Dendrite-Resistant Solid Sodium Anodes to Enable Long-Duration Solid-State Sodium Batteries

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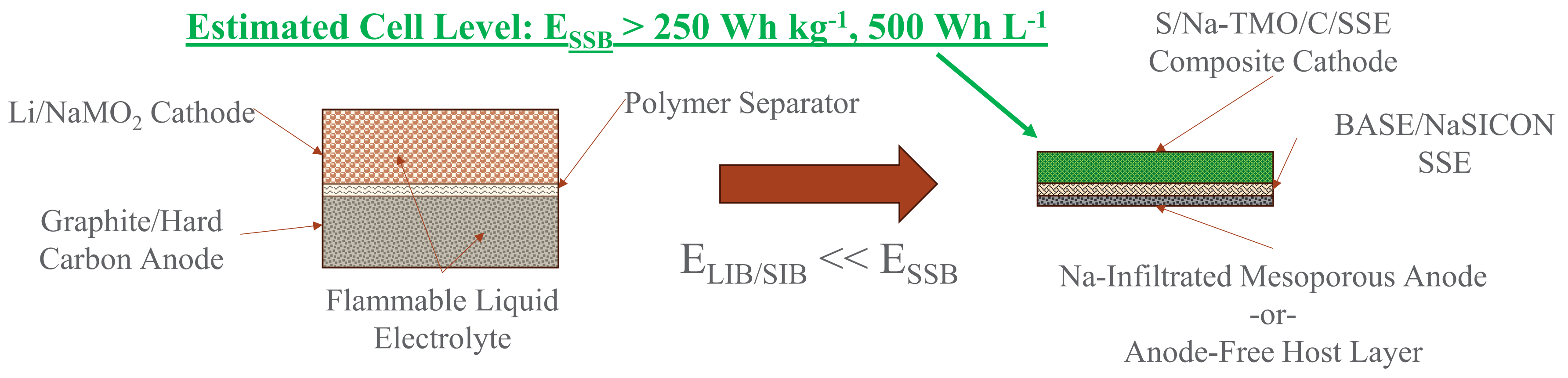
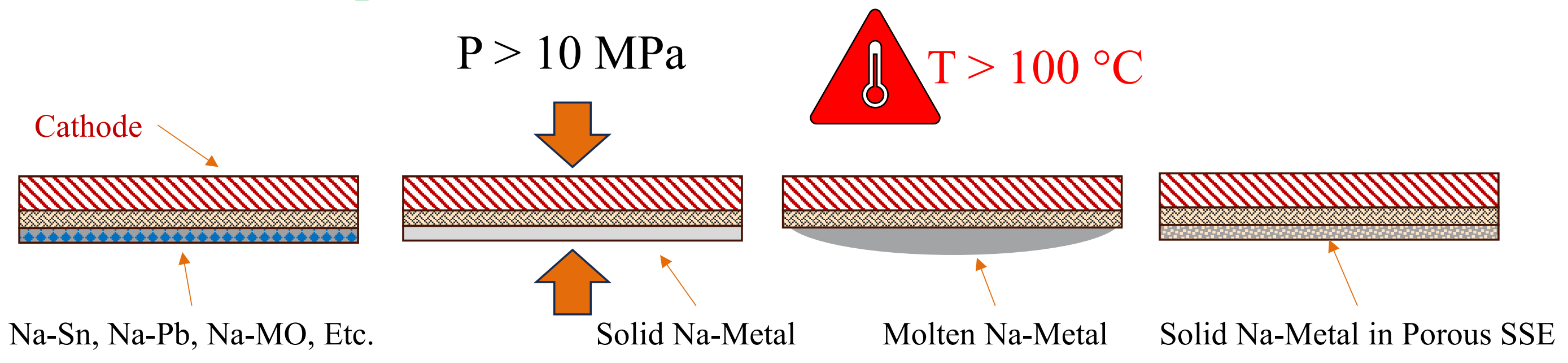
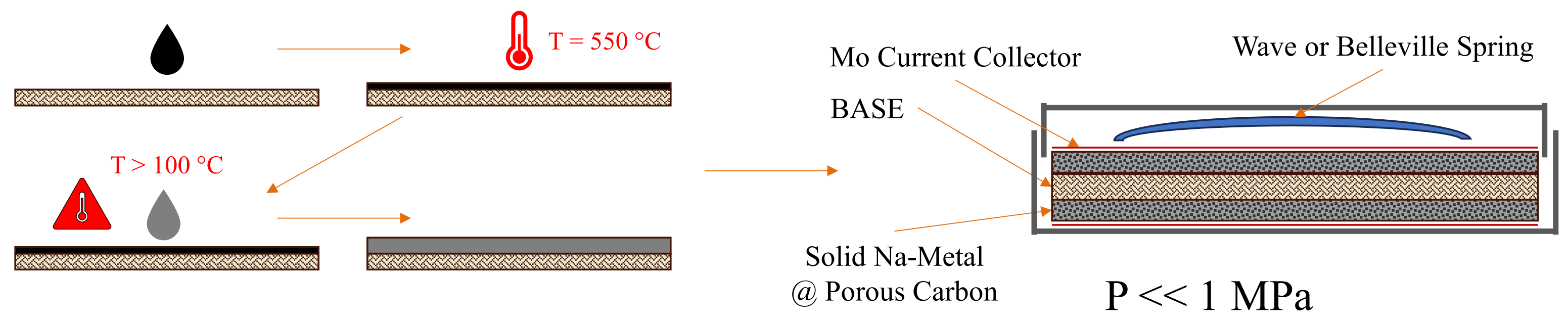
Na-Solid-State Batteries


