

# Low Cost Sodium-ion Battery to Enable Grid Scale Energy Storage: Prussian Blue-Derived Cathode and Complete Battery Integration

Sharp Labs of America, Dr. JJ Lee  
Contact: JJ Lee, 360.817.8439, jjanlee@sharplabs.com

## R&D Aim

- Develop a sodium-ion battery (NIB) that will dramatically increase battery cycle life at a low cost, while maintaining high-energy capacity. Successful battery development will exceed US Government Department of Energy (USDOE) 2015 cost targets for stationary energy storage and facilitate adoption and deployment of renewable energy.
- This SIB technology uses low-cost Prussian Blue (PB) as active cathode material. PB crystals have large interstitial spaces that allow easy intercalation of sodium ions.

## Target Products



## Development Overview

Development Period:  
March 2013 to March 2016

### Cathode Development (60%)

**Material Development:**  
Na<sub>2</sub>Fe<sub>2</sub>(CN)<sub>6</sub>  
Na<sub>2</sub>M1Fe(CN)<sub>6</sub>

**Process Development:**  
Precipitation  
Hydrothermal

**Cathode Evaluation and Target:**  
Capacity: >160 mAh/g  
Energy Density: >500 Wh/kg  
Power density: >3000 W/kg  
Cyclability: >5000x

### Electrolyte Selection (10%)

**Baseline:** Non-aqueous liquid electrolyte  $\sigma > 5$  mS/cm  
**Develop:** Polymer or polymer blend electrolyte,  $\sigma > 1$  mS/cm

**SHARP**  
LABORATORIES OF AMERICA

### Anode Development (15%)

**SHARP**  
LABORATORIES OF AMERICA

**OSU**  
Oregon State University

**Baseline:** Hard carbon  
**Develop:** Nano-Sn, nano-Sb, nano-Sn-Sb on carbon matrix

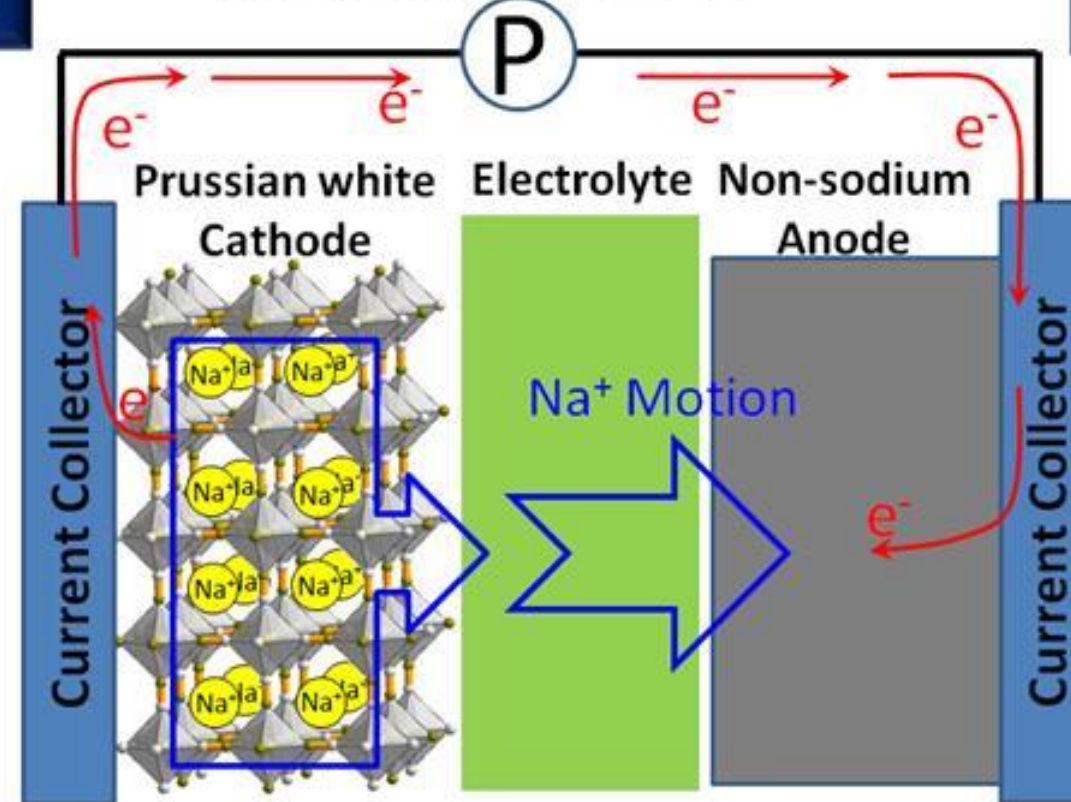
**Anode Evaluation and Target:**  
Capacity: >450 mAh/g  
Cyclability: >5000x

