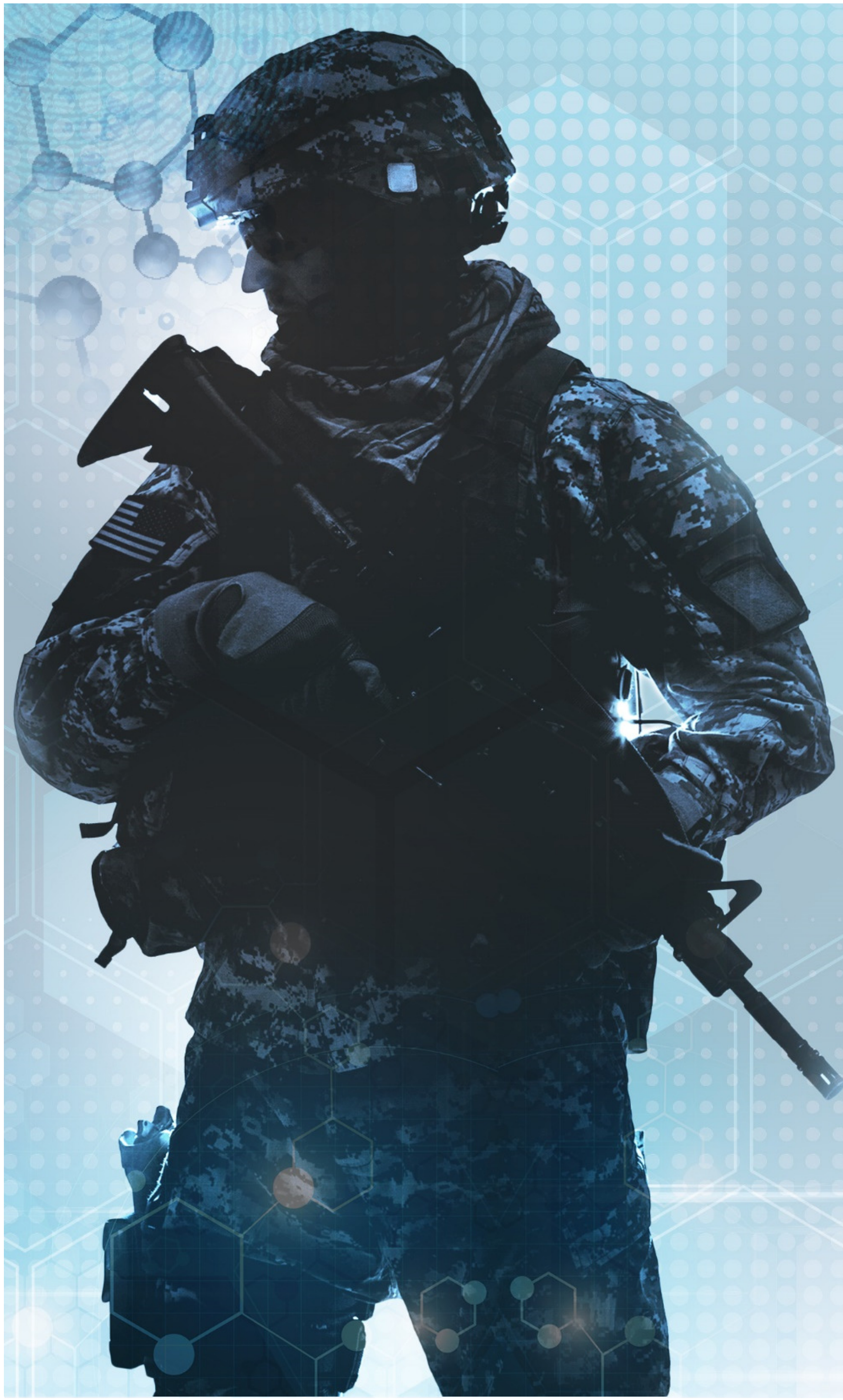

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Impact-Resistant, Shear Thickening Electrolyte Batteries for Soldier Power

Gabriel M. Veith, Ph.D.

HDIAC Subject Matter Expert

Research Staff and Team Lead, Thin Films, and Coatings Group
Oak Ridge National Laboratory

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Introduction

HDIAC & Today's Topic

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HDIAC Overview

What is the Homeland Defense & Security Information Analysis Center (HDIAC)?

One of three Department of Defense Information Analysis Centers

Responsible for acquiring, analyzing, and disseminating relevant scientific and technical information, in each of its eight focus areas, in support of the DoD and U.S. government R&D activities

HDIAC's Mission

Our mission is to be the go-to R&D/S&T and RDT&E leader within the homeland defense and security (HDS) community, by providing timely and relevant information, superior technical solutions, and quality products to the DoD and HDS Communities of Interest/Communities of Practice.

HDIAC Overview

HDIAC Subject Matter Expert (SME) Network

HDIAC SMEs are experts in their field(s), and, typically, have been published in technical journals and publications.

SMEs are involved in a variety of HDIAC activities

- Authoring HDIAC Journal articles
- Answering HDIAC Technical Inquiries
- Engaging in active discussions in the HDIAC community
- Assisting with HDIAC Core Analysis Tasks
- Presenting webinars

If you are interested in applying to become a SME, please visit HDIAC.org or email info@hdiac.org.

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Overview: Soldier Power

- **Current Soldier power solutions require the Warfighter to carry appx. 16 pounds of batteries**
- **Power is provided by a standard brick-shaped lithium ion battery (LIBs)**
  - BA-2590, BA-5590, BB-2590
- **Newer, more flexible versions of LIBs are in production, but LIBs pose an inherent risk of thermal runaway/fire/explosion**
- **Armoring-up a battery casing reduces—but does not eliminate—this risk, while increasing carry load**

BB-2590 rechargeable battery, new (top) and after thermal runaway (bottom)

Sources: Valencourt, L. R. (2017, April 11). Incidents involving: BB-2590/U batteries & PP-8498/U chargers and other (CWB) US Army batteries. Presentation to the Safety and Health (top); Thompson, E. (2009, June 18). Improved battery technology sitting unordered in Army inventory. U.S. Army, retrieved from https://www.army.mil/article/22916/improved_battery_technology_sitting_unordered_in_army_inventory (bottom)

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Overview: Soldier Power

- **The shear-thickening electrolyte (STE) technology in this study may lead to Warfighter-borne battery power solutions that:**

- Provide electrical power supply (Wh/L and Wh/kg) equal to or superior than best-of-class standard LIBs, on a per-unit-power basis
- Resist thermal runaway after taking an impact or suffering physical damage
- If impacted, will provide uninterrupted and undiminished power to warfighter equipment

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Gabriel M. Veith, Ph.D.

Research Staff and Team Lead, Thin Films and Coatings Group

Oak Ridge National Laboratory

Gabriel M. Veith received his Ph.D. in 2002 from Rutgers University working in Solid State Materials Chemistry with Professor Martha Greenblatt, focusing on structure-magnetic property correlations. He joined ORNL in 2002 as a post-doctoral researcher and became a Staff Scientist in 2005. His research has focused on developing new approaches to characterizing materials interfaces and relating surface chemistry to specific electrochemical and catalytic processes. In 2009 he was awarded the UT-Battelle Early Career Scientific Achievement Award. He is the Associate Editor for the Journal Catalyst. He is also the Honorary Scientific Advisor to the Charlotte-Mecklenburg (NC) Burglary Division. He has 169 published papers, 3 patents and 6 patents submitted.

Overview

EXPIRE and SAFIRE projects: Focusing on battery fundamentals and way-out ideas

- **Solid state batteries**
- **Lithium metal**
- **Multifunctionality to enable safer, lighter, and more robust rechargeable batteries**

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EXPIRE

EXtremely Passive Impact Resistant Electrolyte

SAFIRE

SAFe Impact Resistant Electrolyte

Based on experimental data, should stop a ballistic projectile

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Conventional batteries prone to explode upon mechanical impact

Mechanical impact (e.g. car crash, bullet)

↓

Short circuit for the battery

↓

Thermal runaway

↓

Fire and explosion

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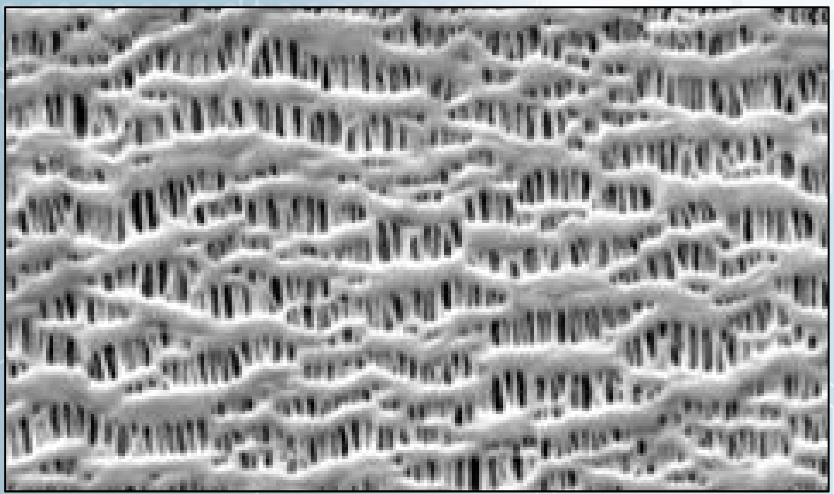
Use a specially designed separator stable under Li-ion voltages and chemistries