Estimated Cell Level: E_{SSB} > 250 Wh kg^{-1}, 500 Wh L^{-1}

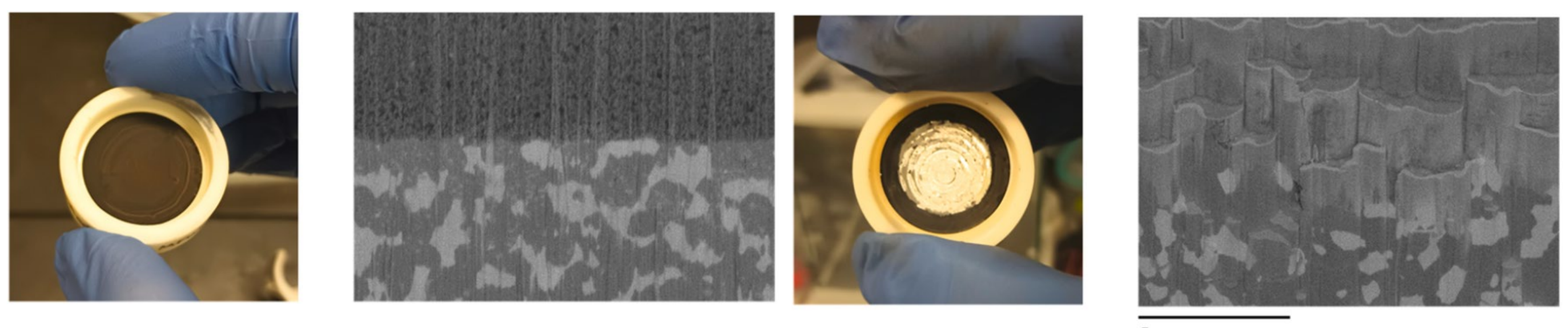
- Pure alkali metal anodes can significantly improve energy density[1], but have significant safety[2] and performance issues:
  - More reactive → fires and explosions
  - Short circuit failure → dendrites
- Na-Solid-State Batteries (Na-SSB) emerging alternative to Li-SSB
  - Lower cost, potential for better energy density than current LIBs
- Solid-state batteries can mitigate fire risk → **dendrites are still a major issue**:
  - Limited current density, areal capacity, difficult to achieve long-duration
    - Metal alloys[3]
    - High stack pressure[4]
    - Molten metal electrode[5]
    - Solid-Na in porous host*