### Battery Evaluation & Optimization (15%)

**SHARP**  
LABORATORIES OF AMERICA

**Electrode Composition Optimization**  
**Battery Performance Optimization:**  
Cell Chemistry, Operation Temperature, Charge and Discharge Characteristics, Pulse Performance, Deep Discharge, Self Discharge, Ragone Plots, Internal Impedance, and Cycle Life

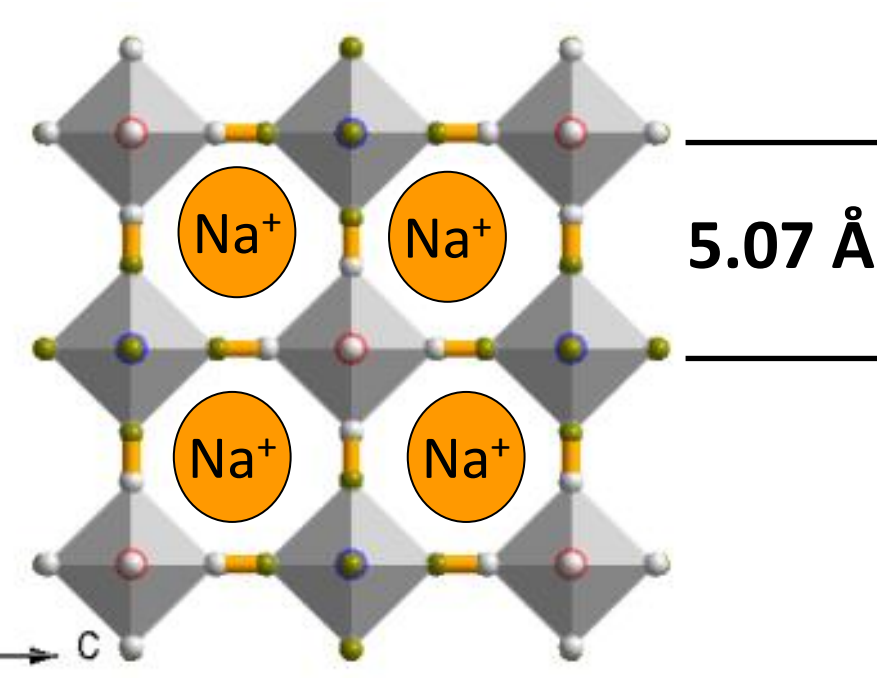
**Integrated Battery Target**  
Specific Energy: >120 Wh/kg  
Specific Power: >2000 W/kg  
Cyclability: >5000x  
Nominal Cell Voltage: 3.0V



