Large Format Aqueous Electrolyte Polyionic Devices for Low Cost, Multi-Hour Stationary Energy Storage

J.F. Whitacre[1,2], T Wiley[2], S. Shanbhag[2], S. Chun[1], W. Yang[2], D. Blackwood[2], A. Mohamed,[1,2] E. Weber[2], D. Humphreys[2]

[1] Carnegie Mellon University, Department of Materials Science and Engineering, Department of Engineering and Public Policy, 5000 Forbes Ave, Pittsburgh PA 15213

[2] Aquion Energy ,32 39th Street, Pittsburgh PA 15201

Energy Storage, Clean and Simple.

Aquion Energy - Leading Energy Storage Provider

COMPANY

+ Spun out of Carnegie Mellon in 2010
+ HQ in Pittsburgh, PA
+ Investors include Kleiner Perkins, Foundation Capital, Bill Gates, ATV
+ History of solid execution

MANUFACTURING

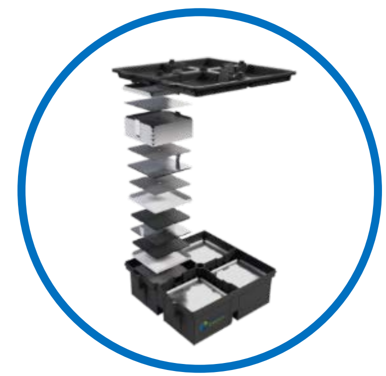
+ 350,000 sq ft facility in Pennsylvania
+ State-of-the-art manufacturing line in place & operational
+ Shipping product to customers globally

PRODUCT

+ 48V stack and module building blocks
+ Scalable to 1000 Vdc and multi-MWh installations
+ Battery Monitoring only, no active management required

TECHNOLOGY

+ Aqueous Hybrid Ion (AHI) intercalation battery system
+ Invented by Aquion
+ Optimized for long duration (4+ hr) and very high cycle life
+ Cost-effective, safe, and sustainable



The Economic Reality of Microgrid Energy Storage

- Defining metric: Levelized cost of stored energy (LCOSE) as amortized over the lifetime of the system

Useable discharge capacity

$$LCOSE(\$/kWh) = \frac{Cost}{\#\,cycles \times efficiency} = \frac{(\$/kWh)}{\# \times \eta}$$

Delivered energy on discharge

The Economic Reality of Microgrid Energy Storage

+ Another key - cycle life:
  - Issue: typically energy density and cycle life are inversely correlated

$$LCOSE(\$/kWh) = \frac{Cost}{\#\,cycles \times efficiency} = \frac{(\$/kWh)}{\# \times \eta}$$

+ Assuming we must have a have a LCOSE of < $0.1/kWh
+ Then we need > 5000 cycles
+ Price point of under $300/(usable kWh installed)

The Economic Reality of Energy Storage

Must use:

+ Cheap materials (<$4/kg),
+ Simple manufacturing approach ("borrowed technologies")

Solution: Low Cost and Sufficient Enough Energy Density

- Goal was to identify the “sweet spot” between specific cost, energy density, and cycle life
- Significant testing yielded a finding:
  - Aqueous electrolyte sodium ion functional materials and battery structures
  - If you set aside energy density as requirement, using neutral pH electrolyte allow for very substantial cost savings, and benign electrode reactions

Aqueous Hybrid Ion (AHI™) Chemistry

Aqueous Electrolyte:

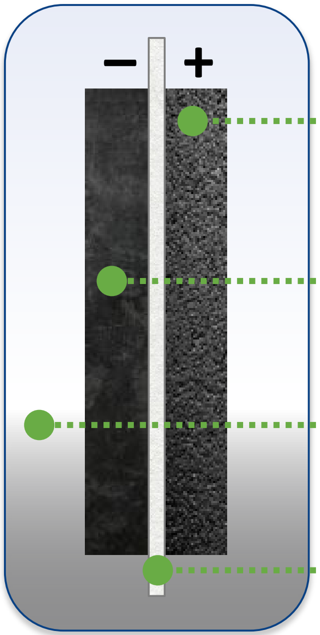
+ Water-based, ambient temperature, sodium sulfate electrolyte.

Hybrid Reactions:

+ An asymmetric/hybrid electrode configuration:
  - **Cathode:** Intercalation reaction
  - **Anode:** Pseudocapacitive and intercalation interaction

Multiple Ions:

+ The chemistry uses sodium and lithium ions as the primary charge carrier to store energy inside the battery.



+ **CATHODE:** Manganese Oxide spinel structure hosts intercalation reaction

+ **ANODE:** Carbon composite with pseudocapacitive and intercalation reactions

+ **ELECTROLYTE:** Na_2SO_4 in an aqueous solution

+ **SEPARATOR:** Non-woven cellulosic material

Building Block: Internal Contents and Structure

Building a battery that is **high-performing**, **safe**, **sustainable** and **cost-effective** using abundant, nontoxic materials.

