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Sodium Metal Batteries Using Earth Abundant Materials

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U.S. DEPARTMENT of ENERGY

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Project Overview

Duration: FY26
Vertical: Materials and Systems Innovation
Alignment: Grow grid capacity

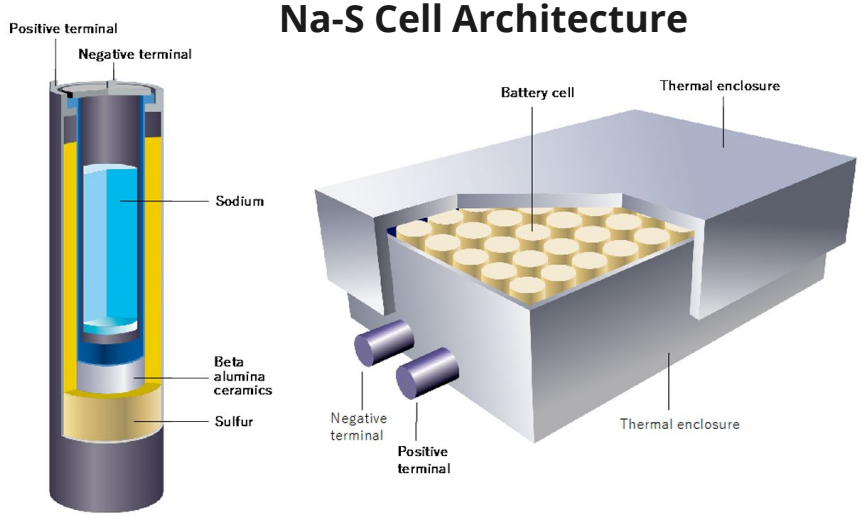
Goal: Lower the cost of sodium metal batteries for grid scale energy storage

1. Earth abundant materials (Na, Si, P, Al, etc.) and commodity chemicals (Na_2CO_3, SiO_2, etc.) to avoid supply chain disruptions
2. Dramatically increase performance metrics at low temperature (<150 °C) to decrease relative cost of inactive materials.

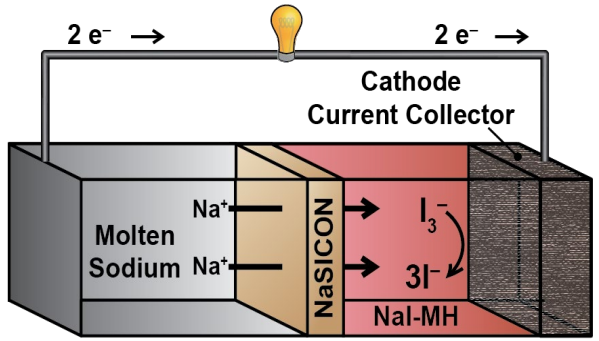
Current Practice: High Temperature (~300 °C) Batteries - Na-S or ZEBRA

- High temperature makes inactive materials (seals, housing, wiring) expensive!

Na-S Cell Architecture



Schematic of sodium batteries developed at Sandia.



Anode $Na \rightarrow Na^+ + e^-$

Cathode $I_3^- + 2e^- \rightarrow 3I^-$

$E^0_{cell} = 3.24$ V

DOE Energy Storage Handbook Chapter 4. Sodium-Based Battery Technologies. 2018.

Why Sandia?

People and Knowledge Base

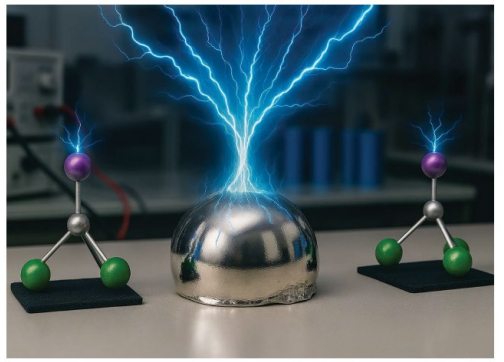
- Sandia has >60 years experience in “thermally-activated batteries.”
- Expertise in molten salt electrochemistry
- Experts in ion conductors, especially NaSICON
- Mechanical properties of solid electrolytes (Prof. Cheng @UKy)

Facilities

- Battery testing, materials characterization, custom fabrication
- Specialized test facilities (e.g. CINT, BAT Lab)

Track Record. In last 5 years…

- >10 patents related to electrochemical energy storage, including one licensed to a startup
- >20 peer reviewed publications



Showcasing research from Sandia National Laboratories' (USA) Grid Scale Energy Storage Program.

A high power, low temperature molten sodium battery

Low temperature molten sodium batteries promise low-cost, grid-scale energy storage using earth-abundant materials. To be economically viable, they must demonstrate high current (power) at relevant discharge times. This work demonstrates up to a 100× increase in operating current, with charging currents as high as 250 mA cm^{-2} (1,070 mW cm^{-2}). A key factor to improving performance is the ratio of graphite felt current collector to molten salt catholyte, consisting of NaI-$AlCl_3$. Depicted are the key active materials – molten sodium and $AlCl_4^-$ molecules sitting atop pieces of graphite felt.

Image created with AI.