## Prussian White and Low Cost Synthesis

### Open Structure

Prussian Blue (PB):  
Na<sub>2</sub>M1M2(CN)<sub>6</sub>



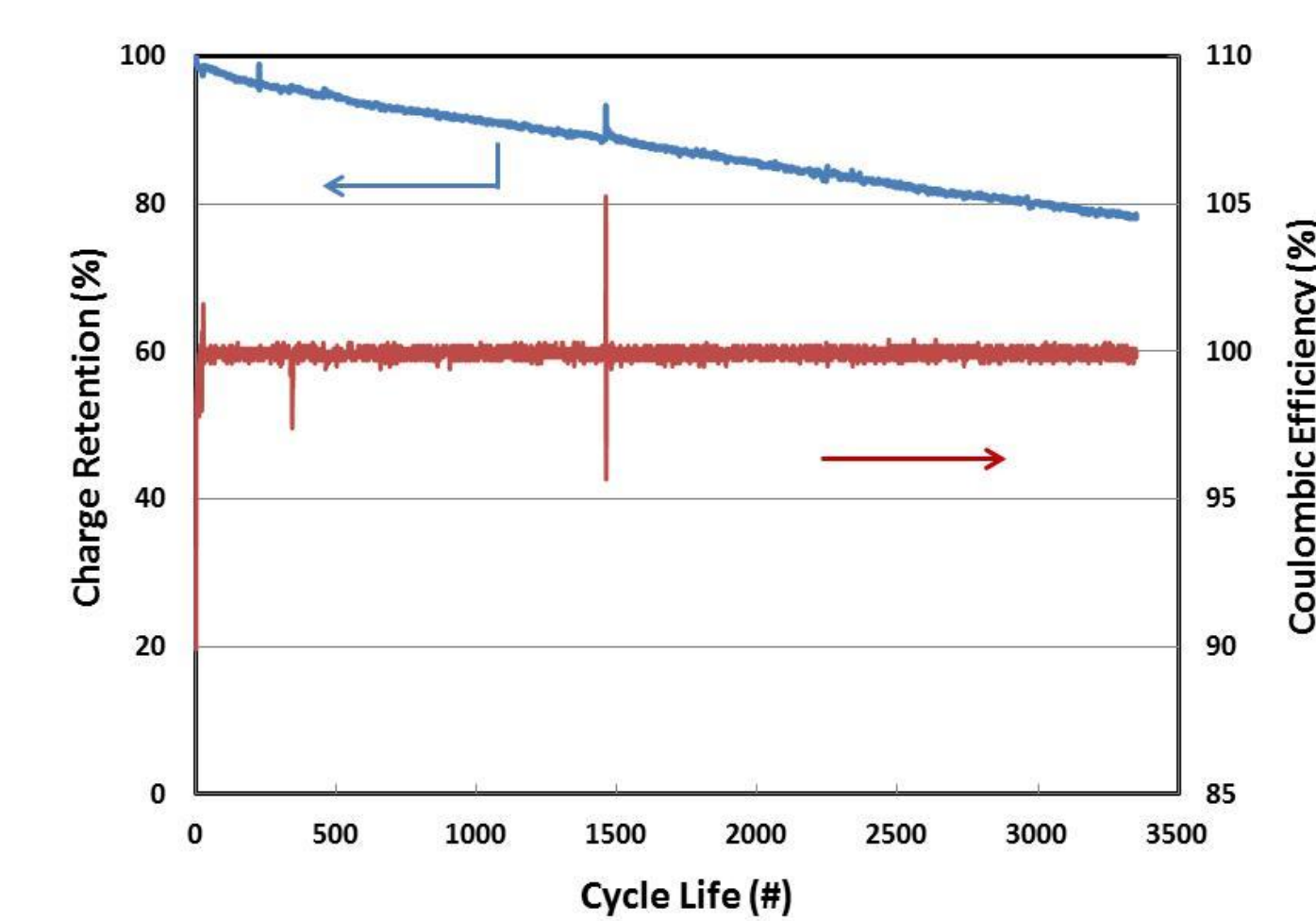
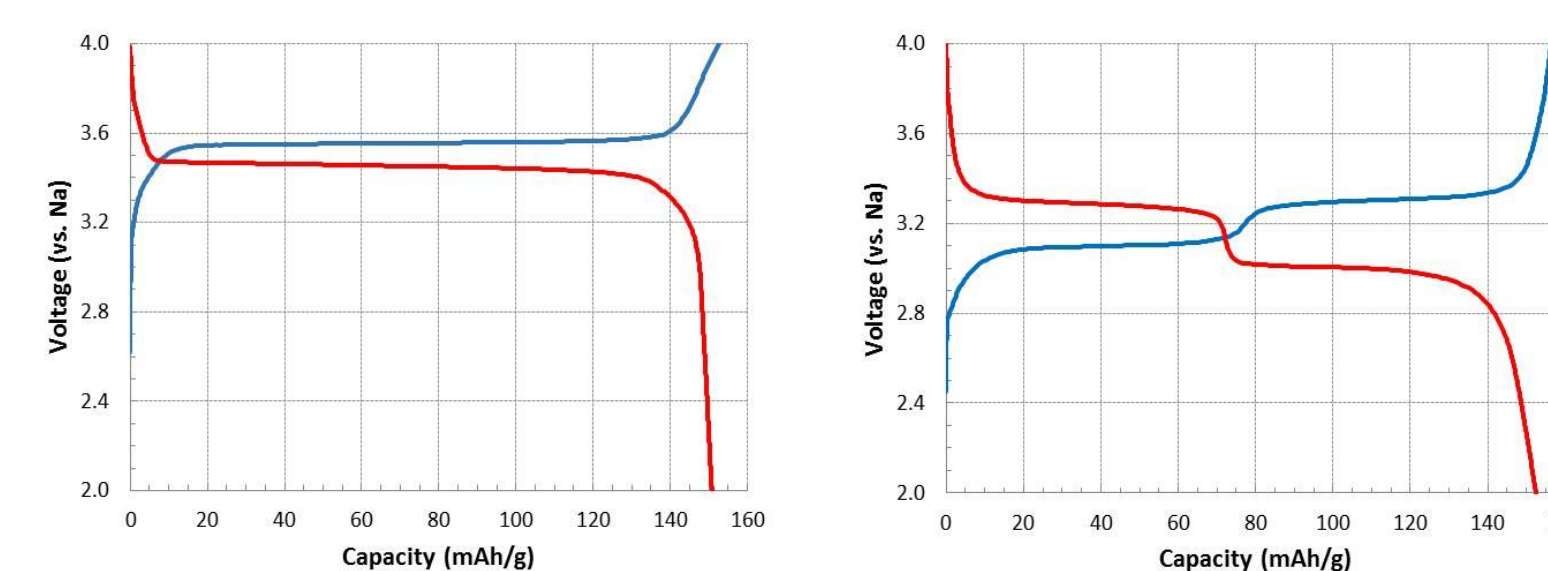
M1 and M2:  
Fe, Ni, Mn, Cu, Ni,  
Co, Mg, Zn, Ca,  
Cr, Ti, V, etc.