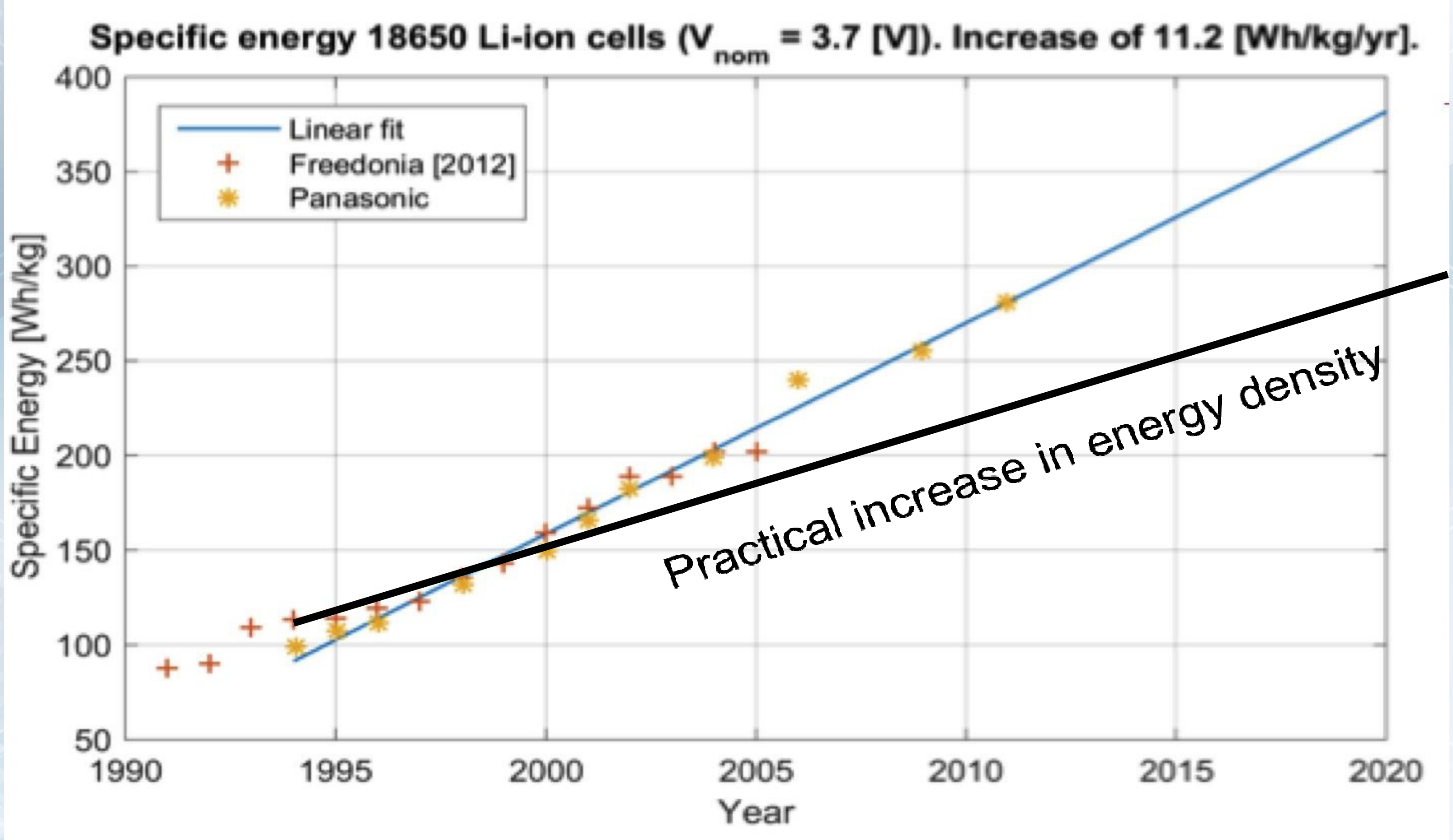
25 µm polypropylene separator



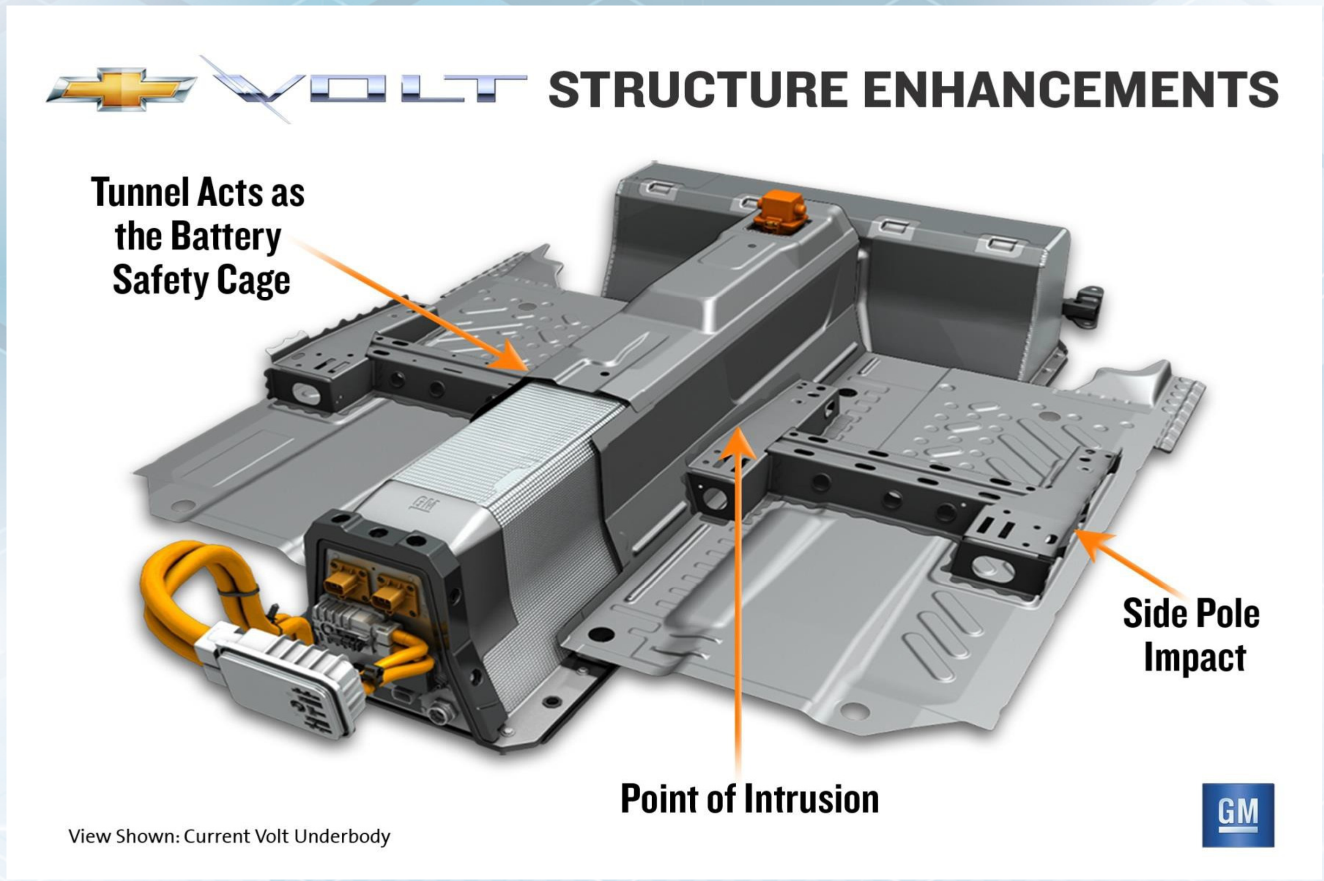
Thin and porous to optimize transport

Survives 90% crushing, but not tearing

Every time you make a higher energy density battery you need more armor



Up-armoring the battery results in more mass that needs to be dragged around – 200+ lbs

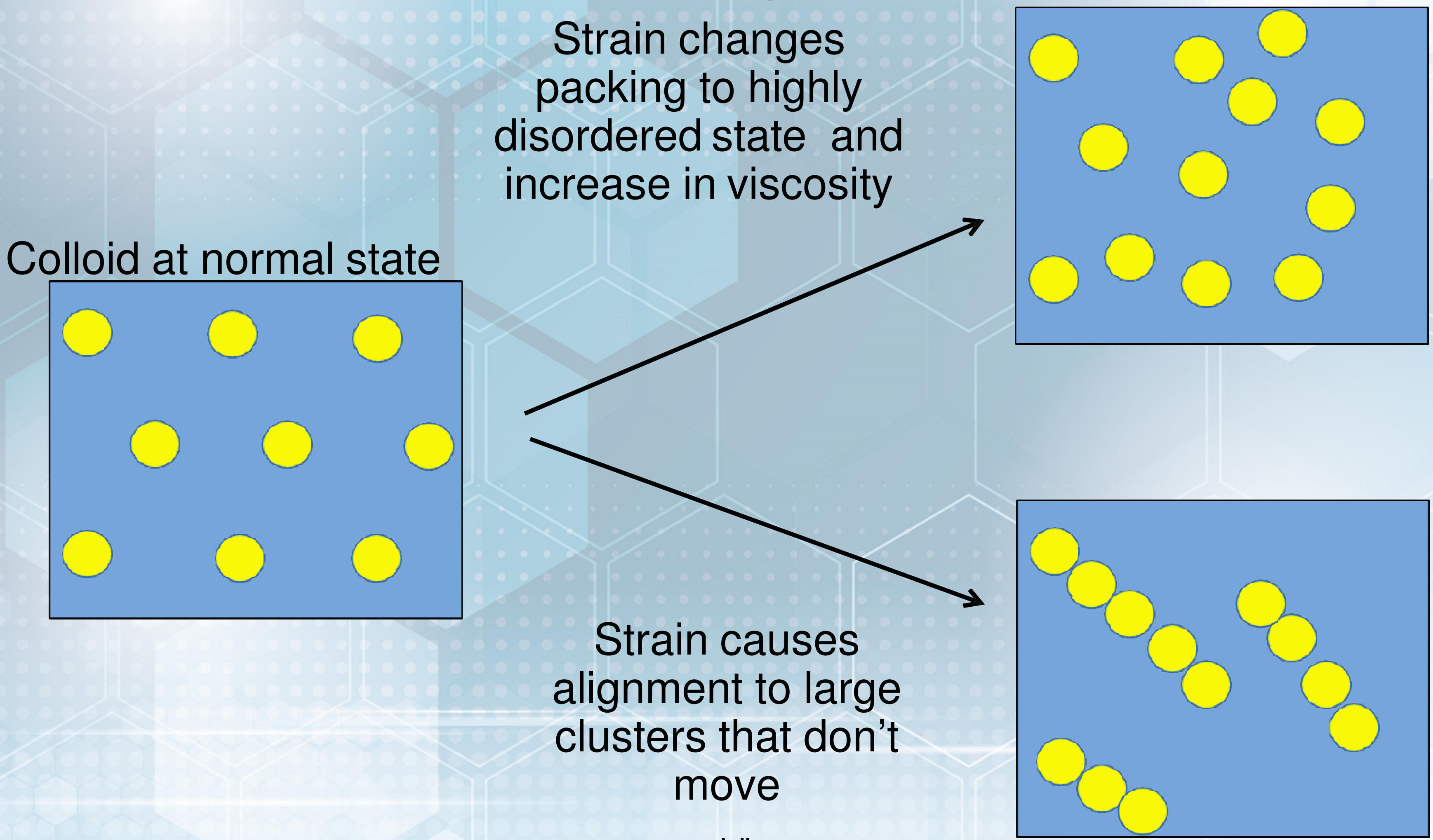


Are there new approaches to increase safety without armor?

Non-Newtonian fluid: Oobleck

- One day while playing with my kids…
  - 50/50 mixture of water/corn starch
  - Mix together and play with
  - Hours of entertainment for small children or adults

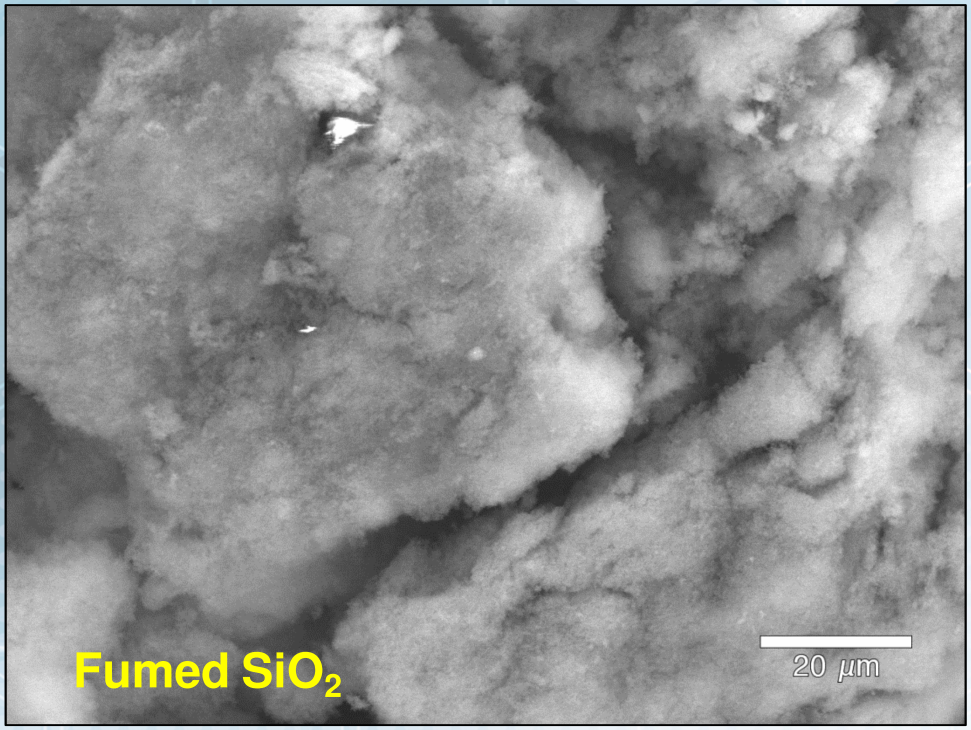
Shear thickening is a rapid change in viscosity from restructuring of colloids



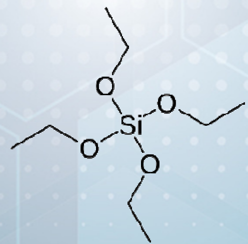
Looked at materials stable in battery

- Made and characterized a lot of SiO_2
- 5 Fumed SiO_2 – Flame pyrolysis of $SiCl_4$
- 100-300 m^2/g - ~$7.50/lb

- Plate-like SiO_2
- Alfa - $6/lb
- 2 μm particles



Focusing on SiO_2 materials made by the Stöber process because gives best performance



+ NH_4OH + H_2O in ethanol

Wash with ethanol

Collect using centrifuge

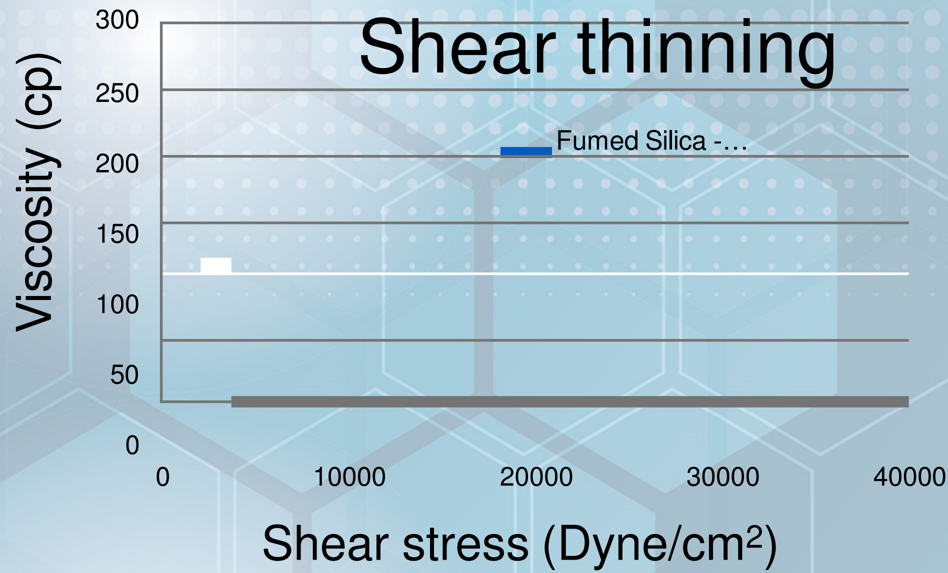
Typically make 30 grams

200 nm particles that are very uniform

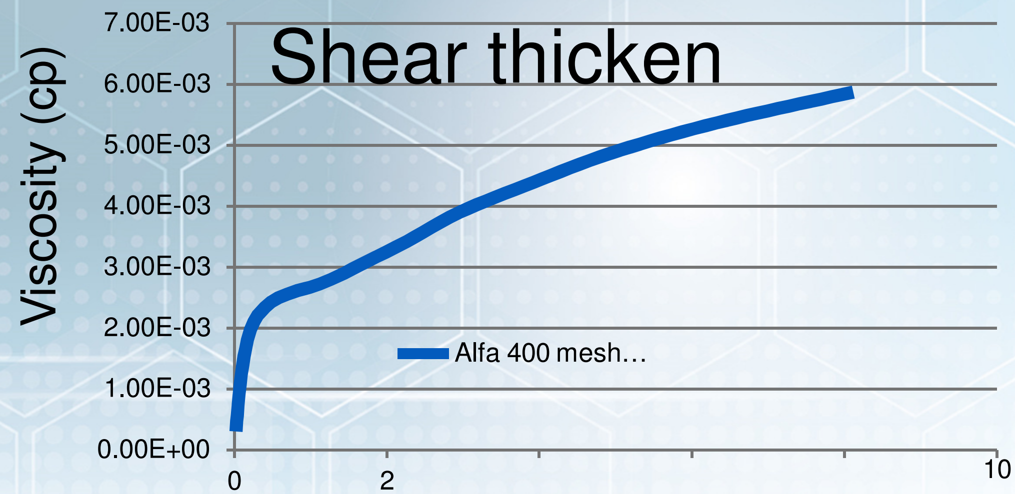
Electrolyte fabrication uses standard battery solvents: Just add SiO_2