As featured in:

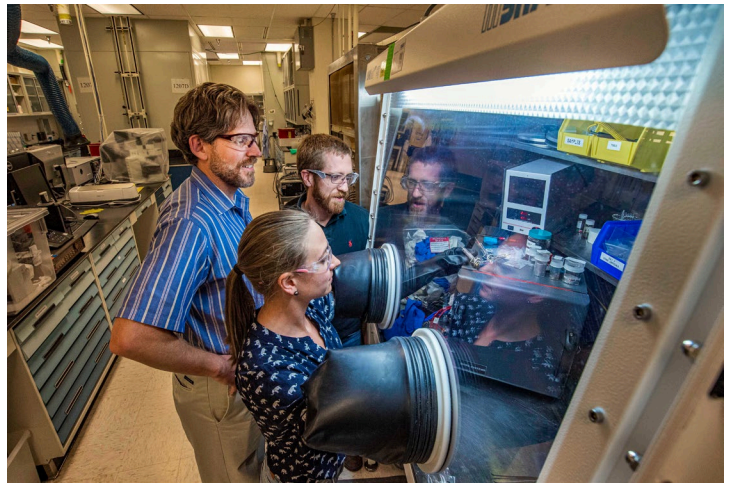
See Leo J. Small *et al.*, *RSC Sustainability*, 2026, **4**, 1846.

ROYAL SOCIETY OF CHEMISTRY

rsc.li/rscsus

Registered charity number: 207890

Urena et al. *RSC Sustainability* **4** (2026) 1846-1856.



Building sodium batteries at Sandia in 2021.

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Innovation and Impact

We are optimizing battery cost based on 6-12 hour discharge time.

- Higher currents → more active material → lower cost per kWh

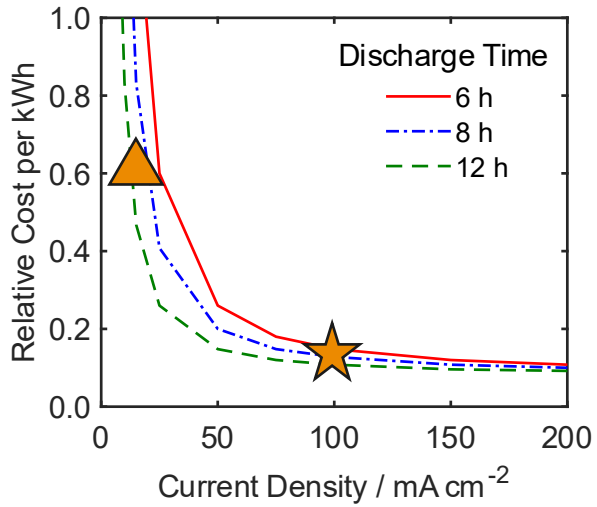
To achieve higher currents (≥100 mA cm^{-2}) we need

- Quantification of electrochemical constants for each battery component and interface
  - Understand limitations and optimize design
  - Design unique interface geometries tailored to materials system
- Novel materials to solve fundamental electrochemical limitations

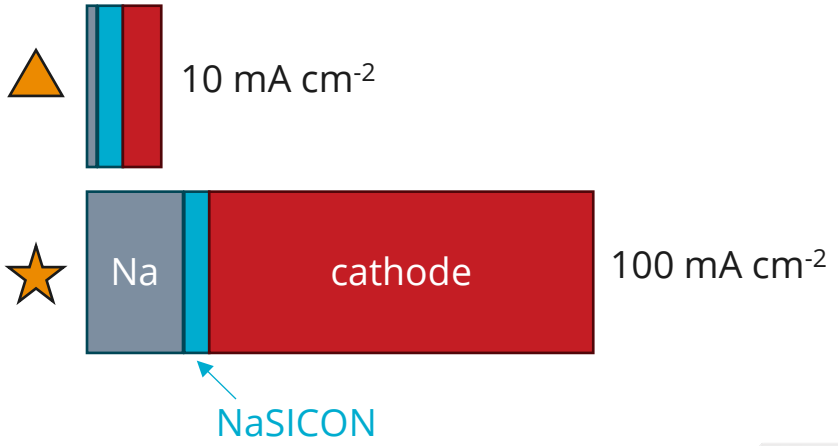
Who cares? If successful…

- Sodium battery cost <$20 kWh^{-1}, earth abundant materials, robust supply chain, insensitive to external temperature
- Fundamental understanding of interfacial behavior and constraints, can also be applied to room temperature sodium metal batteries and more widely alkali metal-solid electrolyte interfaces

Our battery cost decreases nonlinearly with increasing current.



When scaling battery, many inactive components, such as NaSICON, don't necessarily change.



