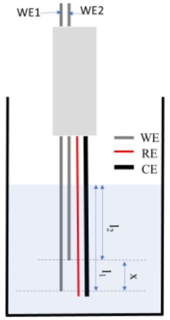
- Quantitative voltammetry requires a well-defined working-electrode area, but stable fixation in molten salts remains challenging under harsh, long-duration conditions
  - Immersion depth is hard to directly measure in opaque, high-temperature systems
- Several approaches exploit relative length differences instead of absolute area
  - Electrode withdrawal method [1]: stepwise control of immersion depth; not real-time
  - Multiarray electrode [2]: multiple WEs with well-defined length differences; real-time capable
- ML-assisted multiarray sensing extends this relative-area concept [3]
  - Trained on 3,432 electrochemical data points, the ML model predicts effective immersed length/area from inter-electrode feature ratios with MAPE < 6 % across diverse molten-salt systems



Fixed-area failure [3]



Electrode withdrawal setup [1]



Multiarray electrode schematic [3]

Relation: $i_p \propto A = 2\pi rl + \pi r^2$

Guo [2]: $\Delta i_p \propto \Delta A = \Delta l$

Yang [3]: $i_p^{long}/i_p^{short} = A^{long}/A^{short} \approx l^{long}/l^{short}$

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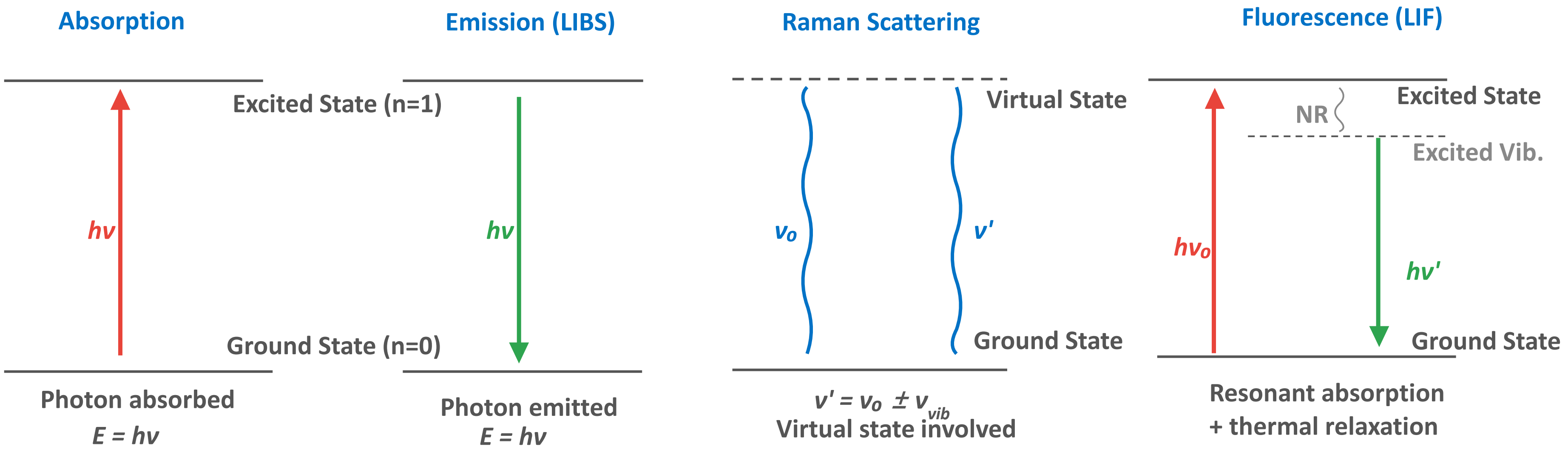
[1] Tylka, M. M., et al., "Method development for quantitative analysis of actinides in molten salts.", 2015
[2] Guo, J., et al., "Multielectrode array sensors to enable long-duration corrosion monitoring and control of concentrating solar power systems", 2021
[3] Yang, W., et al., "Machine Learning-Enhanced Electrochemical Sensors for High-Temperature Molten Salts Enabled by Rich Experimental Data Production.", under revision

Laser-based Spectroscopy for Molten Salt Monitoring

- **Three fundamental light-matter interactions:**
  - Absorption: species-selective attenuation of incident light
  - Emission: characteristic photon release from excited atoms/ions (LIBS)
  - Scattering: inelastic photon scattering revealing molecular vibrations (Raman)
- Additional mode: Fluorescence - resonant absorption followed by re-emission (LIF)

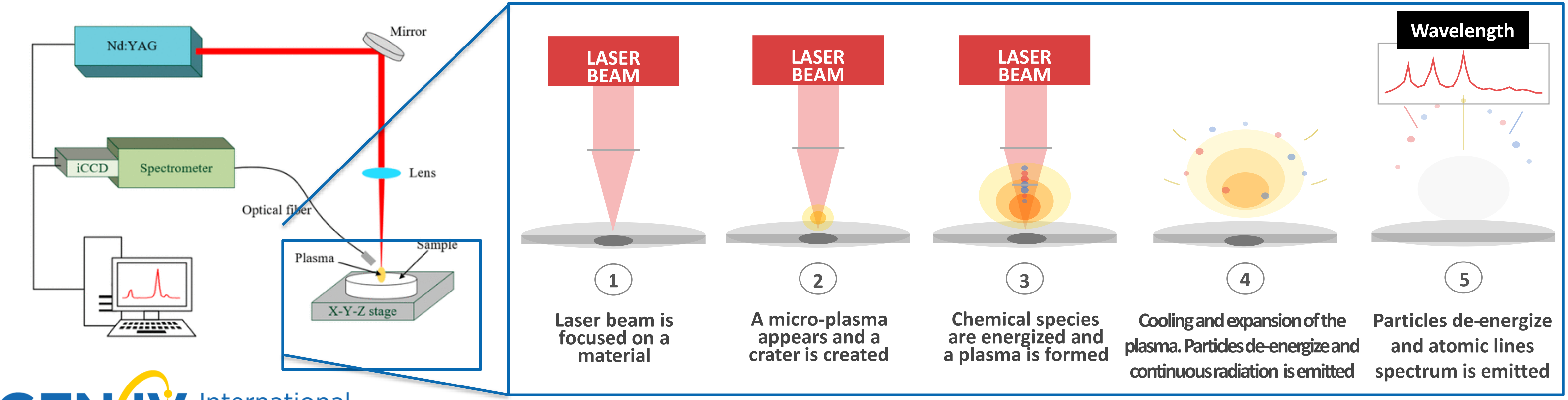


Four Fundamental Light-Matter Interactions in Spectroscopy

Laser induced breakdown spectroscopy (LIBS)

- Analytical technique where laser is used to vaporized a small portion of a sample, creating a plasma, and the emitted light from this plasma is then analyzed determine the elemental composition
- Advantages

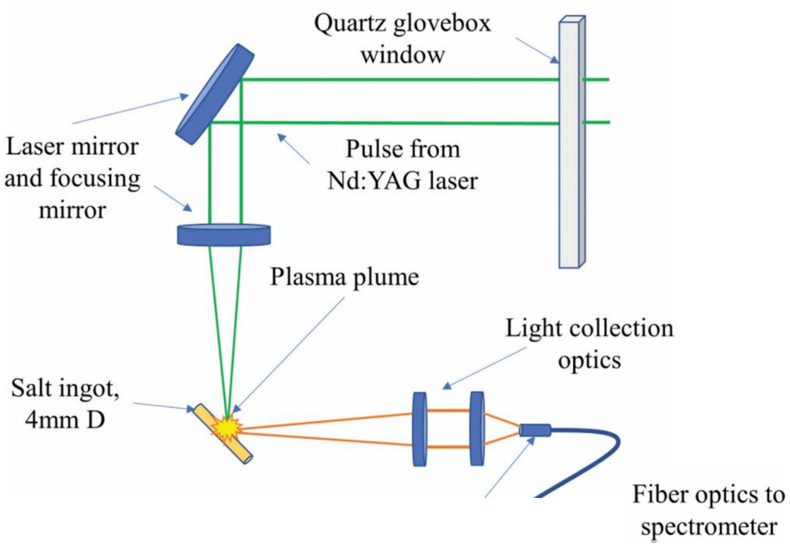
(1) No sample preparation (2) Remote (3) Noninvasive (4) Real-time monitoring (5) Multi-element detection



