LEO Cycling Performance of Lithium-Ion Batteries with Carbon Nanomaterials

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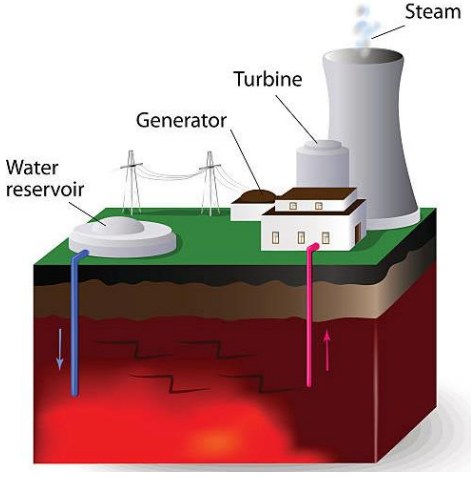
Renewable Energy

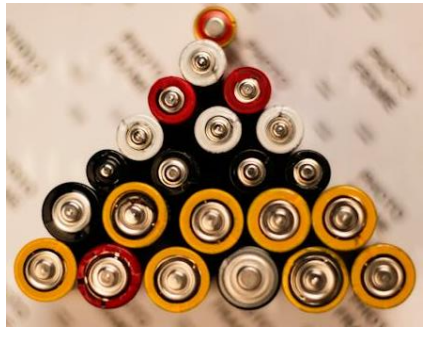


Transmission
- Electrical grid

Production
- Wind
- Heat
- Solar

Usage
- Buildings
- Electronics
-Electric Vehicle

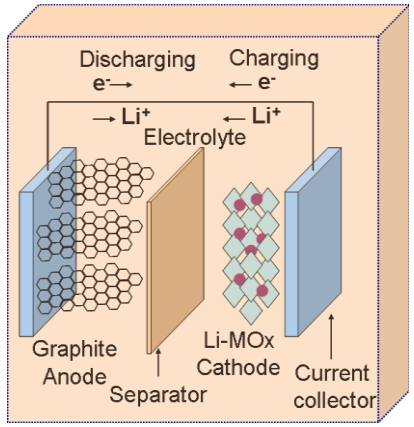
Storage
- Electrochemical
- Chemical fuels

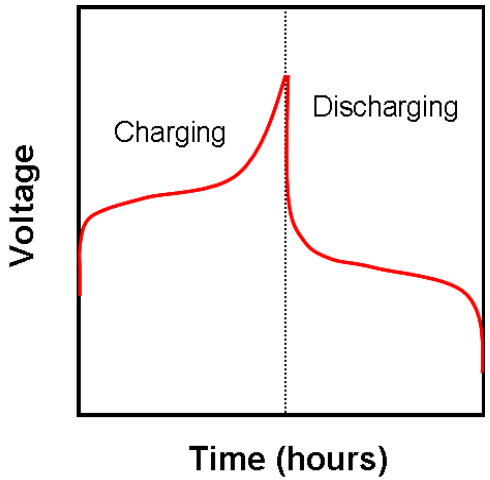


Energy Storage – The Fastest Growing Market

- The most innovative period for energy storage technologies
- Tremendous scaling rates
- Increased demand for reliable domestic supply chain
- Li-ion technologies will continue to dominate the growing market

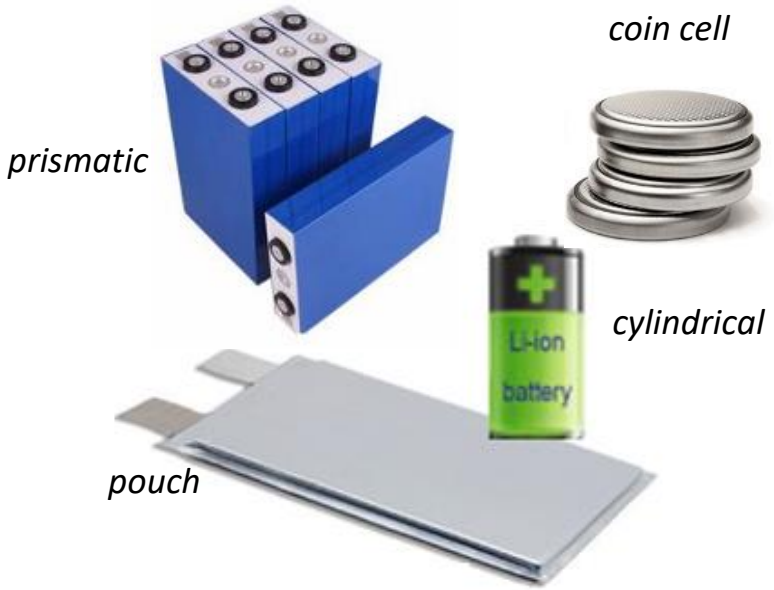
Battery: Working Principle, Materials, Design