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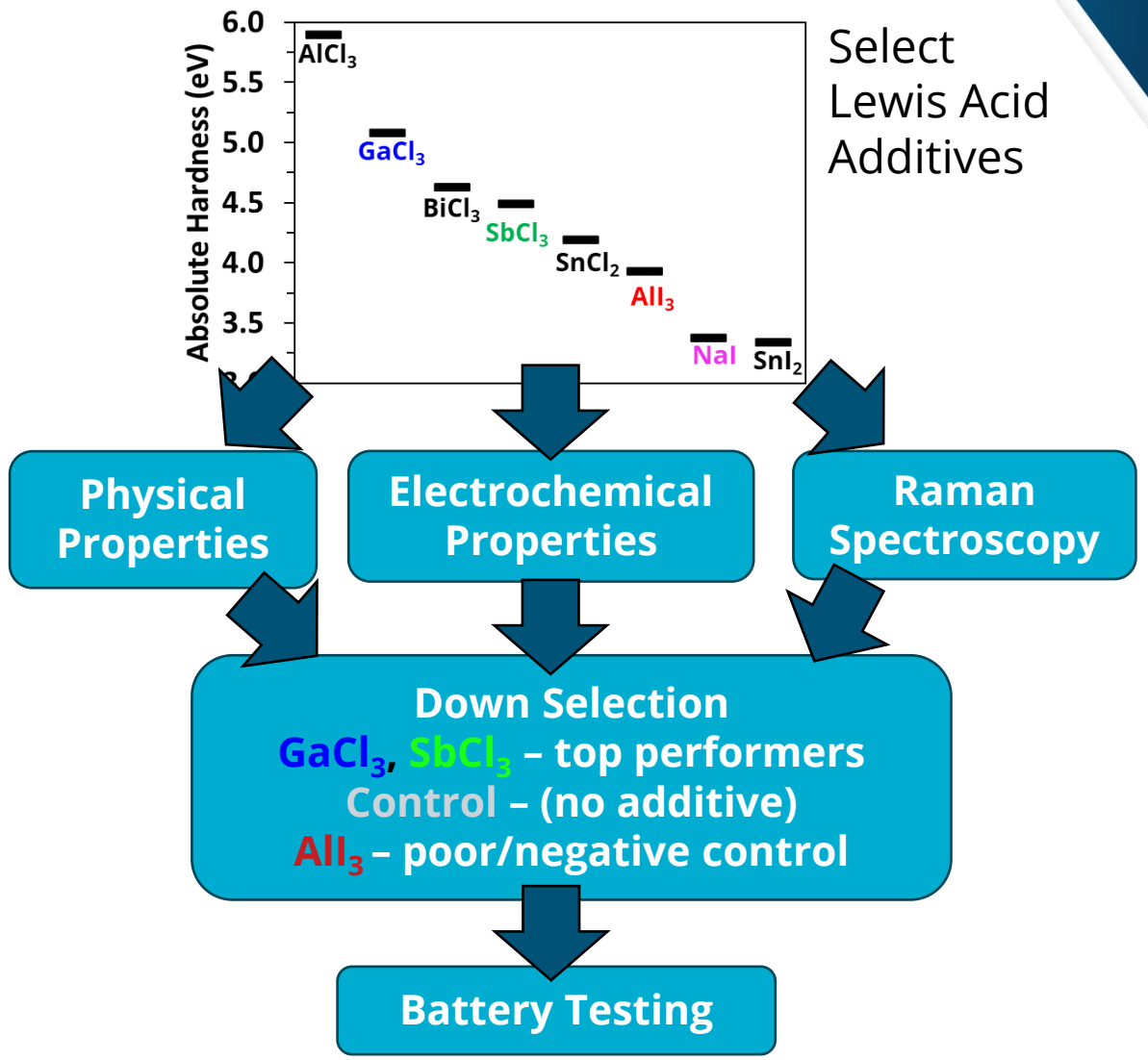
Controlling Interfacial Resistances via Lewis Acid Additives

Problems

- NaI-$AlCl_3$ catholyte is susceptible to NaI precipitation on high power discharge → battery "turns off."
- NaSICON-catholyte interface is relatively high impedance → lowers battery energy efficiency.

Approach

- Tune Lewis acid-base environment by replacing 1 mol% $AlCl_3$ with other Lewis acids.
- Choose 6 molecules over a range of Lewis hardnesses
- Initially screen physical properties, electrochemical properties, and bonding (Raman)
- Down select most promising to test in battery.



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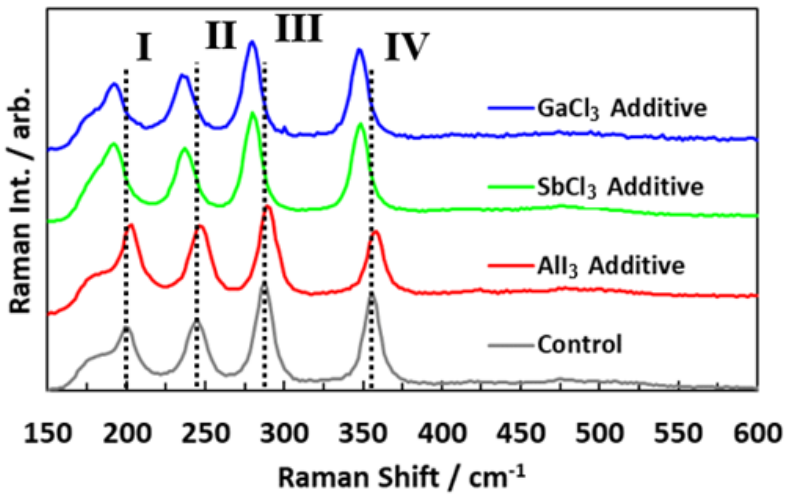
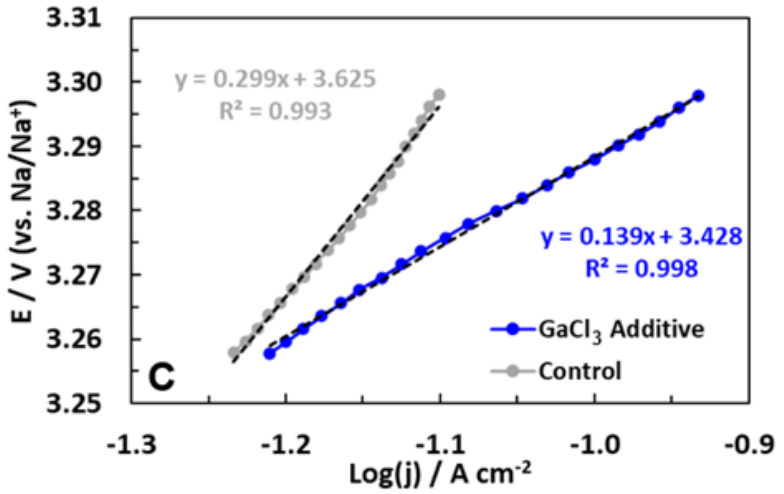
Down Selection of Lewis Acid Additives

Raman spectroscopy reveals peak shifts to lower wavenumbers for **$GaCl_3$** and **$SbCl_3$**, suggesting weakened Al-X bond strength.