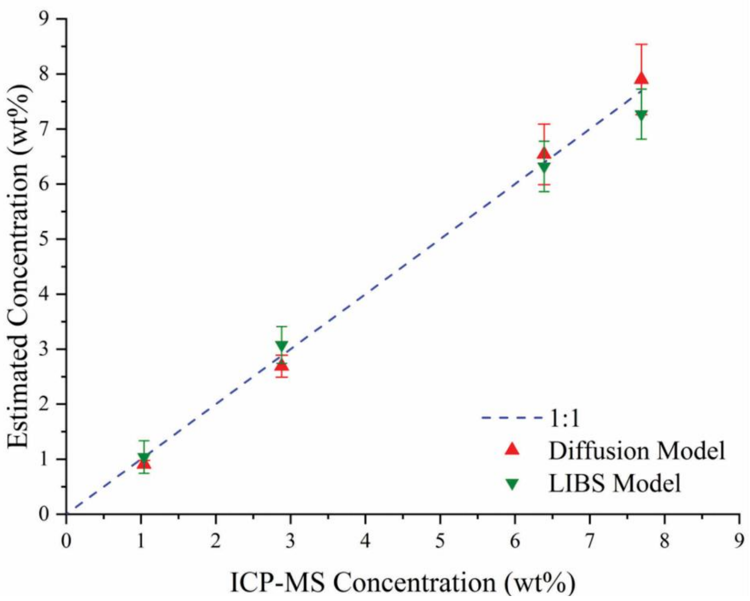
Process of Laser Irradiation on the Sample and Plasma Generation

Case 1: Solid-LIBS

- Solidified salt ingots provide a stable, reproducible matrix for LIBS quantification
  - Molten LiCl-KCl drawn into a Pyrex tube and frozen into 4 mm cylindrical shapes
  - Calibration on Sm I peaks (484.8 / 490.5 / 546.7 nm): LOD ~0.5 wt.%, RMSEC ~0.5 wt.% [1]
  - Validated against ICP-MS over 1-8 wt.% - relevant to electrorefiner salt composition



LIBS setup with solidified salt ingot inside the glovebox

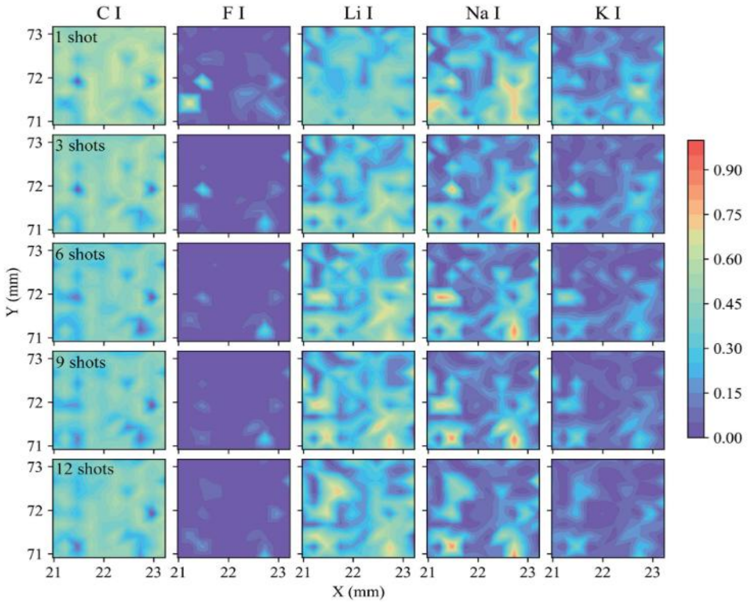


LIBS-estimated $SmCl_3$ concentrations match ICP-MS measurements (1–8 wt%)

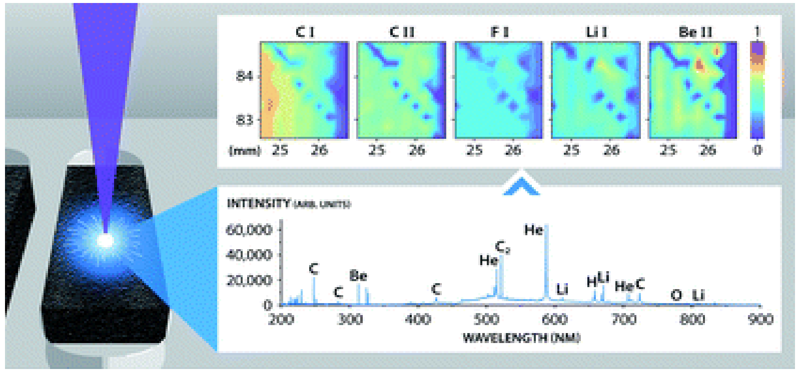
[1] Andrews, H. B., et al., “Development of an Experimental Routine for Electrochemical and Laser-Induced Breakdown Spectroscopy Composition Measurements of $SmCl_3$ in LiCl-KCl Eutectic Salt Systems”, 2019.

Case 1: Solid-LIBS

- 3D LIBS reveals molten salt infiltration in graphite, enabling quantitative evaluation of MSR material degradation
  - To analyze molten salt infiltration in graphite using 3D LIBS
  - 3D mapping via LIBS depth profiling and scanning
  - Li and F penetrate tens-hundreds of µm with salt-dependent behavior
  - Enables quantitative evaluation of MSR material degradation



Depth-resolved LIBS mapping showing Li and F infiltration in graphite [1]



Schematic illustration of LIBS-based elemental mapping from emission spectra [1]

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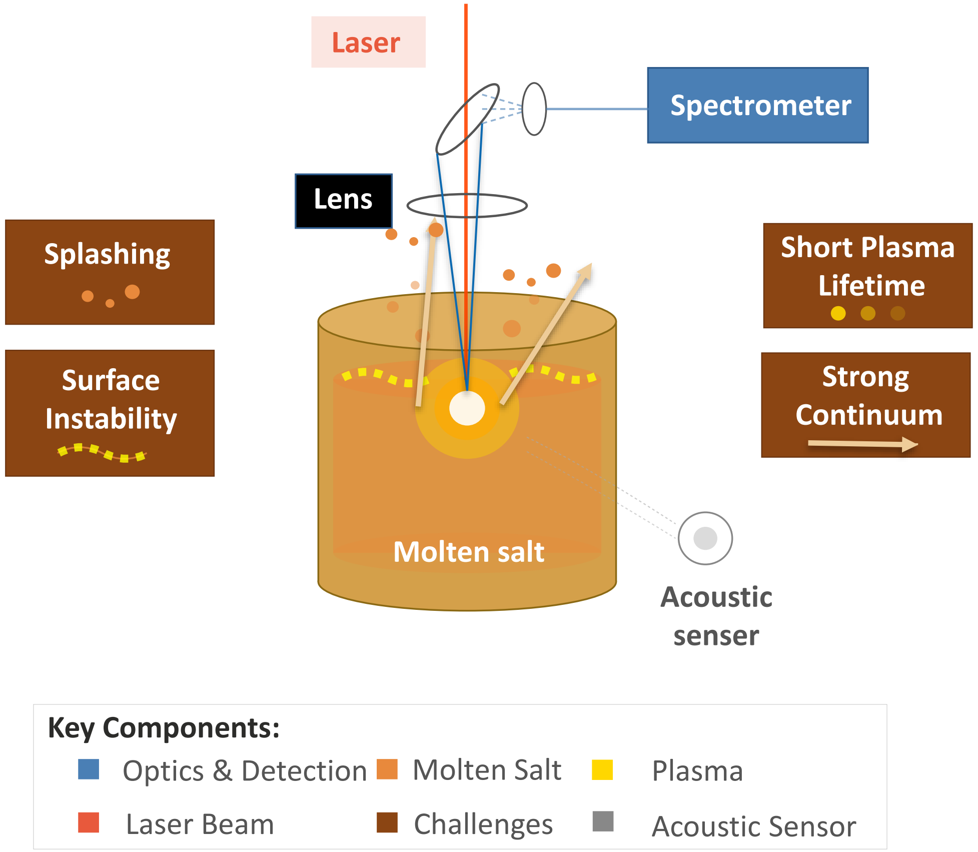
[1] Myhre, K. G., et al., “Approach to Using 3D Laser-Induced Breakdown Spectroscopy (LIBS) Data to Explore the Interaction of FLiNaK and FLiBe Molten Salts with Nuclear-Grade Graphite”, 2022