### Low Cost Synthesis



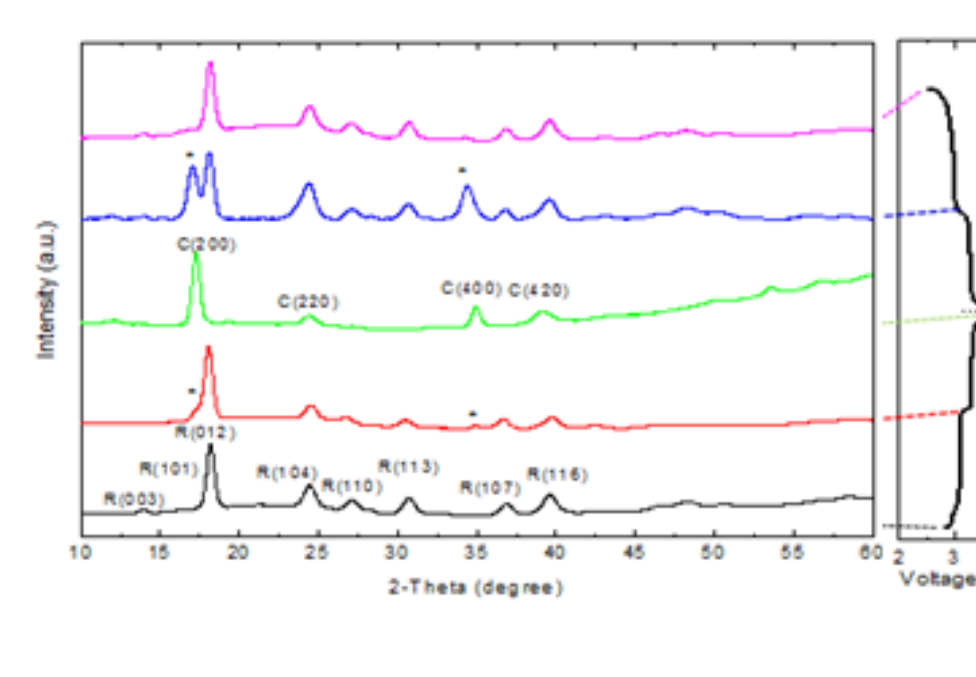
## Core Technology

### PB Cathode: High Capacity & Long Cycle Life

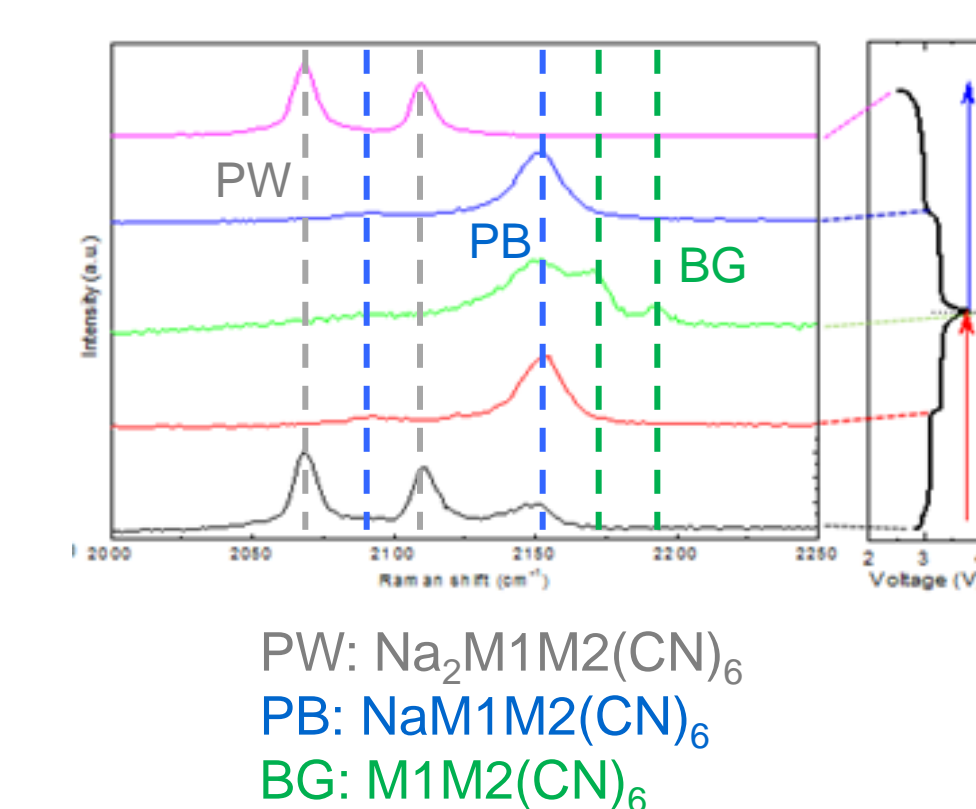


### PB Cathode: Reversible Structure Change

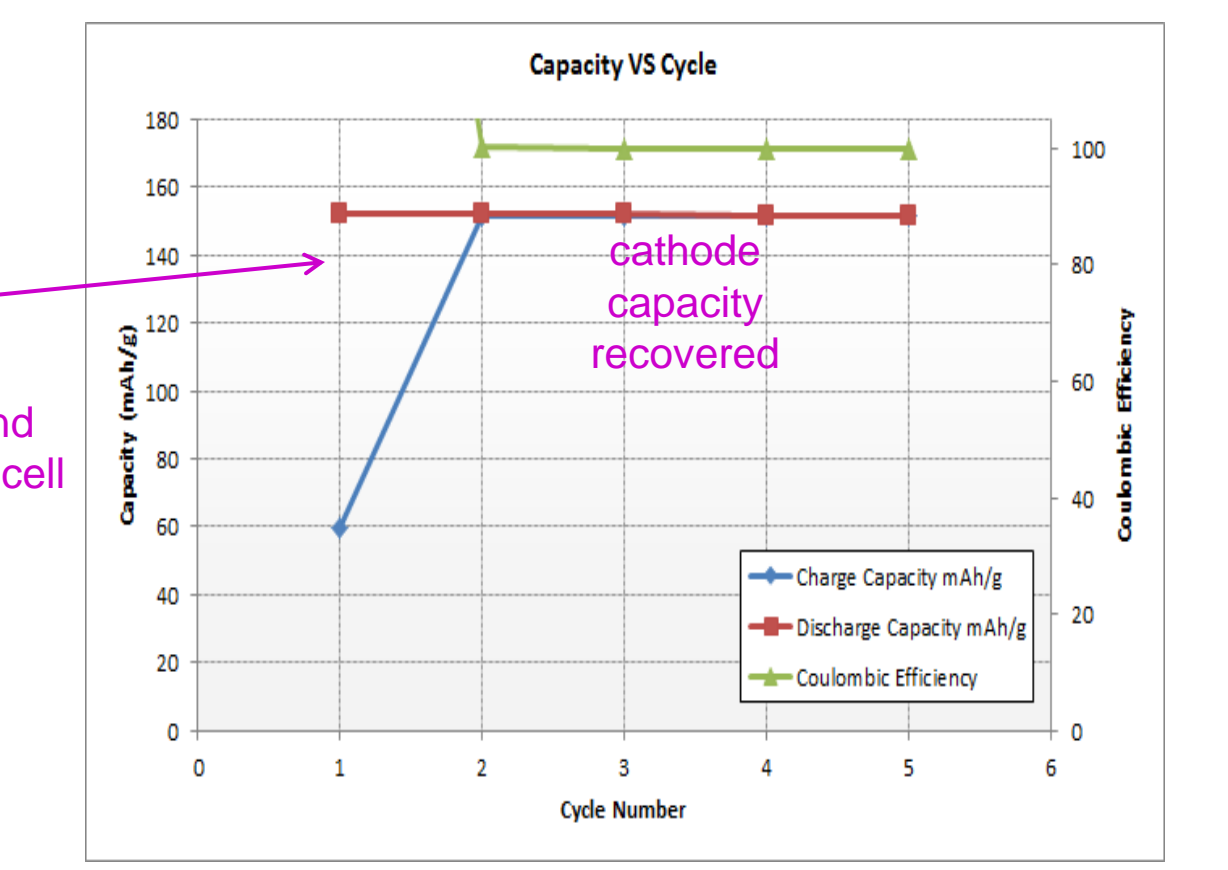
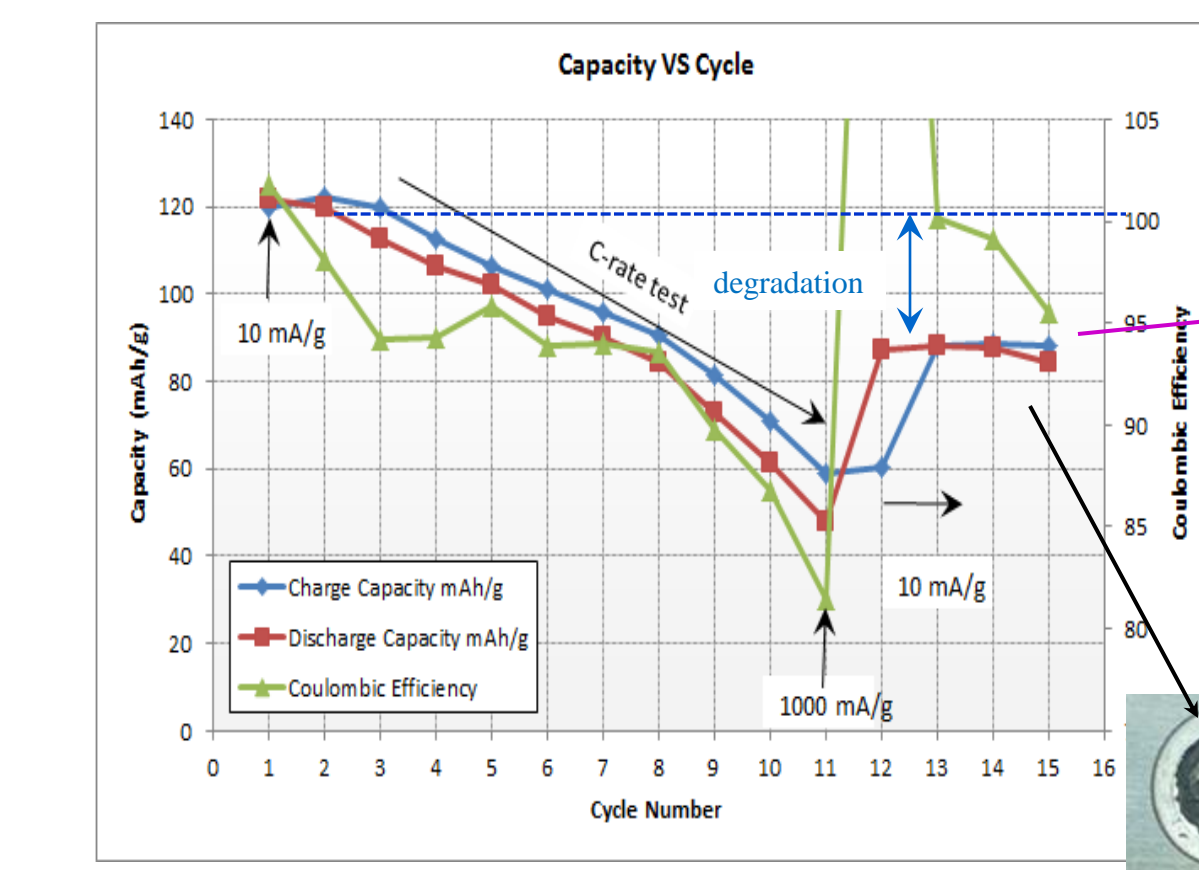