Tafel analysis in a standard 3-electrode cell demonstrates enhanced iodide oxidation kinetics for **$GaCl_3$** vs. the **control**.



Lewis acid additives present at only 1 mol% can alter the Lewis acid-base bonding environment to enhance charge transfer processes.

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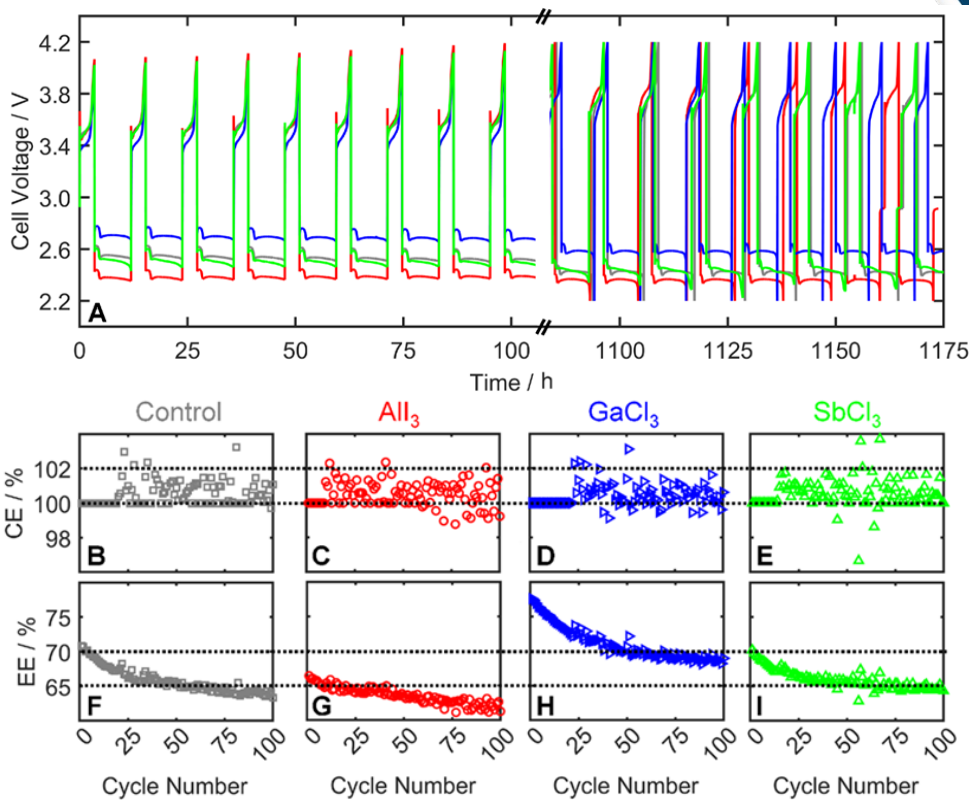
Certain Lewis Acid Additives Improve Battery Performance

- Batteries were subjected to rate testing, capacity testing, impedance spectroscopy (interfacial resistance), and long-term cycling (>1200 h).
- **$GaCl_3$** and **$SbCl_3$** are beneficial additives.
  - Pulse (brief) discharge current increased: 50 → 100 mA cm^{-2}
  - Interfacial impedance decreased: 24.2 → 9.40 Ω cm^2
  - Energy efficiency increased: 65% → 70%
  - Accessible capacity increased: 60% → 70% (119 mAh cm^{-2})
- **AlI_3** performed worse than the **control**, reversibly adsorbing and desorbing from the NaSICON surface, impeding charge transport.
- Higher current, higher accessible capacity → lower costs for grid scale energy storage

Long term battery cycling



There is an ideal hardness range of Lewis acid additives that can significantly improve battery performance.

See poster by Stephen Percival for more details.