Case 2: Direct LIBS on Liquid Molten Salt

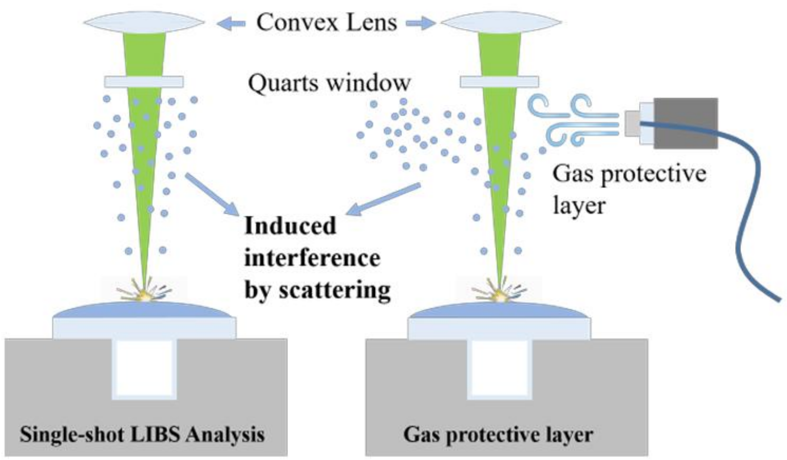
- Real-time monitoring requires direct laser ablation on liquid salt surface
- **Key challenges:**
  - **Splashing:** liquid ejection contaminates optics, disrupts plasma formation
  - **Surface instability:** fluctuating salt level changes laser focus position
  - **Strong continuum emission:** high background from hot dense plasma near liquid
  - **Short plasma lifetime**: rapid quenching by surrounding high-temperature medium

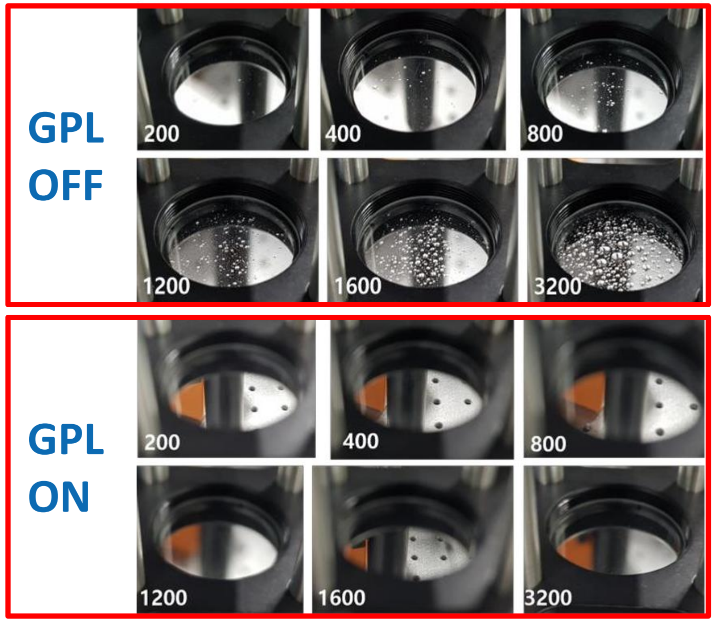


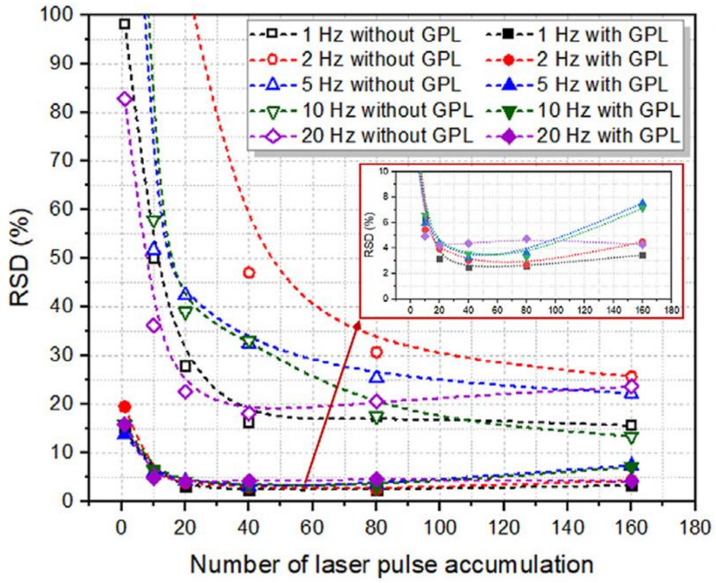
Liquid LIBS on Molten Salt: Challenges & Setup [1]

Case 2: Liquid-LIBS (Gas Protective Layer)

- Gas-protective layer (GPL) suppresses droplet-induced splashing and stabilizes plasma formation
  - Maintains a clean optical path during repeated laser shots, enabling signal accumulation
- Significant improvement in detection performance
  - LOD reduced from ~245 ppm to ~15 ppm for Sr in LiCl-KCl [1]
  - Enables reliable signal accumulation







Reasonable RSDs of about 2–4% were consistently for 40 pulses for all repetition rates [1]

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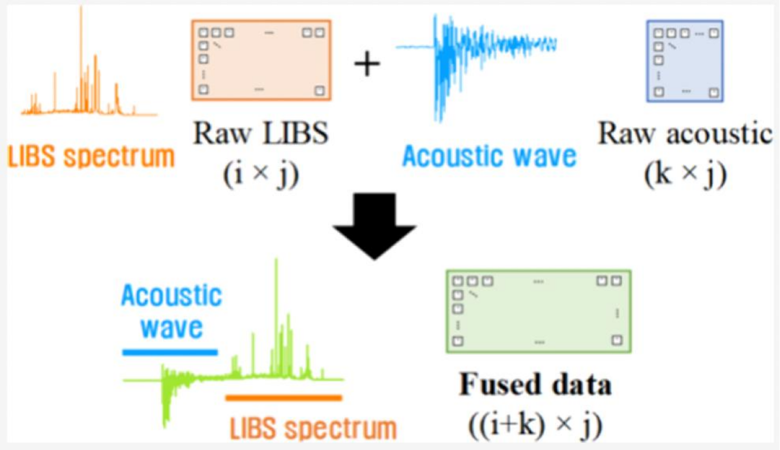
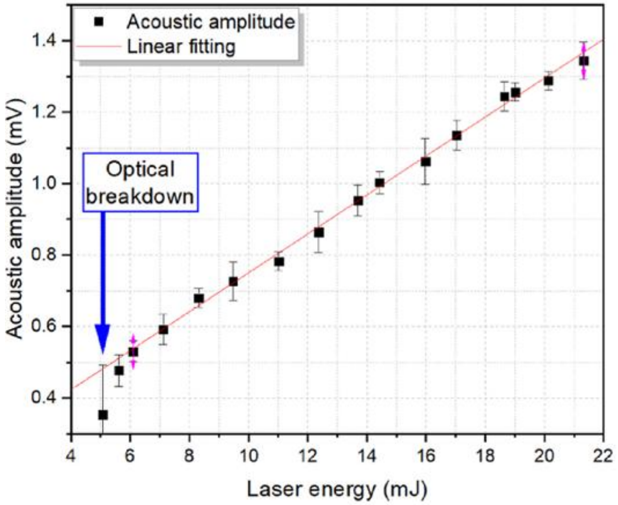
[1] Lee, Y., et al., "In-situ measurement of Ce concentration in high-temperature molten salts using acoustic-assisted laser-induced breakdown spectroscopy with gas protective layer", 2022

