Pacific Northwest
NATIONAL LABORATORY

Zinc Battery Development at PNNL

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Presentation #1002

U.S. DEPARTMENT of ENERGY BATTELLE

PNNL is operated by Battelle for the U.S. Department of Energy

Zinc Team

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- External Collaborators
  - Prof. Xingbo Liu (West Virginia University)

Project Overview

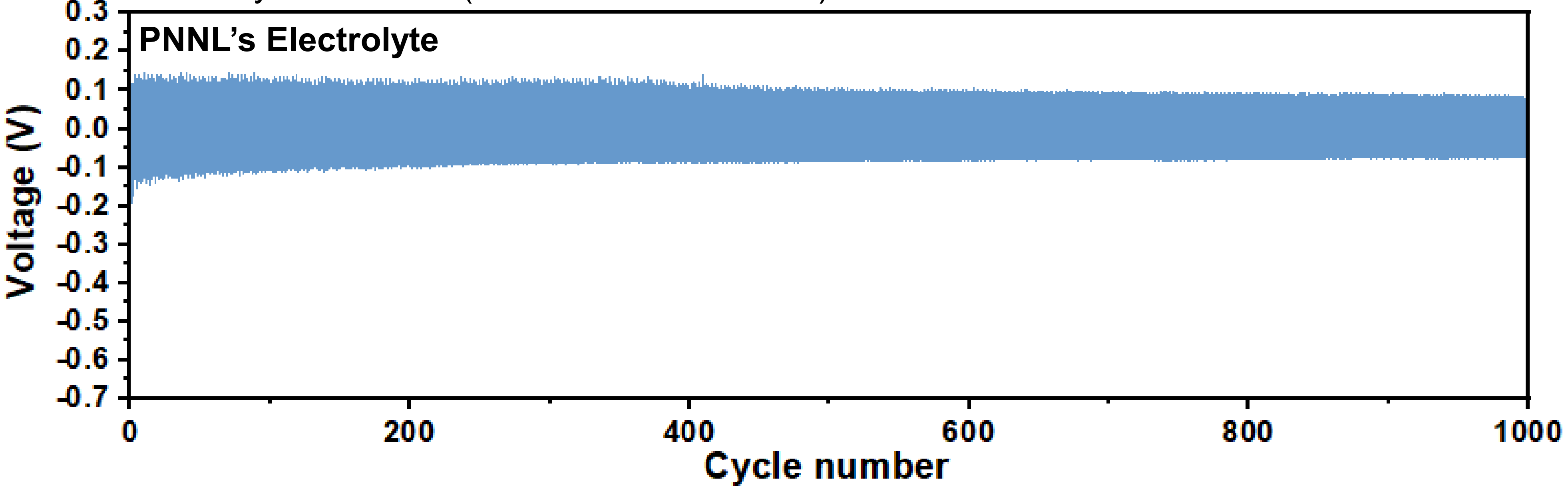
- PNNL's overall goal is to **understand the fundamental mechanism** of rechargeable aqueous Zn batteries at mild acid or neutral conditions, to develop innovative low-cost chemistries to improve the cycle life and to drive it to commercialization.
- Li-Ion batteries currently dominate the market and suffer from high cost (due to use of Nickel and Cobalt) and safety concerns. Aqueous Zn batteries use earth abundant materials (H_2O, Zn, MnO_2, etc) that have **high degree of safety, low cost, and high specific energy** but are predominantly limited to primary battery applications.
- PNNL is leveraging our expertise in both aqueous and non-aqueous batteries to drive the development of alternatives to Li-ion (Zn-battery) to ensure a supply of resilient energy.
- Our approach to Zn-battery development is multi-faceted by characterizing at fundamental levels the current issues with the cathode, electrolyte, and anode. The accumulation of this knowledge will allow PNNL to develop Zn-based batteries that have high degree of safety and cycle life.
- The success of this project has the capability to ensure dependable, affordable energy for the country coupled with increased manufacturing and industry development.
- This project is accelerating the development and testing of zinc battery technology that is more cost-effective, safe, and durable, which is crucial to meeting the Administration's goal of providing reliable, affordable, secure, and resilient energy.

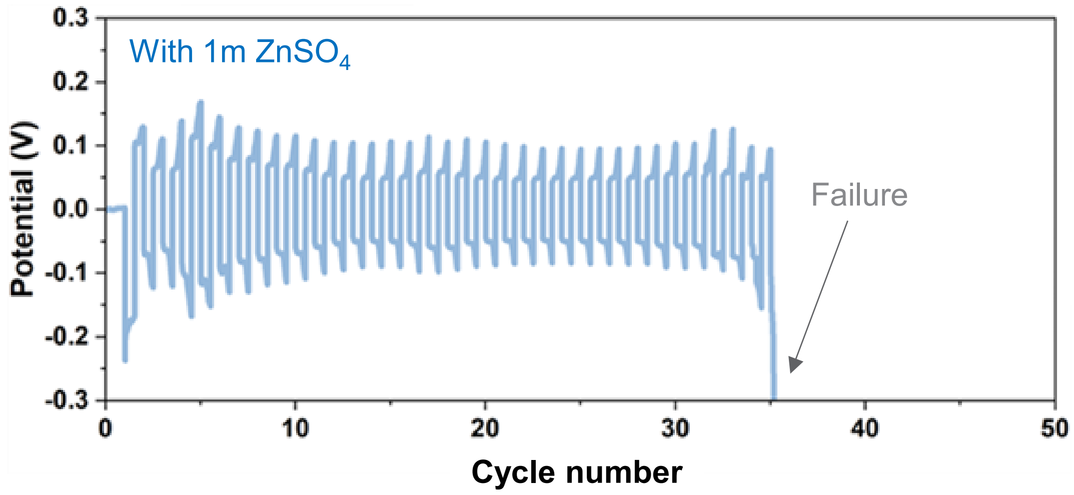
Project Milestones

- FY2026 Milestones
  1. Develop electrolytes that suppresses dendritic Zn growth and interfacial side reactions to achieve >1000 cycles at > 20% Zn utilization in Zn||Zn symmetric cells. (12/31/2025) (completed)
  2. Demonstrate full cells with >80% capacity retention over 200 cycles at an areal capacity of ~3 mAh/cm^2 (03/31/2026) (completed)
  3. Demonstrate the fabrication of double-side-coated Zn anodes that can deliver 50 stable cycles at an areal capacity of ~3 mAh/cm^2 and >20% DOD. (06/30/2026) (completed)
  4. Publish >1 journal papers and deliver >1 conference presentations. (09/30/2026) (in-progress)