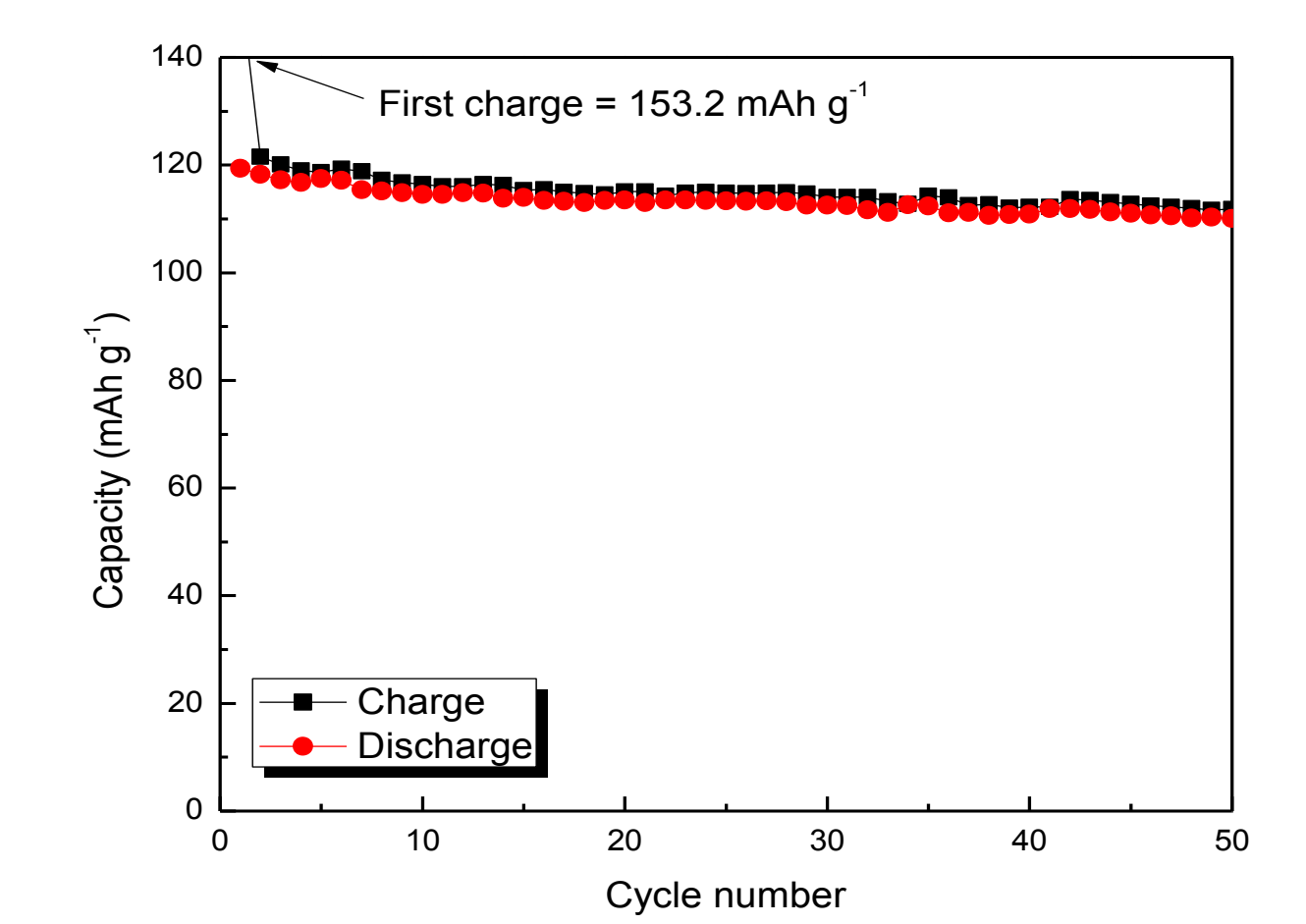
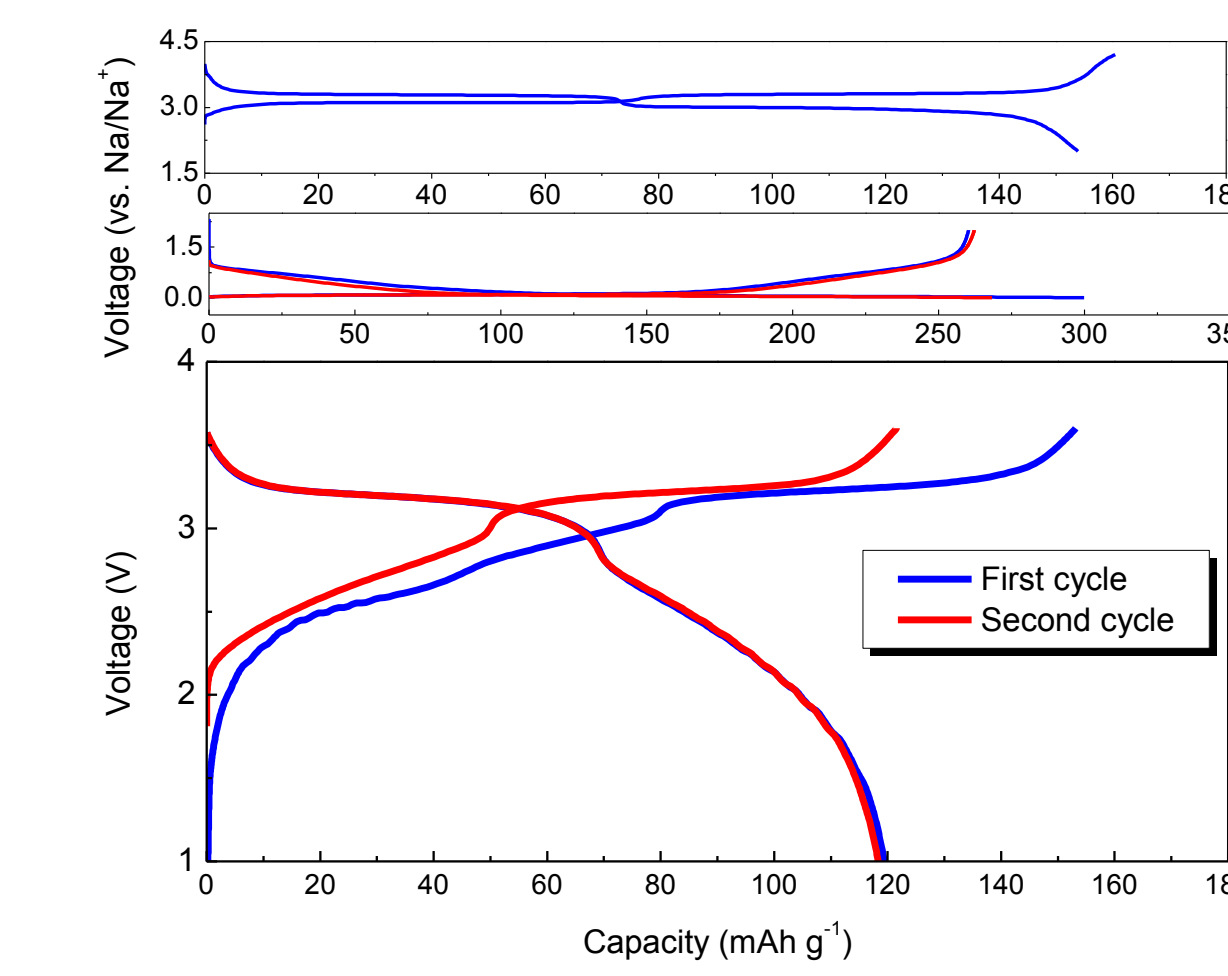
#### XRD