Case 2: Liquid-LIBS (Acoustic-assisted)

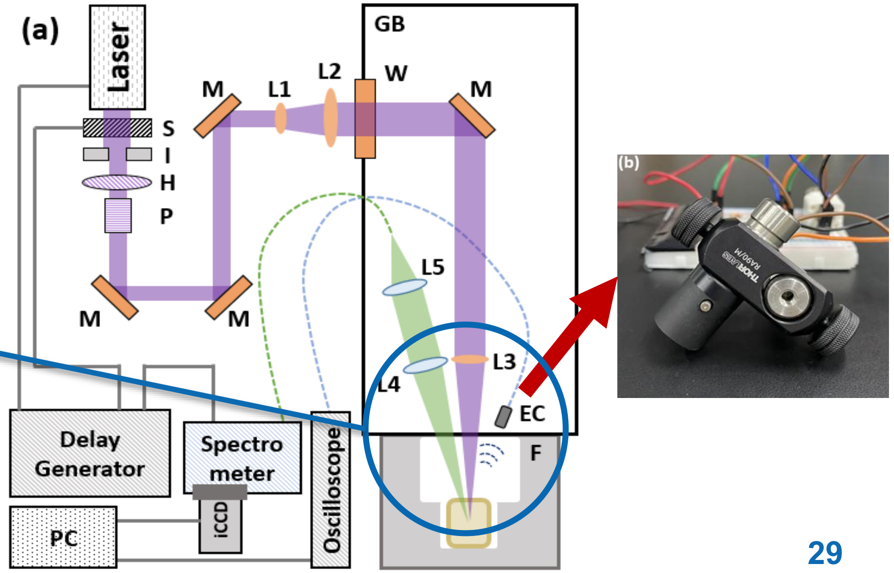
- The glove box was carefully customized for the molten salt LIBS monitoring system
  - Movable furnace can control the lens-to-sample distance
  - Gas protective layer can block the contamination of optical lenses
  - Acoustic signal measurements simultaneously with LIBS signals



Schematic of the molten salt LIBS system with acoustic signal acquisition for lens-to-sample distance estimation



The LIA amplitudes exhibited a linear increase with laser energy[1]



Electret condenser for measuring lens-to-sample-distance

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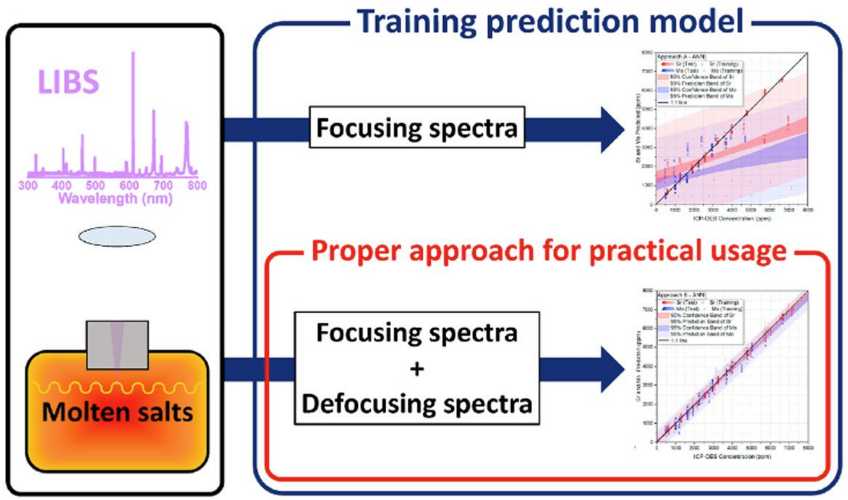
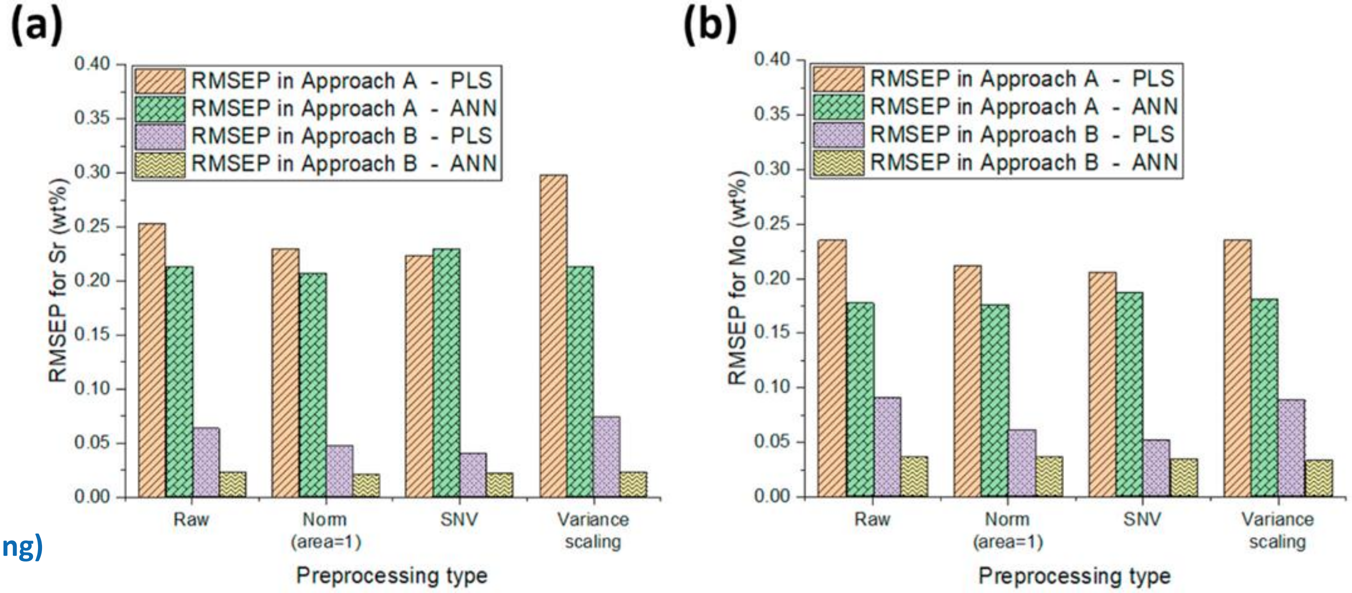
[1] Lee, Y., et al., "Acoustic-filtered laser-induced breakdown spectroscopy for monitoring fission products in molten LiCl–KCl eutectic during salt fluctuations", 2026

Case 2: Liquid-LIBS (Machine Learning-assisted)