1.2M $LiPF_6$ in 3:7 wt% ethylene carbonate: dimethyl carbonate

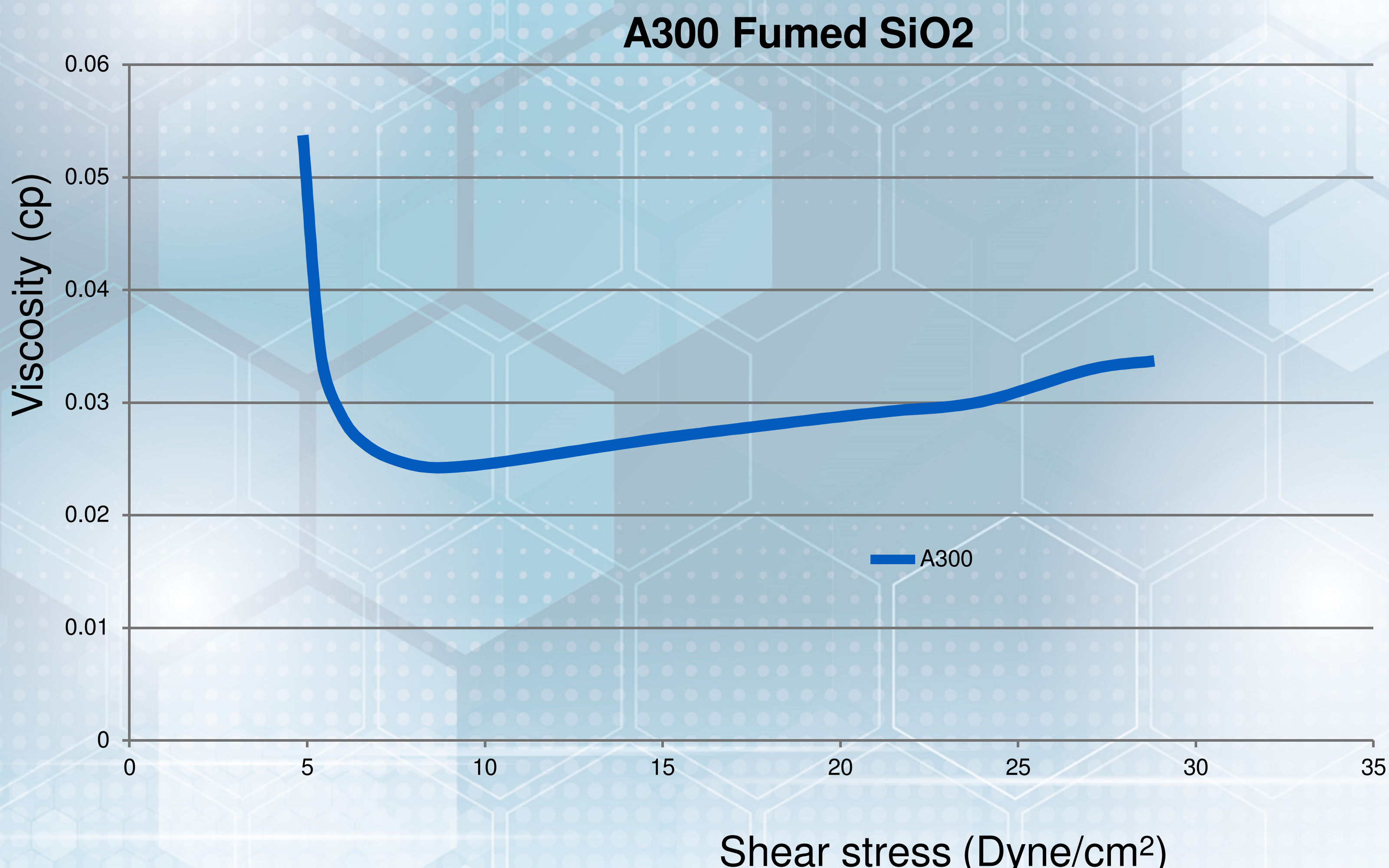
Rheology data orientation



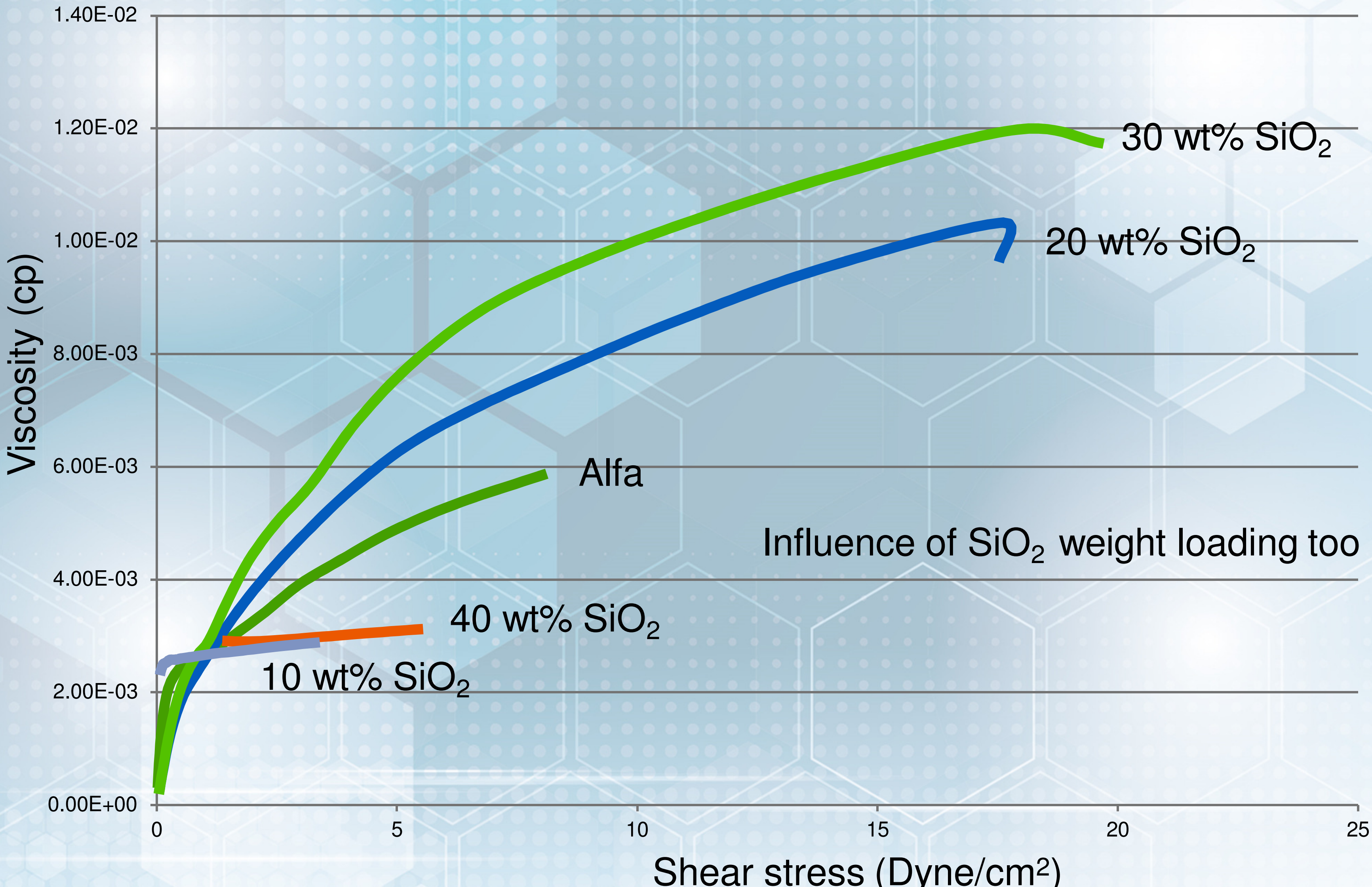
Spreadable material



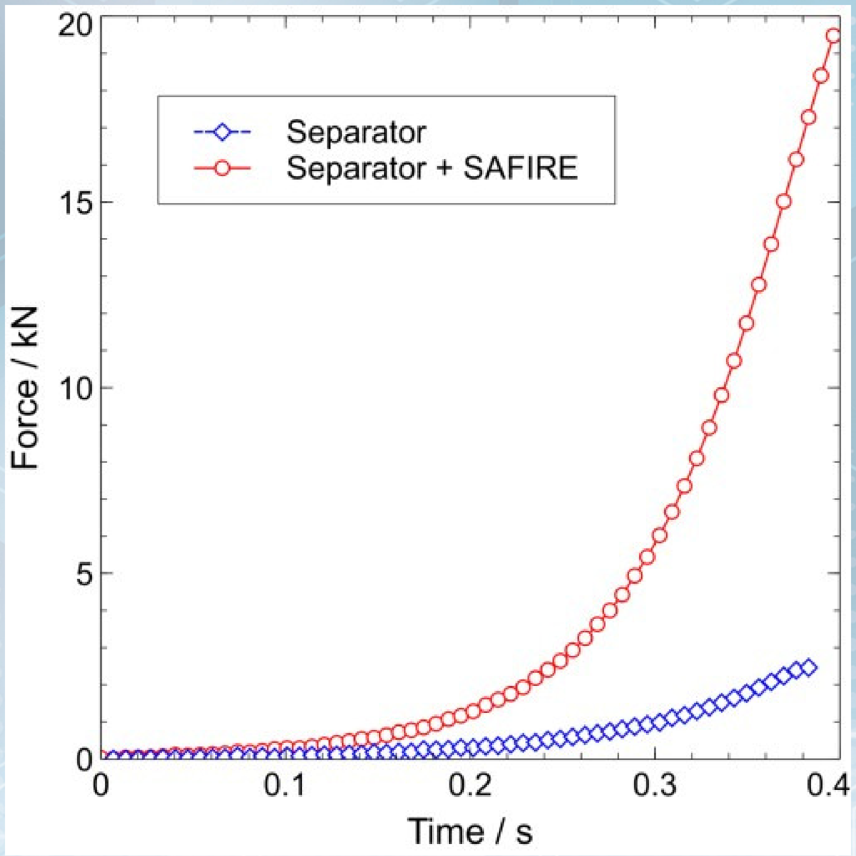
Fumed silicas in 1.2M $LiPF_6$ EC/DMC all shear thin regardless of weight loading



Large shear thickening response for plates and Stöber SiO_2 in 1.2M $LiPF_6$ EC/DMC



Order of magnitude difference in force in compression!
With higher speed, the effect would be more significant



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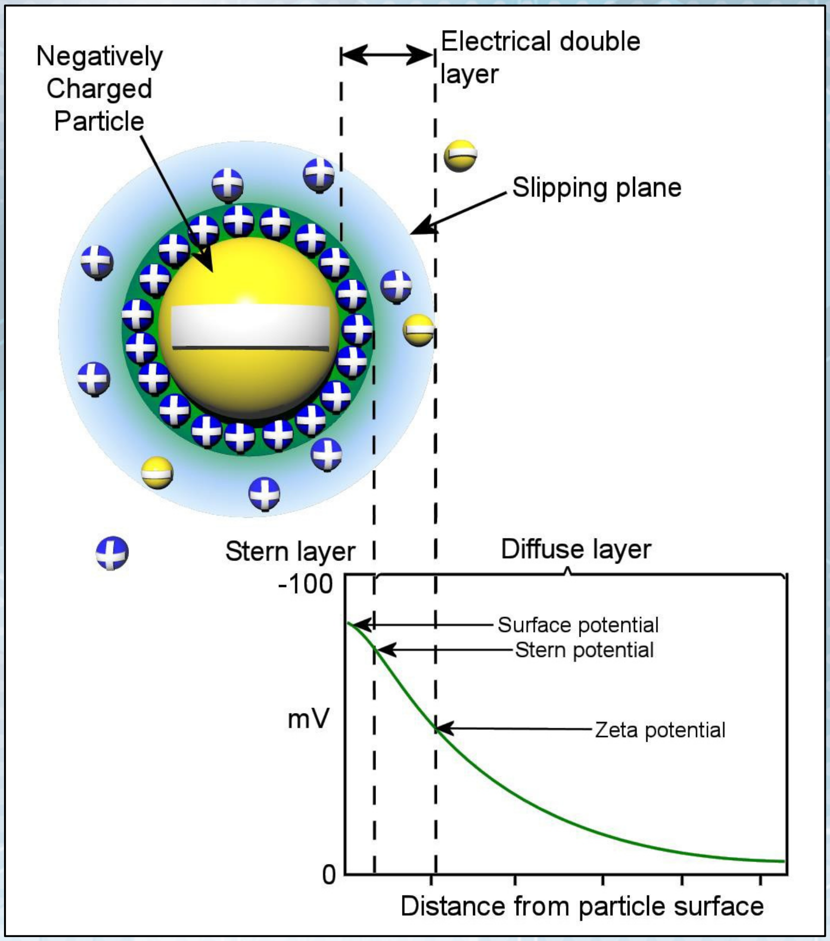
What makes one silica better than other silicas?

Colloid uniformity critical

Shear thin or thicken	Material	Polydispersity
Thin	5505 Fumed	0.156
Thin	A300 Fumed	0.495
Thin	R972 Fumed	0.16
Thin	Stöber batch 16	0.243
Thin	Stöber Batch 20	0.187
Thicken	Diatomaceous	0.005
Thicken	Stöber batch 06	0.087
Thicken	Stöber batch 07	0.005
Thicken	Stöber batch 21	0.005

