Understanding the degradation mechanism of rechargeable alkaline zinc batteries under the influence of externally applied pressure

Deepak Kharel[1], Timothy N. Lambert[2,3], and Yang-Tse Cheng[1,4]

[1]Physics and Astronomy, University of Kentucky, Lexington, KY 40506, USA

[2]Department of Photovoltaics and Materials Technology, Sandia National Laboratories, Albuquerque, NM 87185, USA

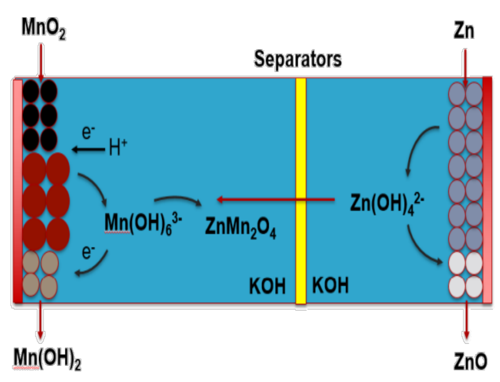
[3]Center for Integrated Nanotechnologies, Sandia National Laboratories, Albuquerque, NM 87123, USA

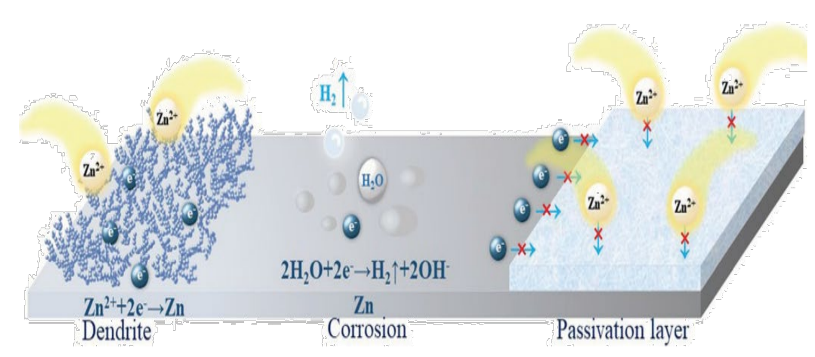
[4]Chemical and Material Engineering, University of Kentucky, Lexington, KY 40506, USA

PROJECT PROFILE
Topic: Zinc & Lead Batteries| Vertical: Materials and System Innovation
Strategic Pathway: Grow
Project start and finish: FY26-FY28, Storage Innovations-2030

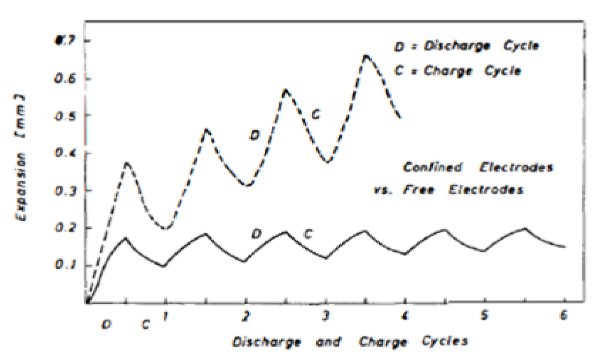
Problem

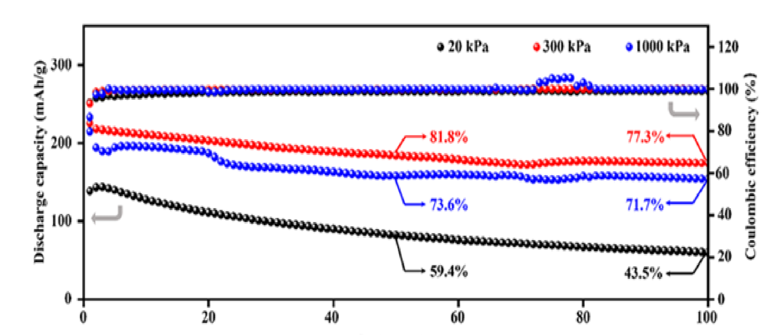
- **Background:** Rechargeable alkaline zinc batteries (AZBs) offers safe, abundant, and low-cost pathway for large-scale grid applications but face significant challenges,[1,2] including short cycle life and poorly understood degradation mechanism.