- AI-assisted LIBS
  - Salt level fluctuates ±7.5 mm → laser defocusing distorts LIBS spectra
  - Proposed Approach B: train ML models with both focused and defocused spectra
  - ANN + Approach B: RMSEP improved ~10× (0.19 → 0.02 wt%) for Sr and Mo in LiCl-KCl



Conceptual model: Approach A (focus only) vs. Approach B (focus + defocus training)



RMSEP comparison of PLS and ANN under two training strategies for (a) Sr and (b) Mo in molten LiCl–KCl[1]

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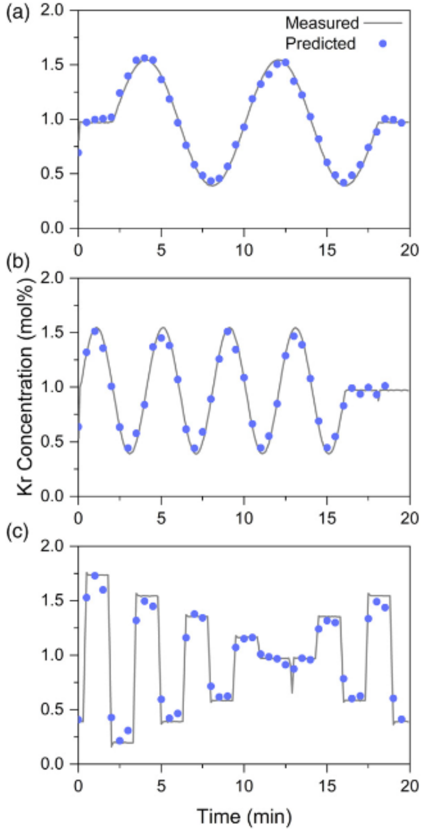
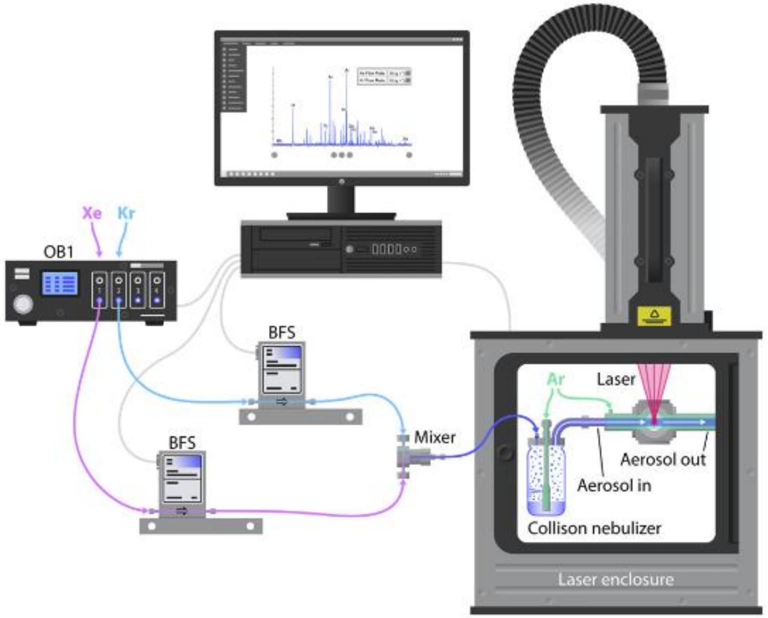
[1] Lee, Y., et al., "Machine learning-assisted laser-induced breakdown spectroscopy for monitoring molten salt compositions of small modular reactor fuel under varying laser focus positions", 2023

Case 3: Gas and Aerosol LIBS

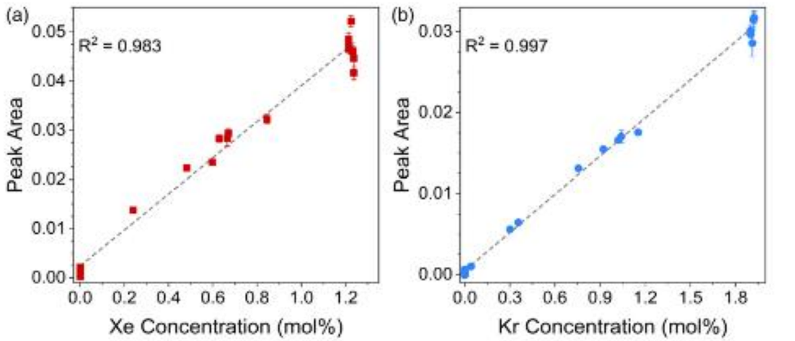
- LIBS enables real-time monitoring of noble gases and aerosols in MSR off-gas, mostly led by the ORNL
  - LIBS applied to surrogate MSR off-gas: simultaneous detection of noble gases (Xe, Kr) and aerosols (Cs, Rb)
  - Strong correlation between LIBS signals and concentration and successful real-time tracking
  - Demonstrates in-situ, multi-species monitoring capability for MSR off-gas system



Real-time monitoring of Kr concentration demonstrating dynamic tracking capability of LIBS [1]



Schematic of LIBS system for monitoring gas and aerosol in MSR off-gas

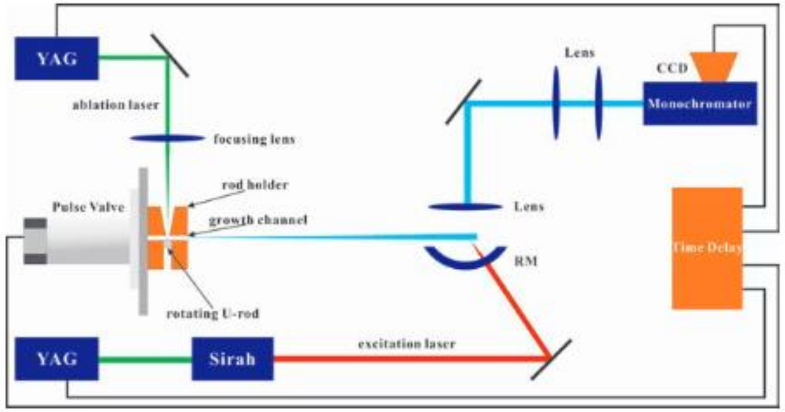


Calibration curves showing strong correlation between LIBS signal and gas concentration [1]

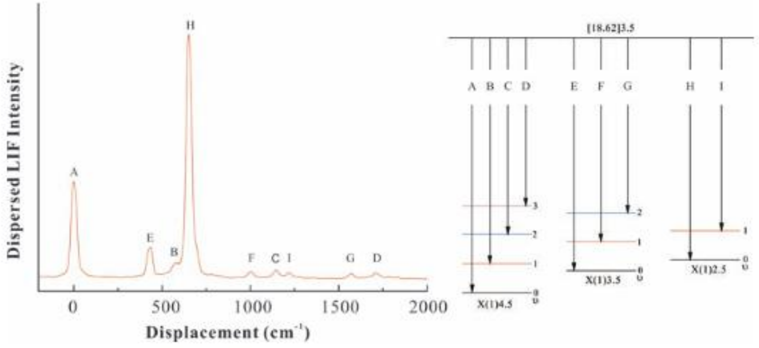
[1] Andrews, H. B., et al., “Monitoring Noble Gases (Xe and Kr) and Aerosols (Cs and Rb) in a Molten Salt Reactor Surrogate Off-Gas Stream Using Laser-Induced Breakdown Spectroscopy (LIBS)”, 2022

Case 4: Laser-induced Fluorescence (LIF)

- LIF enables selective detection of uranium species and electronic states in nuclear systems
  - LIF selectively detects uranium species via resonant excitation + dispersed fluorescence
  - Distinct spectra and lifetimes reveal different electronic/vibrational states of UF
  - High-sensitivity speciation capability for actinide chemistry in nuclear fuel systems