A Lighter, Low-Cost Alternative: Porous Carbon

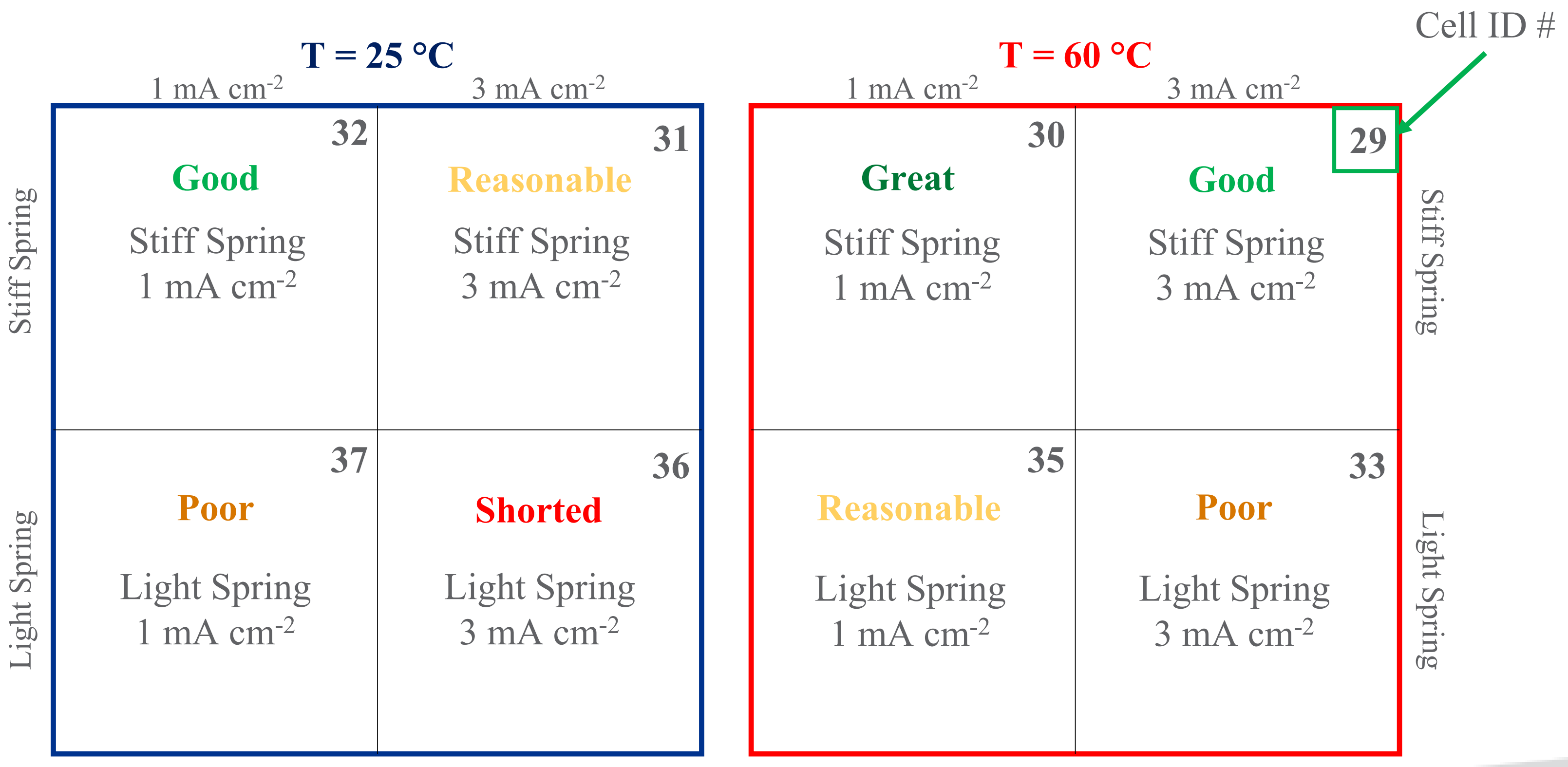
- 'Metal-Free Wetting Layer' (MFWL) composed of porous carbon previously showed excellent Na-wettability on Na-ß"-Al$_2$O$_3$ (BASE) for molten Na cells[6]
- Also showed better solid-state Na-cycling than Na-Pb alloy
- Need **to determine the limits** of this anode design for solid-state Na batteries
- Na-MFWL-BASE → 'platform' for stationary Na-SSBs