Electrolyte Design

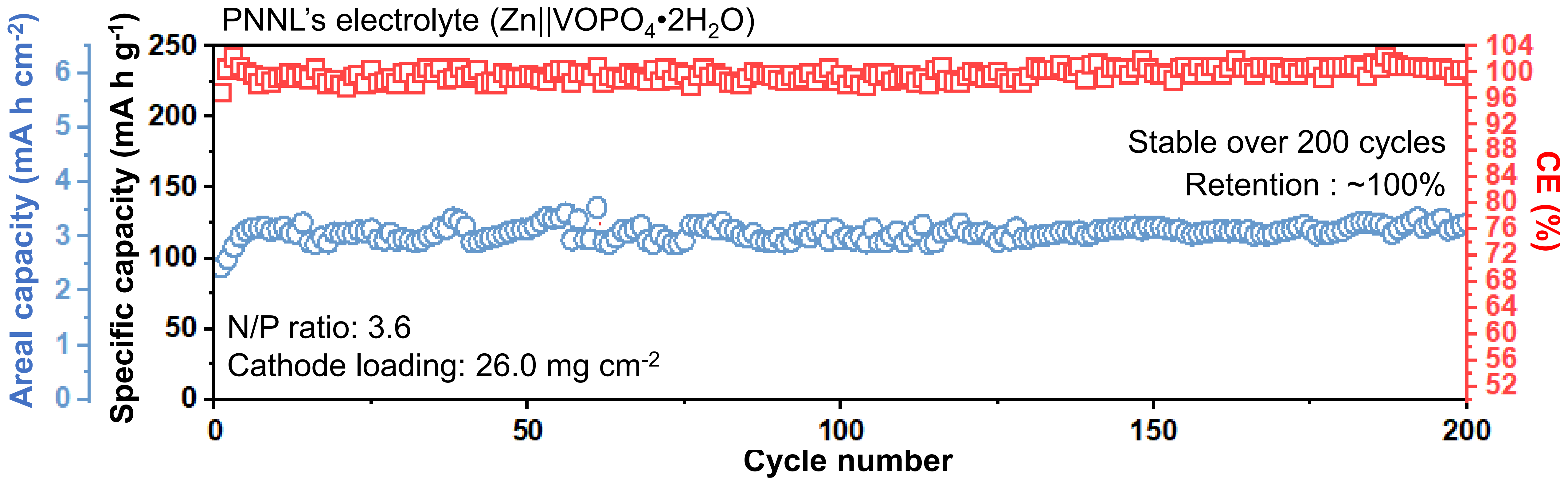
Zn//Zn symmetric cell (20% Zn utilization ratio)





- **PNNL's electrolyte achieves >1000 cycles at 20% Zn utilization in symmetric cells**
- **Reference electrolytes show cell failure at < 50 cycles.**

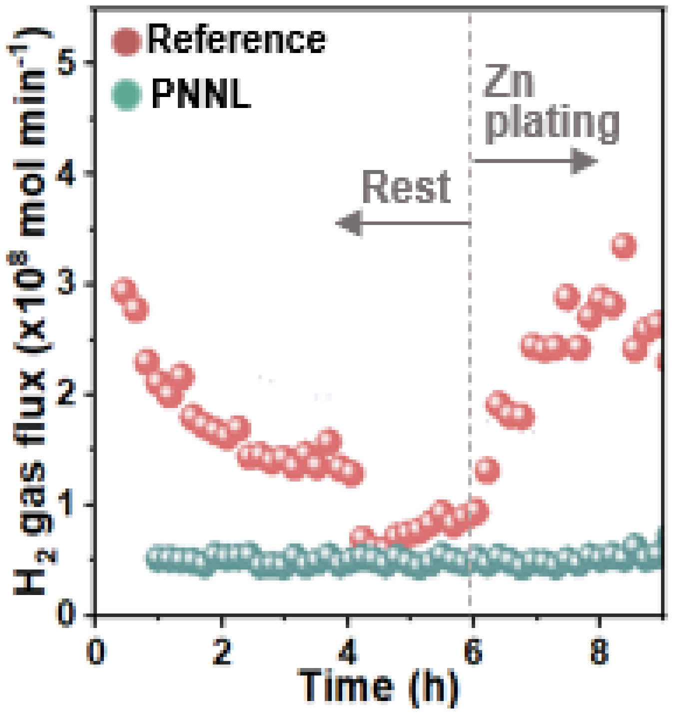
Electrolyte Design



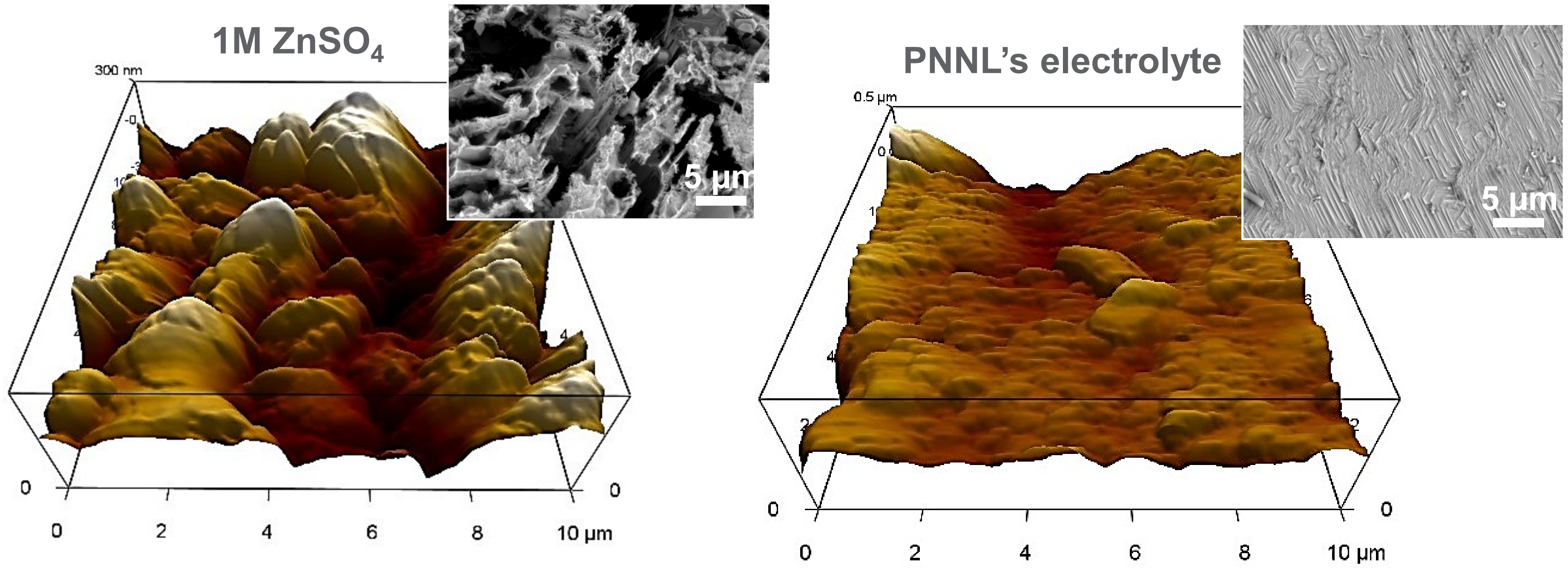
- **Zn//VOPO$_4$•2H$_2$O full cells achieve >80% capacity retention over 200 cycles at ~3 mAh/cm^2.**