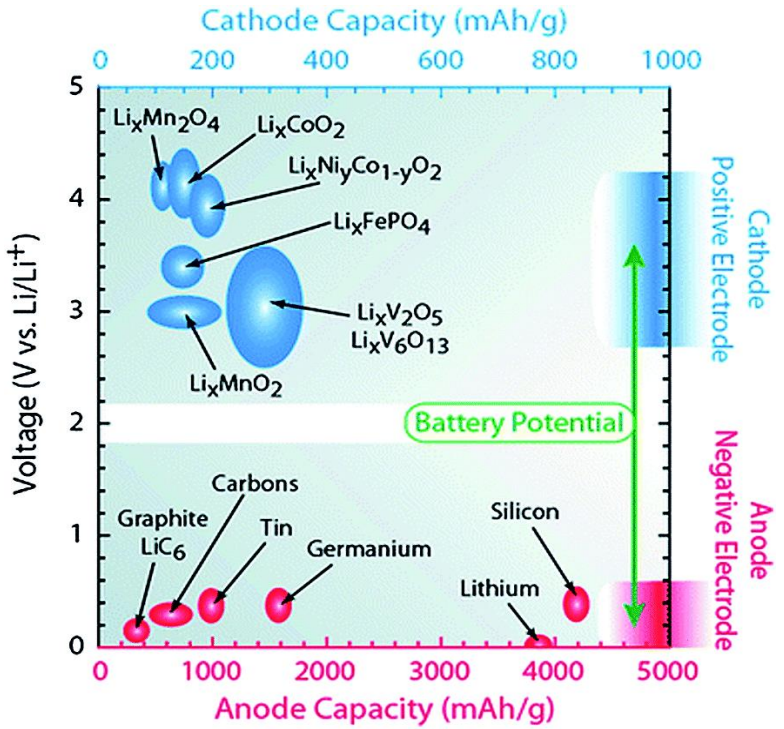


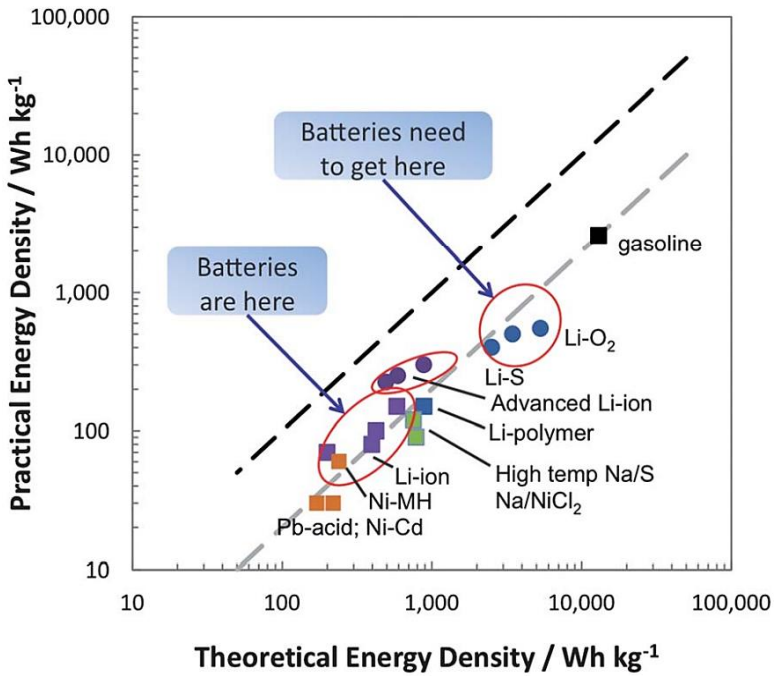
Conventional Materials
Anode: graphitic carbon, Li
Cathode: LFP, NCM, NCA

Different Li-ion Battery Packaging



Challenges in Li Ion Batteries





Energy Environ. Sci., 2012,5, 7854-7863

How to move closer to theoretical values?

- Innovations in materials and battery manufacturing

CSI Battery Technologies

- ✓ Novel Materials, Chemistry and Design
- ✓ Tailored Anodes, Cathodes & Membranes for Enhanced Operation Parameters

CSI BATTERY CELLS

Power Cells Fast Discharge, Fast Charge

- very high current delivered in minutes

Energy Cells High Current

- high current at reduced weight

Pulse Cells Low Resistance

- very high current at high frequency (10–100 Hz)

High-Voltage Cells Operating Voltage 5 V

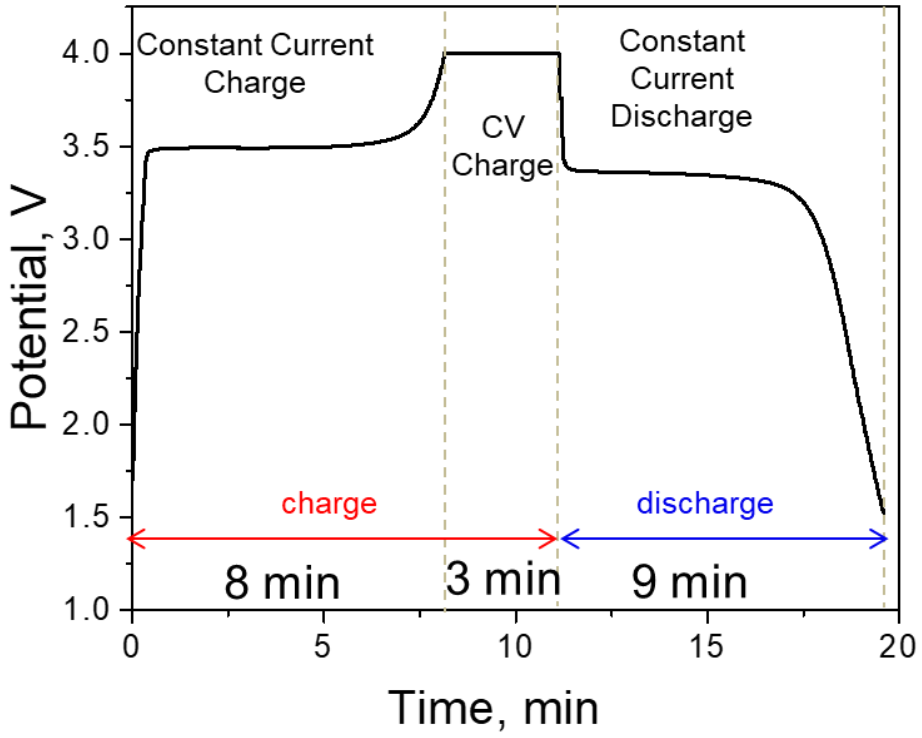
- dramatic weight reduction for cells in series connections