Schematic of LIF experimental setup for detecting uranium species

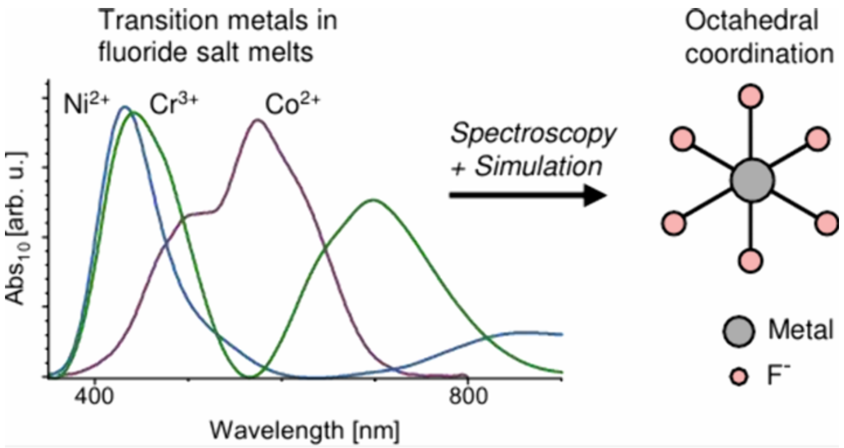


Dispersed fluorescence spectrum showing state-specific emission of uranium species

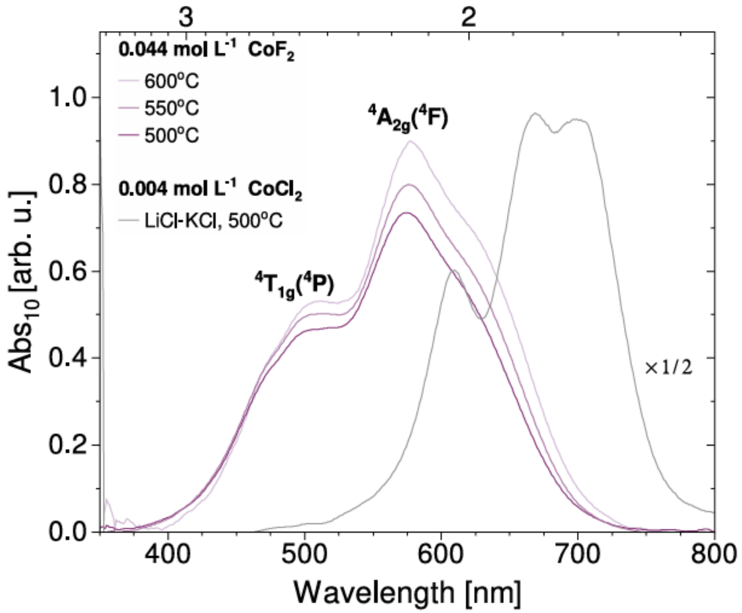
[1] Bai, X.-L. et al., “Laser-induced fluorescence spectroscopy of uranium monofluoride”, 2022.

Case 5: UV-Vis Absorption

- UV-vis optical cell design for corrosive salt
  - Fluoride melts (FLiNaK) are highly corrosive → INL developed BN + sapphire + gold gasket optical cell
  - Measured electronic absorption of Co^{2+}, Ni^{2+}, Cr^{3+} at 500–600°C: all in octahedral F^- coordination
  - Very weak absorptivity in fluorides vs. chlorides → longer optical paths needed



Spectroscopy + AIMD simulation reveal octahedral F^- coordination of corrosion products in FLiNaK

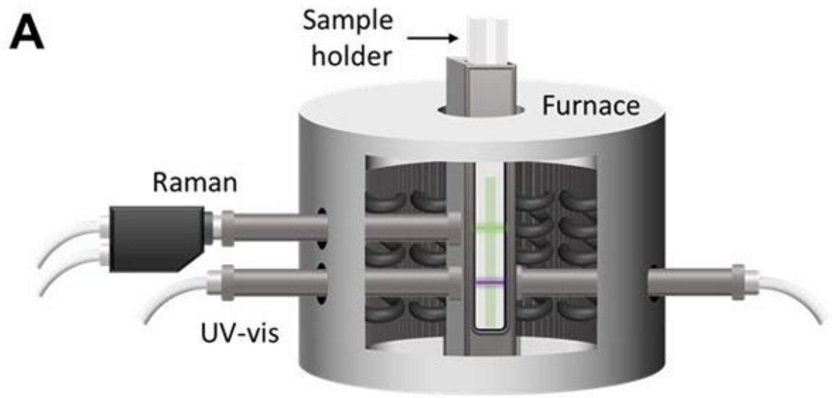


Co^{2+} absorption in FLiNaK (octahedral) vs. LiCl-KCl (tetrahedral): coordination geometry governs spectral intensity [1]

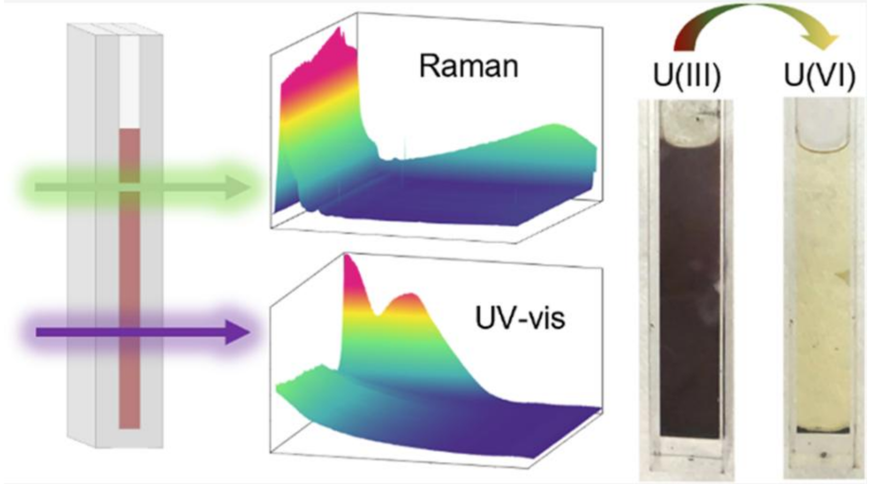
[1] LeCroy, G. S., et al., "Versatile Cell Design for Molten Fluoride Salt Spectroscopy: Investigating Metal-Ion Speciation in Molten Fluoride Salts", 2025

Case 6: Raman coupled with UV-Vis

- In-situ monitoring of U redox in chloride melts
  - PNNL developed simultaneous UV-Vis + Raman fiber optic probe system for molten salt monitoring
  - Tracked U(III)/U(IV)/U(VI) speciation in real time; first-ever Pu(III) optical fingerprint at 550°C
  - Challenge: spectral overlap between U/Pu/Nd/Co → chemometrics + wavelength expansion needed



Small-scale furnace with simultaneous Raman and UV-Vis fiber optic probes for molten salt characterization



Simultaneous Raman and UV-vis monitoring of uranium oxidation states (U(III) → U(VI)) in molten chloride salts via a quartz cuvette furnace system [1]