#### Raman



### PB-HC Full Battery Analysis



Na plating at anode

## Performance Comparison

|                                      | LiFePO <sub>4</sub> - Graphite   |   | Prussian Blue Analogues (PBA) – Hard Carbon  |
|--------------------------------------|--|---|--|
| Voltage (V)                          | ~3.5V  | ≡ | Na <sub>2</sub> MnFe(CN) <sub>6</sub> : ~ 3.43 V   |
| Capacity                             | • 170 mAh/g (theoretical)<br>• 160 mAh/g (actual)  | ≡ | • 170 - 200 mAh/g (theoretical)<br>• 150 mAh/g (actual, 0.1C)<br>• 145 mAh/g (actual, 1C)  |
| Material density                     | 3.6 g/cm <sup>3</sup>  | > | 1.9-2.3 g/cm <sup>3</sup>  |
| Cell energy density (Prismatic cell) | 270 Wh/l   | > | • 190 Wh/l (same electrode thickness as LFP)<br>• 220 Wh/l (5 times thick electrode)   |
| Material cost                        | 20 US\$/kg (High temperature (over 600 deg.) and inert atmosphere)   | < | 2.5-3.5 US\$/kg (Room temperature and co-precipitate)  |
| 10 kWh Battery Pack                  | \$3001 (1000 MWh annual production)  | < | \$2280 (based on Argonne National Lab: Modeling the Performance and Costof Lithium-Ion Batteries for Electric-Drive Vehicles)                                    |
| Cycle life                           | 80% ~ 90% after 1,000 cycle  | ≡ | 98% after 1200 cycle*<br>(95% after 10,000 cycle, prospect)  |
| High power density                   | 95% (1.0C/0.1C)  | < | 87% (10C/1C)<br>> 97% (1C/0.1C)  |
| Safety                               | Hard oxygen generation   | ≡ | No oxygen generation   |
| Applications                         | • Stationary energy storage<br>• Grid connected energy storage<br>• Power source for home appliance<br>• Plug-in electric vehicles (PEV) |   | • Grid connected energy storage (time-shift and frequency regulation )<br>• Stationary energy storage<br>• Plug-in hybrid electric vehicle (PHEV) or PEV for bus |