Studies have shown that applied pressure improves Zn-battery performance,[3,4] but the role of external pressure in degradation has not been extensively studied.





- **Objectives:** To understand the pressure-driven degradation in alkaline Zn-MnO_2 batteries to achieve stable and long-lasting performance tailored for grid-scale energy storage.

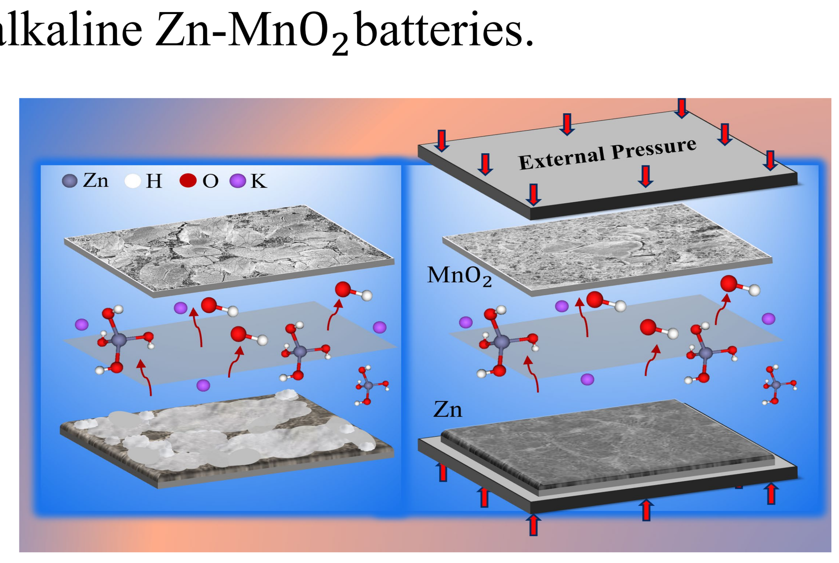
- **Technical challenge:** Pressure-dependent degradation pathways remain poorly understood due to tightly coupled mechanical-electrochemical-morphological interactions.

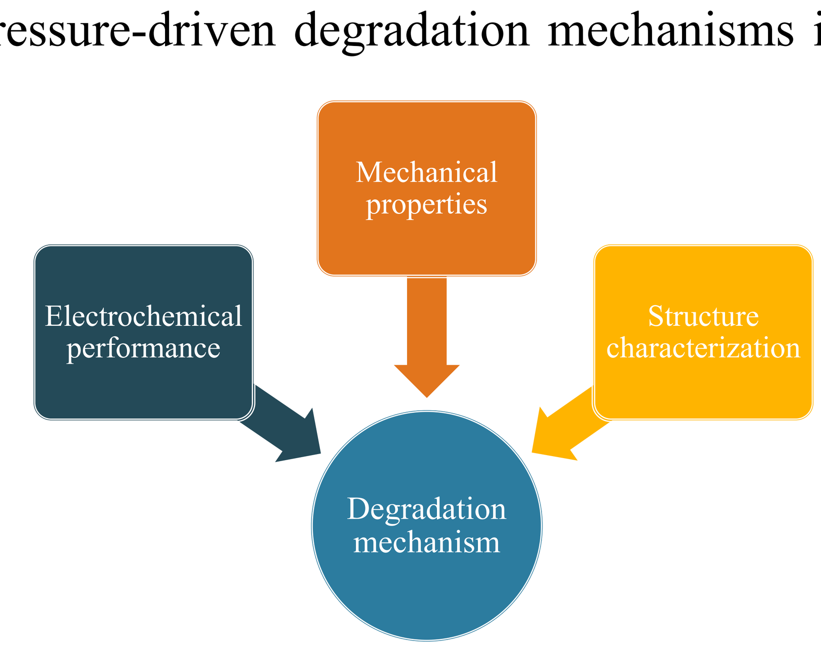
- **Motivation & alignment:** Understanding pressure-driven degradation mechanism with a domestic, facile Zn-battery manufacturing processes provides a pathway for advancing durable, low-cost storage technologies that supports affordable, scalable, and secure U.S. grid modernization efforts.