+ BASE OXIDE

Manganese Oxide Cathode

+ COTTON

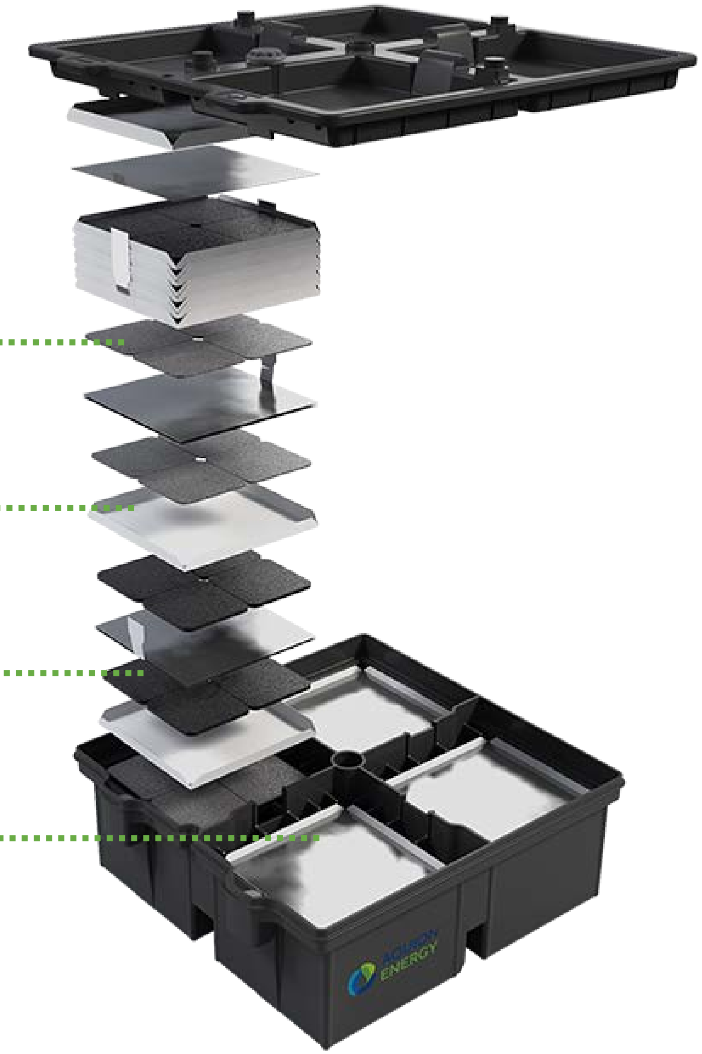
Synthetic Cotton Separator

+ CARBON

Carbon Composite Anode

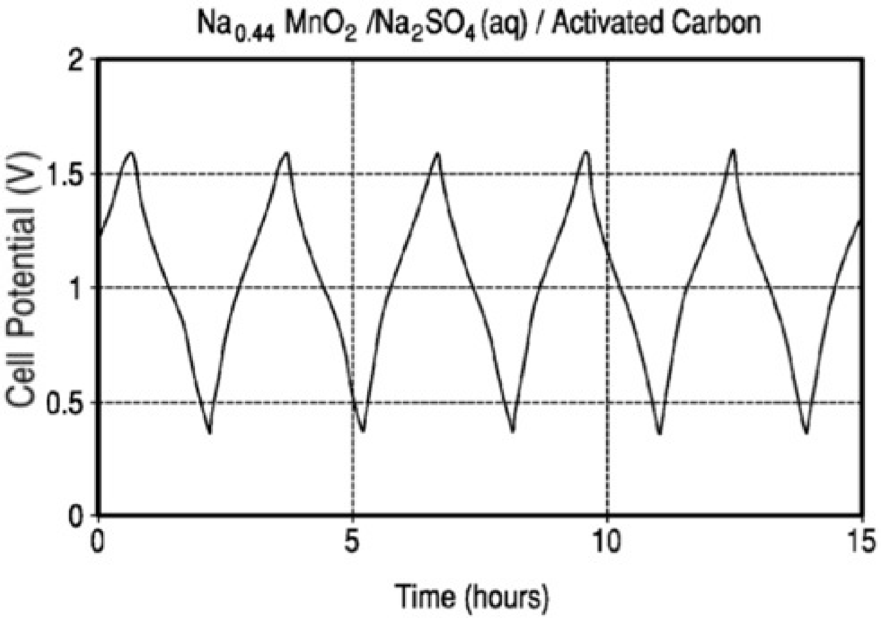
+ SALTWATER

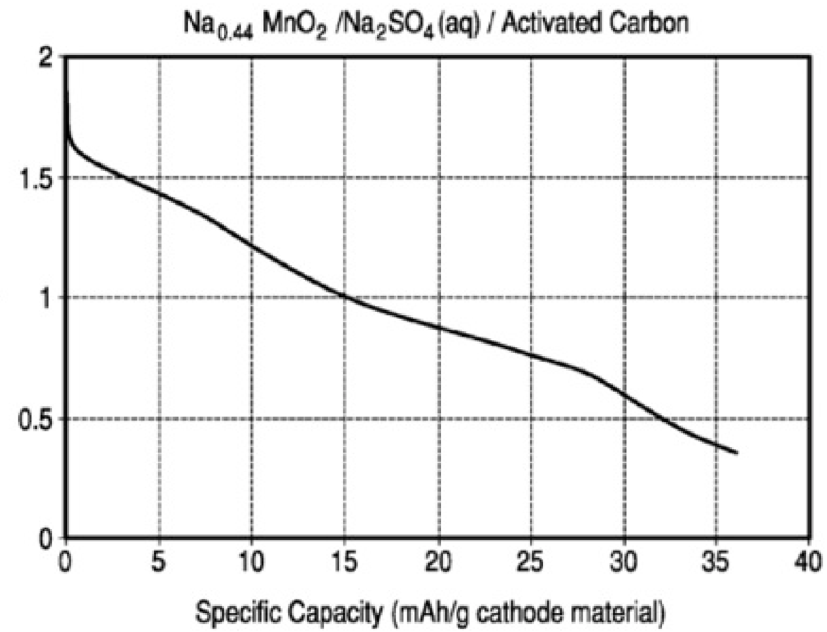
Sodium Sulfate Electrolyte



Stability/Capacity of First Generation Chemistry

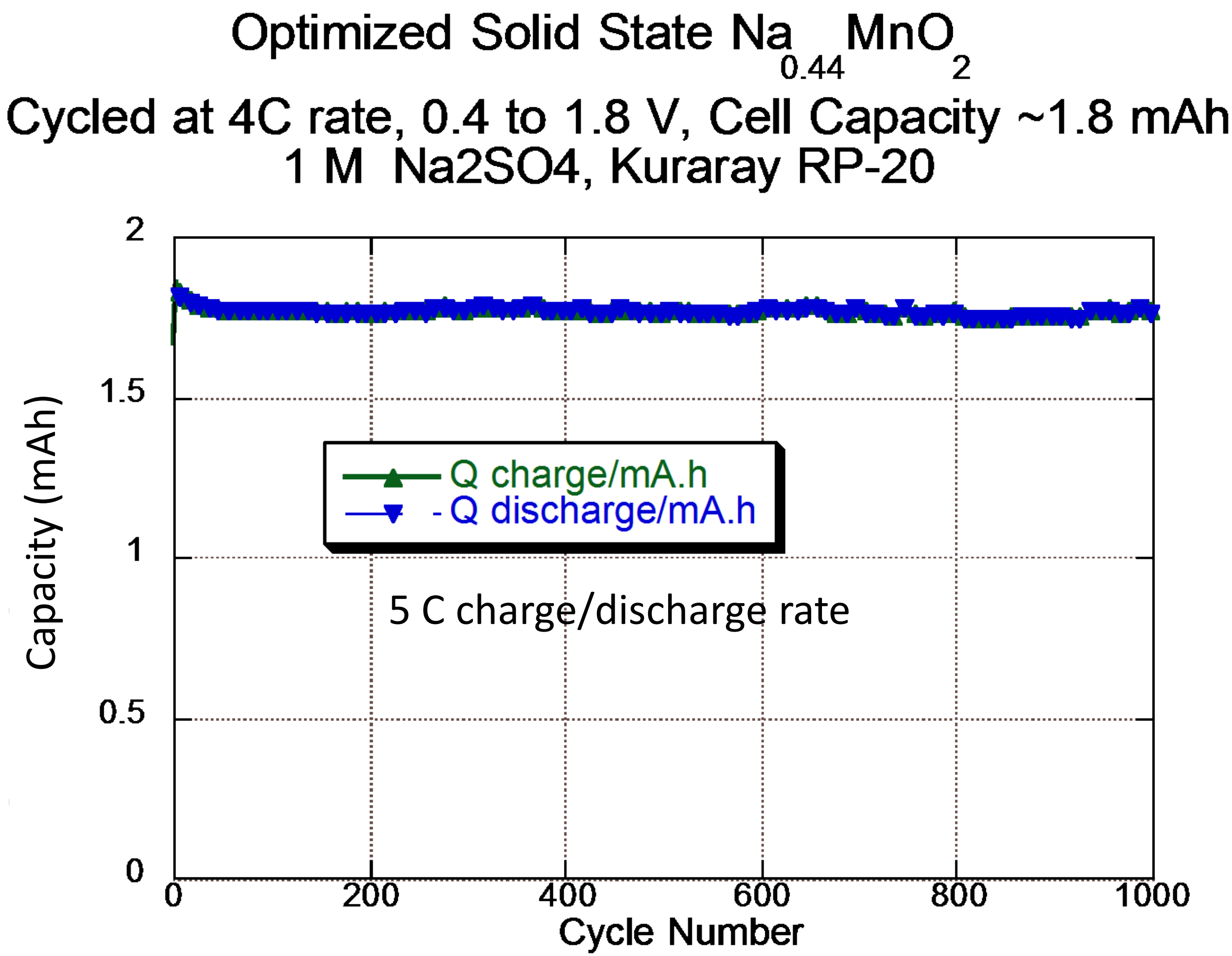
+ $Na_4Mn_9O_{18}$ Cathode Material





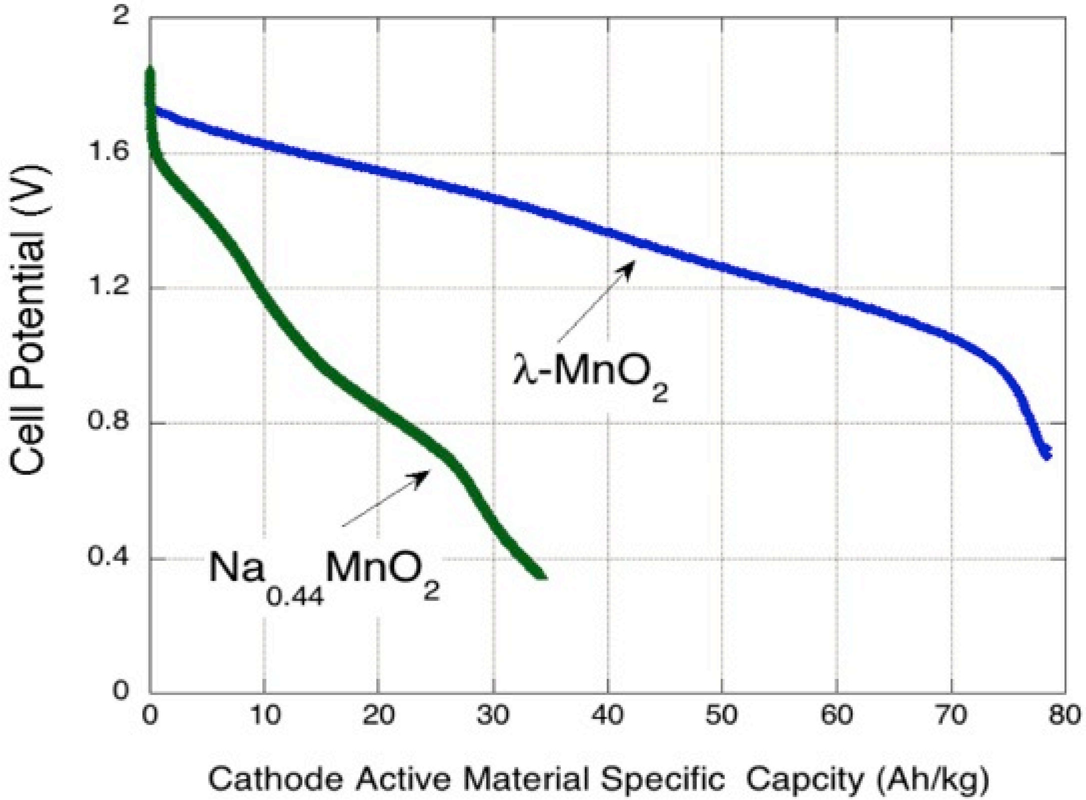
+ Significant energy present,
+ BUT, using costing rules, materials have to be under $2/kg all in to compete
+ Very difficult to do!

Cycle Life/Columbic Efficiency



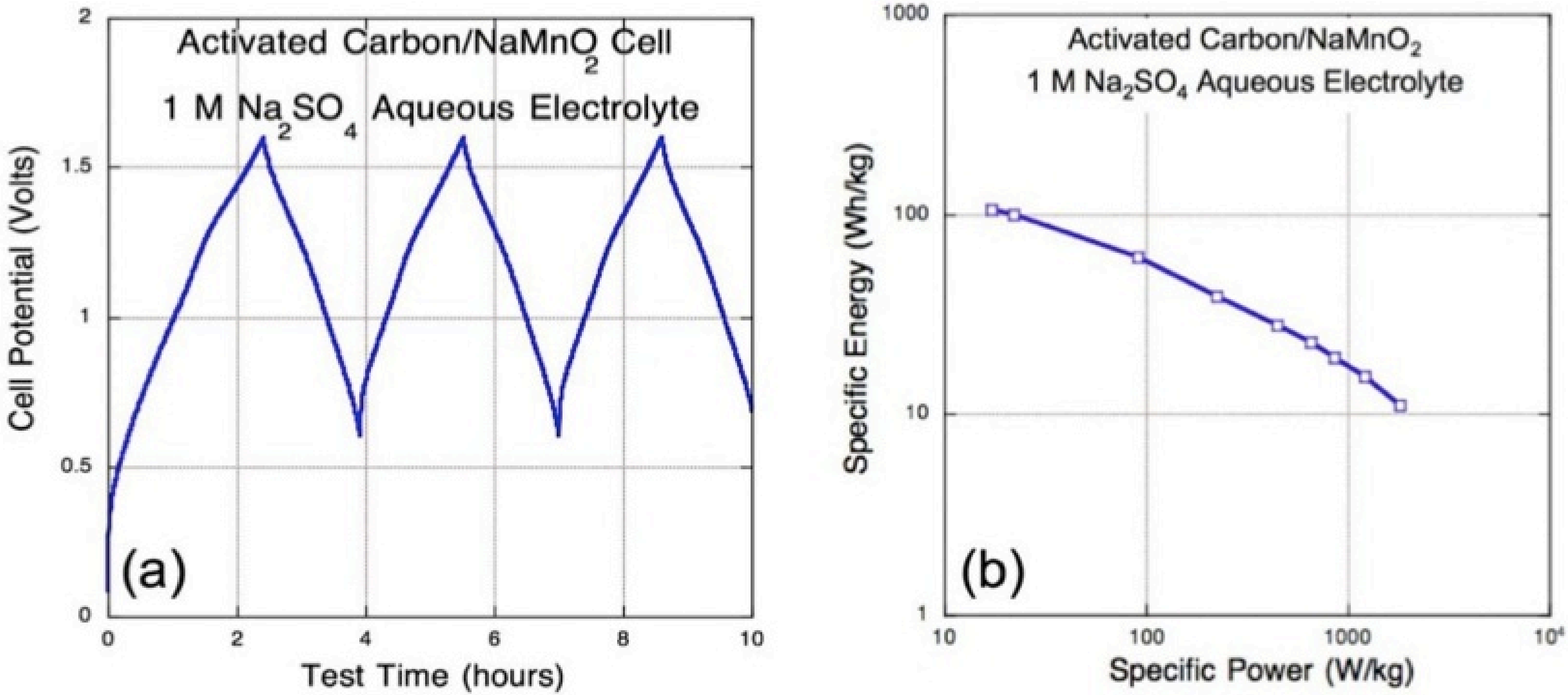
+ 1000 cycles, negligible loss in capacity, ~100% Columbic efficiency