Weller et. al., *Nano Energy*, **2024**, 128, 109815

Cyclability: Temperature, Pressure, Current, Capacity

- For stationary storage – low stack pressure, use of oxides are important
- Operating temperature can be set to optimize performance – similar to ZEBRA
- Effect of stack pressure, temperature, current density, areal cycling capacity
- More than 40 cells assembled to test different conditions, surface treatments

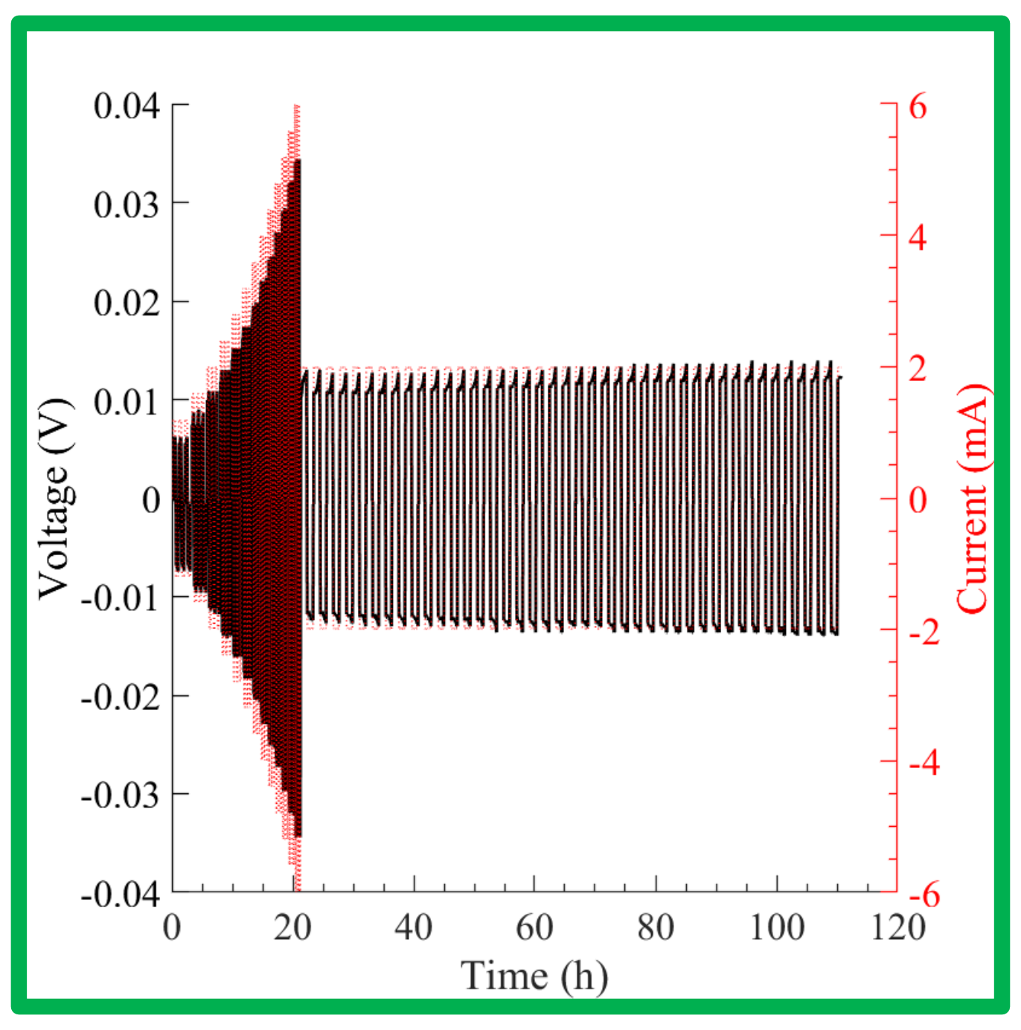


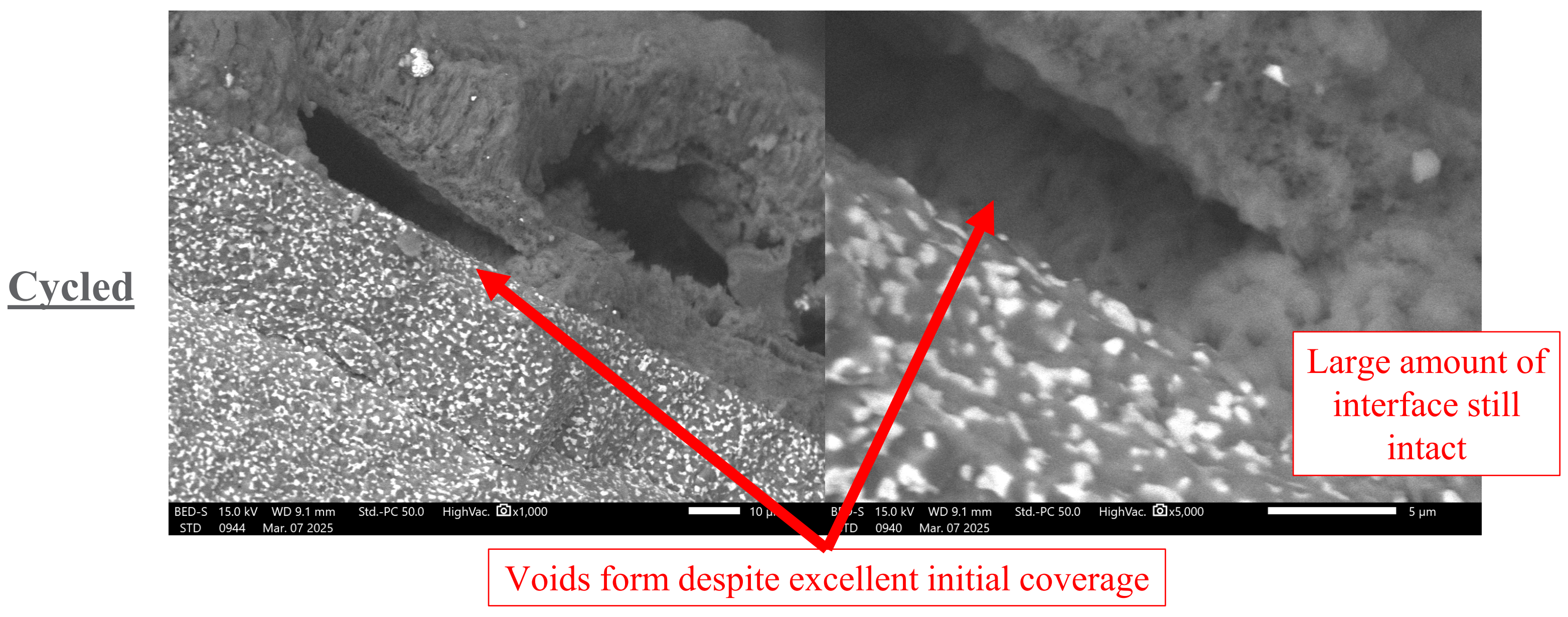
	T = 25 °C 1 mA cm^{-2}	T = 25 °C 3 mA cm^{-2}	T = 60 °C 1 mA cm^{-2}	T = 60 °C 3 mA cm^{-2}	
Stiff Spring	32 **Good** Stiff Spring 1 mA cm^{-2}	31 **Reasonable** Stiff Spring 3 mA cm^{-2}	30 **Great** Stiff Spring 1 mA cm^{-2}	29 **Good** Stiff Spring 3 mA cm^{-2}	Stiff Spring
Light Spring	37 **Poor** Light Spring 1 mA cm^{-2}	36 **Shorted** Light Spring 3 mA cm^{-2}	35 **Reasonable** Light Spring 1 mA cm^{-2}	33 **Poor** Light Spring 3 mA cm^{-2}	Light Spring

This project is accelerating the development and testing of a new energy storage 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.

Morphology Evolution During Cycling

- After sodiation – interface between metallic Na and BASE solid-electrolyte is incredibly tight
- No noticeable voids or gaps between Na and BASE (video)
- After cycling – morphology evolution through void formation, Na removal from porous carbon, intermittent loss of contact area (video)
- Short circuit not observed!