Electrolyte Design

DEMS analysis

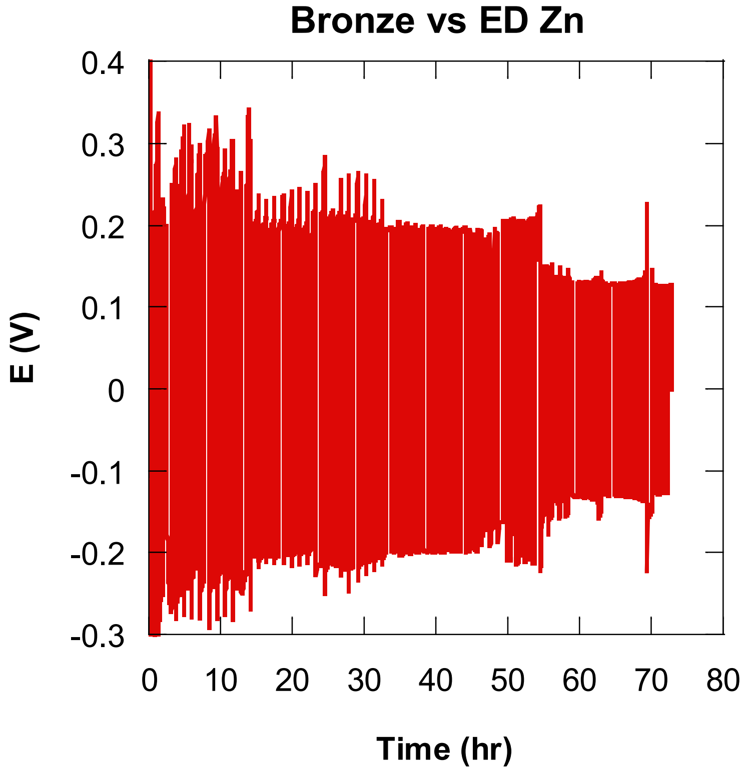


AFM analysis



- **PNNL's electrolyte demonstrates suppressed hydrogen evolution and dendrites.**