- **Current practice:** AZBs are under-studied and often assumed to follow Li-ion mechanism with insufficient experimental validation, leaving a critical knowledge gap.

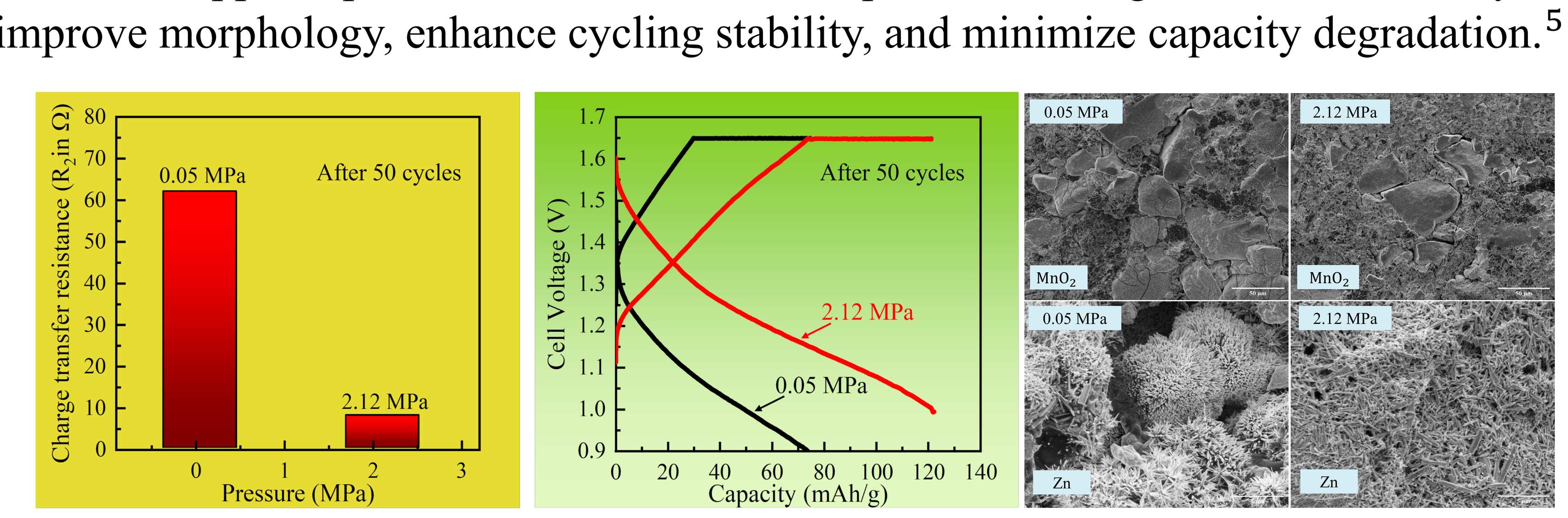
Approach

- **Strategy:** Correlating mechanical, electrochemical, and morphological changes under controlled external pressure to understand pressure-driven degradation mechanisms in alkaline Zn-MnO_2batteries.