Lambda MnO_2 in Na_2SO_4



- λ – MnO2 has over 2 times the capacity and 3 times the energy of $Na_4Mn_9O_{18}$
- Rate capability also found to be very good

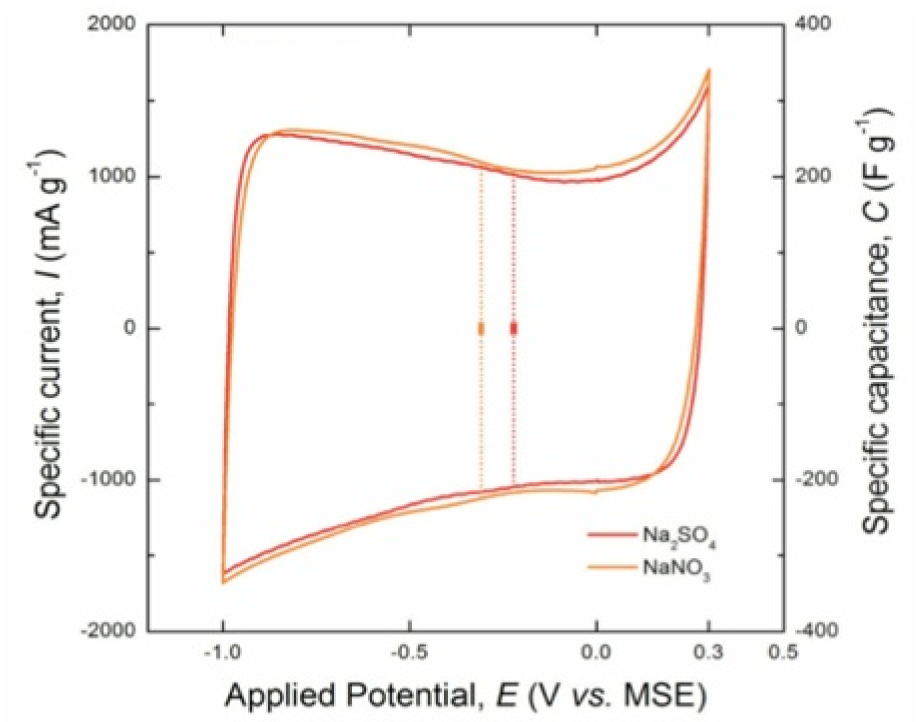
Second Generation Chemistry: Lambda-MnO_2



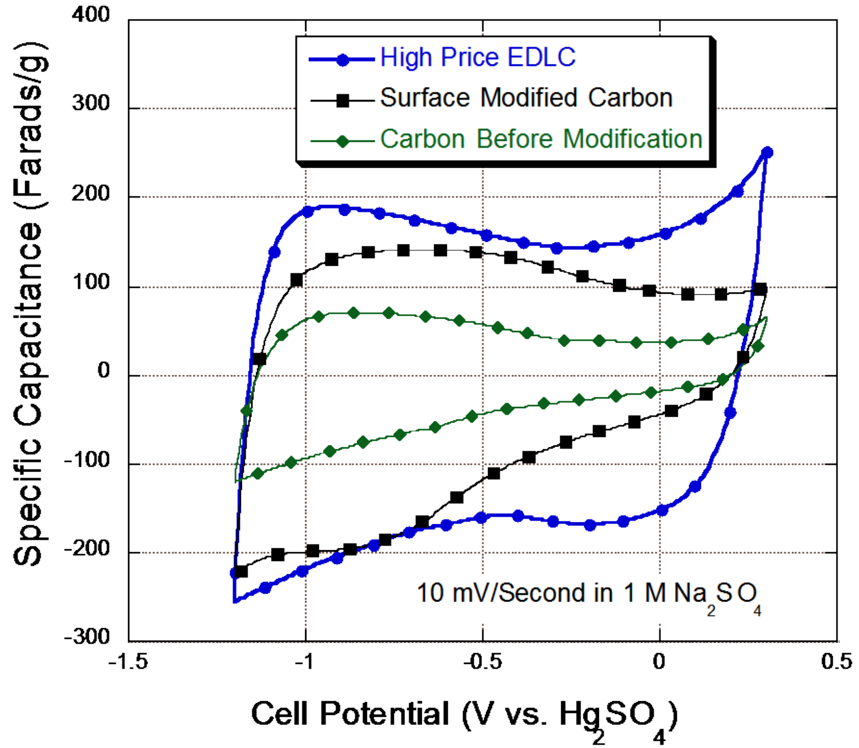
+ Much higher specific capacity compared to $Na_4Mn_9O_{18}$
+ In balanced device, over 100 Wh/kg (cathode) at lower rates
+ Still extremely stable
+ Added cost of using Li_2CO_3 to template material is justified.

The Anode: Activated Carbon in Neutral PH

Dextrose - based



Coconut/wood - based

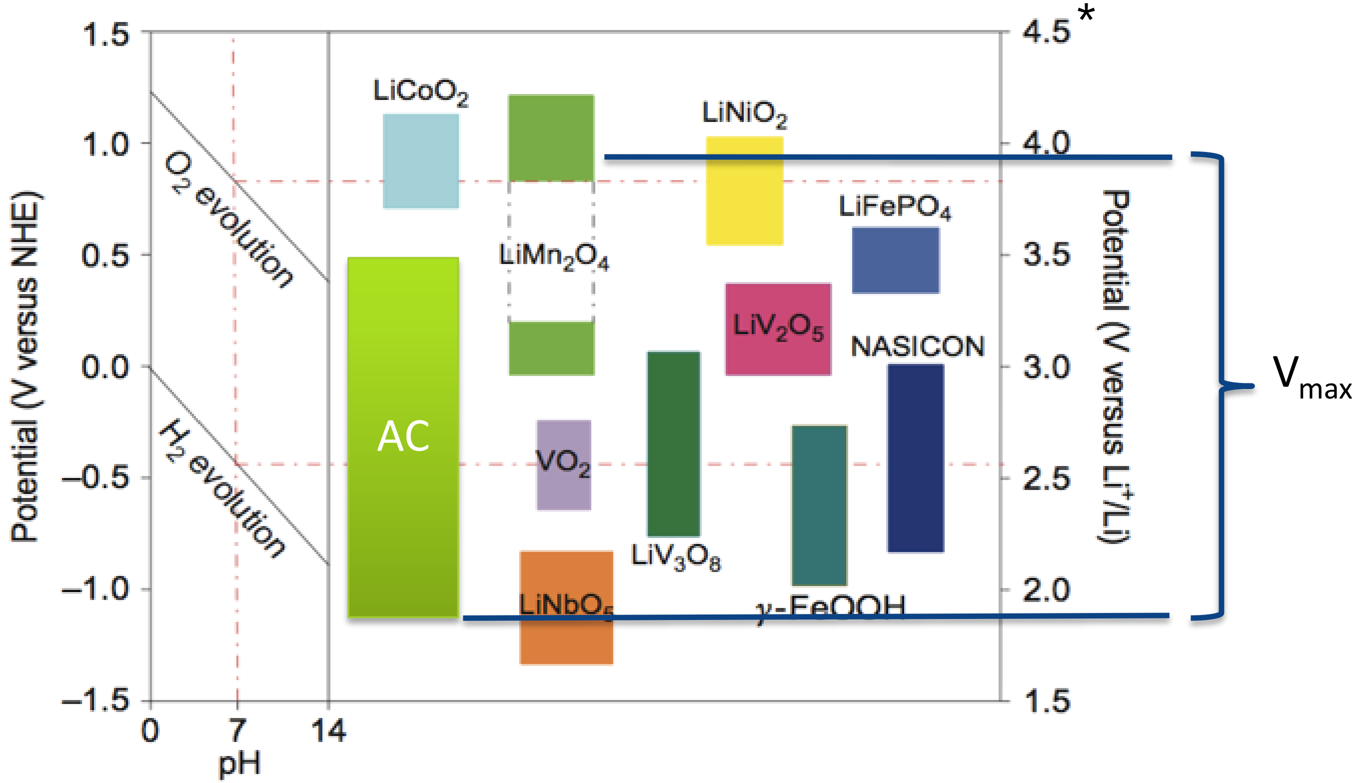


- Over 200 F/g can be had from carbons derived from simple carbohydrates
- Over 120 F/g can be gained from low cost (<$2/kg) carbons derived from woods

Polyionic Functionality

- 3 different species are functional:
  - Lithium – cathode materials templating, extracted into electrolyte during first charge, remains functional
  - Sodium – electrolyte cation, intercalates into MnO_2 of cathode and also performs EDLC function at anode
  - and Hydrogen. . . .