Proof of Concept: Double Sided Zinc Deposition

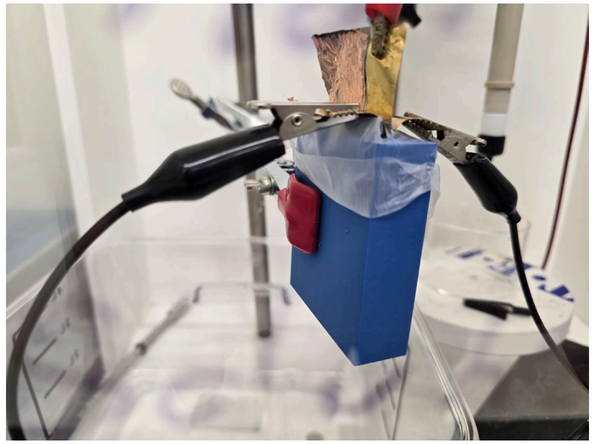


Anode Loading: 10 mAh/cm^2
Utilization: 60%
Current Density: 10 mA/cm^2

Fabrication

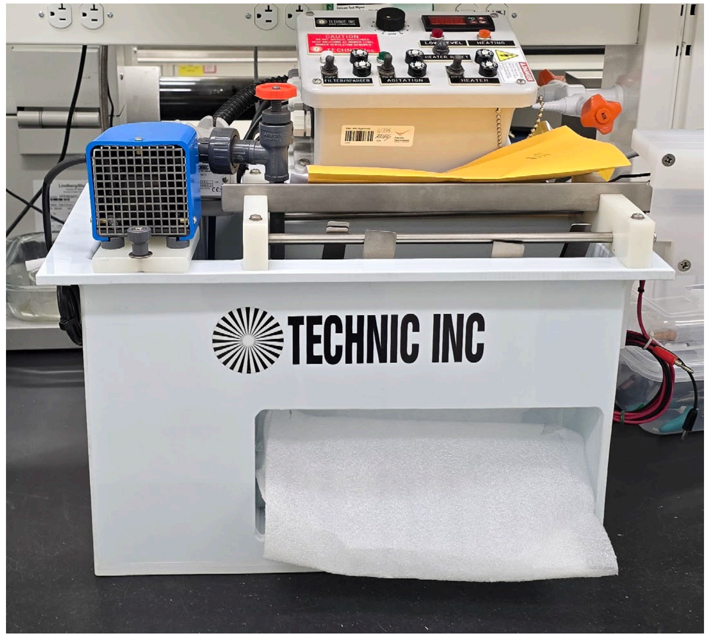
Anode

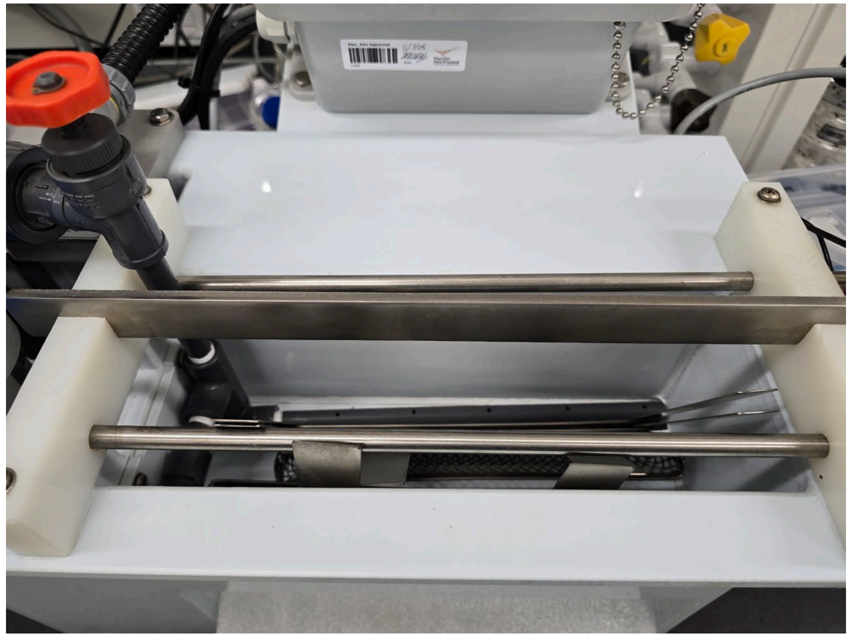
Assembled Cell

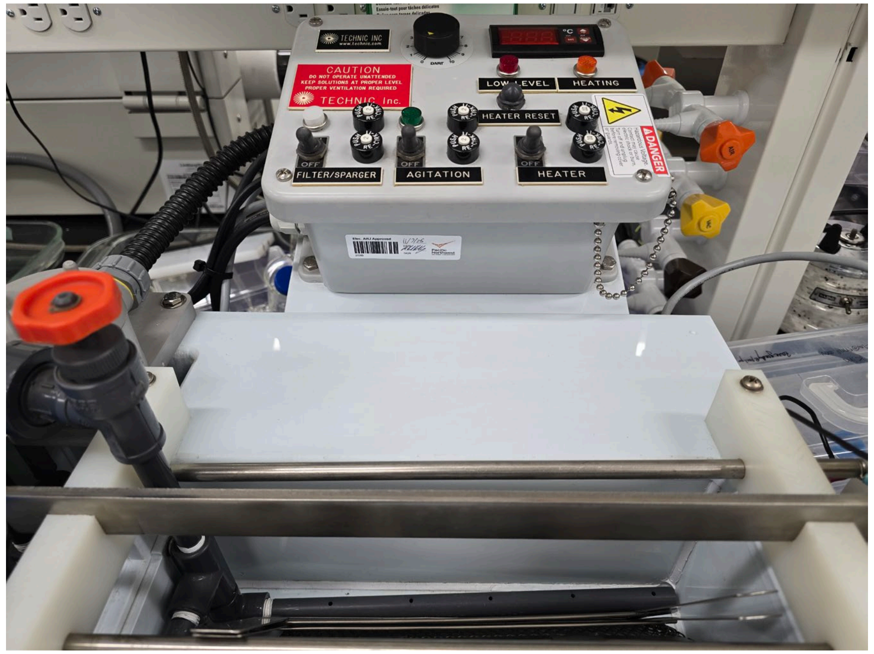


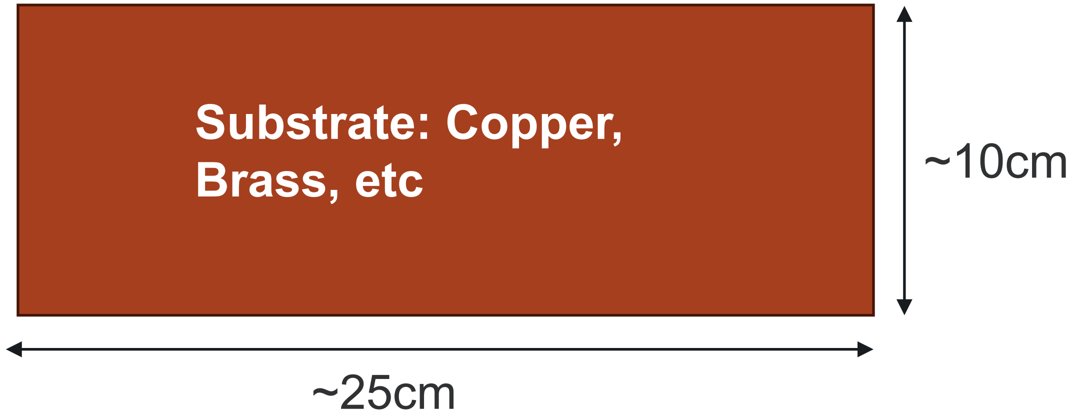
- **Proof of concept double-side coated electrodes with loading of 10 mAh/cm^2**
- **In a prototype prismatic style cell, cycle life exceeded 60 cycles at 60% utilization**