Long Cycle Life Cells > 5,000 cycles

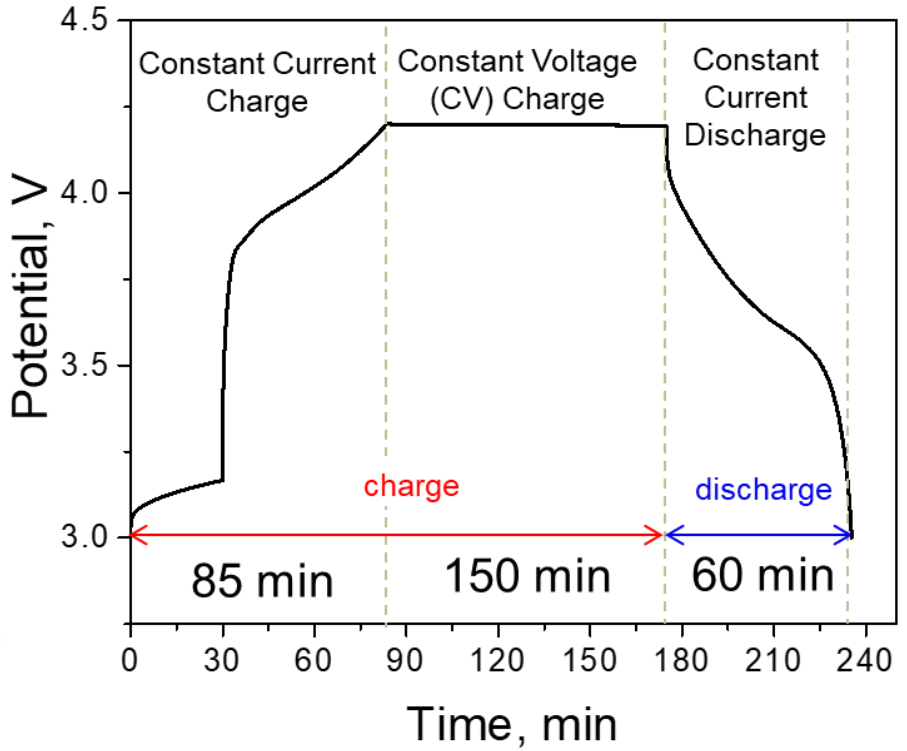
- remote operation, reduced maintenance, increased range

CSI Power Cells vs Commercial Battery

Power Cell: E = 230 Wh/kg; P = 1530 W/kg

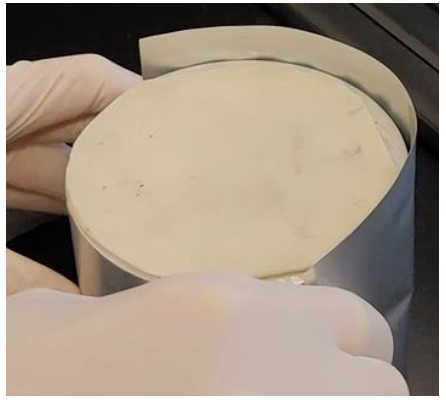


Commercial: E=280 Wh/kg, P=280 W/kg



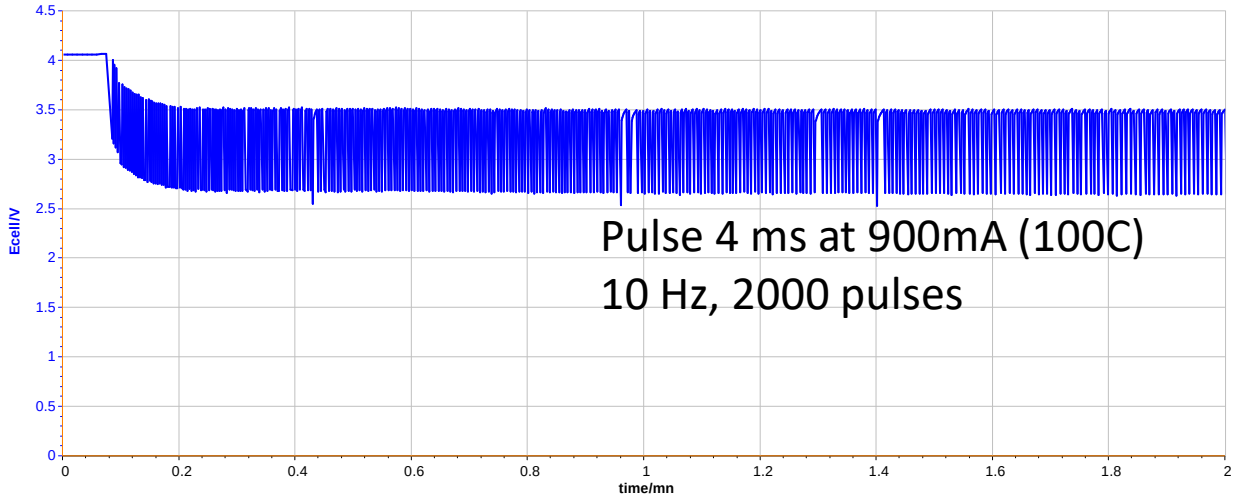
New capabilities provided by the technology

- Fast operation – charge and discharge
- High energy combined with high power
- Reduced weight by 30-50%
- Conformal cell configuration
- Safe operation (no fire, explosion, corrosion)