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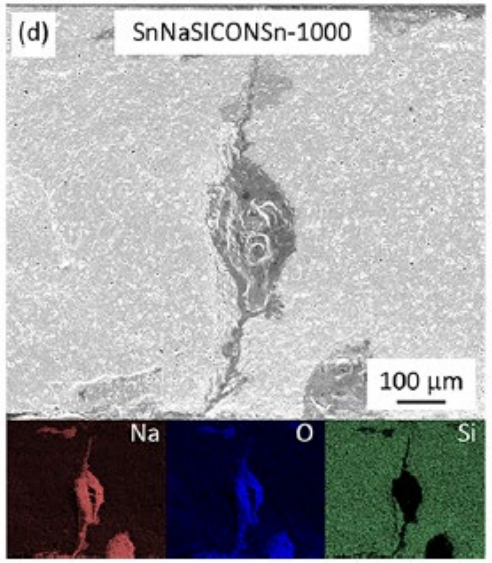
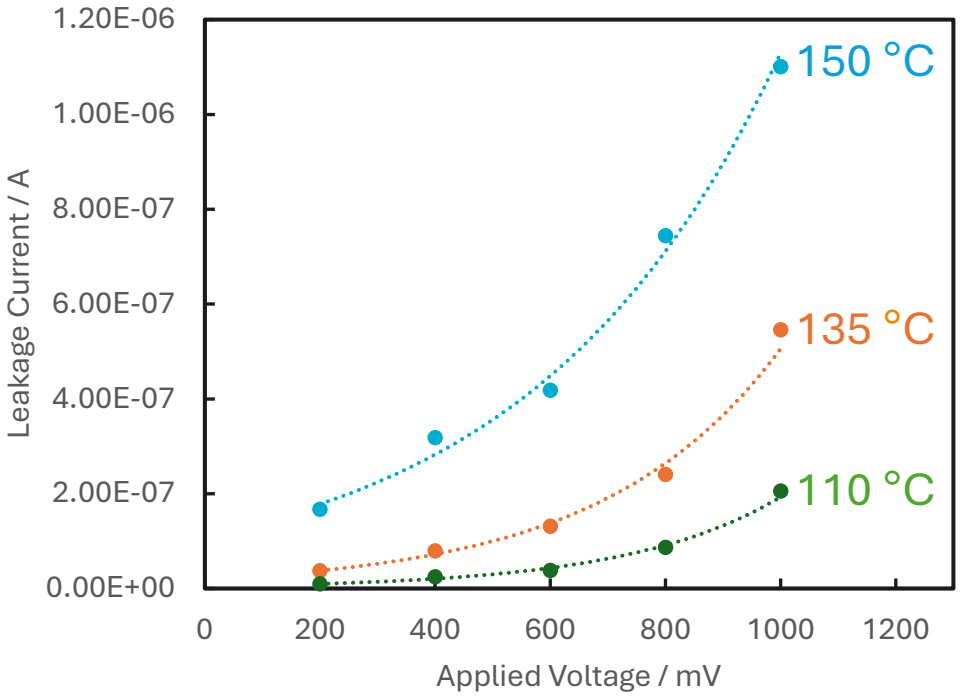
Quantifying Electronic Properties in NaSICON

- **Problem:** Sodium rich regions ("dendrites") can form in NaSICON over many long duration cycles at high currents (>0.5 A cm^{-2}) due to electron-Na^+ recombination.
- **Approach:** To better understand the conduction mechanism for electronic conductivity, we characterized it as a function of applied electric field (voltage) and temperature.
- Electronic conductivity of 10^{-7} S cm^{-1} measured at 135 °C. 10^5× lower than Na^+ conductivity.
- Activation energy of 0.52 eV over 25-150 °C.



Na-rich inclusion formed in NaSICON after testing at 1 A cm^{-2}.

Leakage current behavior suggests space charge limited conduction and/or electron hopping between trap states.

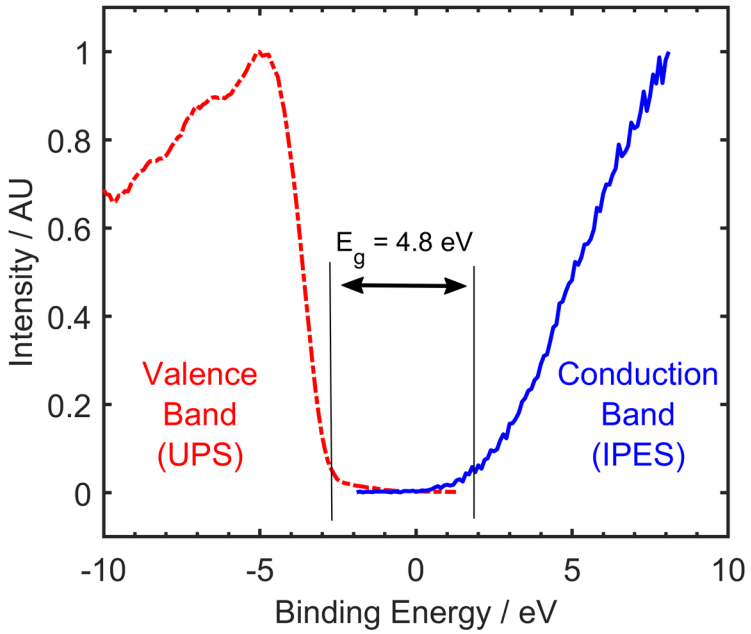


Hill et al, ACS Appl. Energy Mater. 2024, **7**, 810-819

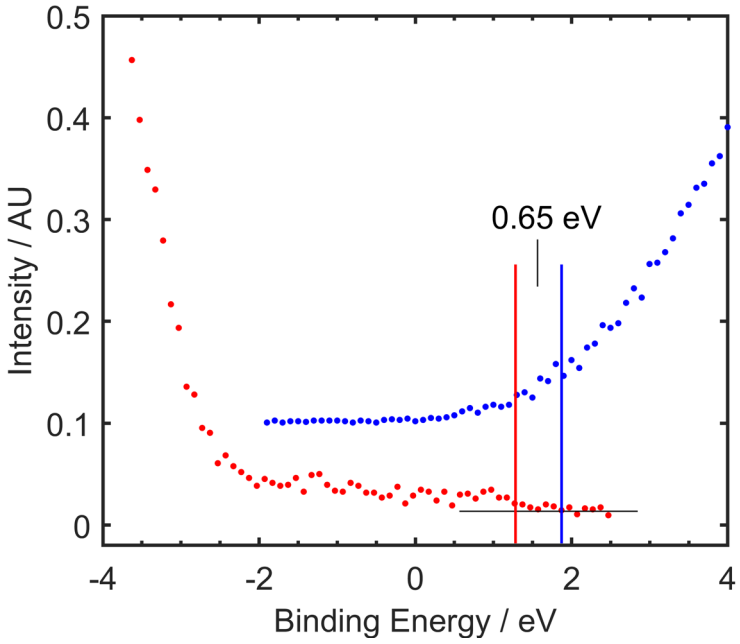
Relating Electronic Conductivity to NaSICON Band Structure