Double Sided Zn Line



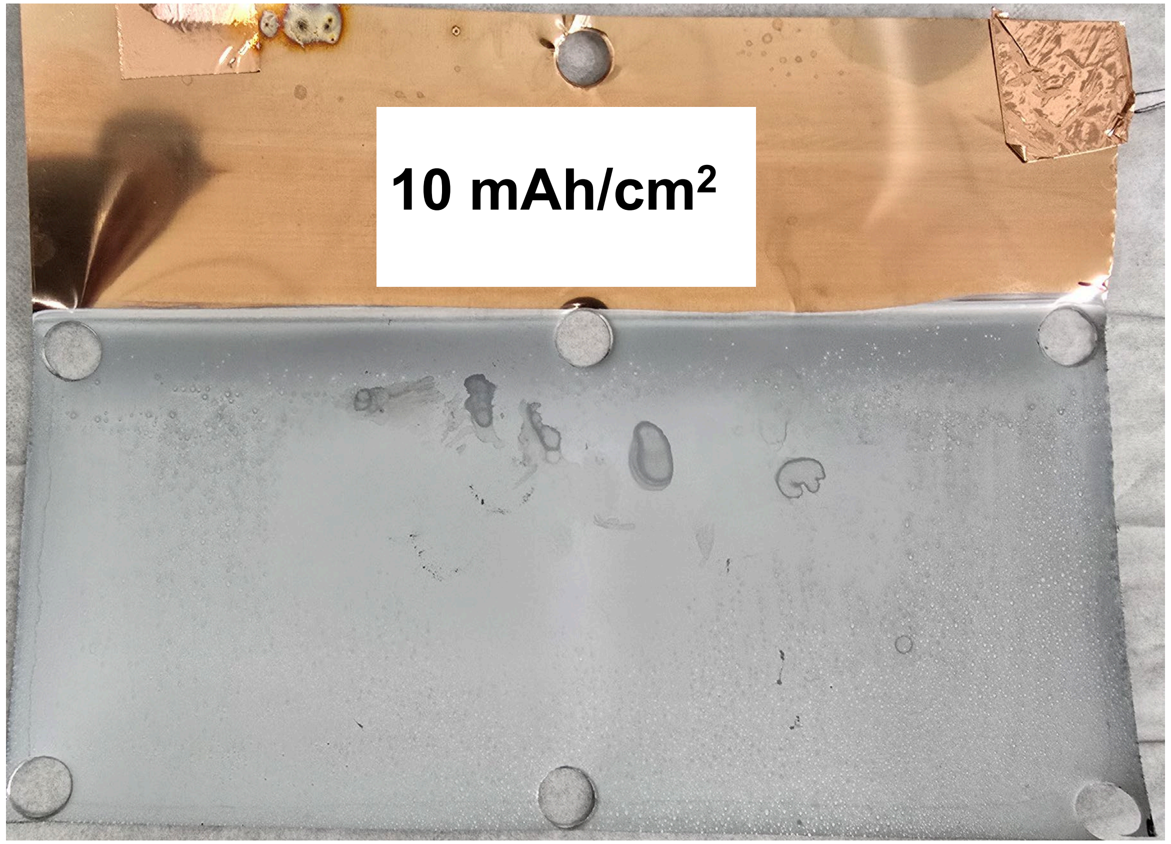


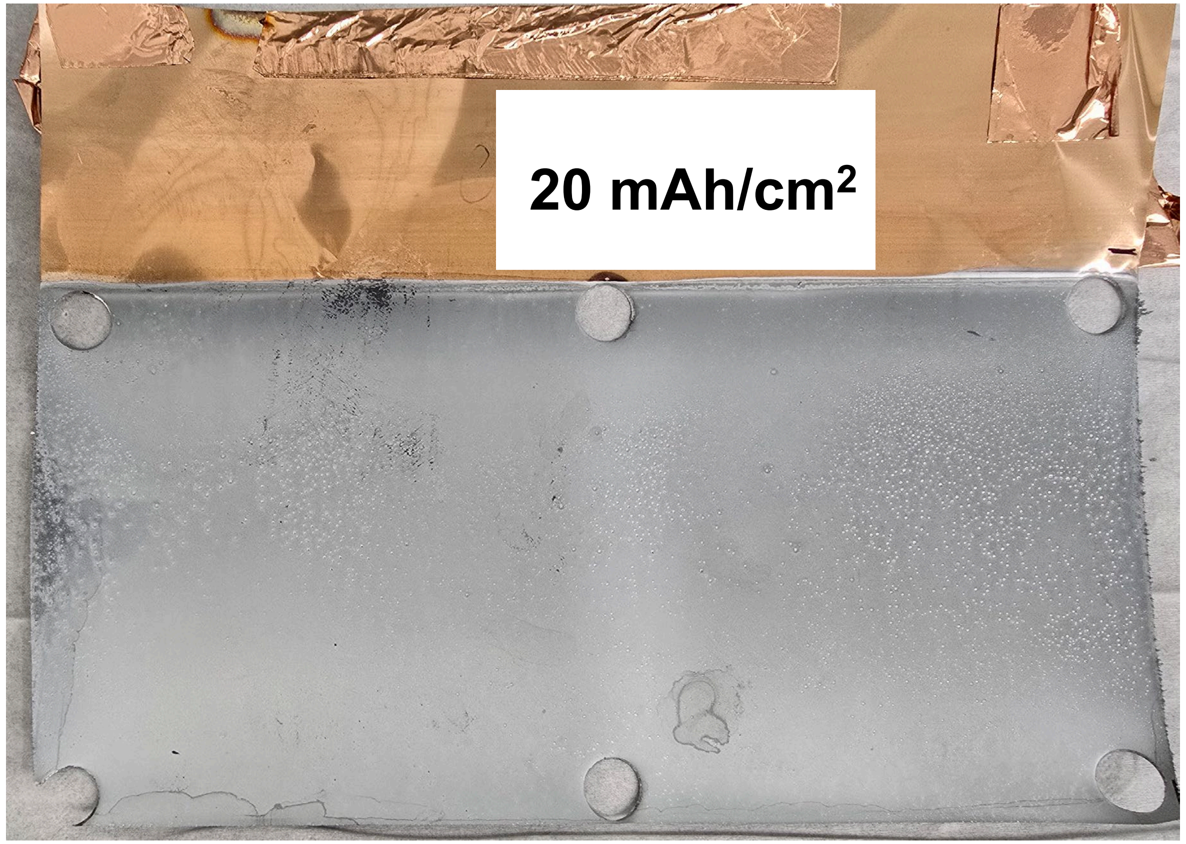




- **PNNL has added new capability to fabricate Zn-based anodes in less than 1 hour.**

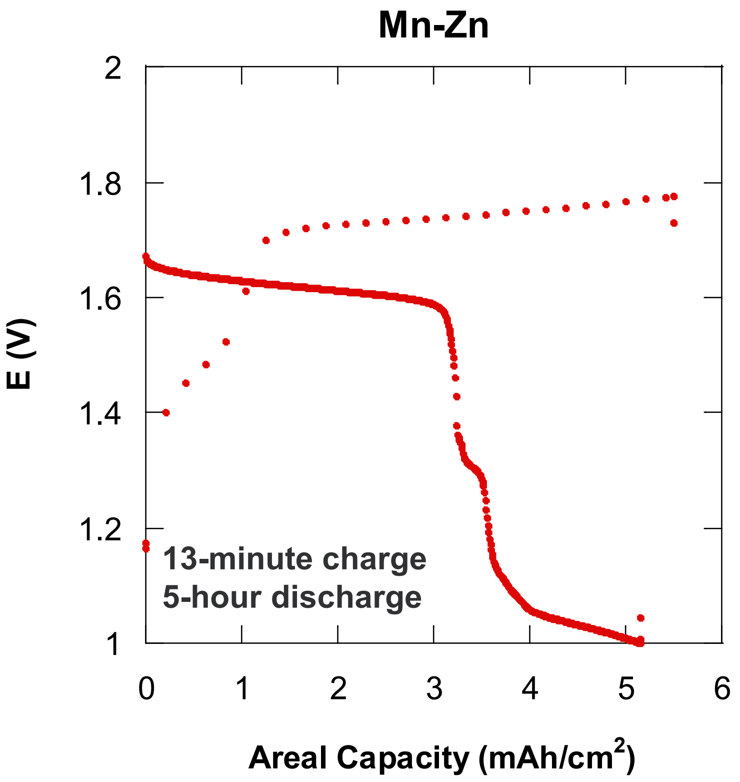
Scaling Doubled-Sided Zn

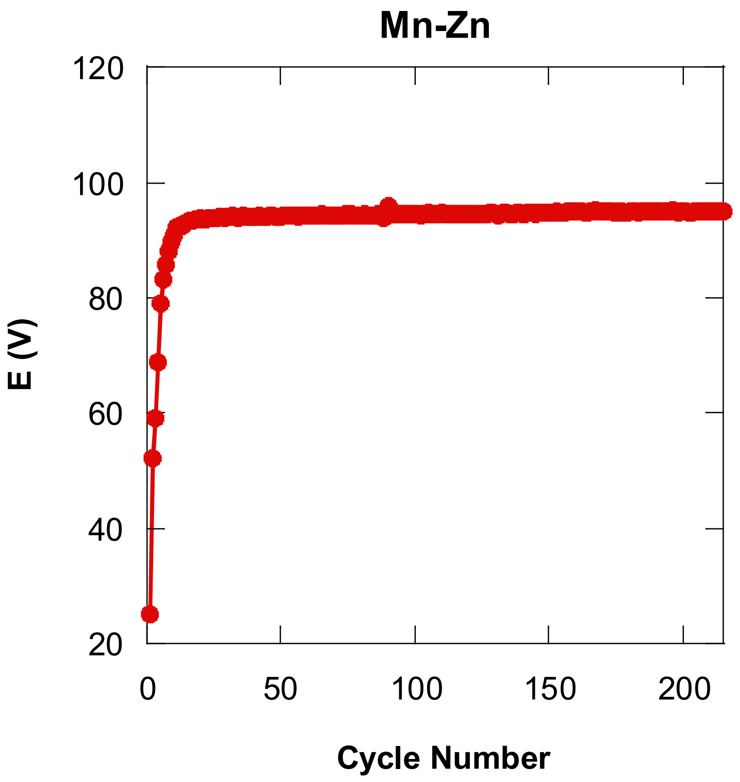




- PNNL can produce double-sided Zn-coated electrodes in less than 1 hour with practical loadings of 10-20 mAh/cm^2.
- Uniformity is <5% difference