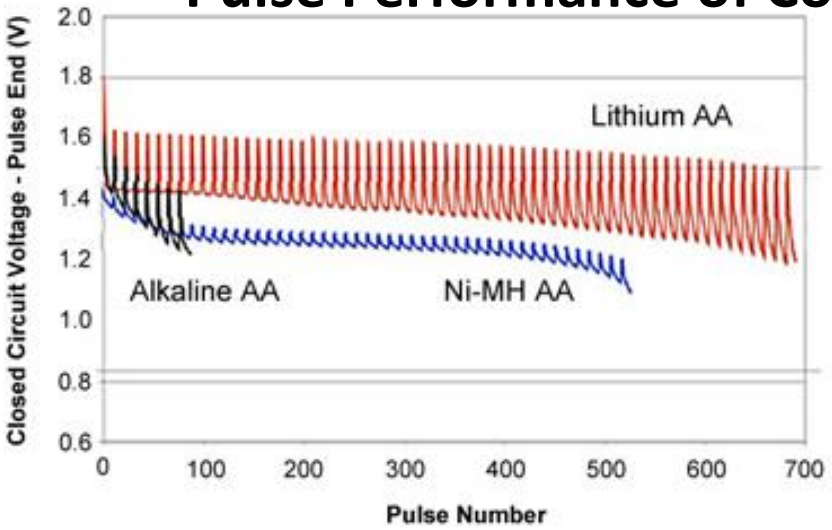
High Current Applications

Pulse Performance of a Hybrid Cell



- High-conductivity materials with fast charge transfer and low resistance
- Ultrafast Li diffusion
- Chemically modified electrodes for improved surface electrochemistry during charge/discharge

Pulse Performance of Commercial Batteries



Number of shots a digital camera can take with:

Li-AA - 690 pulses

NiMH AA- 520 pulses

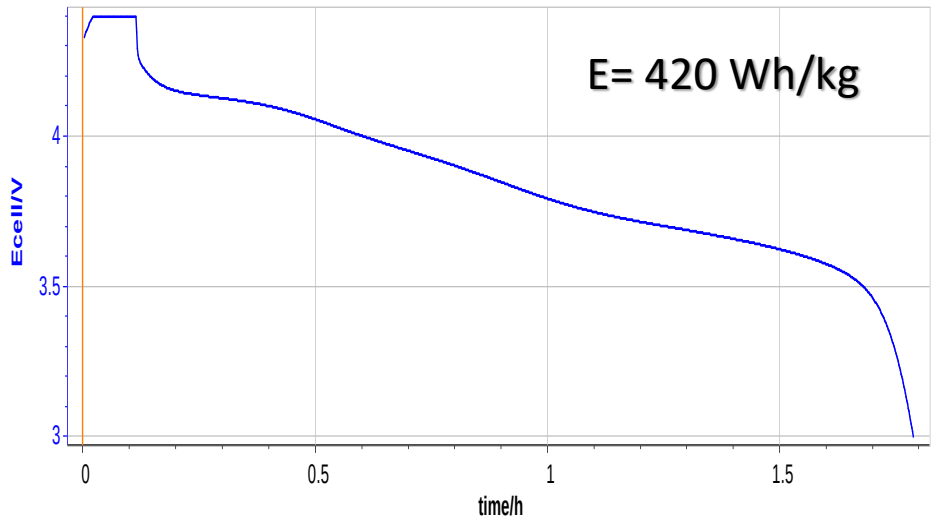
Alkaline AA - 85 pulses

Test: ANSI C18.1

Excellent performance in pulse applications: Hybrid Cells >2000 cycles vs Commercial battery <1000 cycles

CSI Energy Cells & High-Voltage Cells

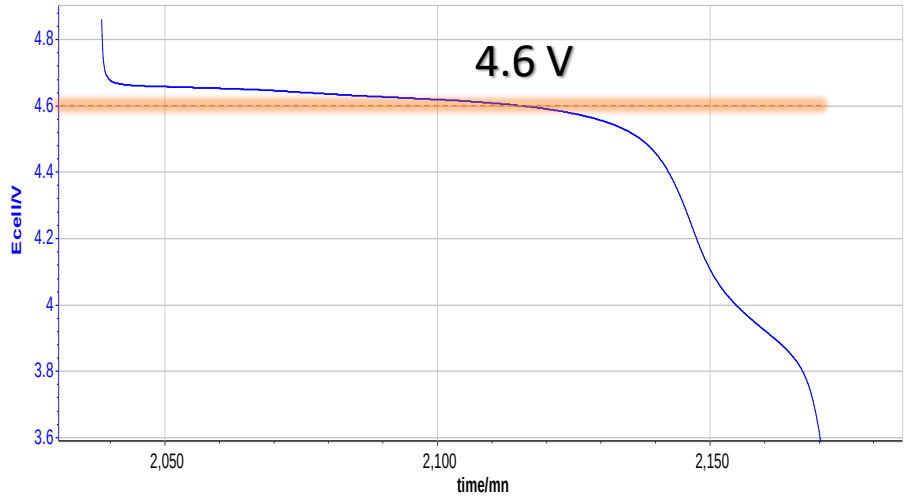
Energy Cells



Capabilities provided by the technology

- Significant weight reduction
- Lower $/kWh cost
- Enabling more powerful electronics

