Transitioning Electrochemical Acoustic Analysis into a Predictive Technique for Understanding Complex Behaviors

Daniel Steingart
Princeton University
Princeton Lab for Electrochemical Engineering Systems Research
Department of Mechanical and Aerospace Engineering
Andlinger Center for Energy and the Environment

Meeting The Challenge ESS
2017-02-22
Thanks in Advance
Anna Karenina was a Battery

“All happy families are alike; each unhappy family is unhappy in its own way”

“If you look for perfection, you'll never be content”

“Anything is better than lies and deceit!”
Group Hypothesis

Many Couplings Create An Unfortunate Tetrahedron

- Capital Cost
- Energy Density
- Power Density
- Amortization/Operating Cost (Cycle life and Safety)

Pick Your Corners

EVs are in the middle

(Ragone Space)

(Utility Space)
The Hidden Metric in Ragone

Energy Density

Power Density

Safety

More Energy @ Unlimited Rate

$$\frac{\Delta E}{C_p \times m} = \Delta T$$

Less Mass

V. Srivansan, GigaOM, 2012
doctor pilot @pilotbacon · 33m

i made it home from manhattan to queens with 1% on my phone the whole time and now i feel like i finally understand the story of Hanukkah.
Cost No Object Tool: EDXRD

Near real time reconstruction of a full cell in operation

Requires White Beam And Serious Flux

Hope the Wiggler Stays Up

\[ d = \frac{n\lambda}{2 \sin \theta} \]

<table>
<thead>
<tr>
<th></th>
<th>( \theta )</th>
<th>( \lambda )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EDXRD</strong></td>
<td>Fixed</td>
<td>Varied</td>
</tr>
<tr>
<td><strong>( \theta-2\theta )</strong></td>
<td>Varied</td>
<td>Fixed</td>
</tr>
</tbody>
</table>
The Allegory of The Cell

(You Cell Phone Estimator) (Synchrotron Radiation)
(Cheap Stuff) (Neutron Sources)
(Fancy Stuff)

Working Systems

(Generally) Deconstructed Systems


truth is expensive but uncalibrated estimation is dangerous
The Allegory of The Cave

What Can Bridge?
For “real systems” I’d argue that the default is EIS

Why Does This Happen?

100% SOC
Why does this happen?
A Complex Story
Mechanics and Batteries

Stress-strain

Acoustic emission

Large-scale delamination

Rhodes et. al. JECS 2010

Sood et. al. IEEE 2013

Cannarella et. al. JOPS 2014
Is there a global connection?

- Is there a way to study the electrochemical & mechanical behavior of all closed batteries, regardless of chemistry and geometry?
- Can we detect the subtle changes that occur in a battery during cycling?

Thoughts about closed batteries during cycling:

- Density distribution must shift
- Modulus distribution will change as well
Basic Acoustics

Sound speed

\[ c = \sqrt{\frac{K + \frac{4}{3}G}{\rho}} \]

Longitudinal/Shear Modulus
Density

Acoustic impedance

\[ Z = \rho \cdot c \]

Hypothesis:
Cycling will affect the behavior of sound traveling through a battery
Simulation of pulse through a cell

1D continuity equations*

\[ p_t + B \cdot u_x = 0 \]
\[ u_t + \frac{1}{\rho} \cdot p_x = 0 \]
Simulation of pulse through a cell

1D continuity equations*

\[ p_t + B \cdot u_x = 0 \]
\[ u_t + \frac{1}{\rho} \cdot p_x = 0 \]

*solved in Clawpack

*Constant SOC
EA Simulation

Waveform evolution as \( f(SOC) \)*

*calculated assuming only density changes

\[ t_{ToF} \ll t_{cyc} \]
Visualizing EA data

Snapshot in cycling time, single SOC

Time-resolved, changing SOC
EA Simulation

*assuming only density changes
More layers, more complexity

*assuming only density changes
Sub Wavelength Handwave

Effective Density Change doesn’t show up if the frequency is too low (mass is conserved)

Elastic Modulus has no need to be conserved, so at low frequencies we are measuring a composite stack
Experimental Setup
LCO Prismatic

LCO Prismatic Cell, C/2.5 cycling

Acoustic Signal (A.U.)

Time of Flight (µs)

Reflection

Transmission

Current Potential (V)

Current (mA)

Cycling Time (hr)

*experimental data

Hsieh et. al. E&ES 2015
LCO Prismatic

Hsieh et. al. E&ES 2015
NCA 18650

Hsieh et al. E&ES 2015
NCA 18650 - cycle by cycle
Alkaline Brand Comparison

Hsieh et. al. E&ES 2015
Bhadra et. al. JMCA 2016
Chemistry/geometry specific
Summary

• Sound *must* be an indicator of battery structure, state of charge, and state of health due to the basics operation of a closed electrochemical energy storage

• In combination with traditional tools, we can provide direct structural information on real batteries, in real time.