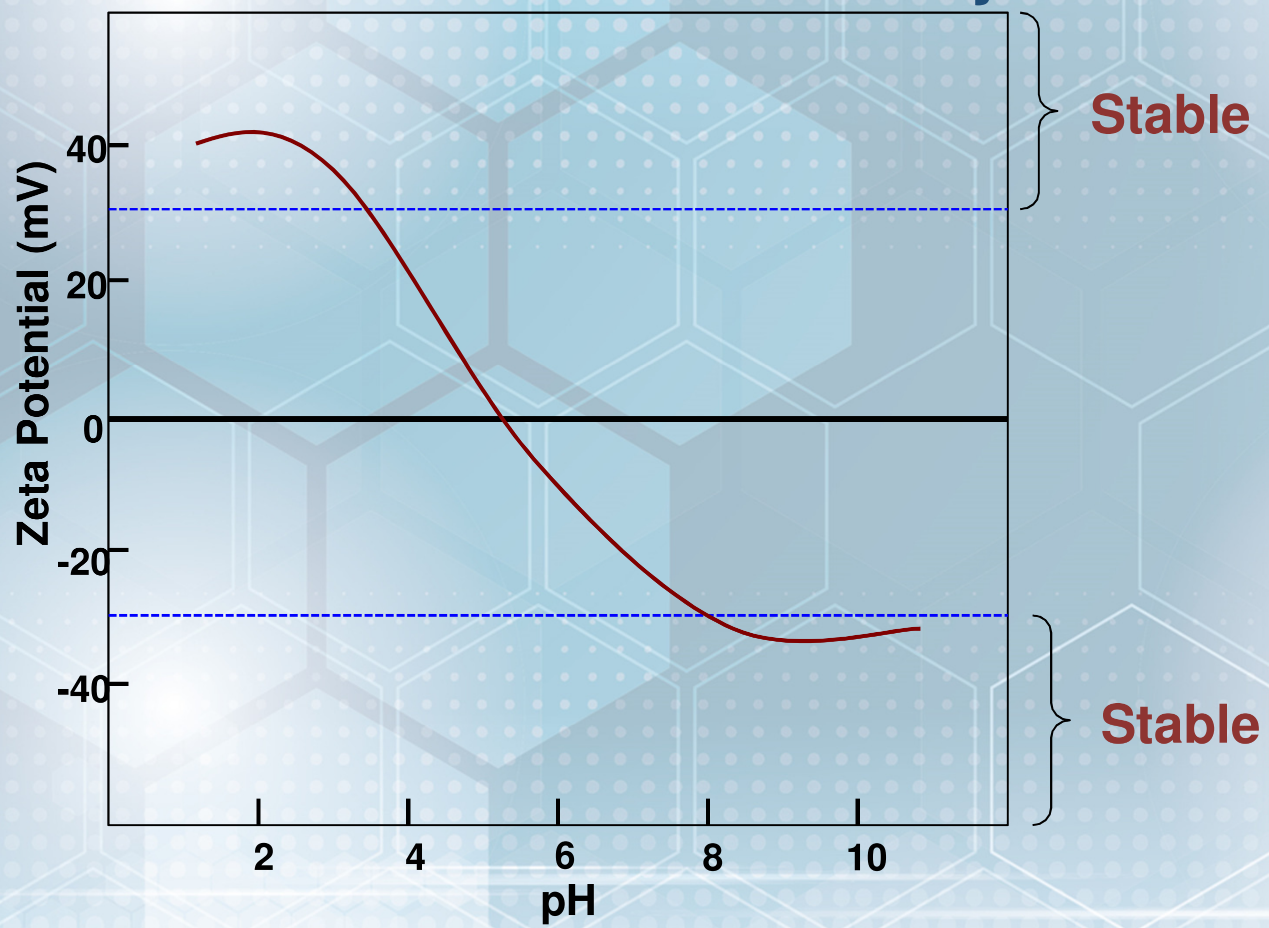
Light scattering data

Zeta Potential as a Tool for the Characterization of Interparticle Forces



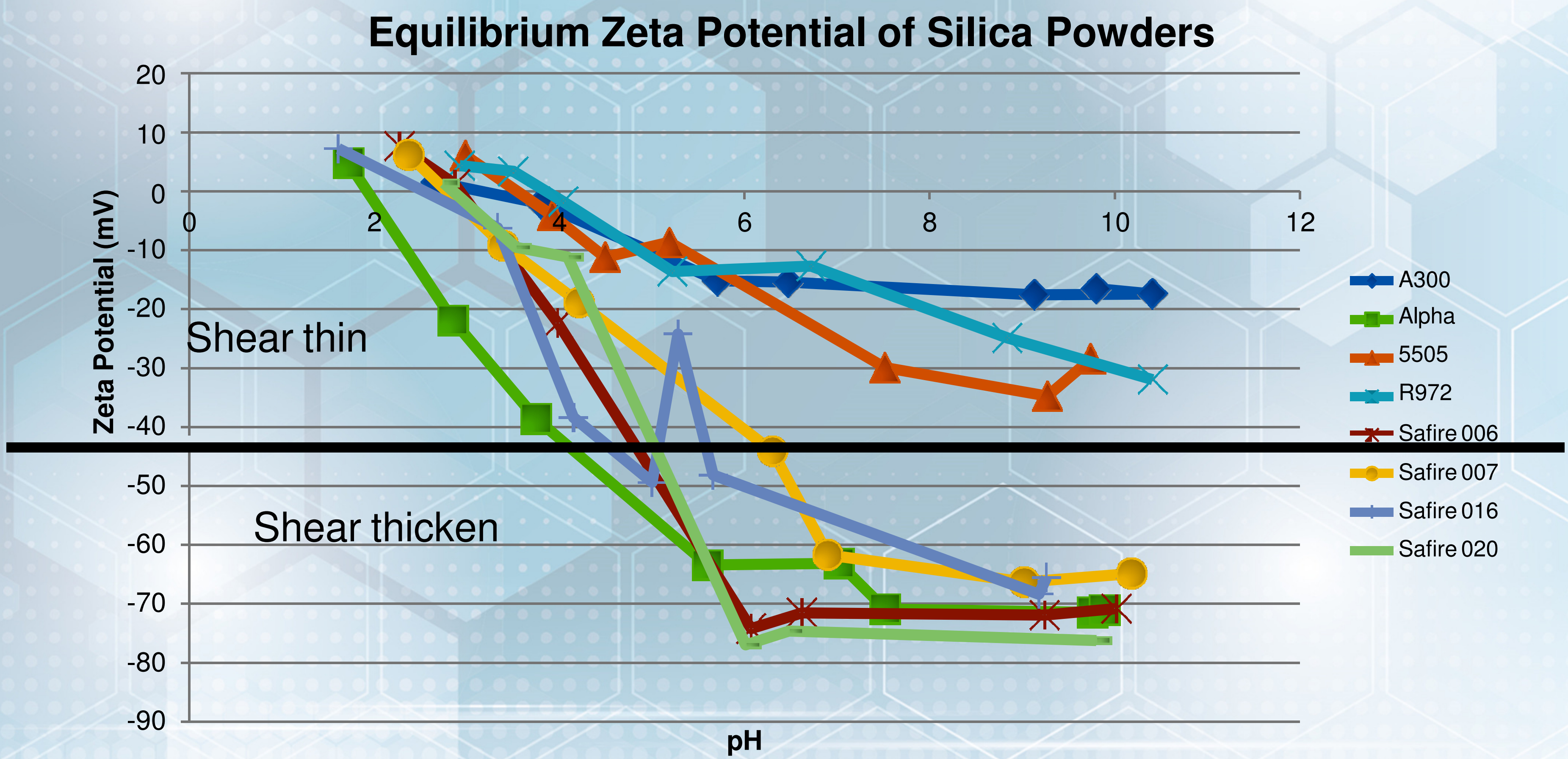
- Zeta Potential is the electrical potential at the junction of Stern layer and the diffuse layer (a point in the bulk fluid away from the interface); i.e., the potential difference between the medium and the stationary layer of fluid attached to the dispersed particle

High charges give repulsion between particles and stability



- > ± 30 mV is considered stable

High surface charge leads to stability and shear thickening – large repulsion between particles



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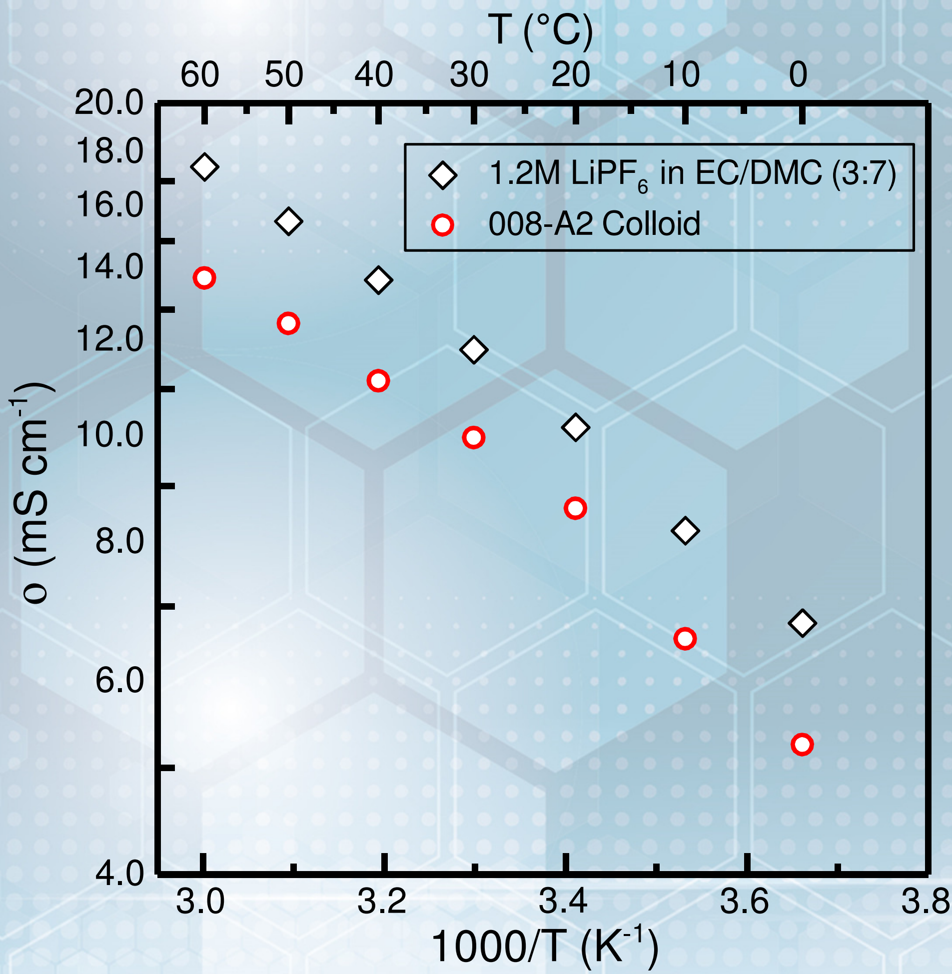
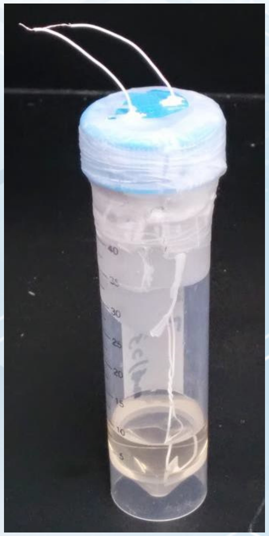
Electrochemistry

Temperature Dependence of Conductivities Perform as Expected



IDES used for *BOTH* the liquid electrolyte and colloidal dispersion



Electrolyte	E_a (kJ/mol)
Std. Liquid Electrolyte	11.7
21 wt% SiO2 in 1.2M $LiPF_6$ in EC/DMC	11.4

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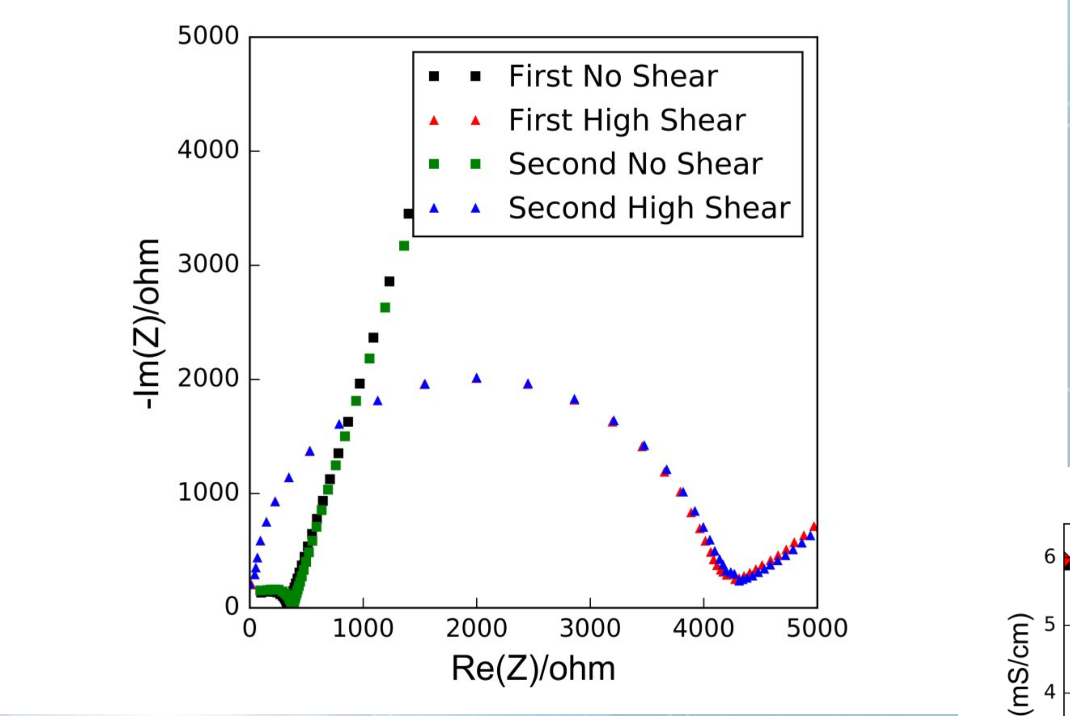
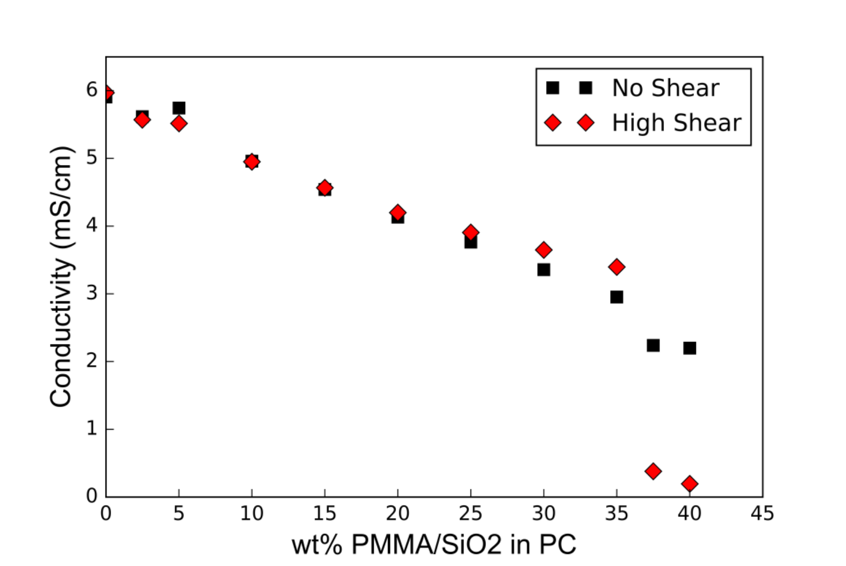
Conductivity Decreases Dramatically with Shearing



- Order of magnitude drop in conductivity with shearing
- Great for safer batteries