- Measured NaSICON's electronic band structure using ultraviolet photoelectron spectroscopy (UPS) and inverse photo electron spectroscopy (IPES).
- Large bandgap of about 4.8 eV observed, consistent with literature reports.
- Small feature observed 0.65 eV from conduction band edge
  - **Electronic conductivity controlled by NaSICON space charge and defect states**

Bandgap Measurement of NaSICON



Zoomed in View



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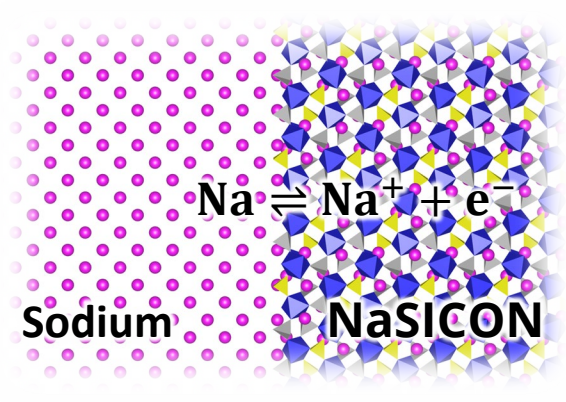
Charge Transport across the Na-NaSICON Interface

Quantifying electrochemical parameters at the Na-NaSICON interface

- allows us to design better batteries and new interfacial architectures.
- enables understanding of how interfacial coatings work.

Parameters of Interest

- charge transfer resistance (R_{ct})
- Activation energy (E_a)
- Exchange current density (j_0)

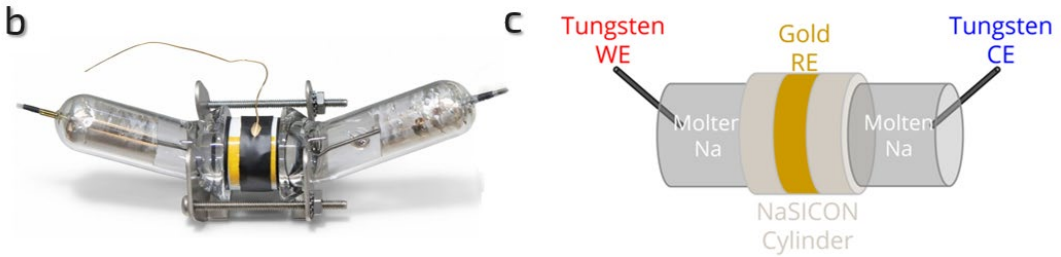


Two Electrode Cell

Simple, measures two interfaces simultaneously

Three Electrode Cell

More complex, isolates a single interface



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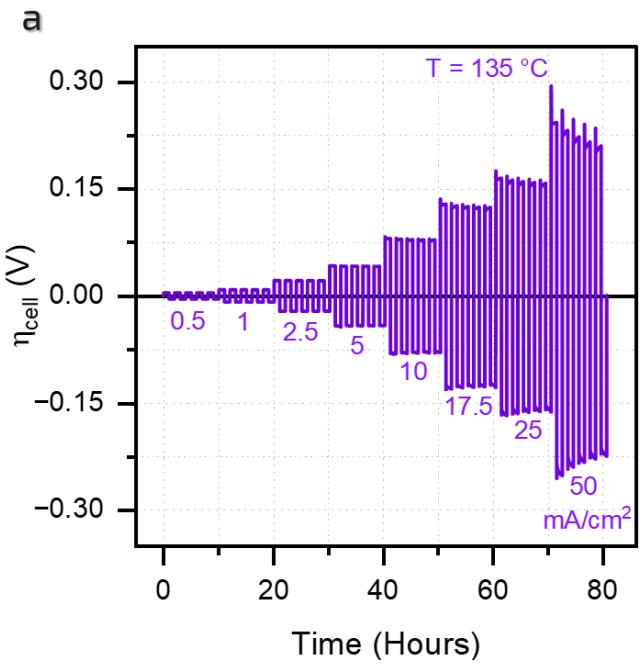
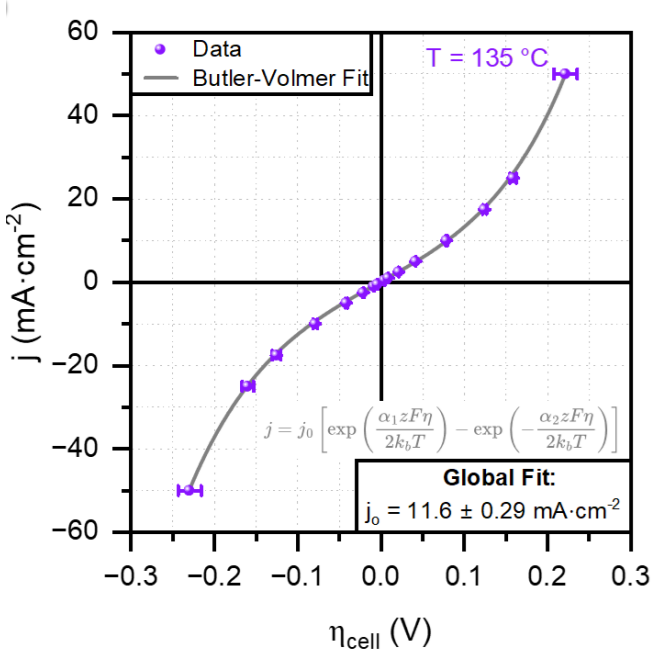
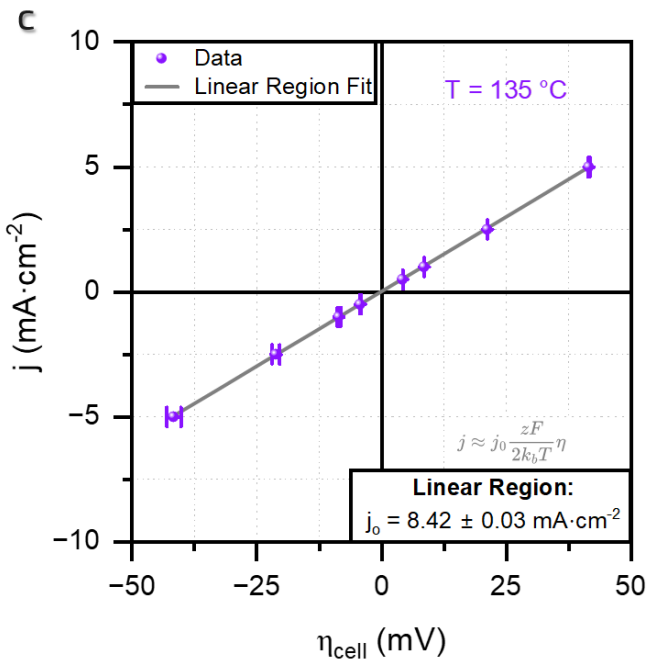
Exchange Current Density at the Na-NaSICON Interface