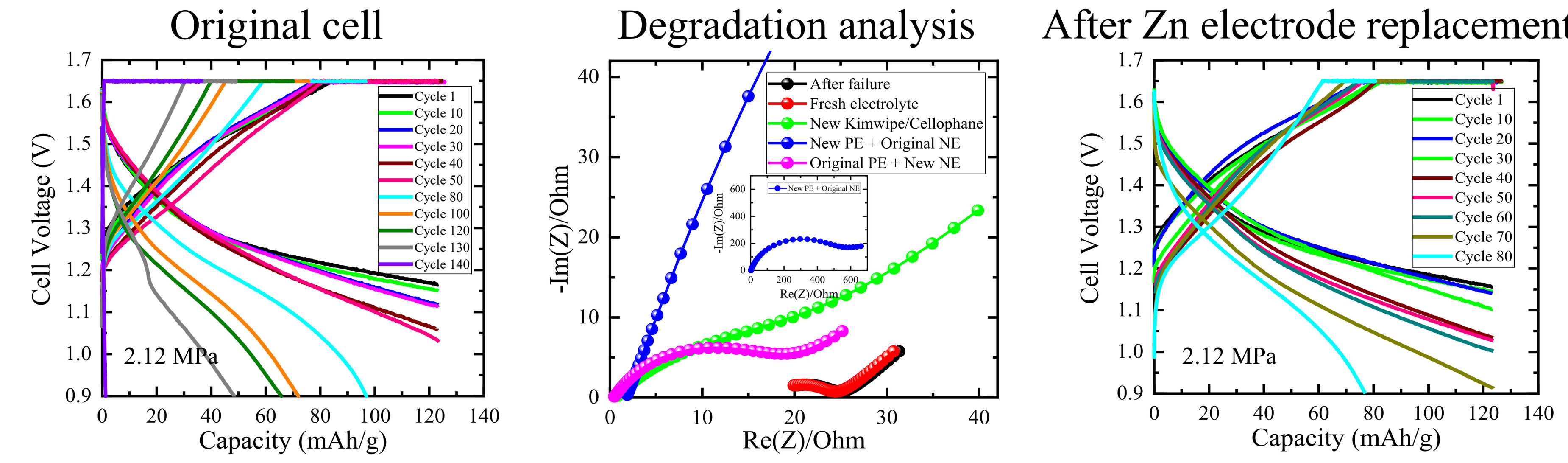
- **Why this approach:** Initial studies at ~5% DOD Zn and 20% DOD MnO_2 utilization show that applied pressure can reduce cell impedance during electrochemical cycling, improve morphology, enhance cycling stability, and minimize capacity degradation.[5]



- **Lab capabilities:** University of Kentucky offers advanced capabilities, *e.g.*, pouch cell fabrication, pressure cell studies, electrode characterization using nanoindentation, AFM, TEM, and cross-section ion beam polisher that help understand the underlying mechanism for advancing AZBs.

Results

Electrochemical measurements and cell repair experiments



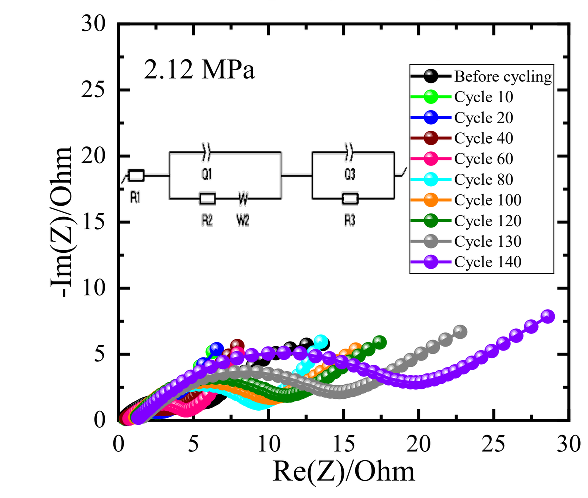
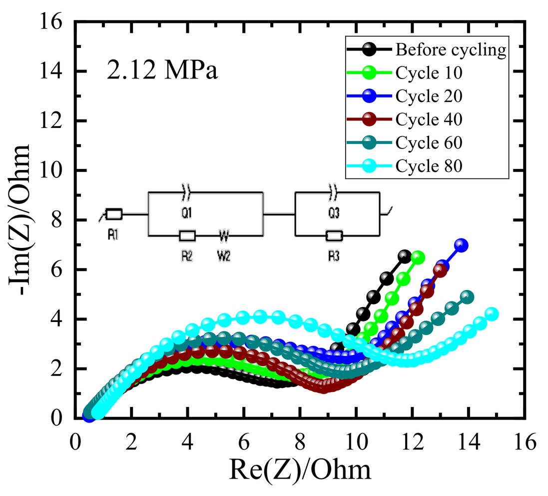