Anodic Pourbaix Shift at Anode Enables High Cell V

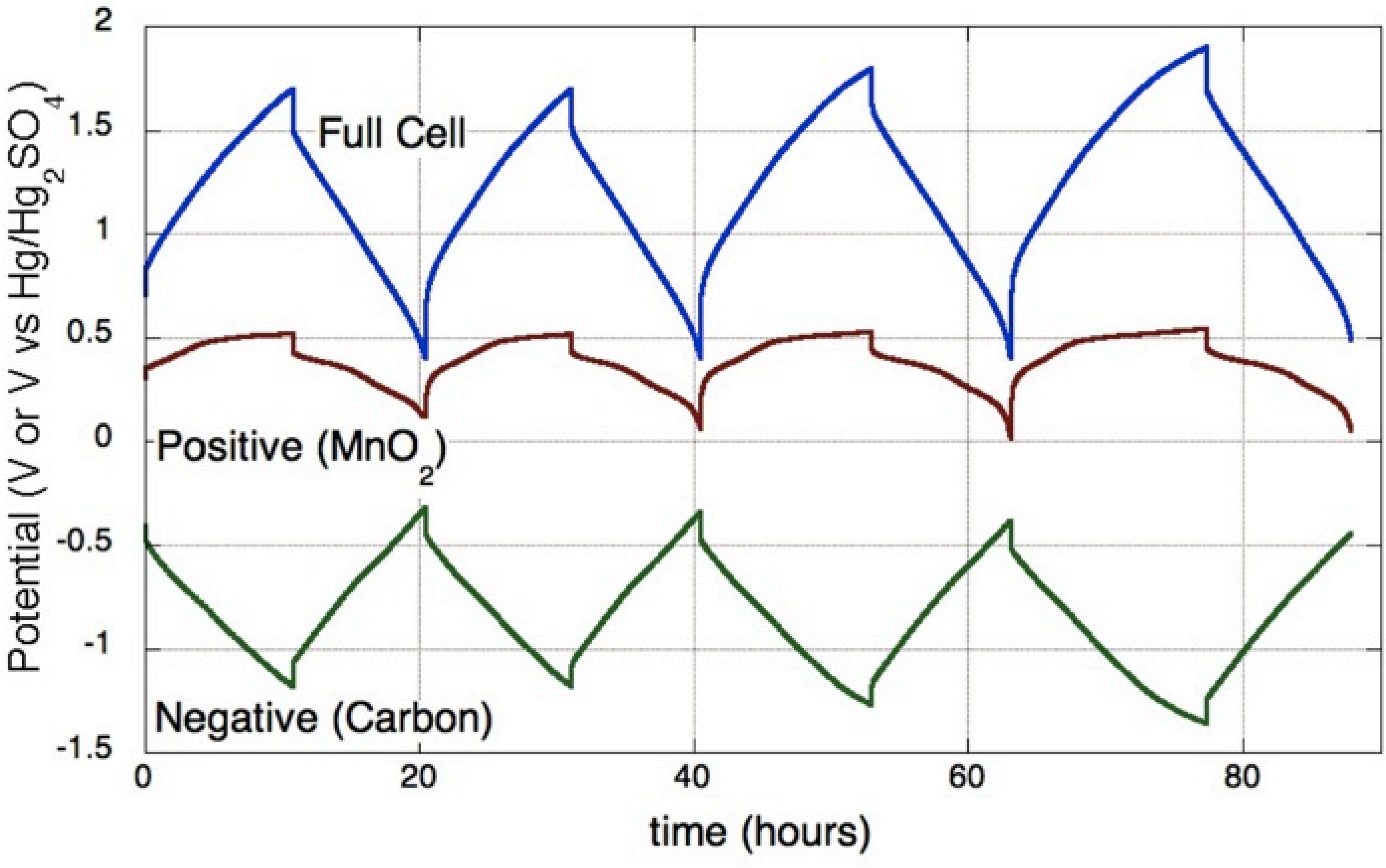


- At the anode: as the potential of hydrogen evolution is reached, local OH^- species are generated, and are not extracted rapidly
- This increases the pH inside the negative electrode, and subsequently re-stabilizes the local water. There is also the natural overpotential of water splitting on Carbon
- So minimum stable anode potential is -0.9 V (vs. NHE) at local pH of 14 plus ~0.2 to 0.4 V of over potential.
- If cathode is pinned at ~+1 V, then, we have a cell voltage of over 2 V
- BUT hydrogen is evolved during this process – what of it?

*Nature Chemistry, 2, 2010, pg 760

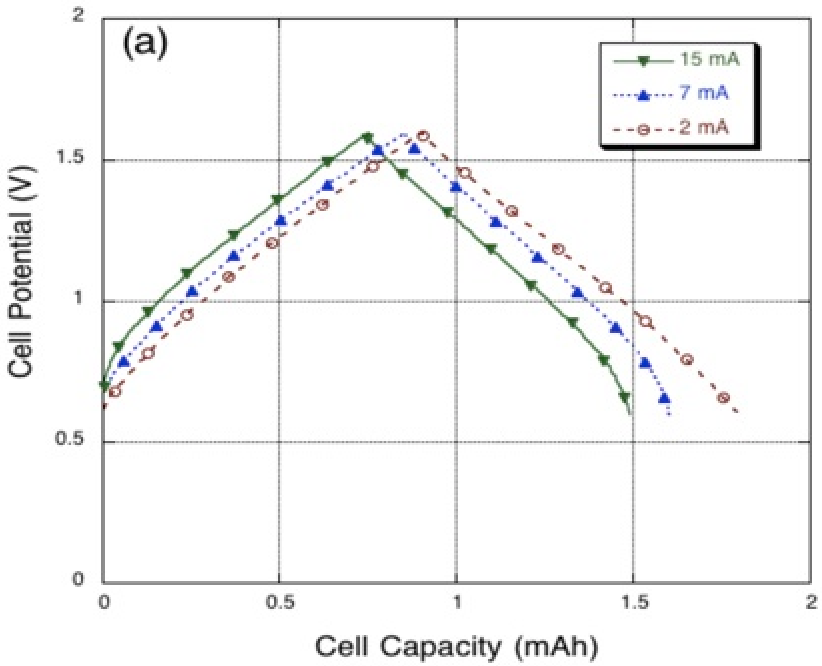
Jia-Yan Luo, Wang-Jun Cui, Ping He and Yong-Yao Xia*

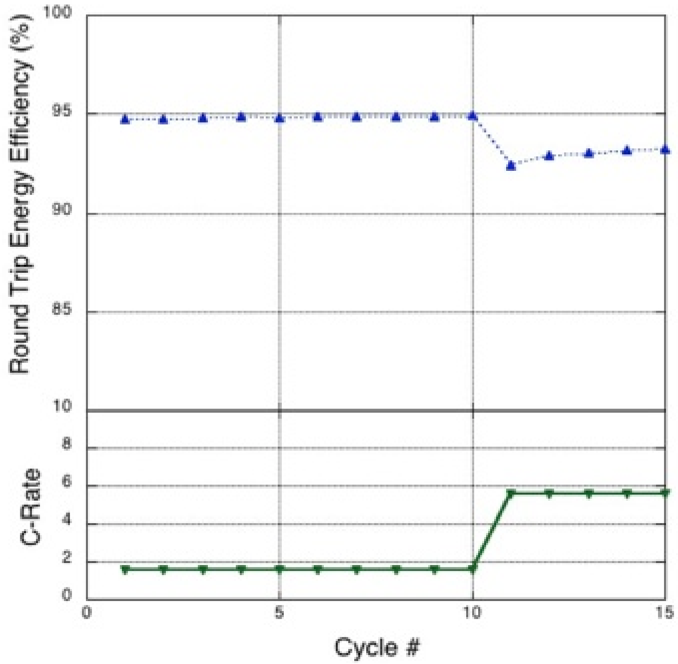
Three-Electrode Data:



- There is excess cathode material to pin the positive electrode potential below the point of oxygen evolution

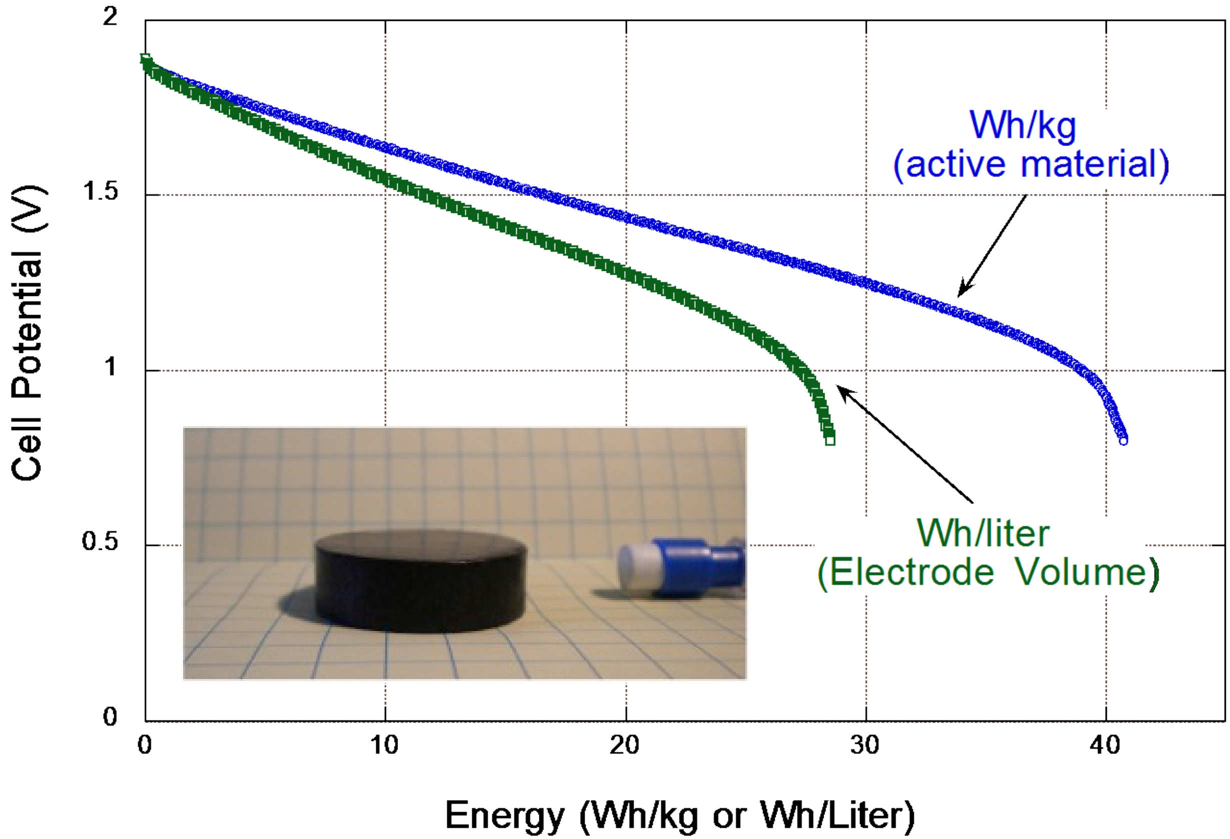
Making it Practical: Electrode Thickness





+ In thin format cells, the material displays excellent rate capability, excellent round trip energy efficiency.
+ However, these cells are far too costly to scale with these dimensions . . .