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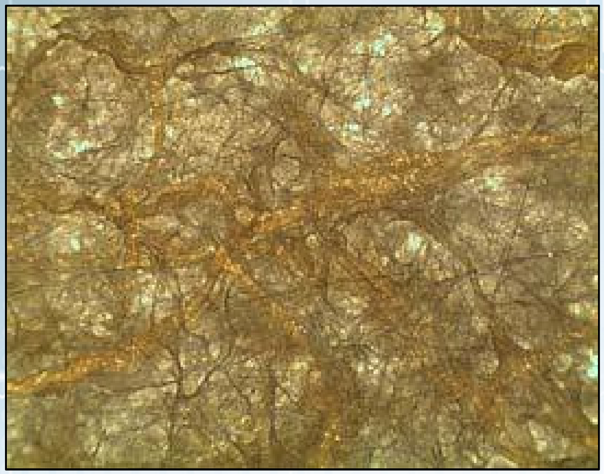
Use Standard Battery Cycling Protocols

- NMC-333 – $LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$ versus graphite
- High porous separator
  - Dreamweaver, porous plastic, glassfiber
- Mix electrolyte and make a thin suspension (20 wt%) → when it goes onto electrodes solvents pulled into electrode leaving about 30 wt% solids in separator

Dreamweaver Au40
Polyimide separator
70% Porous



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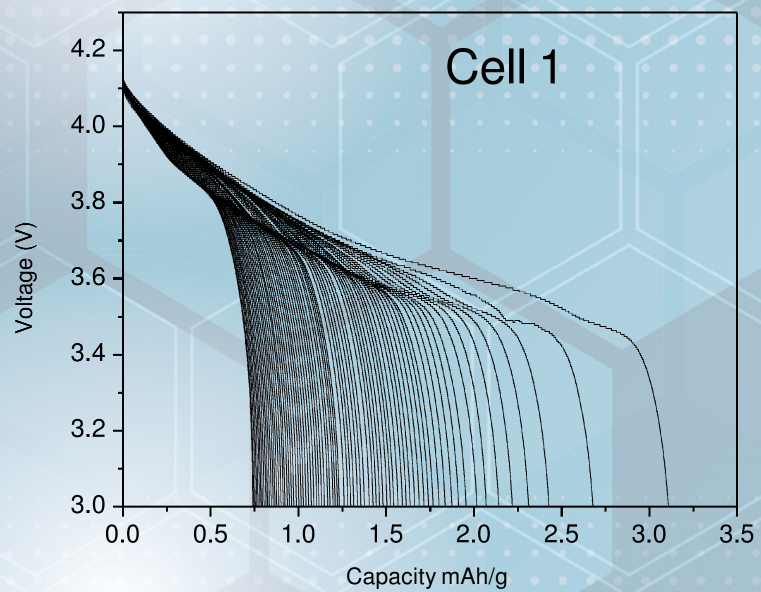
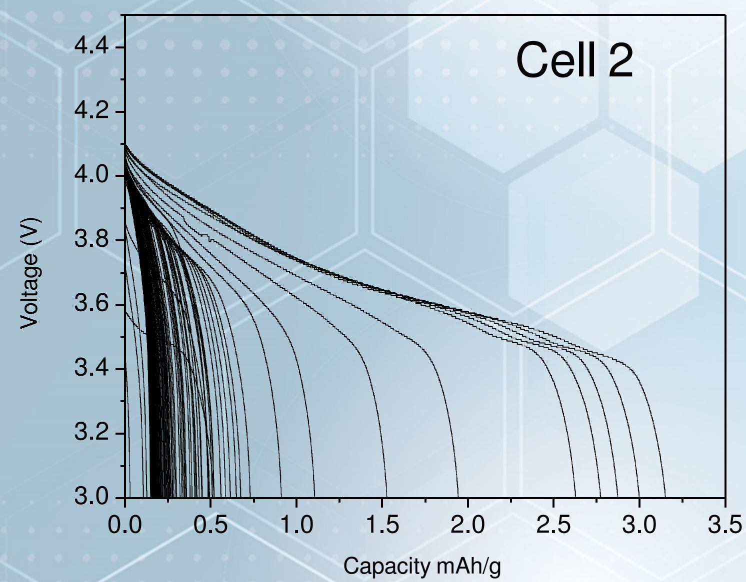
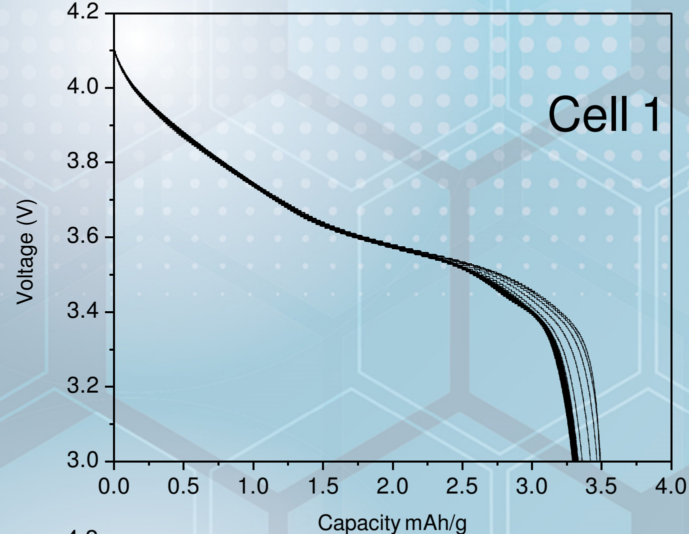
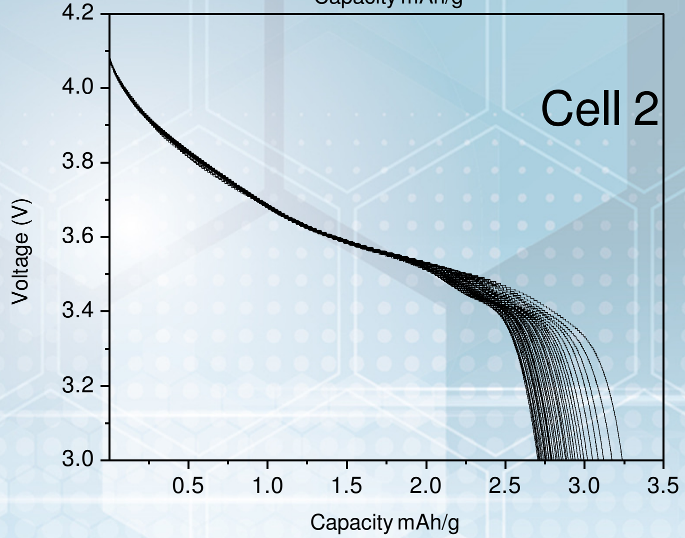
SAFIRE 53 Dry Vacuum No Heat – 19.3 wt% SiO_2

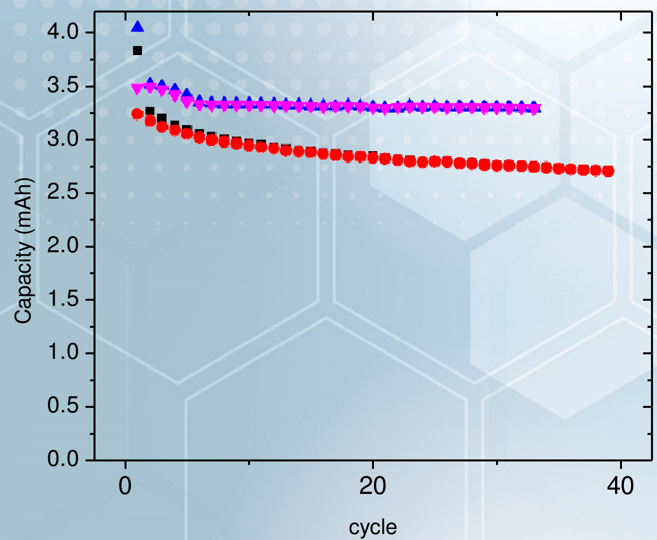




SAFIRE 51 – Dry 80º C - 23.9 wt% SiO_2

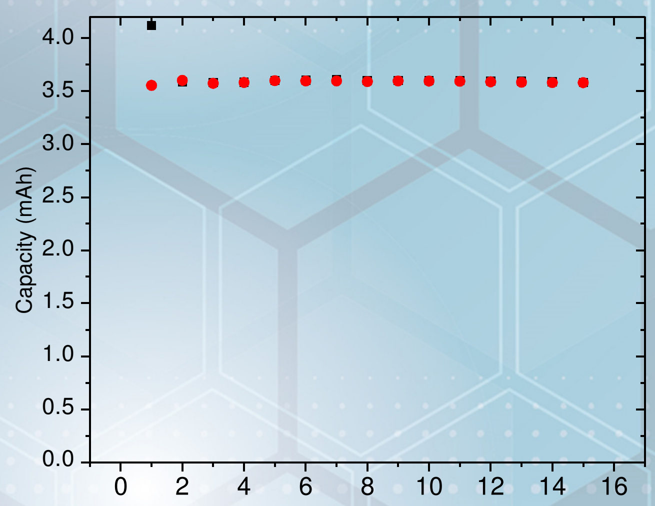


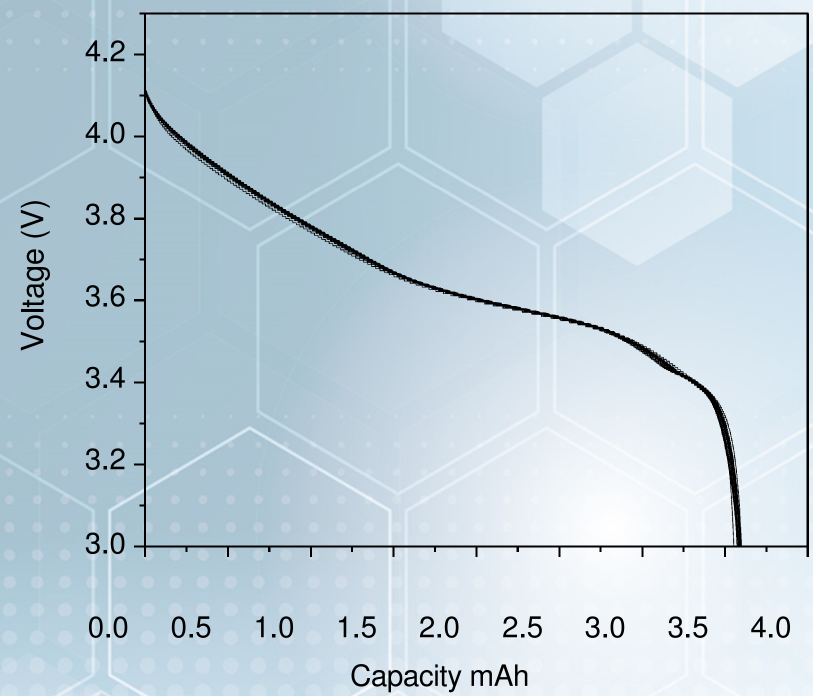




Data shows drying temperature important to get good cycling

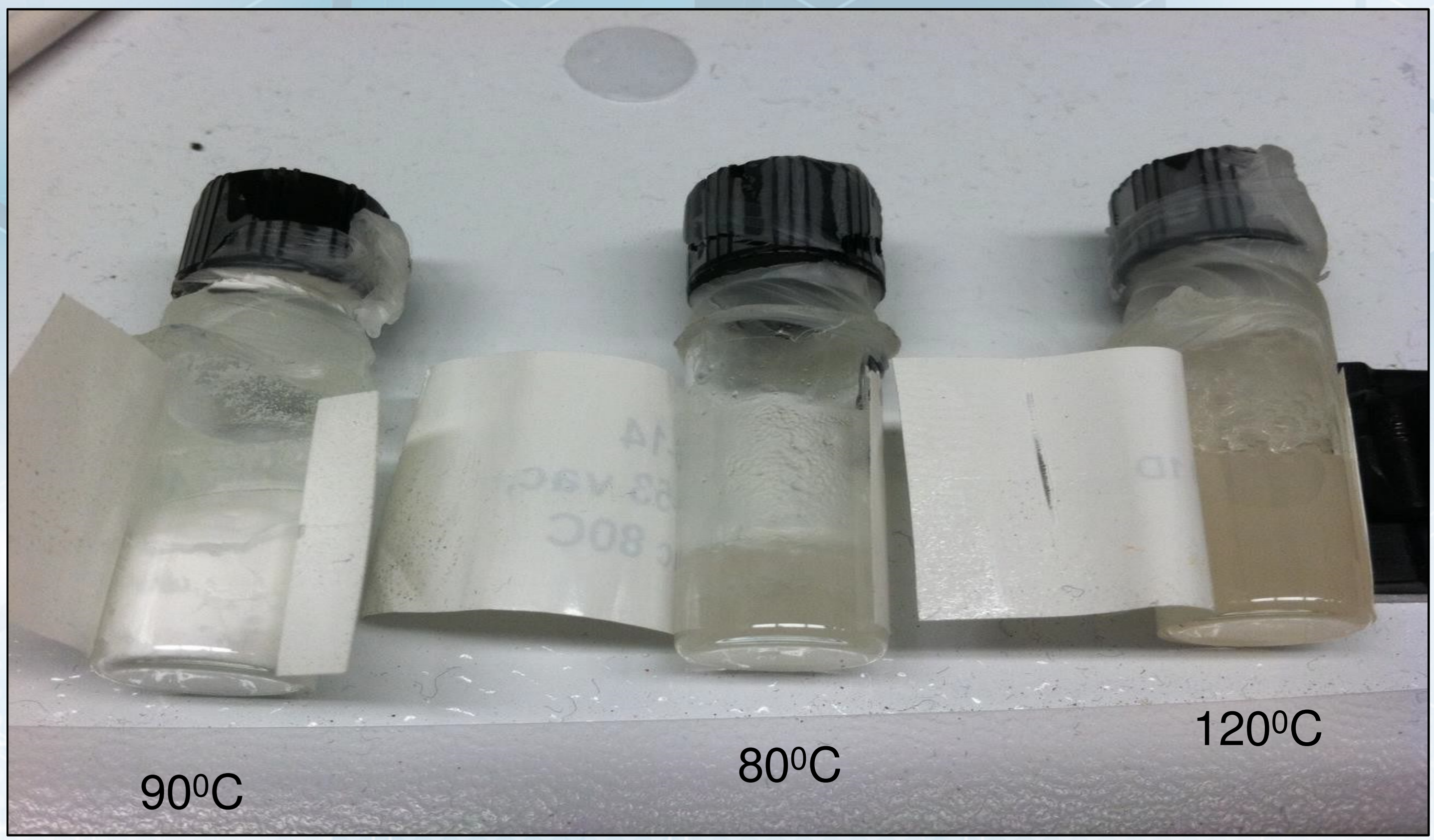
SAFIRE 48 (Standard $H_2O:NH_4OH$ Ratio) – Dry 120^oC – 21.1 wt% SiO_2





Stability test 2 – If they passed the Room Temperature Test Stored 60^{o} C Out of Glove Box

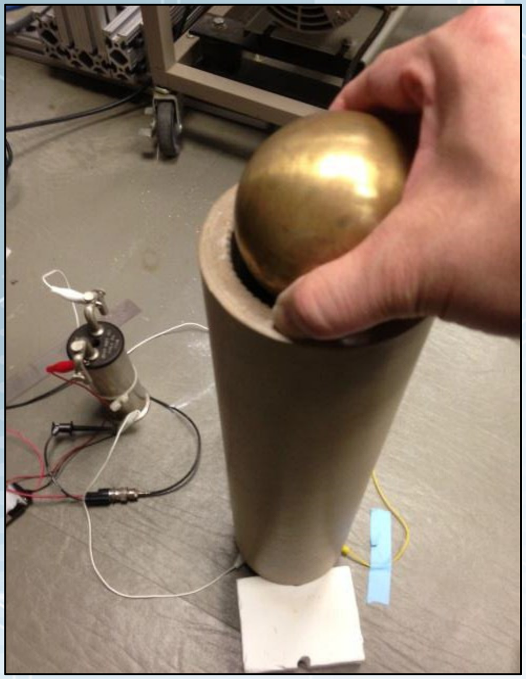
2 Weeks at 60^{o} C – all three samples passed



What about safety/impact resistance?