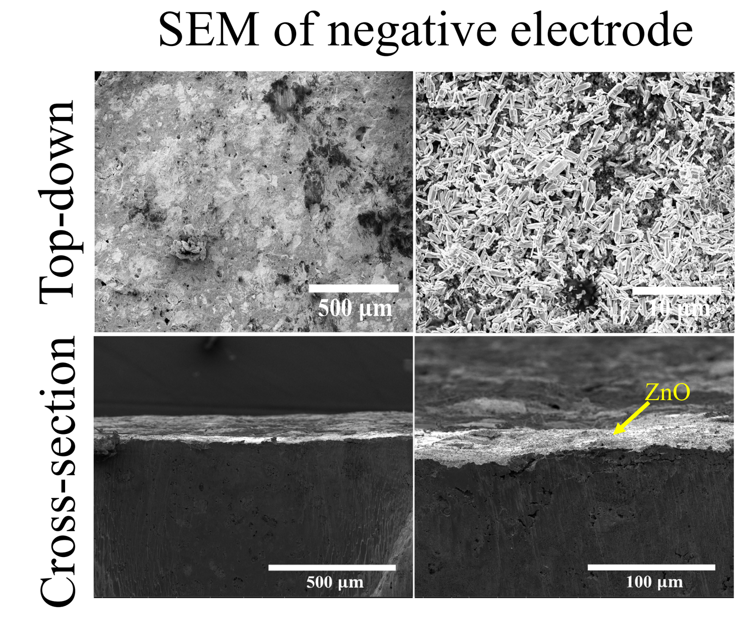
Table: Data from degradation analysis

Cell Status	Cell OCV (V)	R1 (Ω)	R2 (Ω)
After cell failure	0.28	19.56	7.19
After adding fresh electrolyte	0.31	19.10	5.78
New Kimwipe/Cellophane	0.32	0.78	29.78
New PE + Original NE	0.38	2.41	568.2
New NE + Original PE	1.485	0.48	18.86

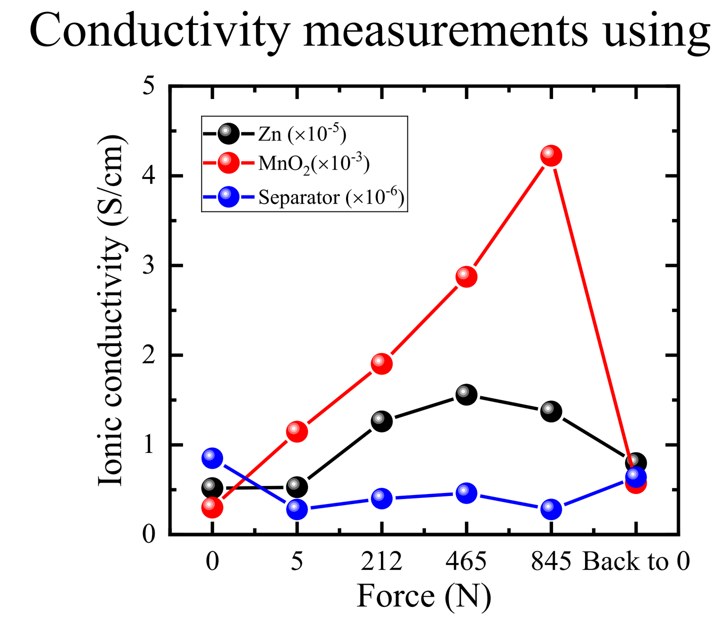


- Surprisingly, the cells failed mainly due to Zn negative electrode degradation, despite zinc being utilized at only ~5% DOD.

SEM of negative electrode



Conductivity measurements using EIS



Conclusions and Impact

- Cell-repair experiments indicate that cell failure is primarily driven by early degradation of the Zn negative electrode.
- Cycled at 2.12 MPa, the repaired cell shows little capacity fade and stable resistance for 70 cycles.
- Top-down and cross-sectional SEM/EDS observations reveal significant ZnO accumulation (passivation) on the cycled negative electrode surface.
- With applied pressure, electrode ionic conductivity increases, while separator conductivity decreases.

Impact: Our experimental results show that applied pressure helps reduce internal resistance and improves cycling stability, but early Zn electrode failure ultimately limits cycle life, despite Zn being utilized at just ~5% DOD—a condition under which much longer cycle life be expected. This project will guide the development of more durable AZBs for affordable, large-scale energy storage systems.

Future Directions

- Understand pressure effects on morphology, composition of electrodes, and cycle life.
- Establish the relationship between electrochemical and mechanical properties of cells before and after cycling.
- Perform detailed characterization using SEM, EDS, and XRD.

References

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Acknowledgments

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