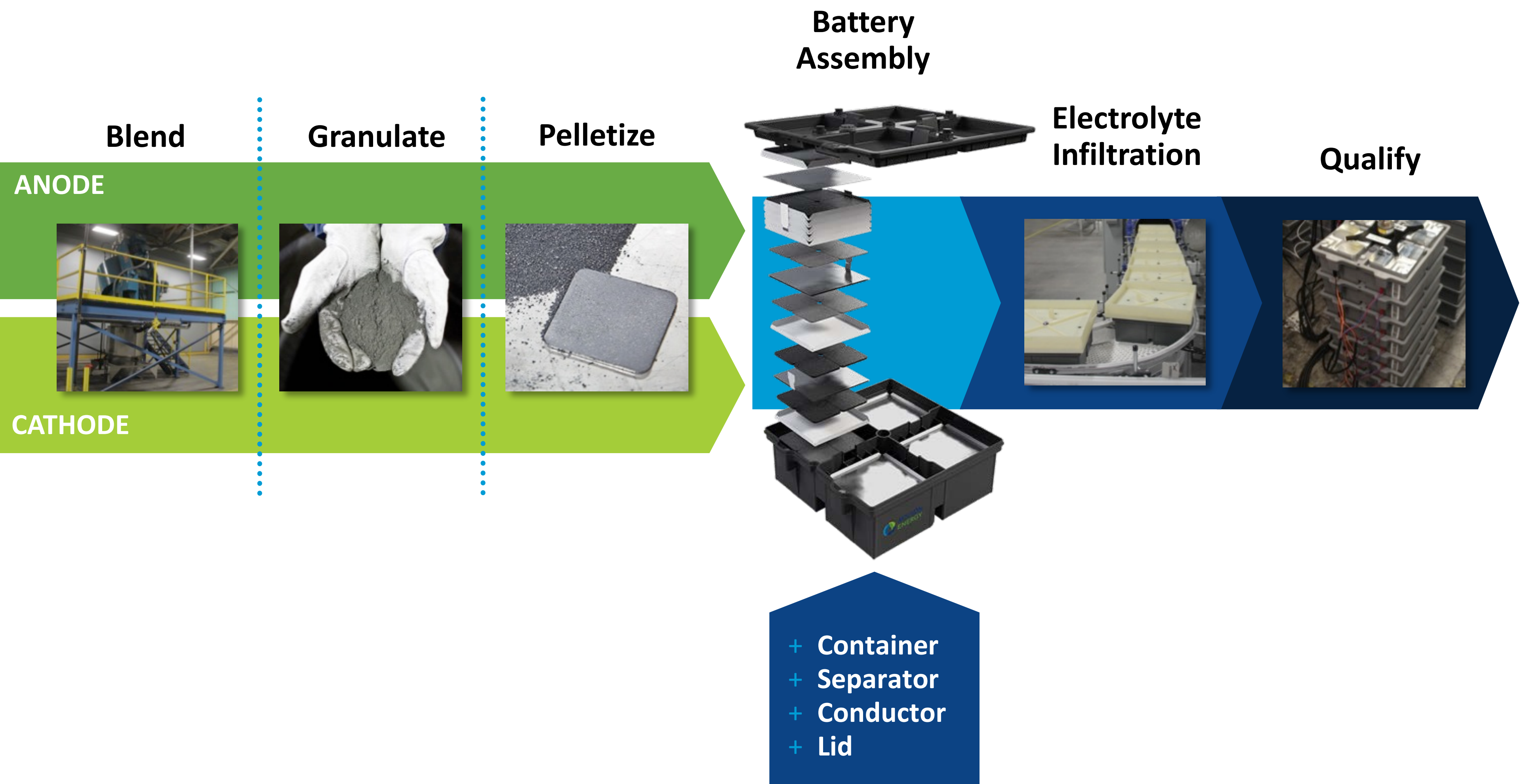
MnO_2-based cells: Energy Density



- Na functional in cubic spinel - different recipe is optimal
- >40 Wh/kg specific capacity, same long term stability
- > 80% round trip energy efficiency

Manufacturing Process and Flow

+ Established, low-cost, and proven manufacturing processes



Flexible, Scalable Energy Storage

AHI PRODUCTS

S-Line Battery Stacks

- 2.4 kWh
- Nominal 48V output
- Smallest product increment

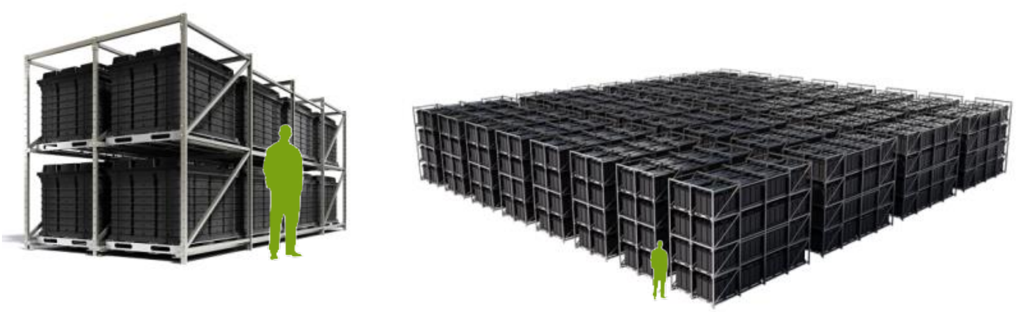
M-Line Battery Modules

- 25.5 kWh
- Nominal 48V output
- Designed for industry-standard racking
- Forklift-ready

SYSTEM CONFIGURATIONS

Stack-Based Systems

Racked Module-Based Systems



Aquion S-Line Battery Stack

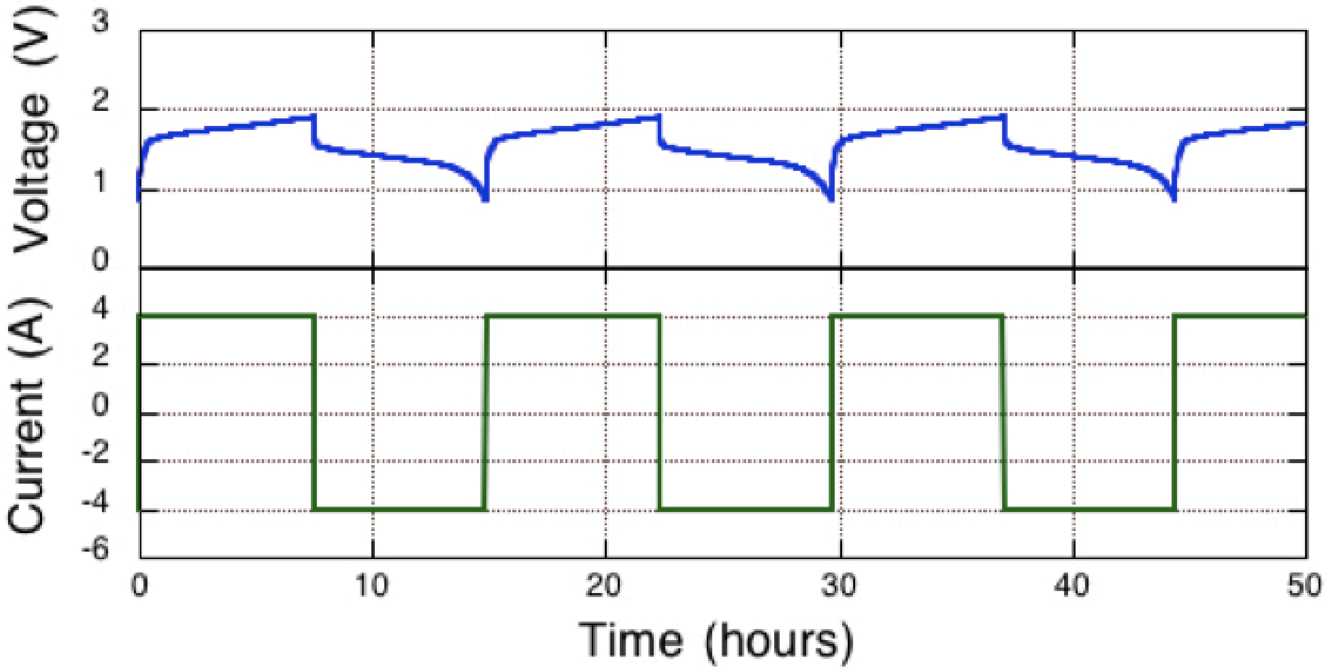
- Smallest product increment
- Eight batteries in series, fused at the stack level
- Nominal 48V output
- Designed for low cost, performance, and modularity

OPERATION & PERFORMANCE	
Nominal Energy	2.4 kWh at 20 hour discharge, 30° C
Cycle Life	>3,000 cycles at 100% DoD*
Operating Temp Range**	-5 to 40° C
Round Trip DC Efficiency	>85% at 20 hour discharge, 30° C
Voltage Range	30 to 59 V
Charge/Discharge Modes	CC, CP, CV, AC ripple tolerant