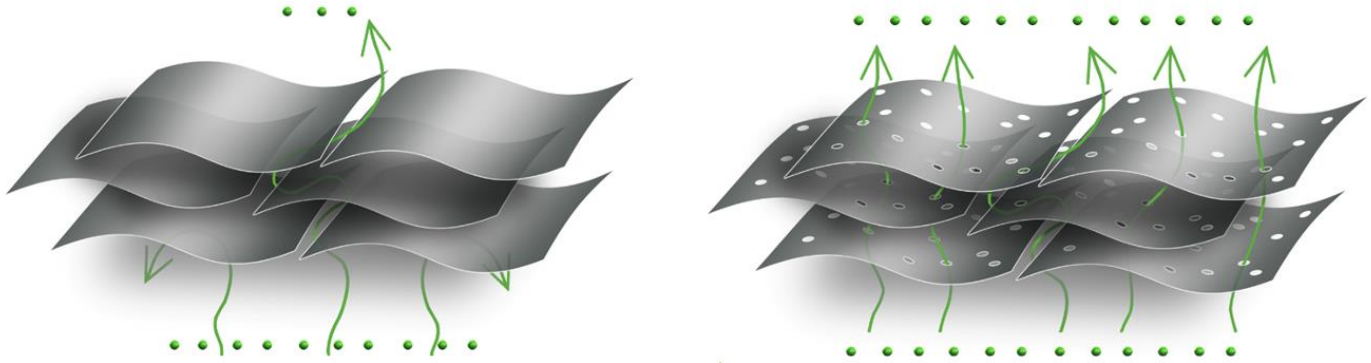
High-Voltage Cells



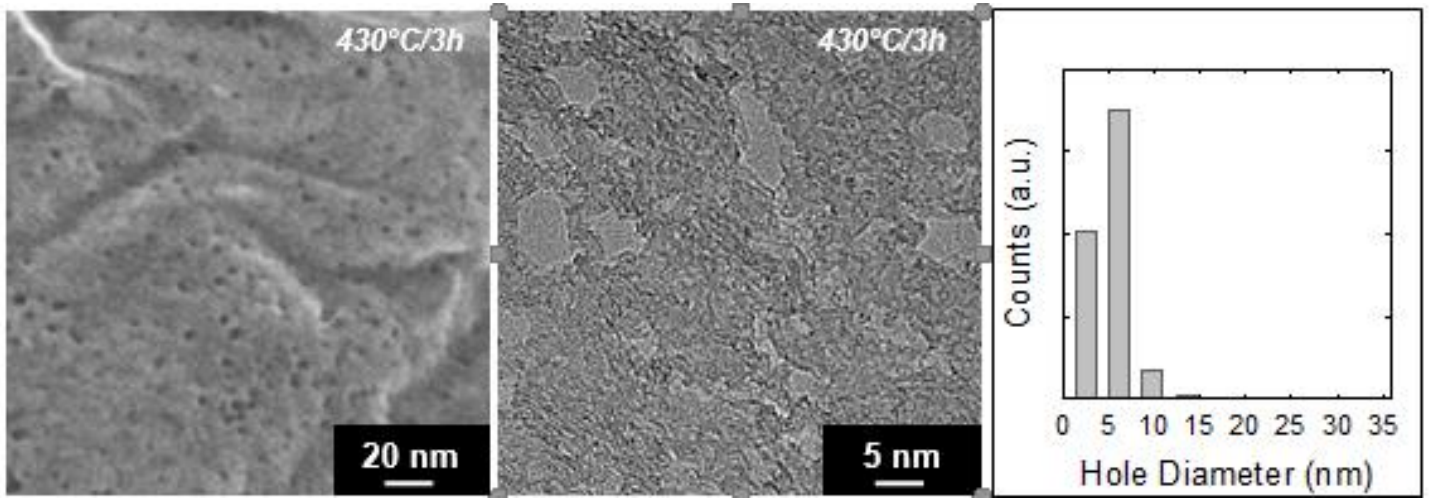
Capabilities provided by the technology

- Reduced number of cells in series connection – decreased pack size
- Lower $/kWh cost

New Structures: Holey Graphene for Fast Ion Transport



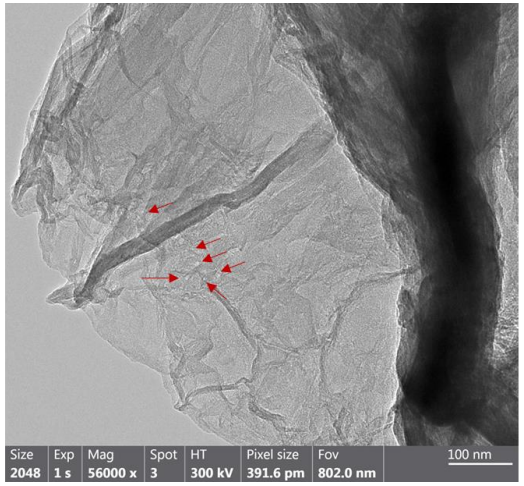
- high energy density per volume
- fast ion transport
- uniform Li deposition and dendrite suppression



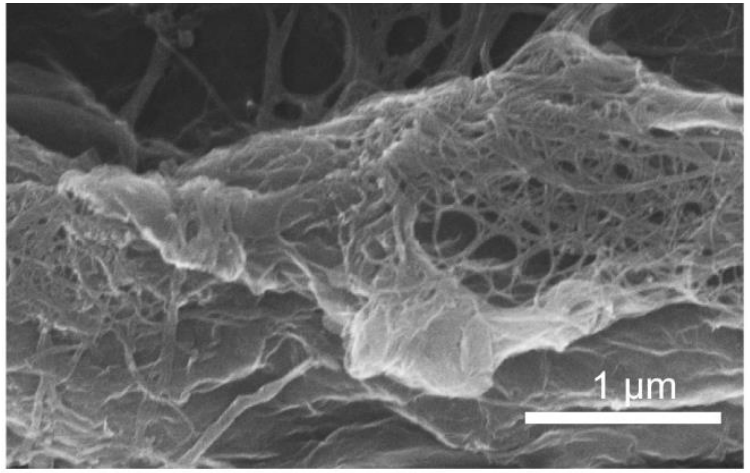
Lin, Y. et. al., Holey Graphene Nanomanufacturing: Structure, Composition, and Electrochemical Properties. *Advanced Functional Materials* **2016,** *25* (19), 2920-2927.