Drop Tests: Impact Simulation

- Dropping a 7.6 cm diameter brass ball from 46 cm height onto a 13 mm diameter stainless steel ball resting on the pouch cell
- Sealed pouch cells: pouch/Cu/Separator/Al/pouch connected to a 1 Ohm resistor and two AA batteries
- Cells were filled with SAFIRE or electrolyte
- Data collection: 500 Hz

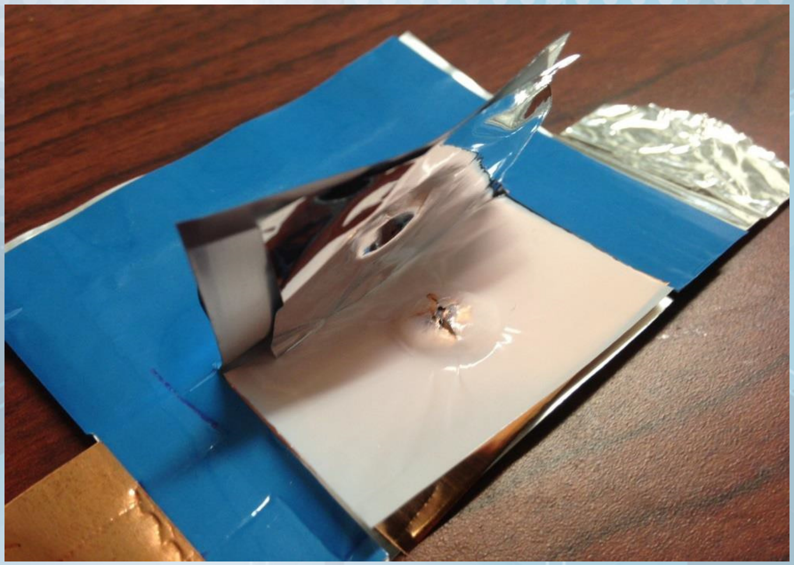


Tested Pouch Cells

SAFIRE Samples

Other Samples

Impact Damages to Separators



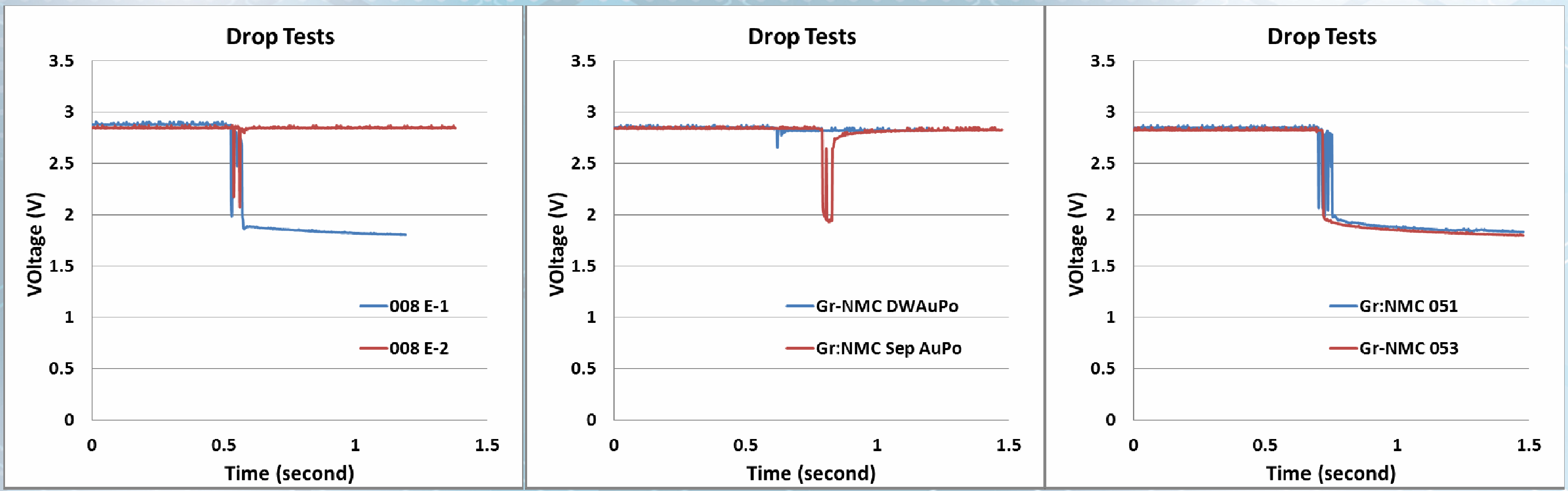
Deformation and puncture in separator

No puncture in separator

Factors affecting the damages:

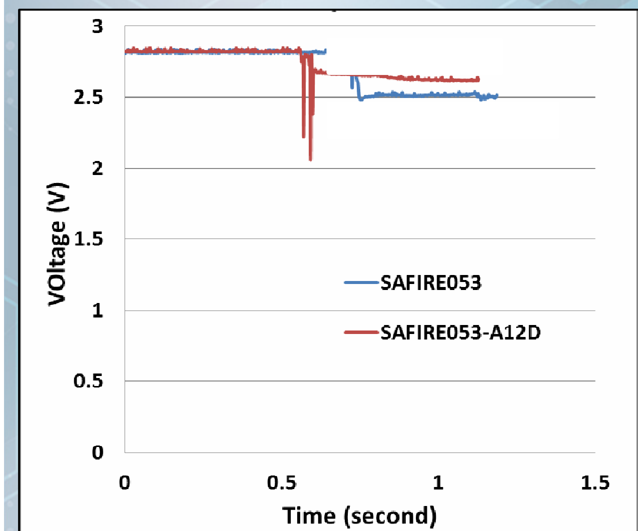
- Drop height, weight
- Brass and steel ball sizes
- Pouch and cell materials
- SAFIRE and electrolyte response to impact

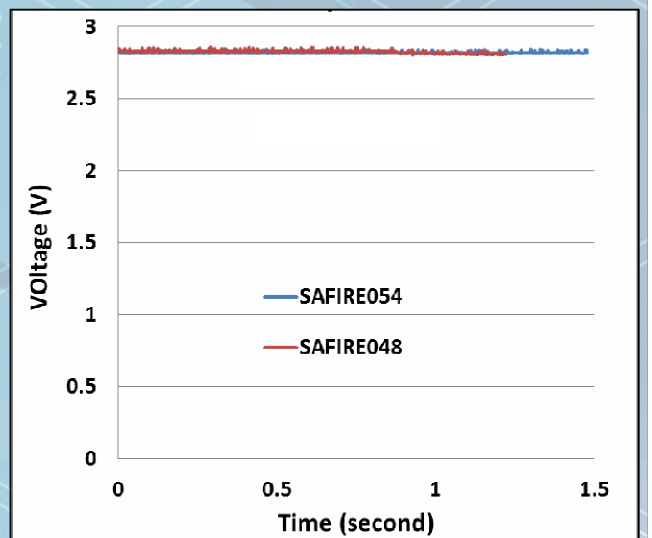
Drop Test Results - Standard Electrolyte

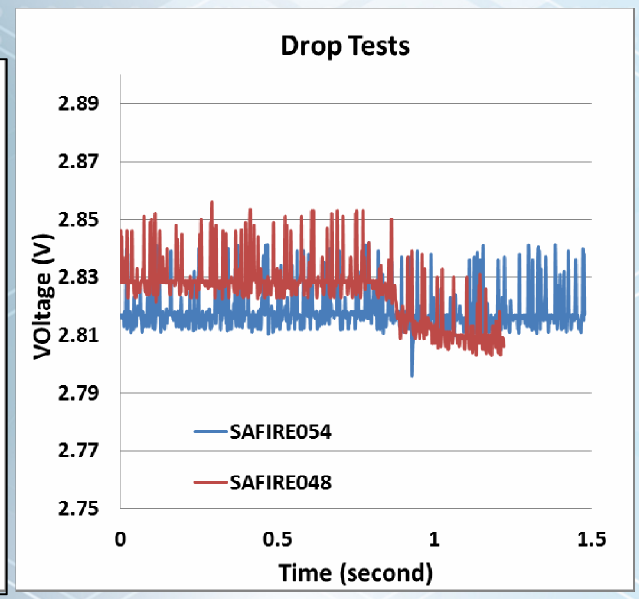


- Separator failure observed in all the tests
- Some small burns

Drop Test Results: SAFIRE







- Very promising results
- Shorting is generally less severe when there is failure

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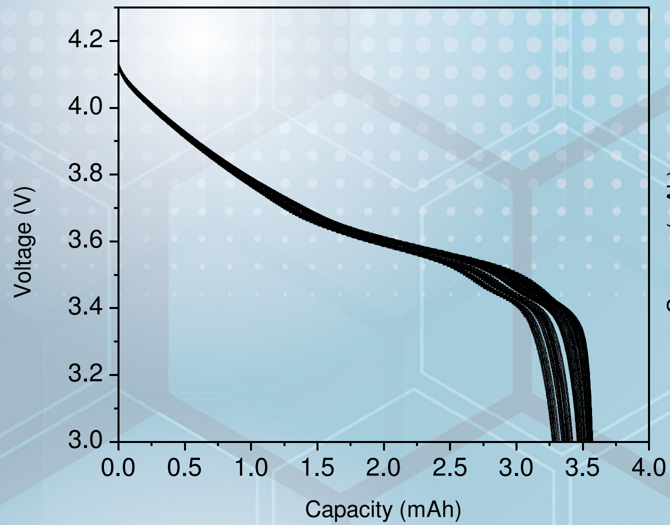
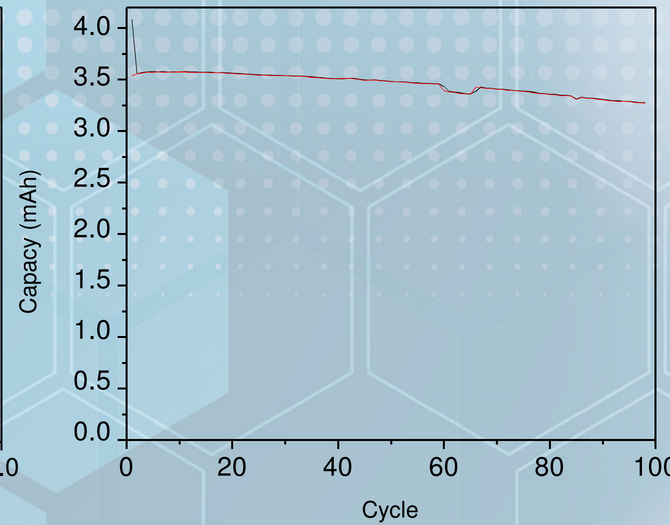
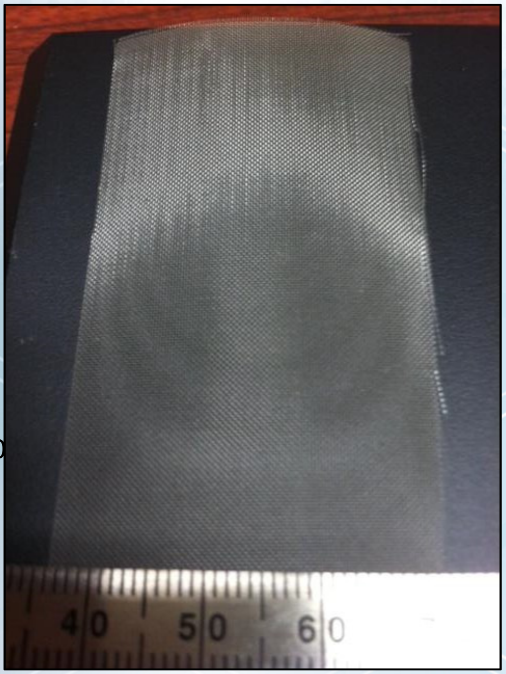
Impact Testing: Mesh Separators

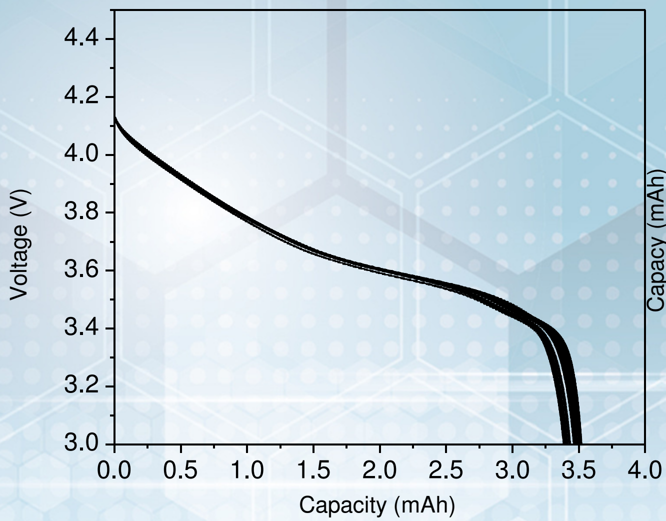
- Large and medium mesh left imprints on pouch
- Fine mesh (PEEK) worked better