PHYSICAL CHARACTERISTICS		
Height	935 mm	36.8 in
Width	330 mm	13.0 in
Depth	310 mm	12.2 in
Weight	113 kg	249 lbs

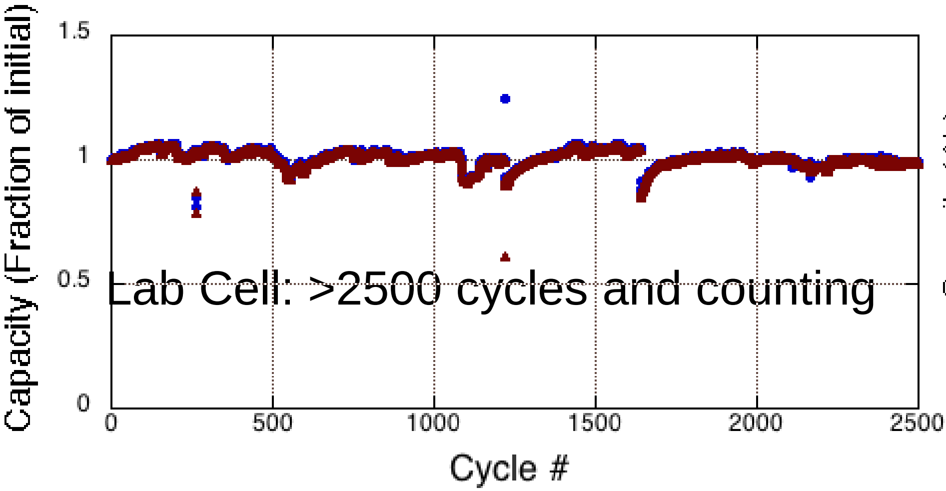
* Cycle life to 80% retained capacity
** 40° C average ambient over 24 hours

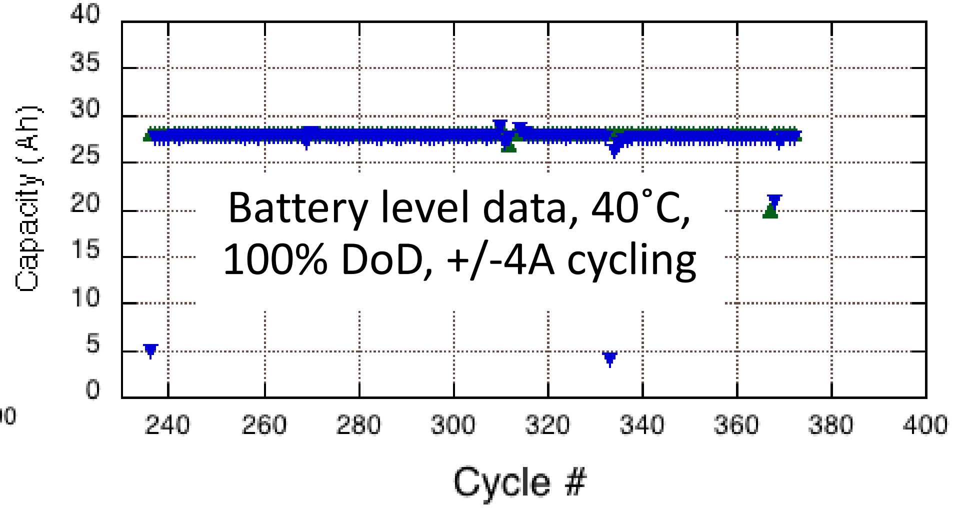
Performance: Cycle Life



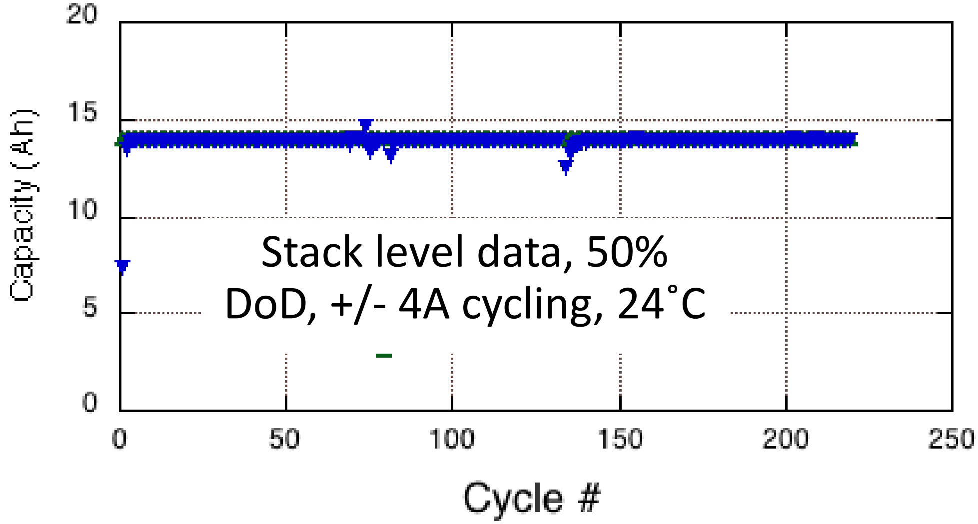
+/- 4A cycling on large format battery; typical voltage response

Performance: Cycle Life



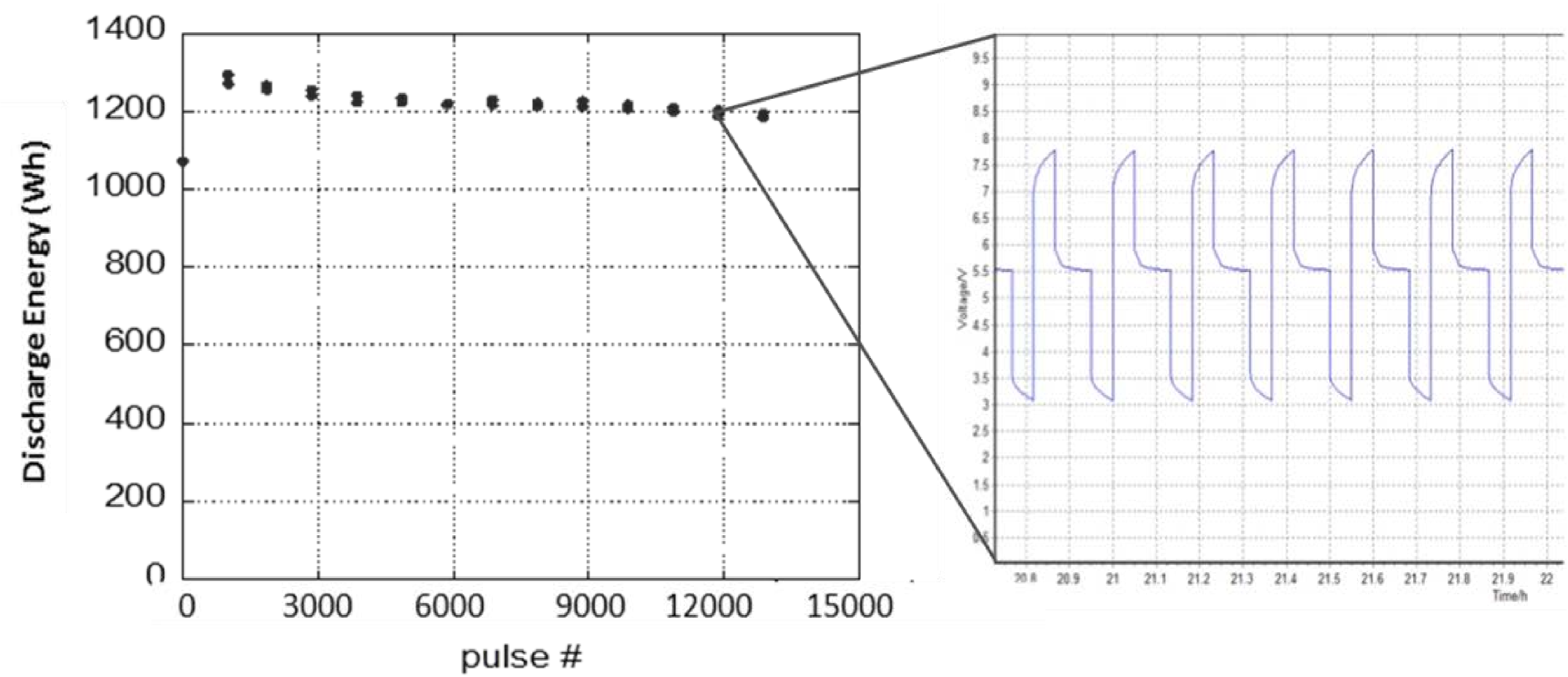


- 100’s of deep cycles on full stack product
- Verified by 3rd party testing
- Over 3000 cycles on small format lab units (with known leaks in cell)
- Fully stable to at least 40˚ C