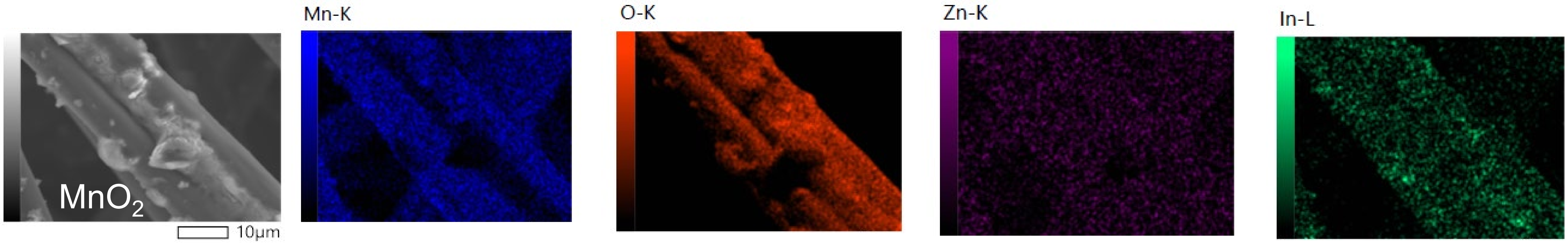
2-electron MnO_2/Zn



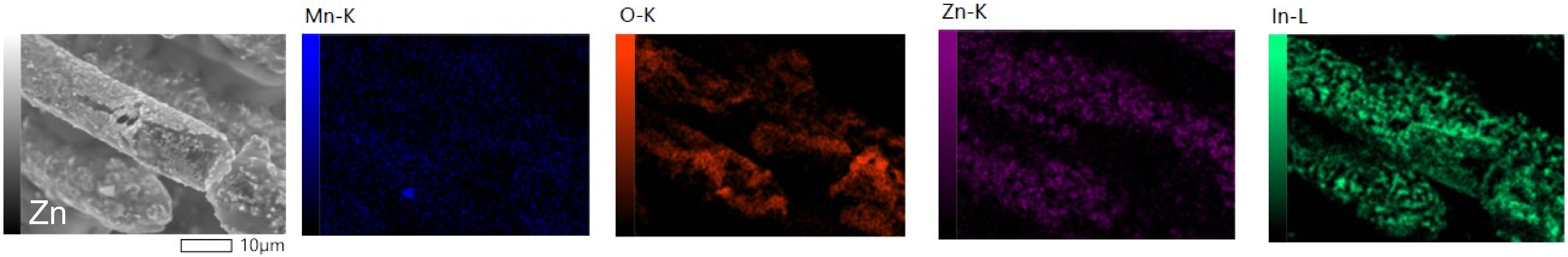


- In a proof-of-concept, the 2e- MnO_2-Zn cell with PNNL-developed electrolyte exhibits high gravimetric and areal capacities (>500 mAh/g, >5 mAh/cm²).
- Cycle stability exceeds 200 cycles.