- Molten Sodium | Solid ceramic interface follows Butler-Volmer relationship
- Fitting galvanostatic cycling data with Butler Volmer Equation, can obtain j_o
- Linear region (low η) fit is a more accurate representation of j_o
- Sn coating NaSICON increases j_o from 7.42 to 12.49 mA cm^{-2} at 135 °C.







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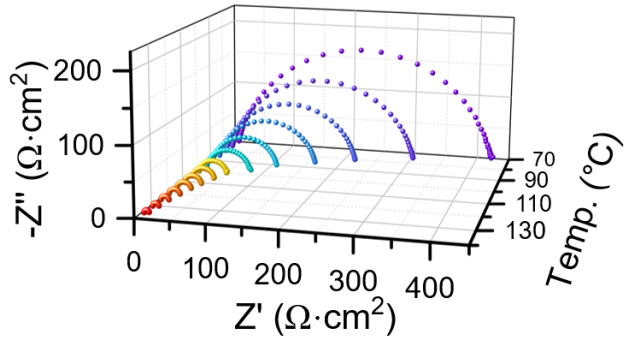
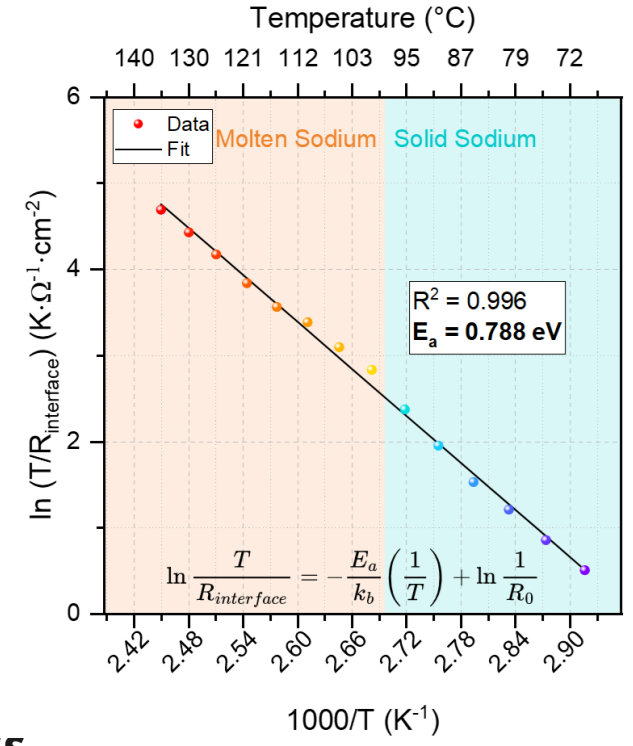
Charge Transfer Resistance & Activation Energy

- Measure impedance spectra over 135 – 70 °C and fit spectra to obtain R_{ct}.
- Interfacial charge-transfer is kinetically limited by a NaSICON-dominated process
- Sodium | NaSICON interfacial kinetics reveal consistent E_a= 0.788 eV.
  - The physical state of sodium (solid vs. molten) does not influence the activation barrier.
- Methodology can be applied to other coatings or interlayers to compare
  - Sn coated NaSICON 135°C E_a = 0.74 eV





See poster by Isaac Dyer for more details.