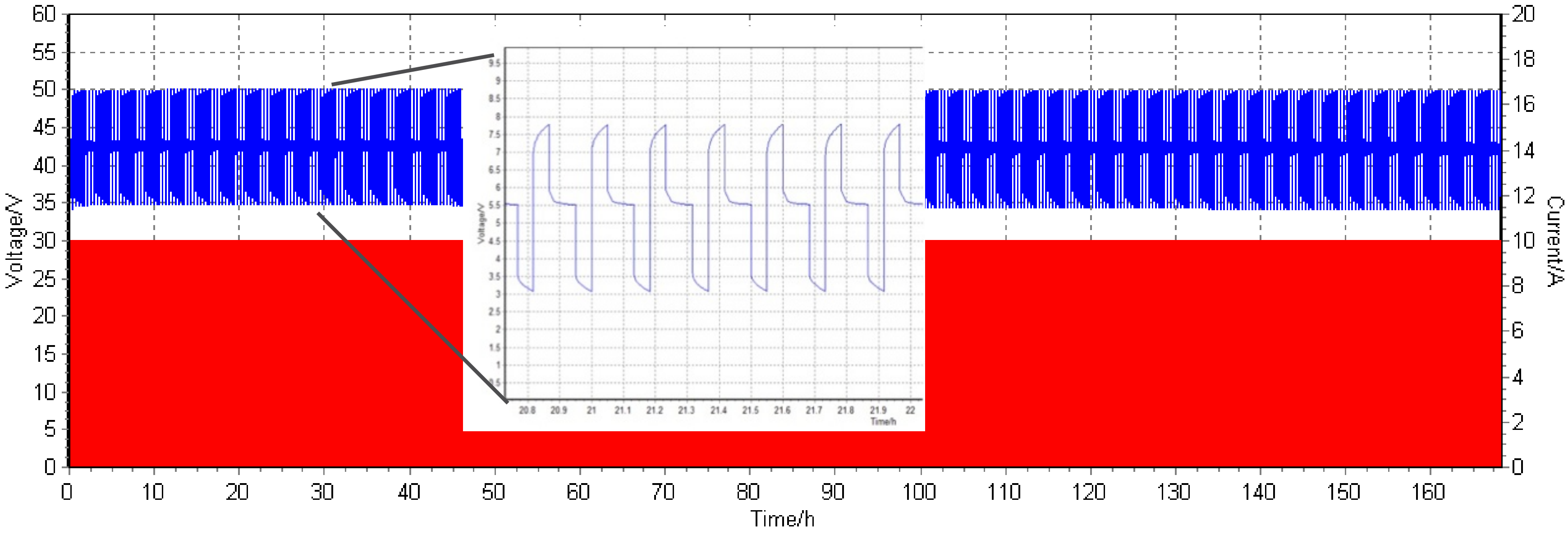
Abuse Tolerance: Partial State of Charge

- Aquion's batteries can stand at partial state of charge with no significant degradation



Pulse: The batteries are cycled between 45-55% SOC using 10A. Two full cycles are run every 1000 pulses.
Data from Aquion S10 Battery Stack

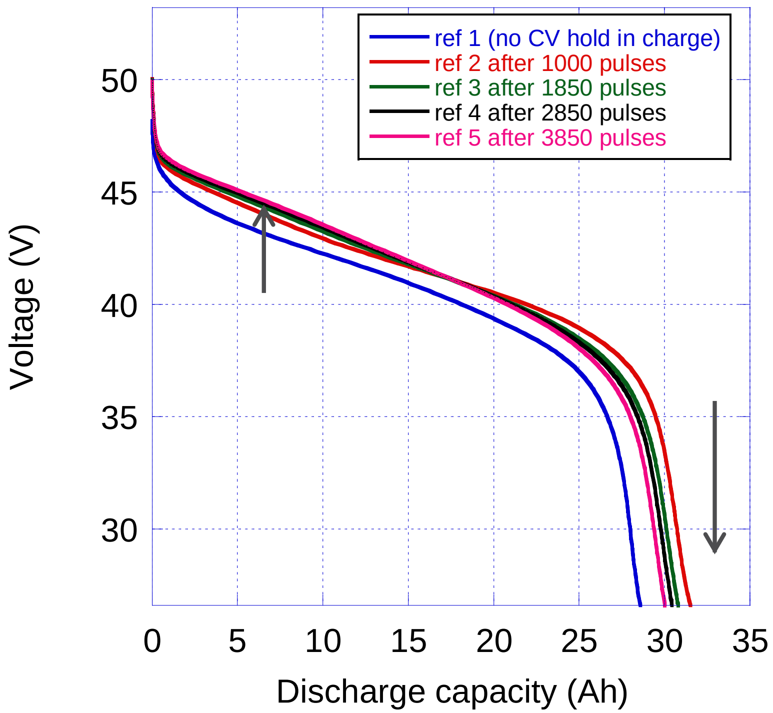
Large Format System Cycle Stability: PSOC Test



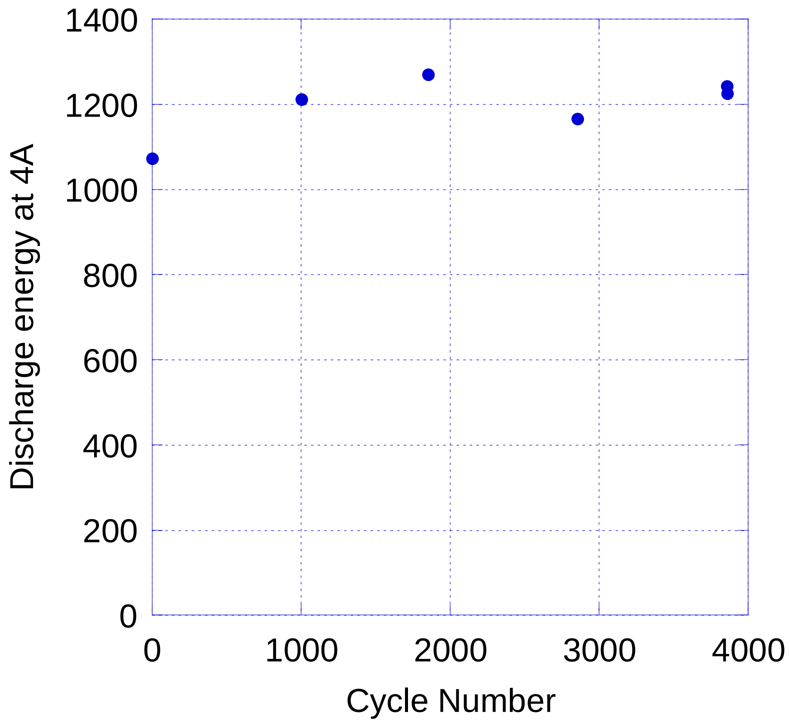
- 4000 Partial State of Charge Swings executed on full stack at 40˚C
- Batteries in string are well balanced
- Similar unit currently at Sandia ASAP for identical testing

Large Format System Cycle Stability: 40˚C PSOC Test

+ Reference Cycle Discharge Voltage vs. Capacity Data



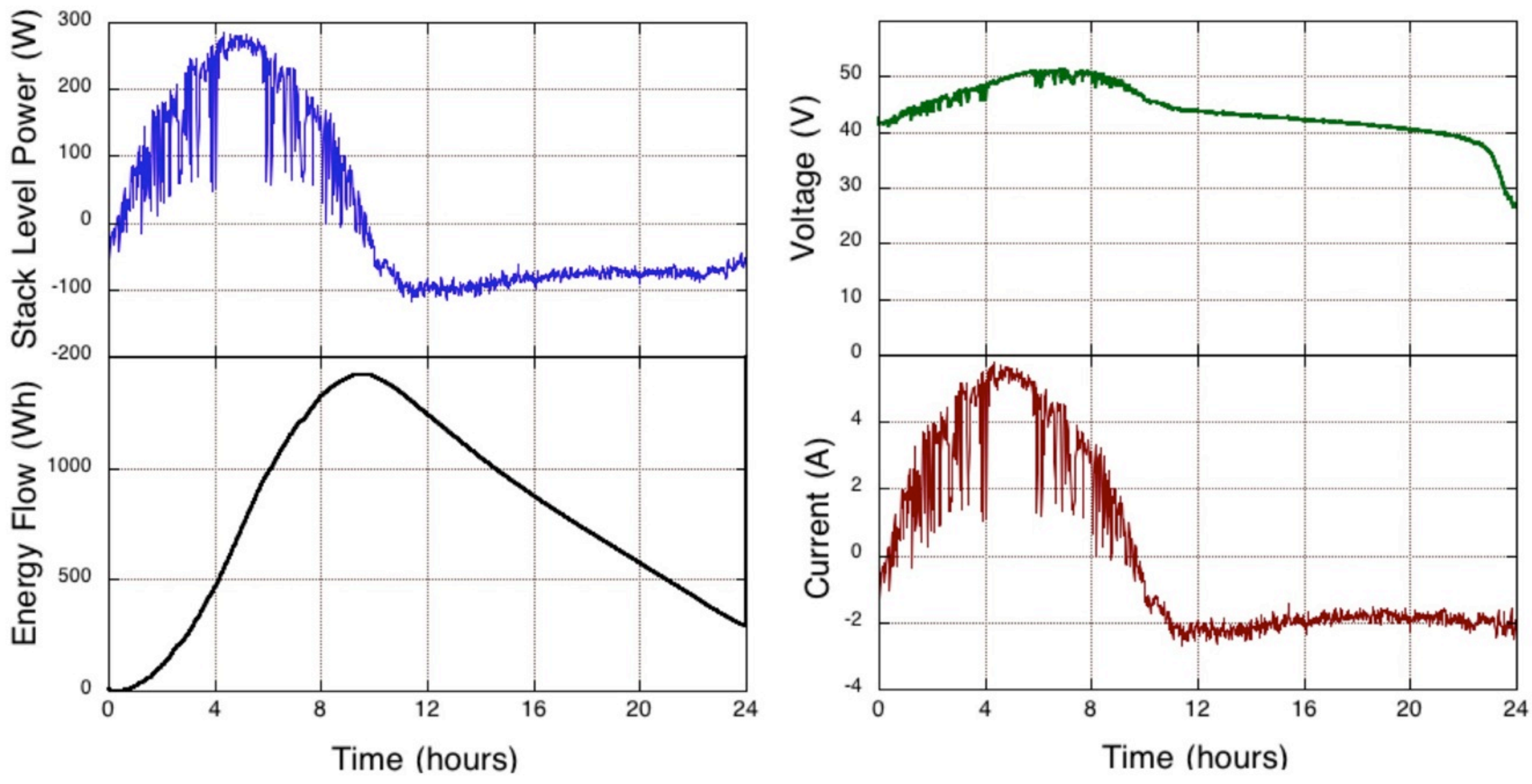
+ Reference Cycle Energy vs. Cycle #



The 4 A constant current discharge reference cycle shows ***more** capacity* after the 1000 cycles than before (slightly different charge regime used, but comparison is indicative of no degradation), **and no change after 4000 PSOC cycles**