EDS Analysis of charged MnO_2/Zn

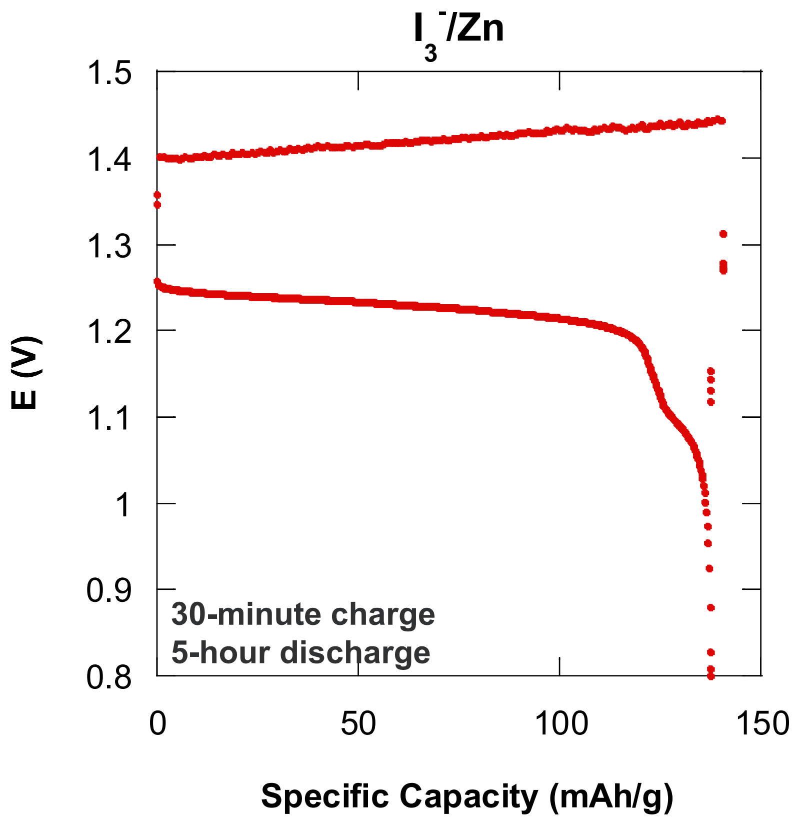


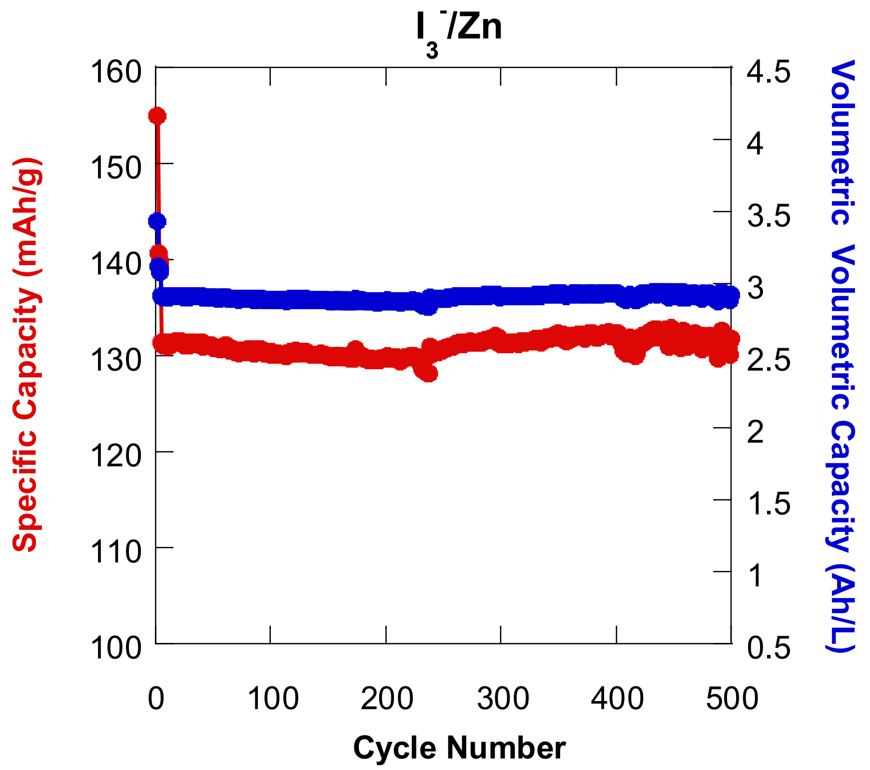
- Mn and O species appear in same regions indicating formation of MnO_2.
- Zn is dispersed throughout MnO_2