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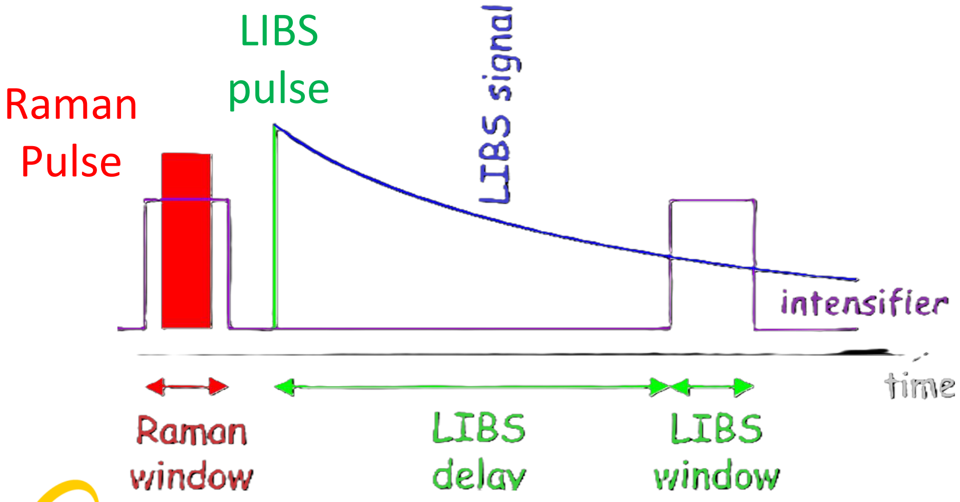
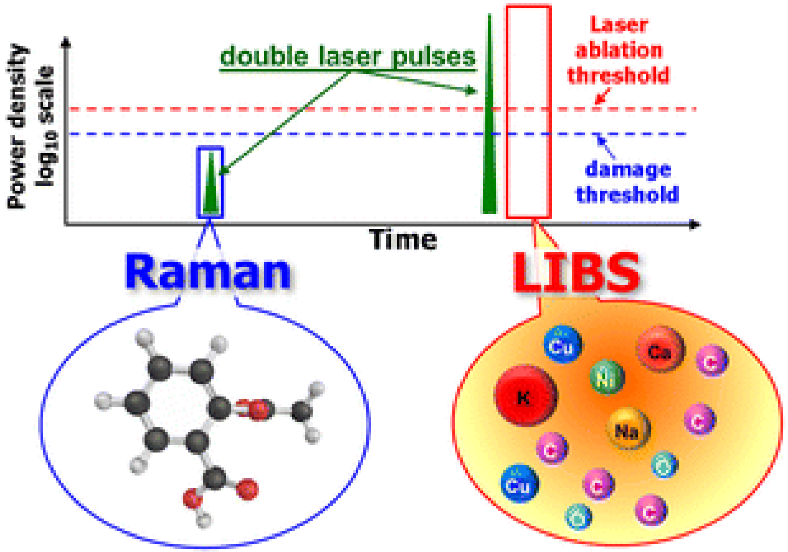
[1] Branch, S. D., et al., “Exploring the Complex Chemistry of Uranium within Molten Chloride Salts”, 2023

Case 6: Raman coupled with LIBS

- Raman spectroscopy and LIBS are representative laser-based techniques for chemical analysis
- Raman provides molecular-level structural(molecular bond/ vibration mode) information through inelastic scattering
- LIBS enables elemental analysis via laser-induced plasma emission





Temporal separation of Raman and LIBS signals enables simultaneous molecular + elemental analysis from a single laser

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[1] Andrews, H. B. et al., “Monitoring Noble Gases (Xe and Kr) and Aerosols (Cs and Rb) in a Molten Salt Reactor Surrogate Off-Gas Stream Using Laser-Induced Breakdown Spectroscopy (LIBS)”, 2022

Data Fusion: Combining Multiple Techniques

- No single technique provides a complete system “fingerprint”

Electrochemical monitoring

- Overlapping redox potentials of multiple species make individual quantification difficult
- Electrode degradation under high-temperature and irradiation lead to long-term data instability
- Electroinactive species (stable complexes, neutral species, insoluble precipitates) cannot be monitored
- Highly localized near the electrode surface, lacking in the representation of the overall system

Spectroscopic monitoring

- Overlapping absorption bands in multi-component system hinders the resolution of individual oxidation states
- High temperatures and radiation darken the optical windows over time, weakening signal intensity
- Susceptible to matrix effects where variations in salt composition significantly influence spectral response

How to overcome these inherent limitations? **An integrated approach is required**

(Combination of multiple techniques → Multi-modal + Data fusion)

Key Take-Home Messages

- Real-time monitoring is essential for safe, reliable, and efficient MSR operation
- Molten salt systems involve evolving chemistry, corrosion, fission products, impurities, and nuclear material accountancy
- Electrochemical techniques provide key information on redox conditions, electroactive species, and corrosion behavior
- Spectroscopic techniques offer complementary elemental, molecular, and oxidation-state information
- Future MSR monitoring requires integrated, multi-modal, and data-driven approaches combining sensors, data fusion, and machine learning

Works Currently Pursued at SNU

- Electrochemical and thermal monitoring for moisture-induced byproducts in molten salts, including species identification
- Thermal property-based composition monitoring for high-concentration U salt (~70–90 wt%)
- High-power optical fiber coupling for remote LIBS deployment
- Liquid molten salt LIBS with gas-protective layer and acoustic assistance
- Electrochemical monitoring of corrosion environments in molten salt systems
- All efforts integrated within a multi-modal, machine learning-assisted monitoring framework

Upcoming Webinars

Date	Title	Presenter
5 May 2026	Joint GIF/IAEA Webinar: AI advances in the nuclear energy sector	Panelists: Prof. Abdel Khalik, Purdue University, USA; Mr Shahab Dabiran-Zohoory OECD - Nuclear Energy Agency; Prof. Pavel Tsvetkov, (Texas A&M University, USA) Moderators: Dr. Alexei Miassodeov IAEA; Dr. Patricia Paviet, PNNL, USA
22 June 2026	Defensive Cyber Security Architecture and Impact on GenIV Reactors	Dr. Rick Bodner, Canadian Nuclear Laboratories, Canada
8 July 2026	The Wider Role of Nuclear in the Energy System – Engagement and education activities to enable	Mr. Robert Alford, UKNNL, United Kingdom

GEN IV International Forum

How to find the recorded GIF webinars – www.gen-4.org

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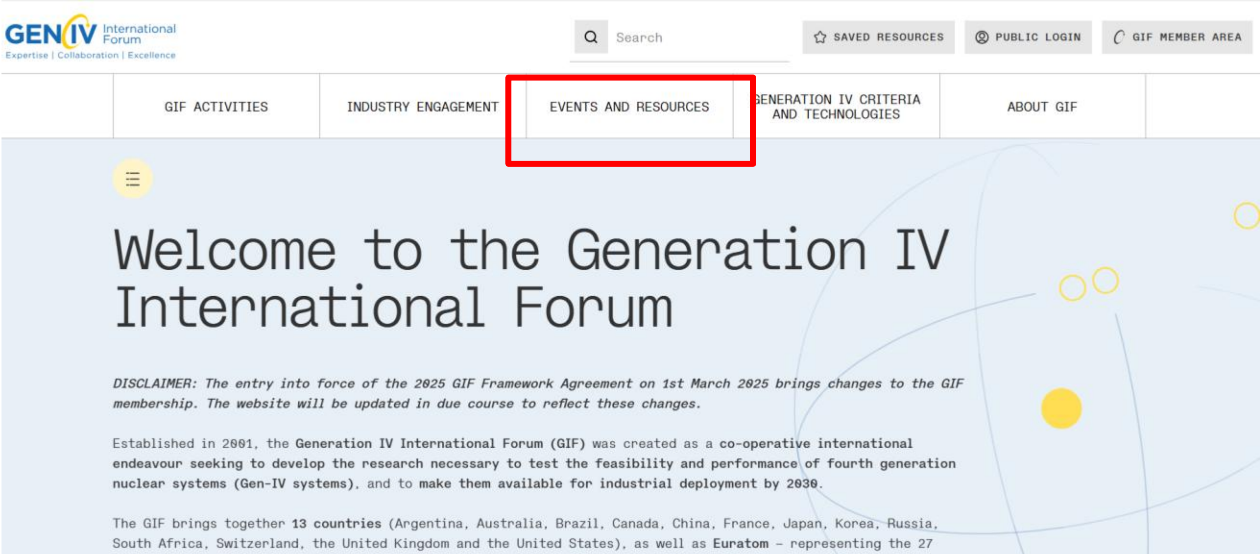