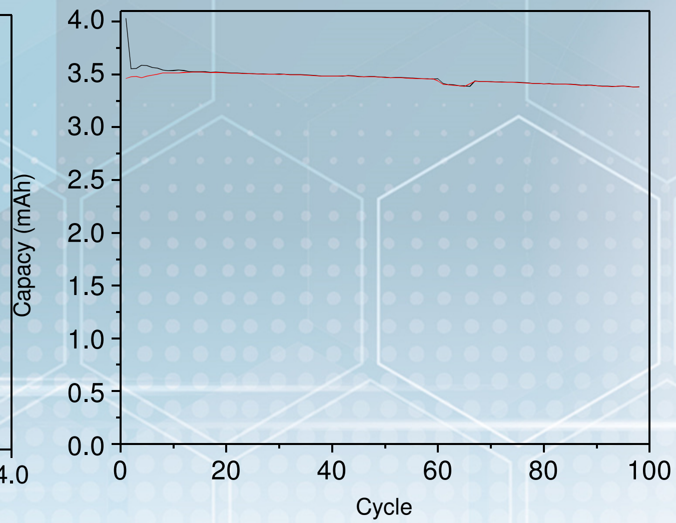
SAFIRE 64 – 2 Pieces of PEEK NMC:Gr 1.2M $LiPF_6$ EC/DMC



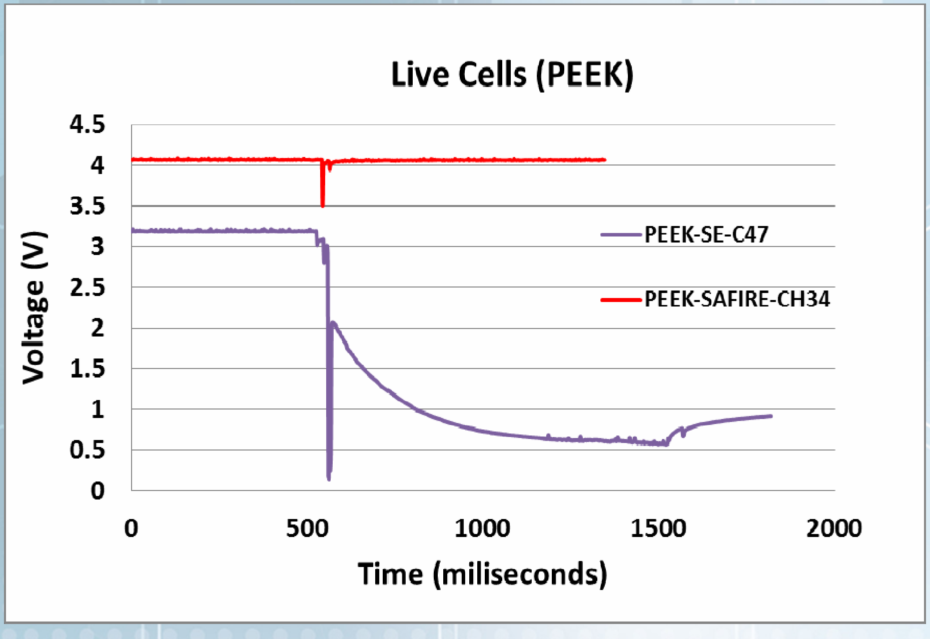




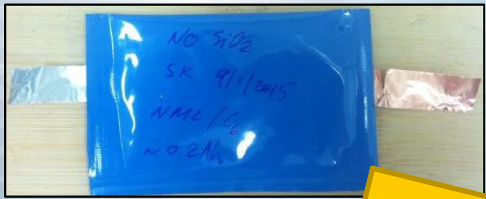


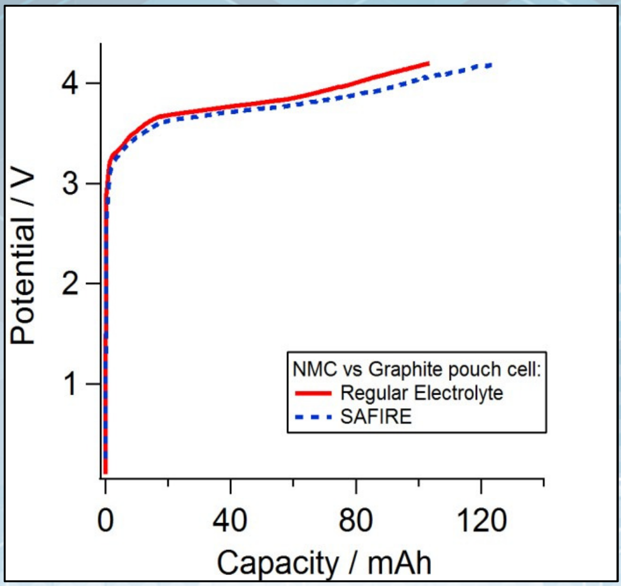


Impact Testing: PEEK
Standard Electrolyte vs. SAFIRE

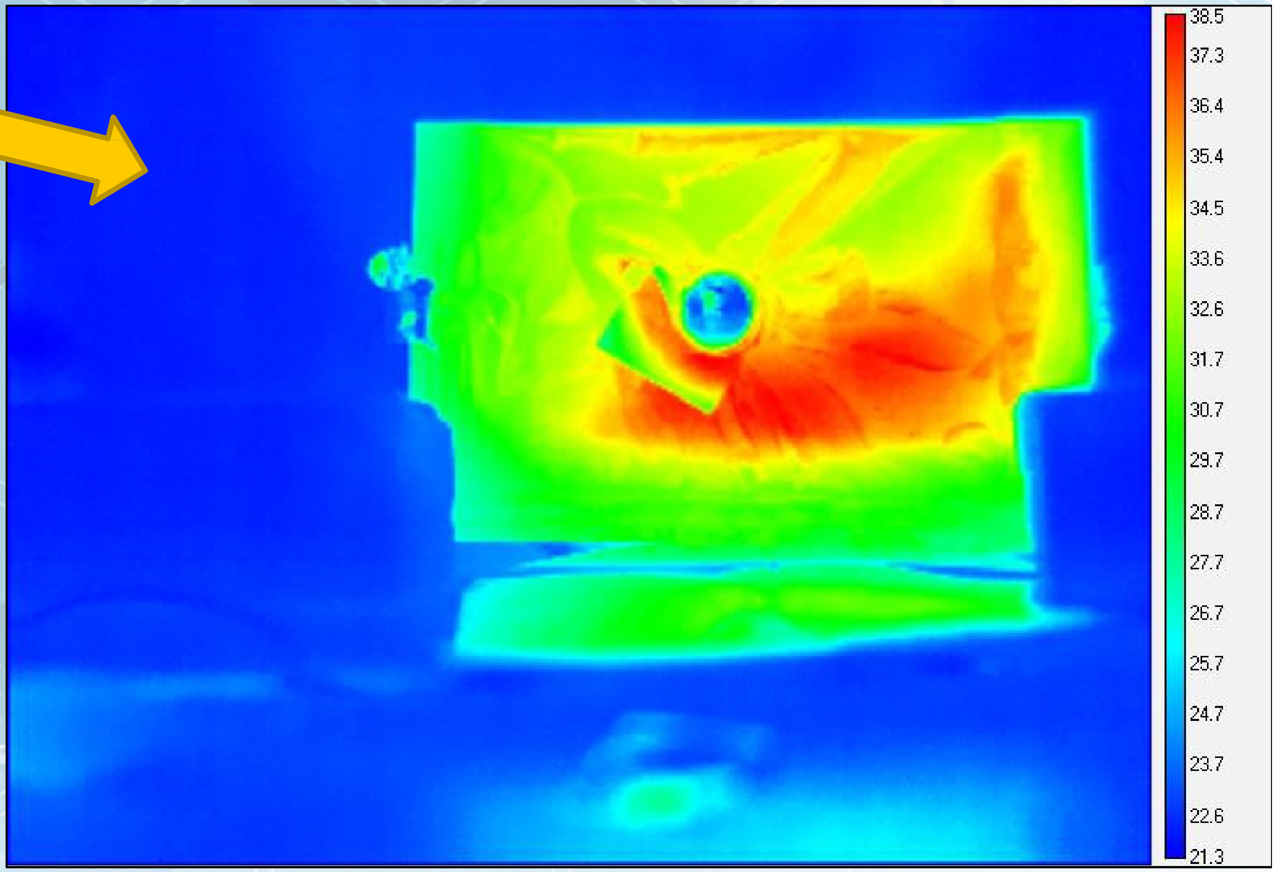


Impact Testing with Standard Electrolyte Results in Increased Temperature During Short