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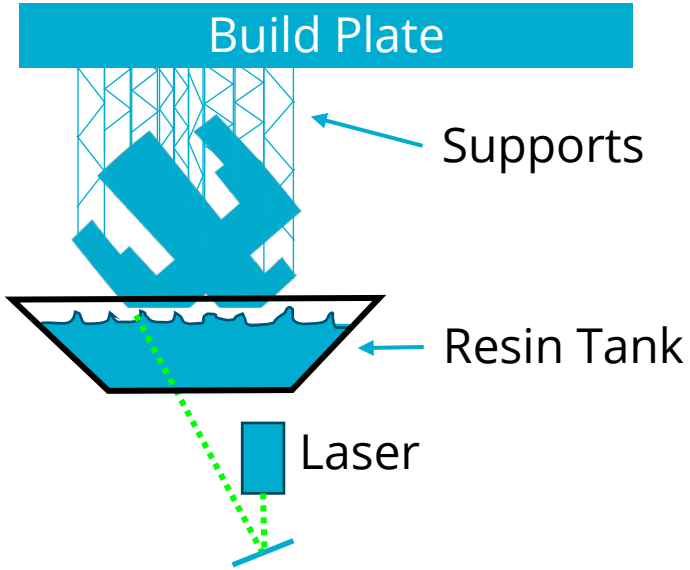
Future Directions

- Use electrochemical constants determined this year to
  - design engineered interface geometries.
  - 3D print NaSICON to enable more complex interface geometries.
  - increase discharge current density to 50-100 mA cm^{-2} for >50% theoretical capacity.
- Design Na-NaSICON interfaces resistant to dendrite formation during high power, long duration cycling.
- Rapid screening and optimization of new catholyte compositions using Lewis acidity lessons learned this year.

SLA Printing Schematic



Resin Test Prints

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Accomplishments

Peer-Reviewed Publications

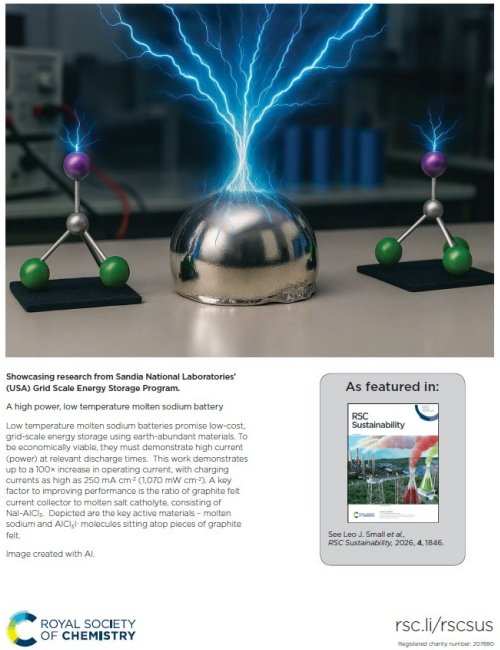
- S.J. Percival, A.M. Maraschky, M. Stalcup, A.S. Peretti, L.J. Small, and E.D. Spoerke. High Voltage, Intermediate Temperature Fe and Al Mixed Metal Halide Molten Salt for Molten Sodium Battery Energy Storage. *Industrial & Engineering Chemistry Research* **64** (2025) 22714-22723. **Invited Paper. Featured on the Cover.**
- M.E. Ureña, A.S. Peretti, S.J. Percival, P.S. Mantos, E.D Spoerke, and L.J. Small. A High Power, Low Temperature Molten Sodium Battery. *RSC Sustainability* **4** (2026) 1846-1856. **Featured on the Cover.**
- S.J. Percival, M.E. Ureña, Z.T. Piontkowski, W. Delmas, A.S. Peretti, E.D. Spoerke, and L.J. Small. Tuning Lewis Acid-Base Interactions in Molten Sodium Batteries to Enhance Charge Transport. (2026) In Review.
- I.D. Dyer, A.S. Peretti, S.J. Percival, C.R. Carlos, R.L. Craig, M.E. Ureña, and L.J. Small. Charge Transfer Kinetics of the Sodium-NaSICON Interface (2026) In Review.
- I.D. Dyer, C.T. Martin, A.S. Peretti, R.L. Craig, M.E. Ureña, and L.J. Small. Influence of Zn-Doping on the Na^+ Conductivity in NaSICON Solid Electrolytes. (2026) In preparation.

Presentations

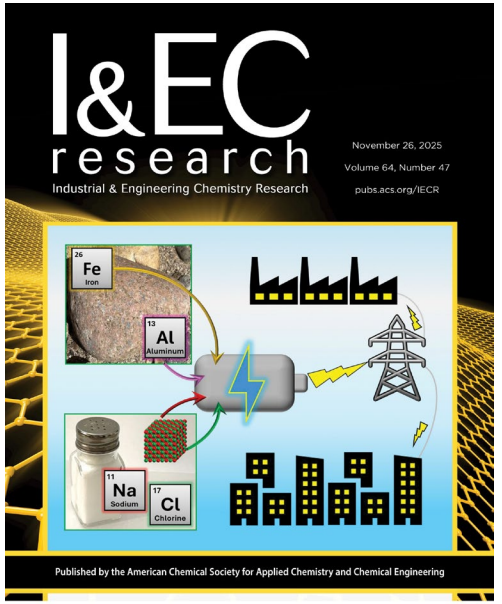
- I.D. Dyer, A.S. Peretti, M.E. Ureña, C. Carlos, R. Craig, S.J. Percival, L.J. Small. Designing 3D Interfaces and Enhancing Sodium Wettability for Next-Generation Molten Sodium Batteries. MRS Fall Meeting. Boston, MA. Dec 6th, 2025.

Awards

- A.S. Peretti. Employee Recognition Award (ERA) for Technical Excellence. Sandia National Laboratories. 2026.



Urena et al. *RSC Sustainability* **4** (2026) 1846-1856.



Percival et al. *I&EC Research* **64** (2025) 22714-22723.

Acknowledgements

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We thank Sandia materials characterization experts for help in this work:

Robert Craig - Scanning electron microscopy (SEM)

Melissa Meyerson - X-ray Photoelectron Spectroscopy (XPS), UPS, IPES

Corey Carlos - Atomic force microscopy (AFM)

Questions?

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