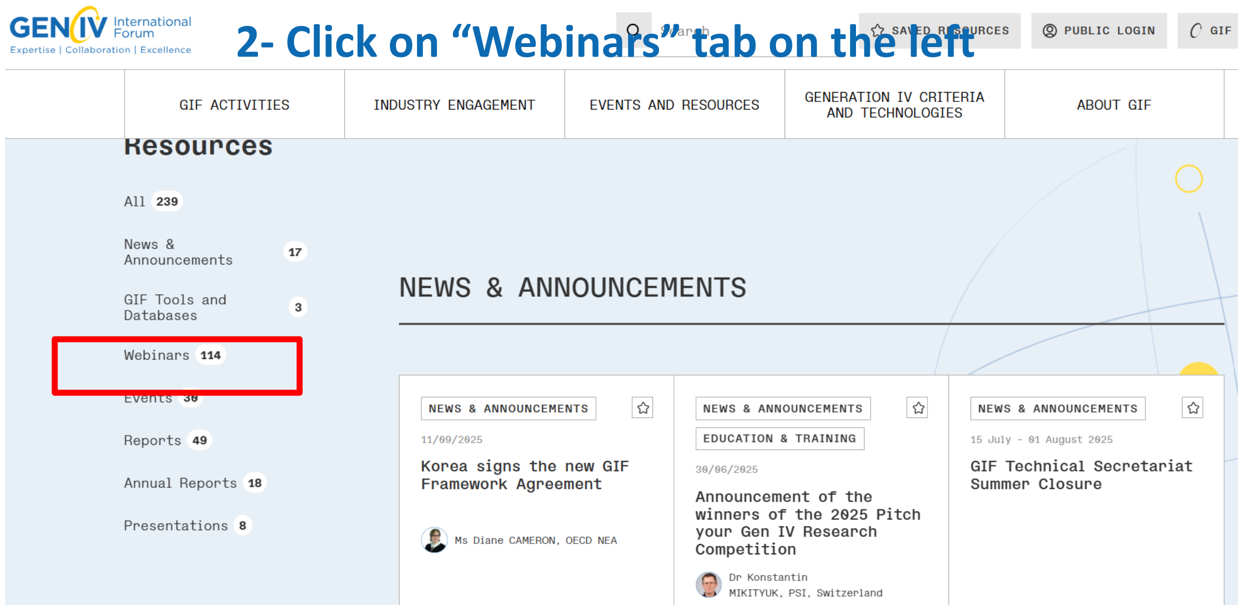
Welcome to the Generation IV International Forum

DISCLAIMER: The entry into force of the 2025 GIF Framework Agreement on 1st March 2025 brings changes to the GIF membership. The website will be updated in due course to reflect these changes.

Established in 2001, the **Generation IV International Forum (GIF)** was created as a **co-operative international endeavour seeking to develop the research necessary to test the feasibility and performance of fourth generation nuclear systems (Gen-IV systems)**, and to **make them available for industrial deployment by 2030**.

The GIF brings together **13 countries** (Argentina, Australia, Brazil, Canada, China, France, Japan, Korea, Russia, South Africa, Switzerland, the United Kingdom and the United States), as well as **Euratom** – representing the 27

2- Click on “Webinars” tab on the left



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NEWS & ANNOUNCEMENTS

NEWS & ANNOUNCEMENTS
11/09/2025
Korea signs the new GIF Framework Agreement
Ms Diane CAMERON, OECD NEA

NEWS & ANNOUNCEMENTS
EDUCATION & TRAINING
30/06/2025
Announcement of the winners of the 2025 Pitch your Gen IV Research Competition
Dr Konstantin MIKITYUK, PSI, Switzerland

NEWS & ANNOUNCEMENTS
15 July - 01 August 2025
GIF Technical Secretariat Summer Closure

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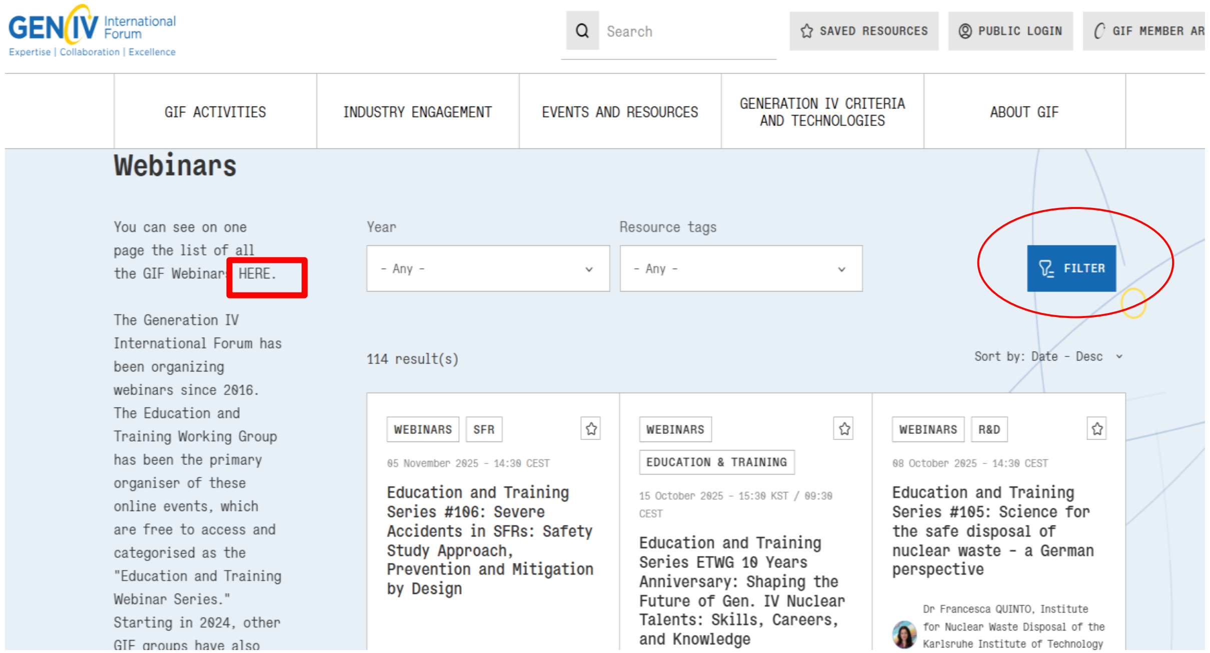

Webinars

You can see on one page the list of all the GIF Webinars HERE.

The Generation IV International Forum has been organizing webinars since 2016. The Education and Training Working Group has been the primary organiser of these online events, which are free to access and categorised as the "Education and Training Webinar Series." Starting in 2024, other GIF groups have also

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Resource tags: - Any -

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WEBINARS SFR
05 November 2025 - 14:30 CEST
Education and Training Series #106: Severe Accidents in SFRs: Safety Study Approach, Prevention and Mitigation by Design

WEBINARS
EDUCATION & TRAINING
15 October 2025 - 15:30 KST / 09:30 CEST
Education and Training Series ETWG 10 Years Anniversary: Shaping the Future of Gen. IV Nuclear Talents: Skills, Careers, and Knowledge

WEBINARS R&D
08 October 2025 - 14:30 CEST
Education and Training Series #105: Science for the safe disposal of nuclear waste - a German perspective
Dr Francesca QUINTO, Institute for Nuclear Waste Disposal of the Karlsruhe Institute of Technology