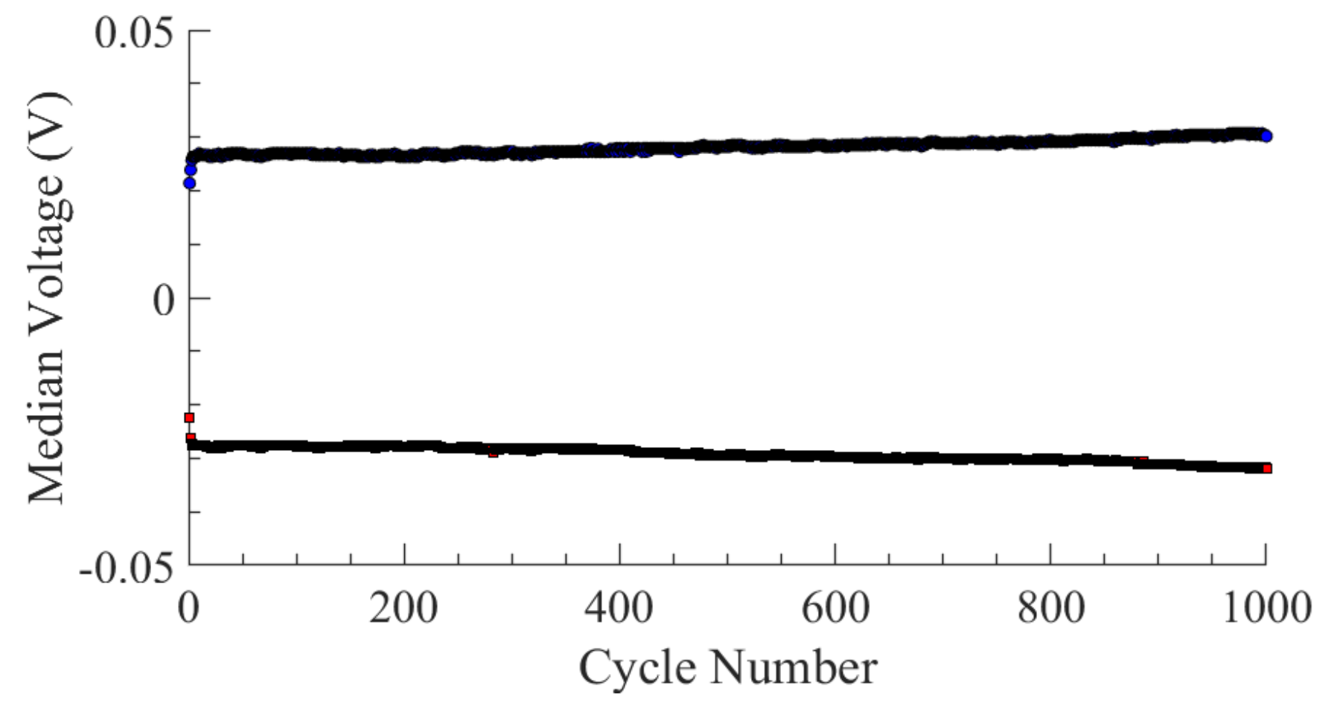




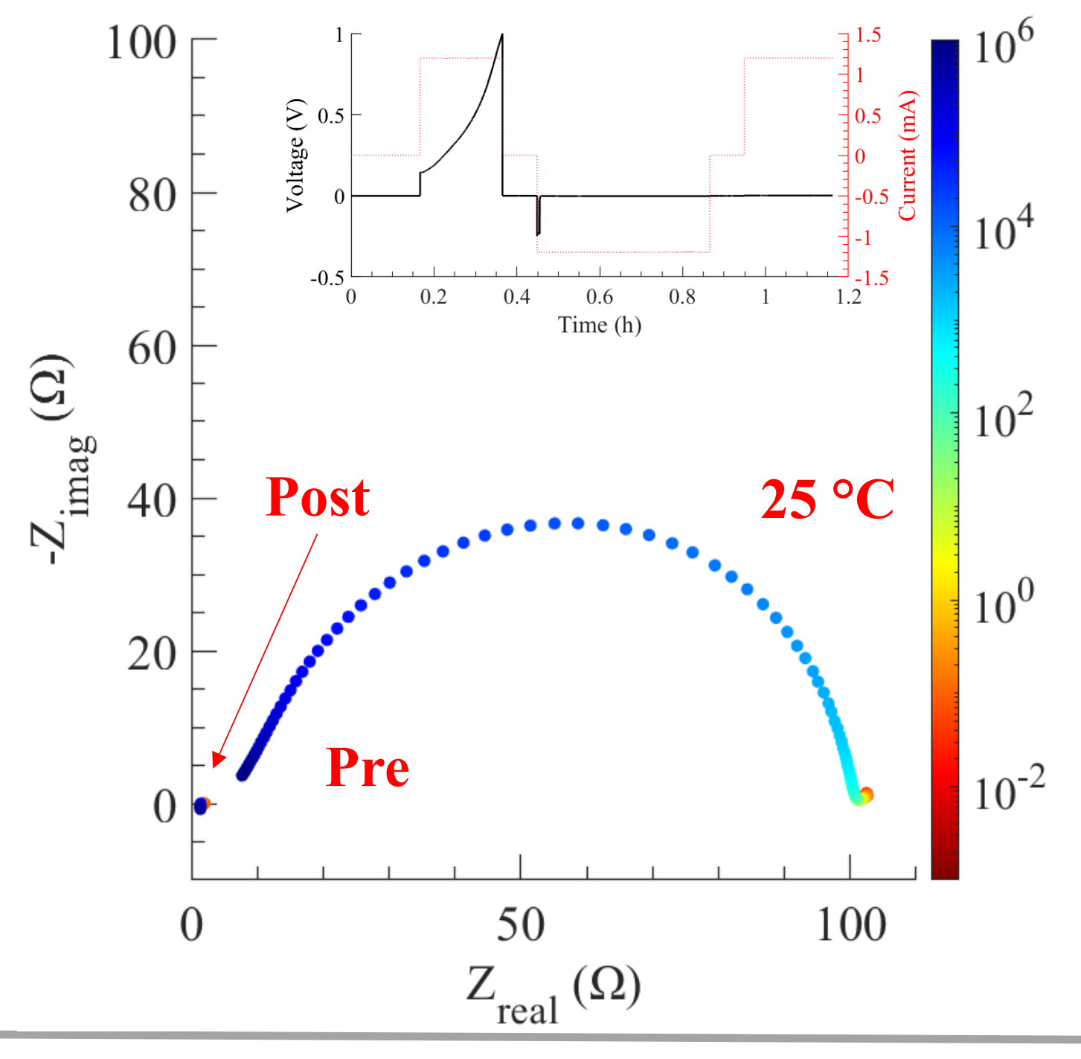
- Cycling above 1 mAh cm^{-2} possible, but voids can form
- Similar cell disassembled – can see void formation while large regions of good contact remain
- Na-porous-carbon interface mitigates but doesn't eliminate void formation