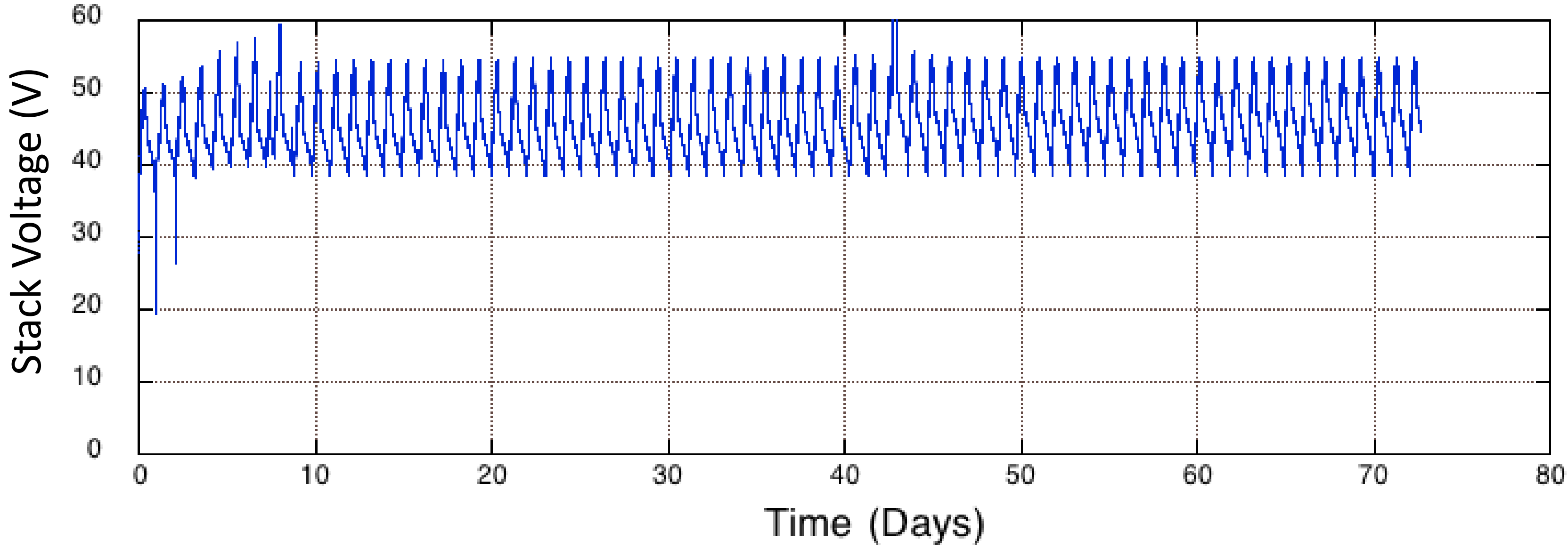
Application Specific Duty Profile; Power vs Time

+ Off grid zero diesel solar/battery hybrid; provided by Optimal Power

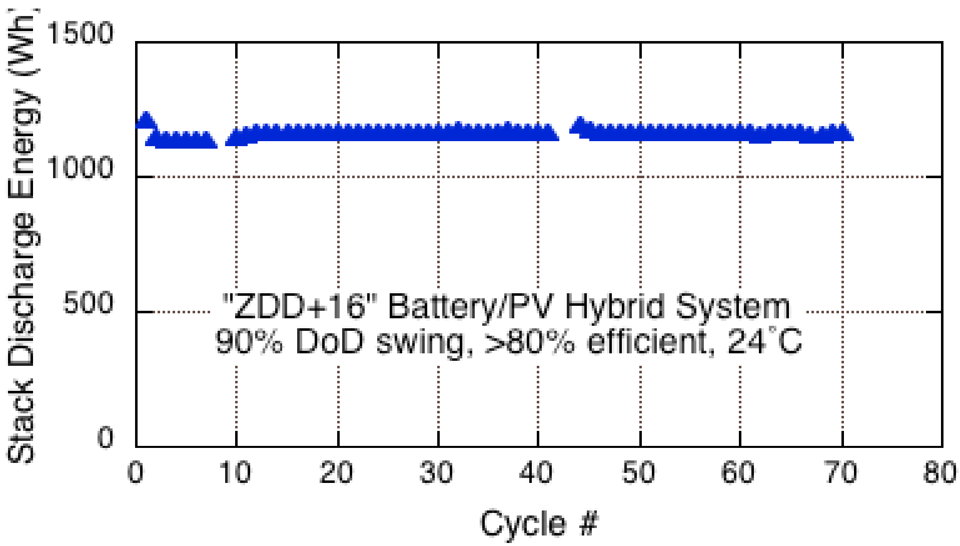


Profile altered to give specific energy flow/efficiency:
1,400 Wh processed each cycle at 83% efficiency

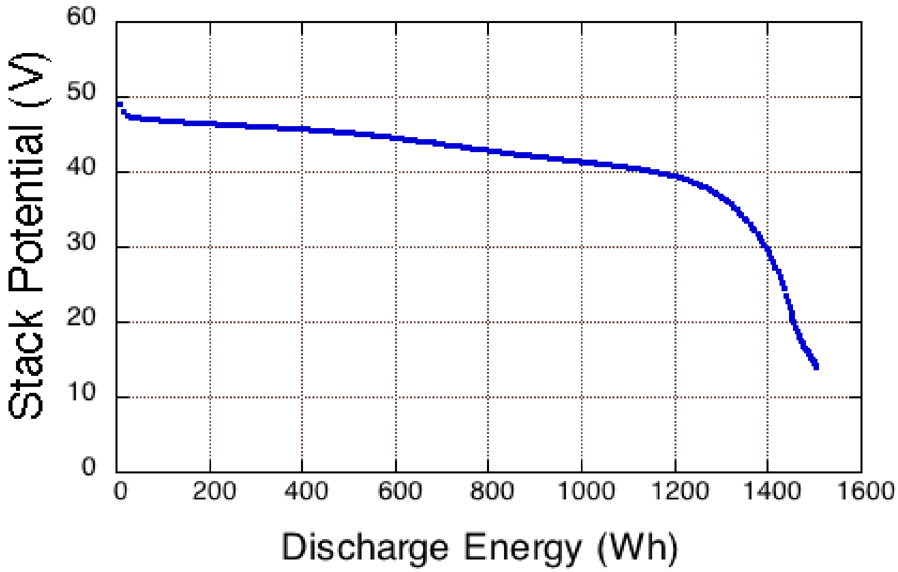
Applications Testing: PV/Battery Hybrid

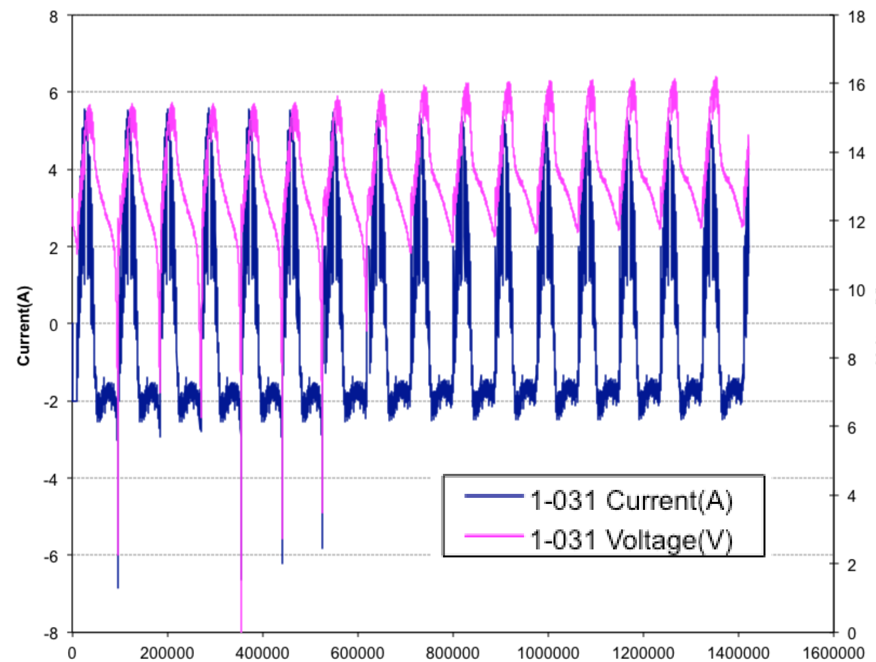


- 70 cycles logged of 90% DoD swing
- 24 hour cycle
- Excellent stability observed
- NO loss in capacity delivered
- NO drift in stack voltage over time
- NO self balancing needed
- Test ongoing
- Tester shutdown/restart on day 44 caused brief overcharge; stack unaffected.



Applications Testing: PV/Battery Hybrid





- Left plot: 2A 100% DoD reference cycle after 70+ days of cycling; excellent capacity documented after significant use.
- Right plot: voltage and current as a function of time after resuming cycling after reference test
  - V increasing; unit is significantly more efficient than 80%

Current Internal Demos

12 S-Line Stacks, Off-grid Demo

+ Off-grid 20’ shipping container simulating a telecom installation
+ Online since April 2013
+ Off the shelf solar and electronics
+ 12 energy storage stacks, 48V
+ Capable of 2 kW continuous load
+ Demonstrated interoperability :

HEART TRANSVERTER

OutBack Power Systems

EGUANA TECHNOLOGIES

MidNite Solar inc

14 M-Line Modules, Grid-tied Demo (In Progress)

+ 168 battery stacks configured into 14 modules
+ ~270 kWh at 20 hour discharge
+ Testing with several PCS providers
+ Operational as of Q214
+ Collaboration with global leading power electronic firms:

DYNAPOWER COMPANY

ABB

SIEMENS

OPTIMAL POWER SOLUTIONS

Summary

+ Augmented electrode chemistry results in very appealing voltage swing, cost proposition.
+ Full scale manufacturing plant is on line; product shipping to customers globally
+ Multiple test beds have been assembled and are in use
    - Including a DoE funded 14 Module test stand
    - Strong data generated to verify product claims
+ Long term test results, systems-level show that this product is ready for market insertion

Thank you

- Contact us to learn more about how our AHI™ technology for your application:
  - www.aquionenergy.com
  - 412.904.6400