Novel Materials and Chemistry for Anode

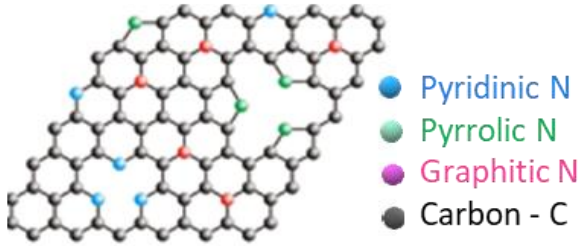
Graphene with Nanosize Holes



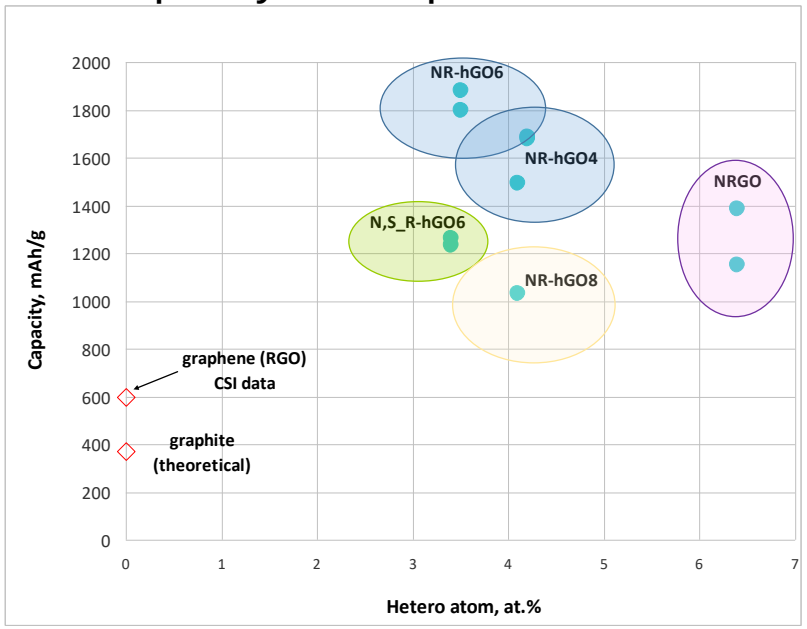
Hybrid Graphene - Carbon Nanotubes



Chemical Modification



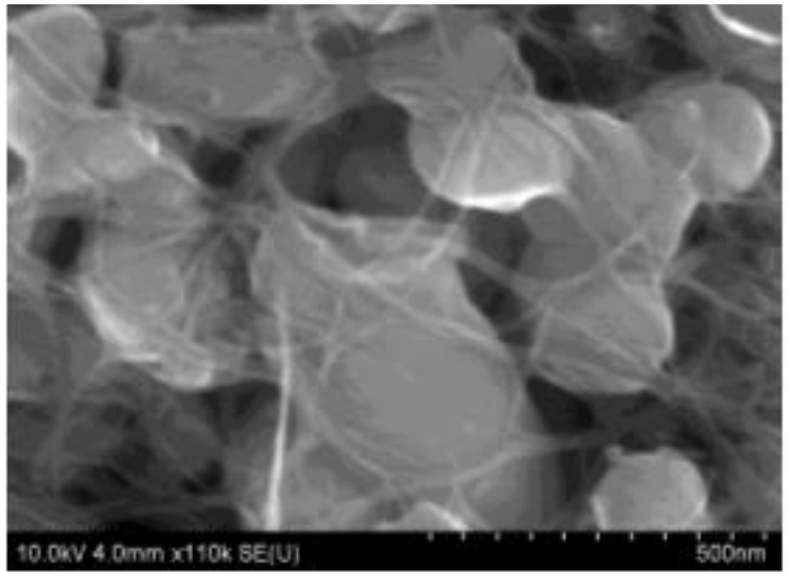
Capacity of Graphene Materials



Public Affairs release approval # AFRL-2022-1365

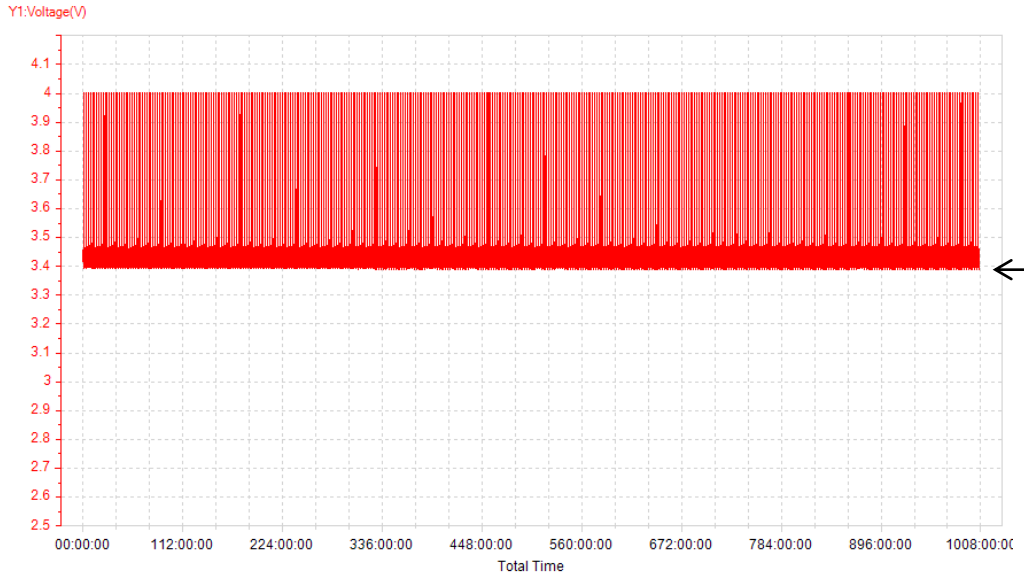
Carbon Nanomaterials and Novel Design for Cathode