Long-Term Cyclability and Critical Current Density

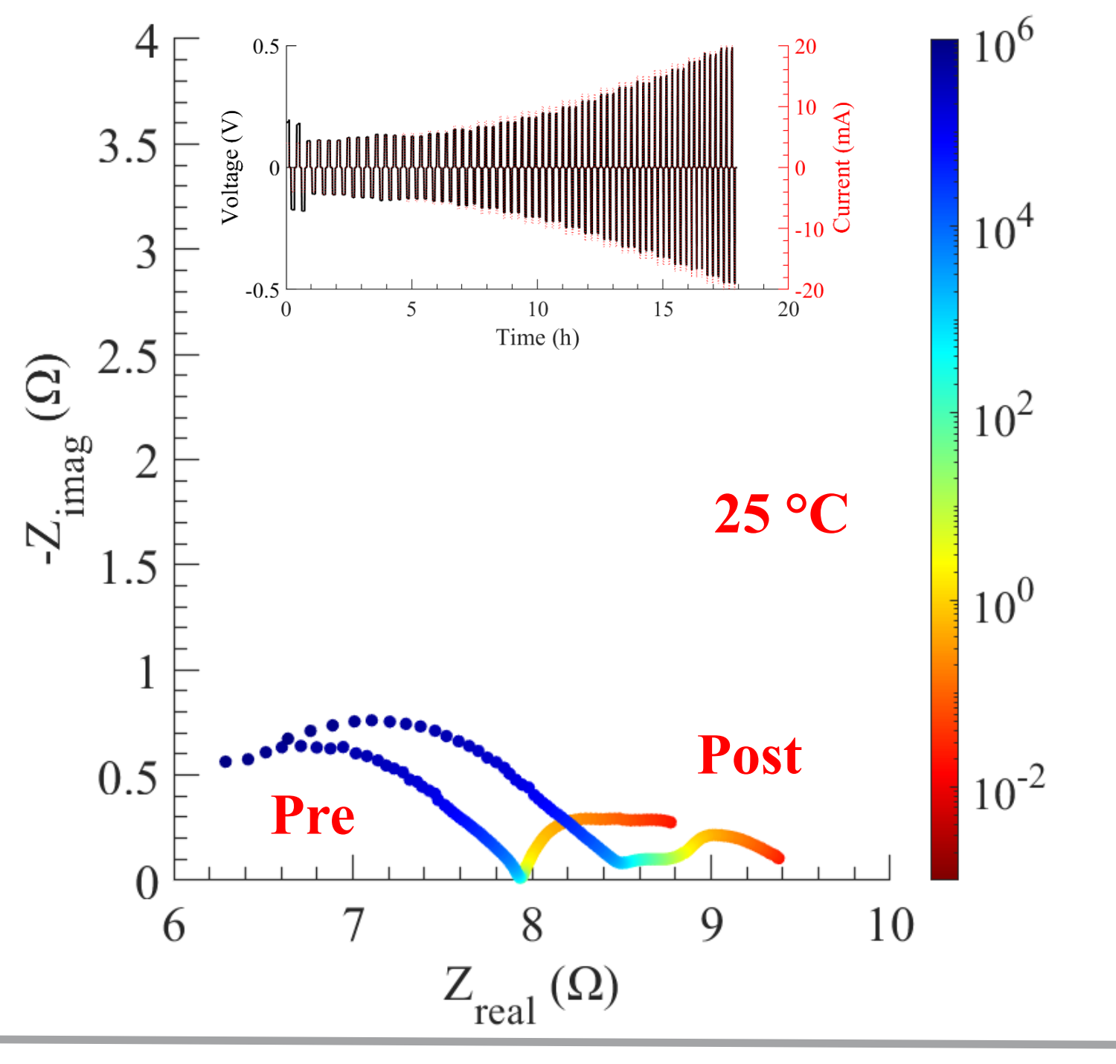
- Cycling at 25 °C
- 1 mA cm^{-2}, 0.25 mAh cm^{-2}
- 1000 cycles achieved
- Some increase in overpotential
- Na-porous carbon cell able to cycle up to **10 mA cm^{-2}** (0.25 mAh cm^{-2}) with no short circuit
- *Uncoated cell failed at only 0.6 mA cm^{-2}*



Short Circuit at 0.6 mA cm^{-2}



No Short – 10 mA cm^{-2}



Conclusions and Future Work

- Mesoporous carbon interfacial layer facilitates **excellent interfacial contact** between Na-metal and Na-ß"-Al$_2$O$_3$ solid electrolyte
- Effects of spring tension, temperature, current density, and areal capacity are explored – 1 mAh cm^{-2} at 1 mA cm^{-2} stable cycling possible at 60 °C
- 1000 cycles stable cycling at 25 °C at 1 mA cm^{-2}, 0.25 mAh cm^{-2}
- Critical current density at least 10 mA cm^{-2}
- Dendrite-resistance – over-polarization *rather than* short circuit – conductive carbon matrix appears to distribute current density
- Improvements to Na-transport to enable > 2 mAh cm^{-2} are ongoing

Acknowledgments

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[1] Albertus et. al., *Nature. Energy*. **2017**, 3, 16-21
[2] Xu et. al., *Energy Environ. Sci.*, **2014**, 7, 513-537
[3] Oh et. al., *Adv. Energy Mater*. **2021**, 11, 2101228
[4] Xu et. al., *Energy Environ. Sci.*, **2014**, 7, 513-537
[5] Xu et. al., *Energy Environ. Sci.*, **2014**, 7, 513-537
[6] Weller et. al., *Nano Energy*, **2024**, 128, 109815