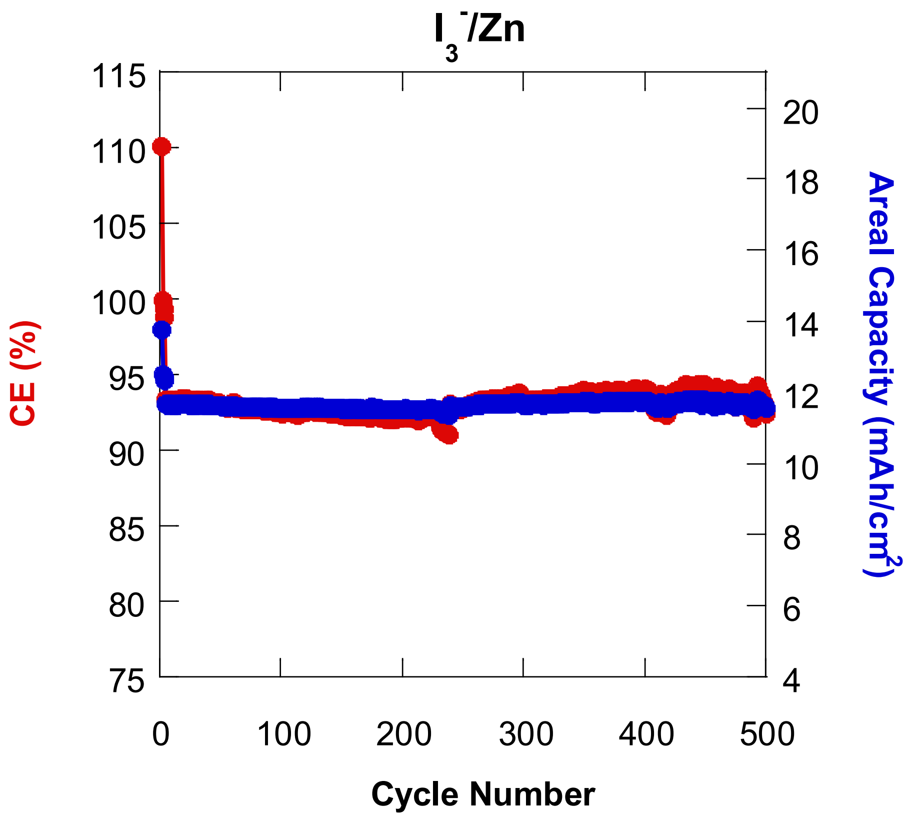


- Zn accounts for most of the anode deposit

Beyond MnO_2: I_3^-

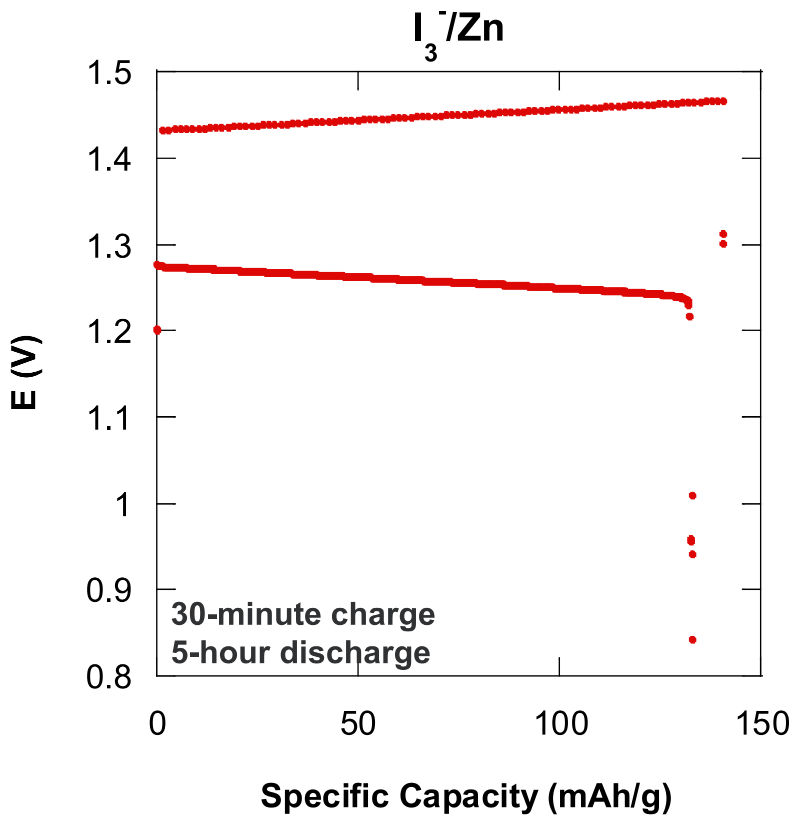


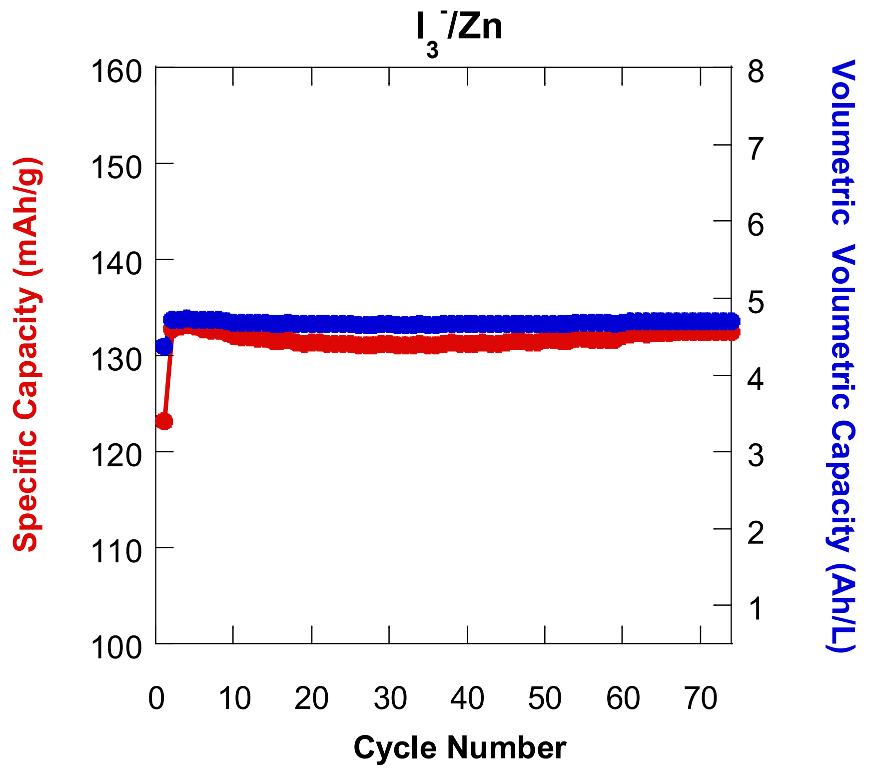


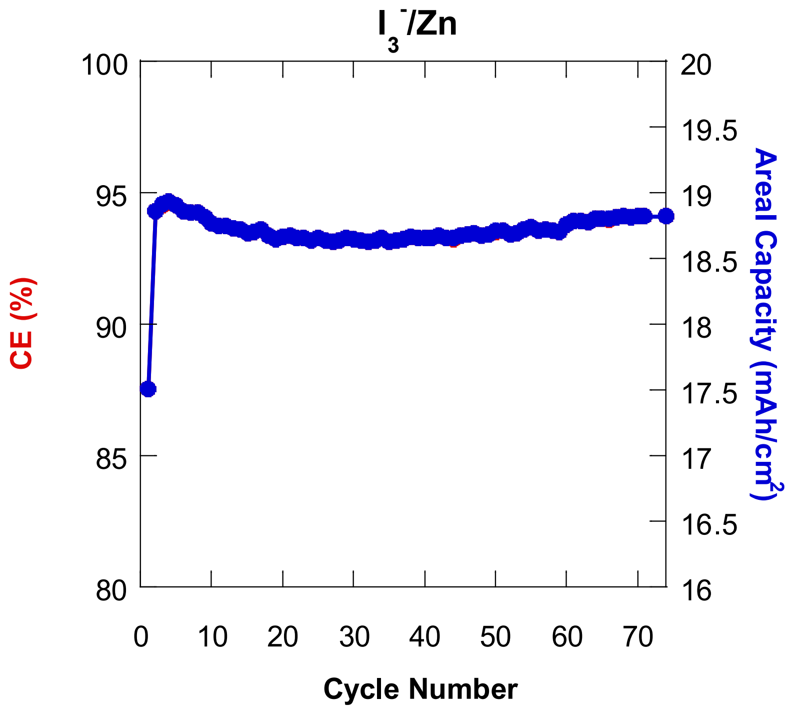


- **The I_3^- cathode with PNNL-developed electrolyte exhibits high gravimetric capacities (>125 mAh/g) and high areal loadings (>10 mAh/cm^2).**
- **Cycle stability exceeds 500 cycles.**

Beyond MnO_2: I_3^-







- In efforts to establish the Zn anode limitations, the I_3^- /Zn system capacity was increased to ~20 mAh/cm².
- The cell has exceeded 70 cycles with an average CE of 94%

Project Achievements

- **Research Highlights**

(1) Further Improvements to the electrolyte design have improved the the performance of the Zn metal anode. Specifically, the anode cycle is over 1000 cycles compared to a standard electrolyte of 1M $ZnSO_4$ (<50 cycles).

(2) The PNNL developed electrolyte allows for both long cycle life and relatively high utilization of the Zn metal anode while mitigating side reactions such as HER. Paired with a $VOPO_4$ cathode, the full cell has demonstrated over 200 cycles at near practical loadings of 3 mAh/cm^2

(3) To further prove the viability of the anode approach, the anode fabrication was scaled to a double-side coated capacity of 10 mAh/cm^2 in line with current industry practices. The half-cell perfomance of the double-side coated anode exceeded 60 cycles at 60% anode utilization

(4) In line with ongoing electrolyte work, the I_3^- chemistry allows for assessment and scale up of Zn-based chemistries. The full cell has shown over 500 cycles at a high areal loading of >10 mAh/cm^2 with a CE close to 92%. Further scale-up to practical cell levels of ~20 mAh/cm^2 have shown the CE and capacity are maintained.

(5) Based upon the work of the I_3^-/Zn, preliminary results with the MnO_2/Zn system appear promising. Currently, cycle life exceeds 200 cycles at an areal capacity of 5 mAh/cm^2 with an average CE of >90%.

Project Achievements

- **Publications: 2 in Preparation, 2 accepted, 1 submitted**
  (1) Lim, W-G. Grady, Z., Fayette, M., Li, X, Reed, D. In preparation 2026.
  (2) Grady Z. Fayette, M., Lim, W-G Li, X, Reed, D. Submitted.
  (3) A. N.Thieu, P. Gao, W. Li, S. Zhang, S. Chen, X. Li, and X. Liu. 2025. "Hybrid Metallic Cation-Anionic Surfactant Additive Regulating Interfacial Chemistry for High-Stability Zn Metal Anodes." Chemical Engineering Journal. 2025, 525, 170125
  (4) Anh Thieu N., W. Li, X. Li, and X. Liu. "Unraveling Spatial Electrochemical Heterogeneity and Additive-Mediated Regulation in Scale-up Aqueous Zinc-Ion Pouch-Type Cells." Advanced Energy Mater. submitted
  (5) X. Li, et al. A Perspective: Accelerating Electrochemical Energy Storage for a Reliable, Affordable, Resilient and Secure Electric Grid. Battery & Supercaps. 2026

- **Society Impact and STEM Outreach**
  (1) Electrolyte development for aqueous zinc batteries, 248the ECS meeting, October, 2025 (Invited)
  (2) Lim W., P. Gao, M.R. Fayette, X. Li, and D.M. Reed. 05/25/2026. "Electrolyte Design Strategies for Functional Additives and Structural Tuning in Aqueous Zinc Batteries." Seattle, Washington. Poster

Proposed Work for FY2027

- Continue to improve the cycling stability/mitigation of side reactions of Zn-based anodes
- Further revisions/improvements to PNNL electrolyte system.
- Continued scale-up of full cell chemistries to demonstrate practical systems

Acknowledgements

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Thank you