Cathode Nanoparticles Embedded in CNTs

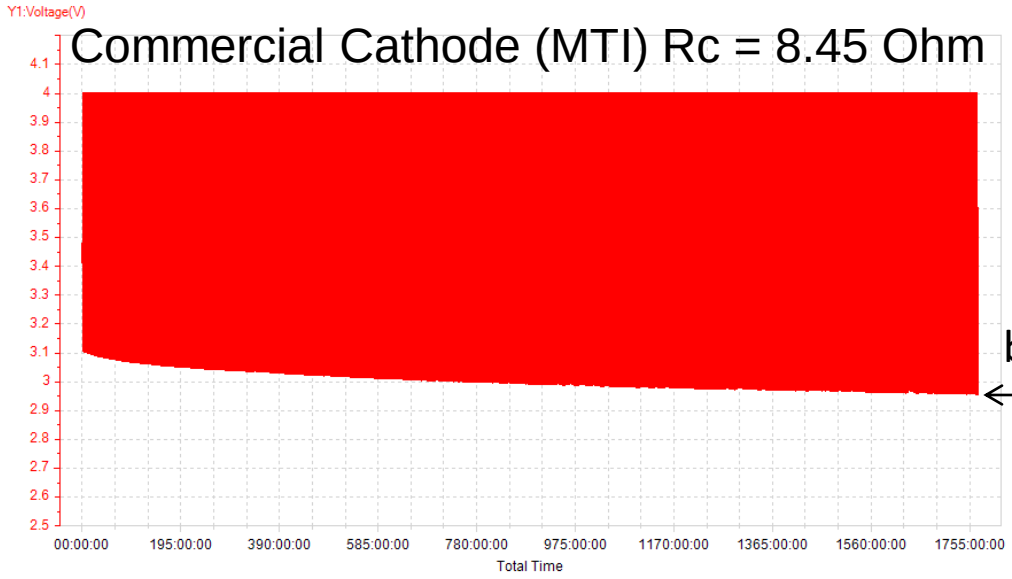


- Improved electrical conductivity
- Better mechanical stability
- Faster Li ion diffusion

Cathode with CNTs Rc = 1.40 Ohm



3.4 V



below 3 V

Batteries for Space Applications

- Critical role in satellite operation
- Low-earth orbit (LEO) satellites: batteries supply power during eclipse

Interplay between
Specific Energy and Cycle Life

Space batteries requirements:

- *High energy density*
- *Lifetime:* 5,000 cycles per year
  - *Charge and discharge rates:* LEO satellites circle the earth in 90 minutes; eclipsed for 35 minutes
  - *Depth of Discharge (DOD):* limited to low levels to reduce stress

Current LIB Parameters:

- Energy density ~ 250 Wh/kg
- Cycle life ~ 300 – 4,000
- Charging time 1-10 h

Desired LIB Parameters:

- Energy density >350 Wh/kg
- Cycle life > 5,000
- Charge time - 30 minutes

- Advanced battery development
- Modernization objectives

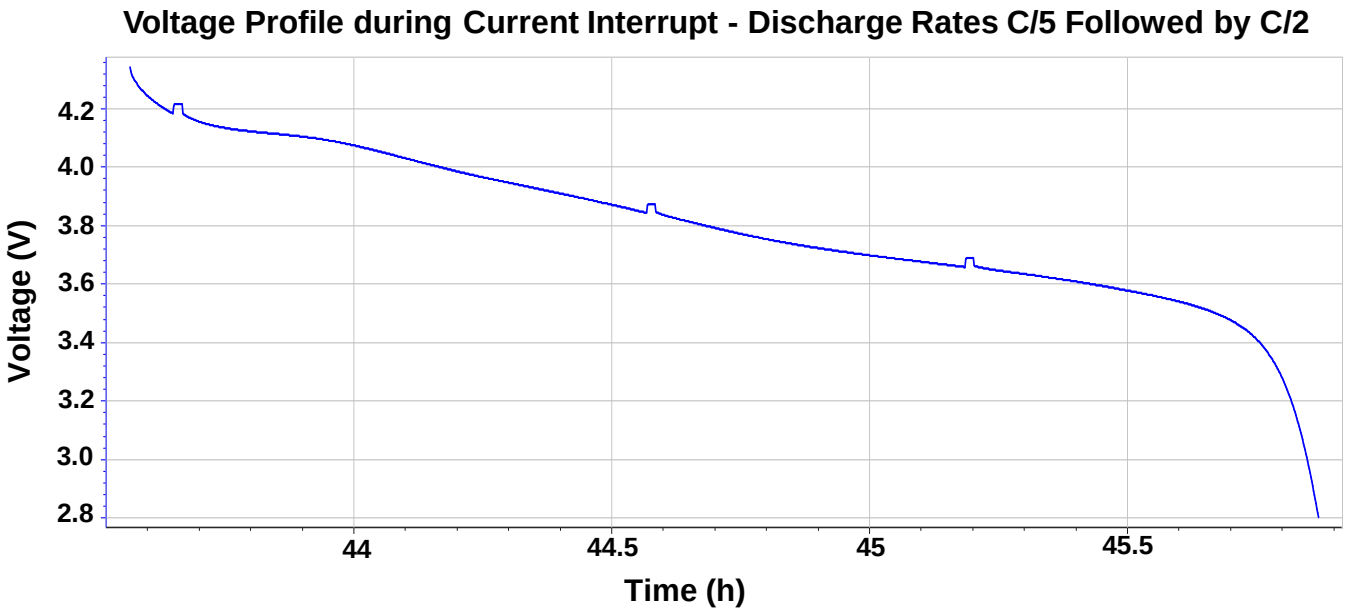
LEO Cycling Tests

- Temperature: 25 ^{o}C
- Rate: C/2.25
- Constant Current Charge to 4.4 V; Constant Voltage Charge
- DOD – 40%
- Cut-off Voltage 2.8 V
- Stop for characterization every 200, 300, 500, 1000 cycles

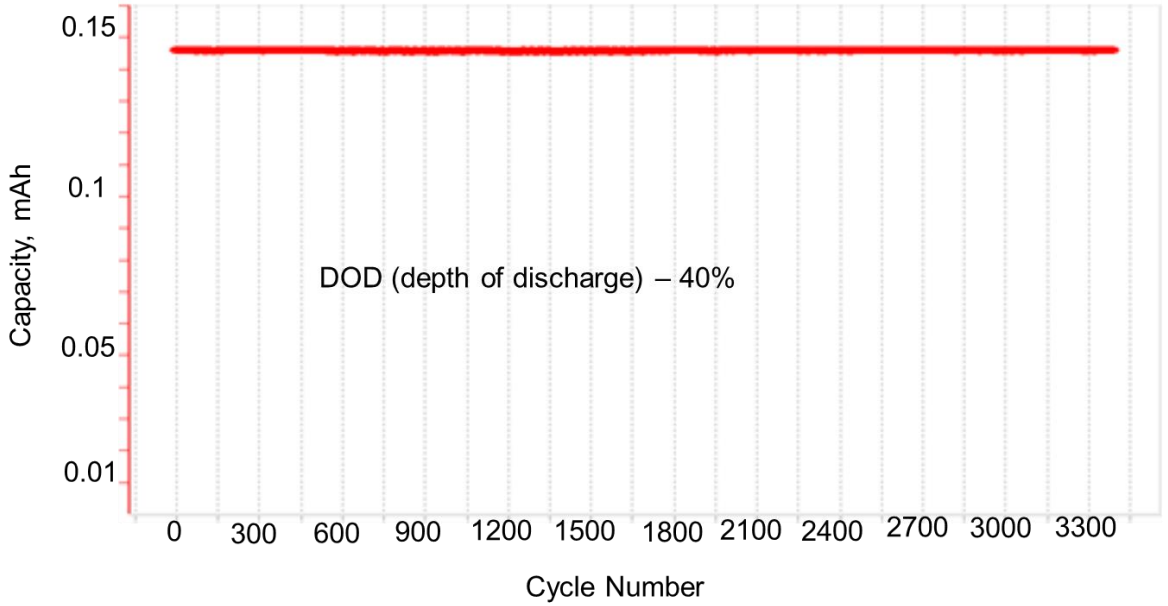
Characterization Tests

Capacity C and Direct Current Resistance (DCR) Measurement

BSR/ANSI/AIAA S-144-2019 “Qualification and Acceptance Tests for Commoditized Space Battery Cells”



LEO Cycling Stability of Graphene Batteries



Public Affairs release approval
AFRL-2022-1365

Literature data for cycling stability of LIB Cathodes

Single cell 18-65 cylindrical NCA, NMC and LFP datasheet specifications

Specification sheet parameter	NCA [23]	NMC [24]	LFP [25]
Low voltage limit (V)	2.5	2.75	2.0
High voltage limit (V)	4.2	4.2	3.6
Nominal voltage (V)	3.6	3.6	3.3
Max continuous discharge (C rate)	2.0	2.0	27.3
Max continuous charge current (C rate)	0.5	1.0	3.6
Discharge temperature range (°C)	-20 to +60	-20 to +60	-30 to +55
Charge temperature range (°C)	0 to +45	0 to +45	0 to +55
Cycle Life to 80% capacity	250	300	4000

Journal of Energy Storage 31 (2020) 101561

Summary

- Graphene and carbon nanotubes play important role in both anode (as the main active materials) and cathode (as additives)
- Tailored chemical modification and structure engineering of the carbon nanomaterials are powerful tools for the design of batteries with fast charge transfer, low resistance and improved surface electrochemistry
- Graphene affords cells with high specific energy > 350 Wh/kg and high Coulombic efficiency
- Demonstrated graphene batteries with 3,000 LEO cycles at 40% DOD

CSI Facilities & Equipment

Capabilities

- Carbon nanomaterials production
- Functionalization & modification for battery applications
- Processing of battery materials, slurry formulations
- Coating and conditioning of electrodes: custom designed anodes and cathodes
- Preparation of battery membranes and electrolyte formulations - gels and solid-state
- Battery cells' fabrication – coin and pouch
- Battery design and optimization to customer requirements
- Battery tests and analysis

Battery Development and Testing Facilities

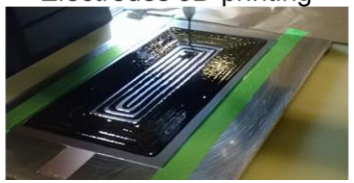
Battery Test Stations

Environmental Chambers:

Glove Boxes

Electrodes Press

Electrodes 3D-printing



SBIR/STTR Projects

1. Air Force Office Research Laboratory, Phase I and Phase II " Development of Graphene Batteries for Use in Space Applications" 2021 – 2024. Program Manager: Alec Jackson

2. Air Force Office of Scientific Research (AFOSR) in partnership with AFWERX, Phase I " Development of Graphene Batteries for Use in Aviation Applications"; 2020 – 2021. Program Manager: Jared Evans

3. ARMY - AMRDEC, Phase I, Phase II and Phase II Enhancement "All-Solid-State Battery-Ultracapacitor Hybrid Devices Based on Nanostructured Materials"; 2013- 2021. Program Manager: Dr. Mohan Sanghadasa

Acknowledgement

Carbon Solutions Inc.

Dr. Mikhail E Itkis
Sergey Kalinin
Nelson Cabrera

US Air Force (AFRL/RVS)

Small Business Innovation Research (SBIR)

TPOC Alec Jackson