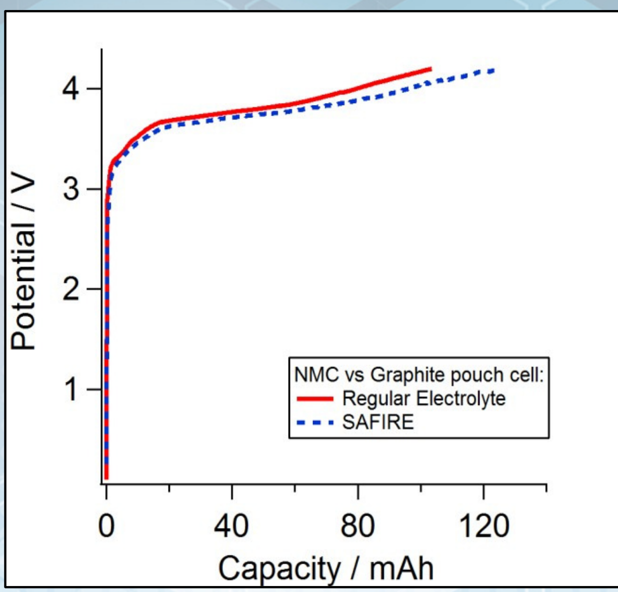


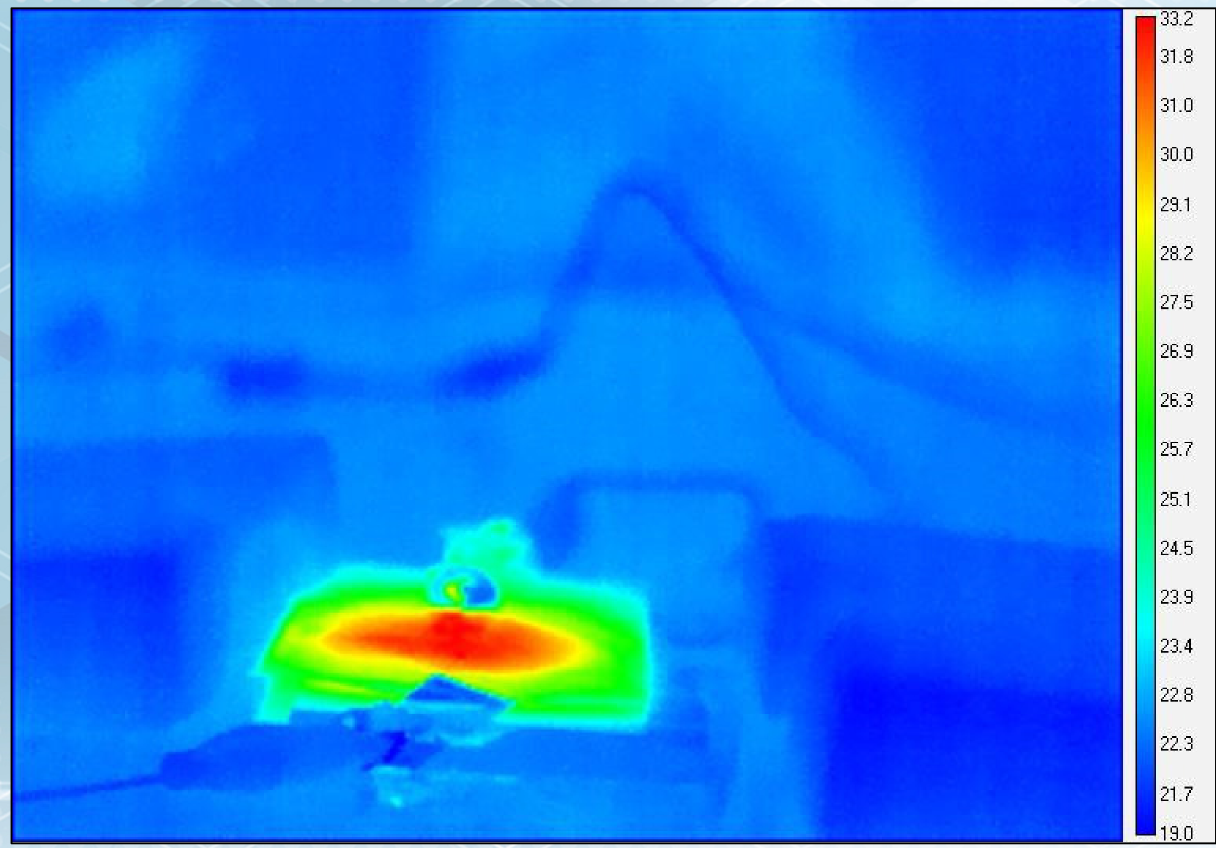
38º C



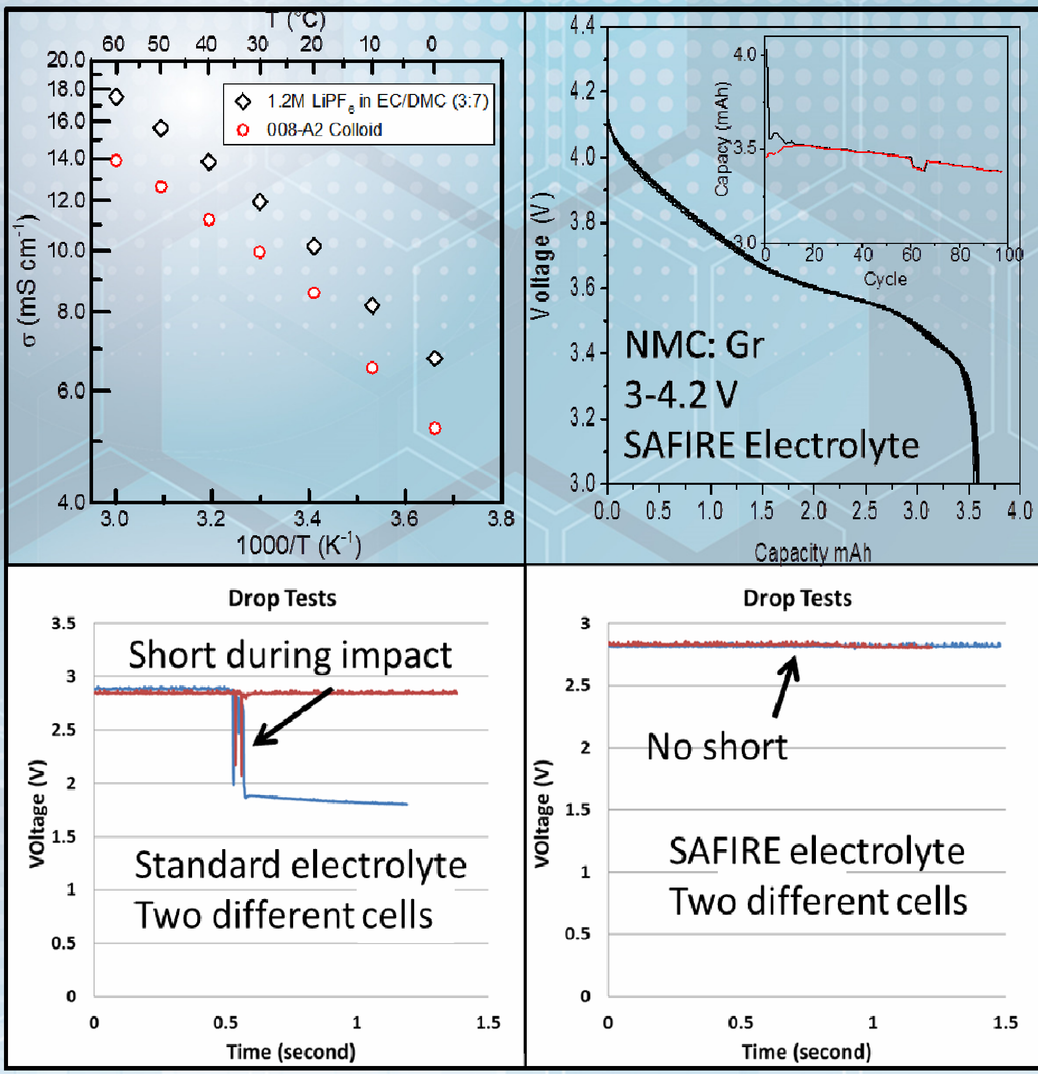
Impact Testing with Silica Results in Reduction of Temperature During Short

33 ^{o}C





Electrolyte is compatible with standard battery chemistries



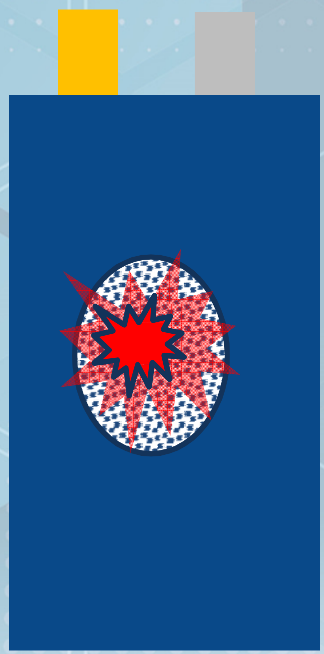
- Colloidal additive to standard electrolytes
- Demonstrated scale-up process
- Could potentially stop projectile

New Current Collectors

Our concept – Design current collectors to break upon mechanical damage to electrically isolate shorts

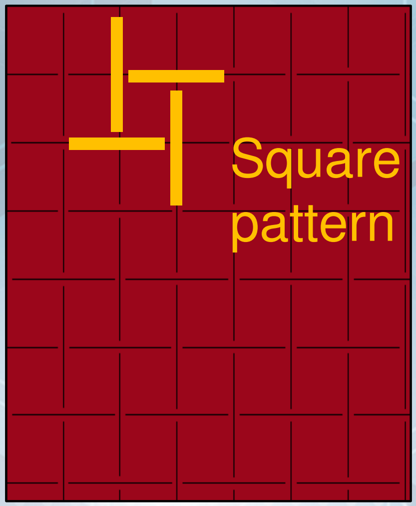
Isolate the damage upon impact

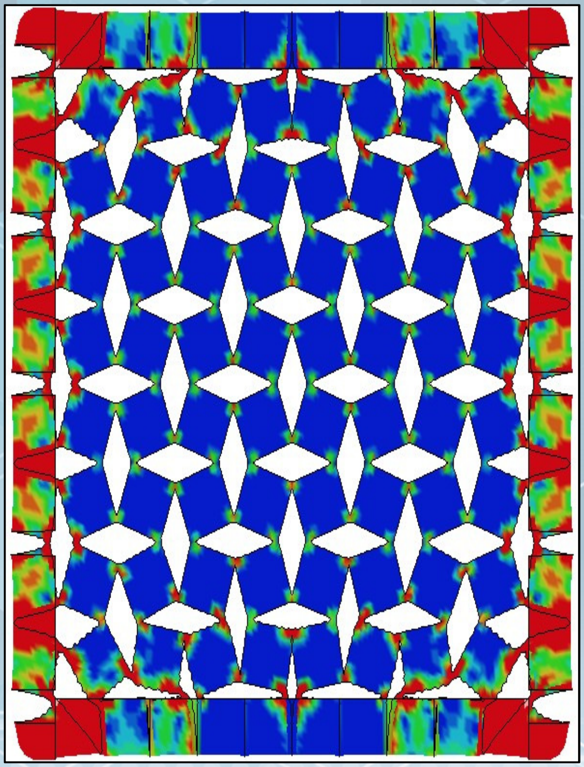
- Limit the current
- Limit the heat
- Minimize damage
- Maintain partial function and capacity

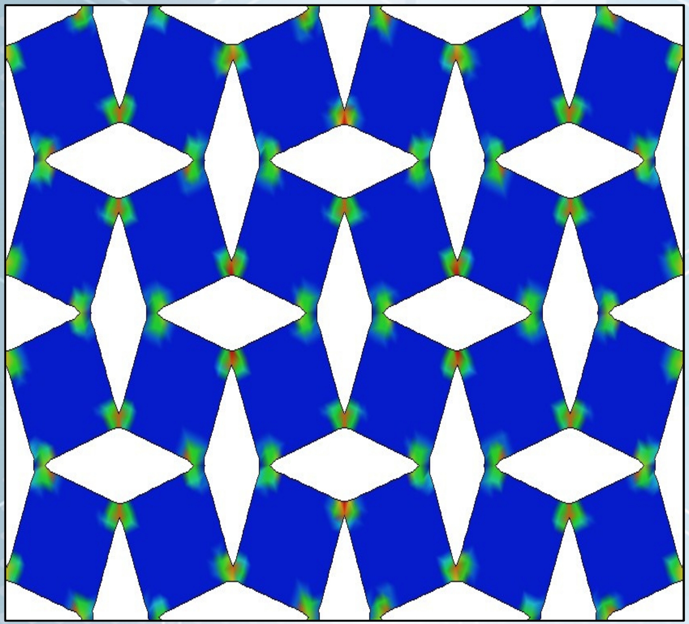


Many approaches to build-in controlled weakness …

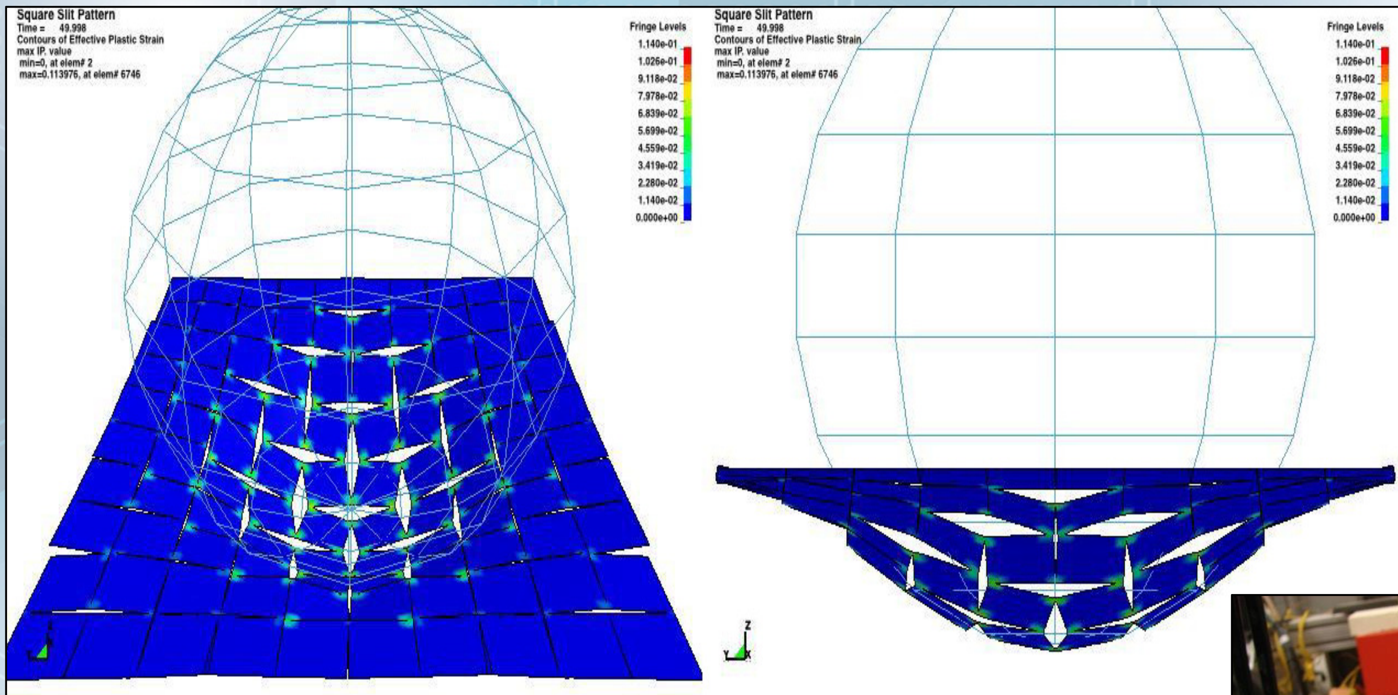
Robustness from Slits Cut Through the Electrodes

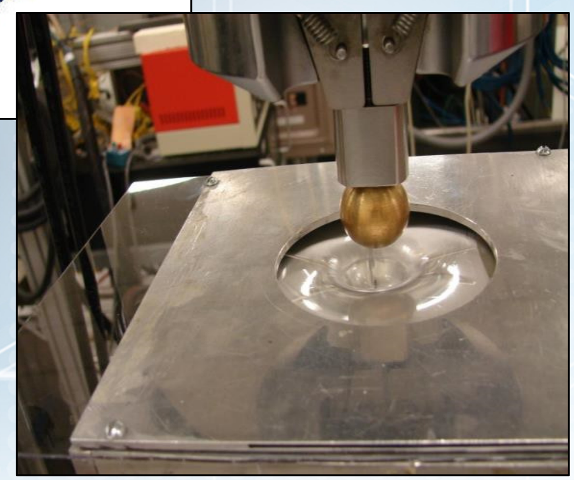






Model of Sphere Indenting Slited Metal Foil

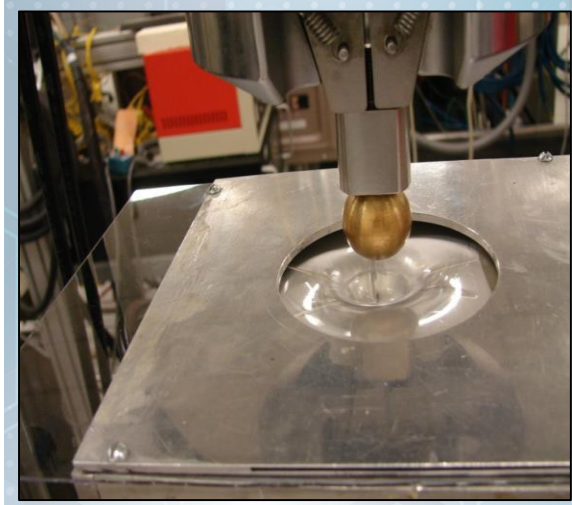


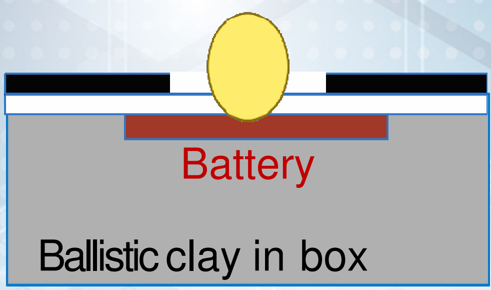


- Diameter of ball must be large relative to slit pattern
- Foil is secured so not wrinkled

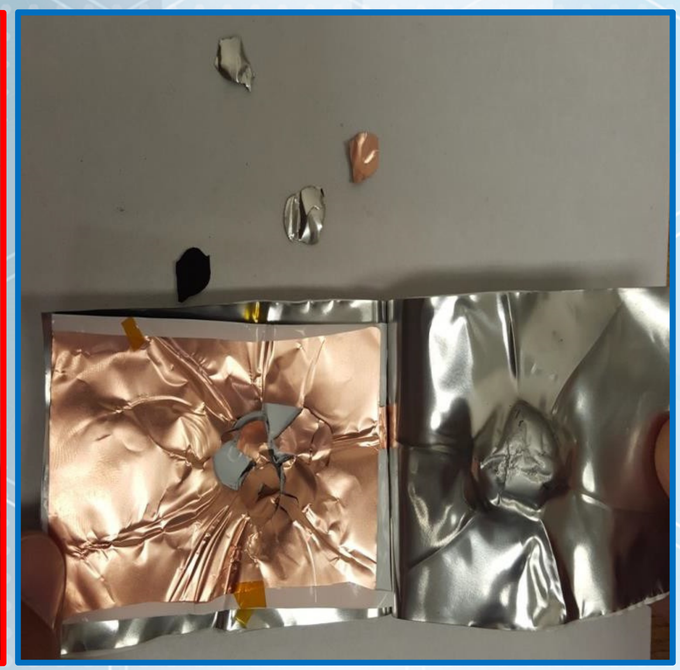
Mechanical Testing Setup

- Perforated electrodes break to small squares
- Without perforations cell is shorted





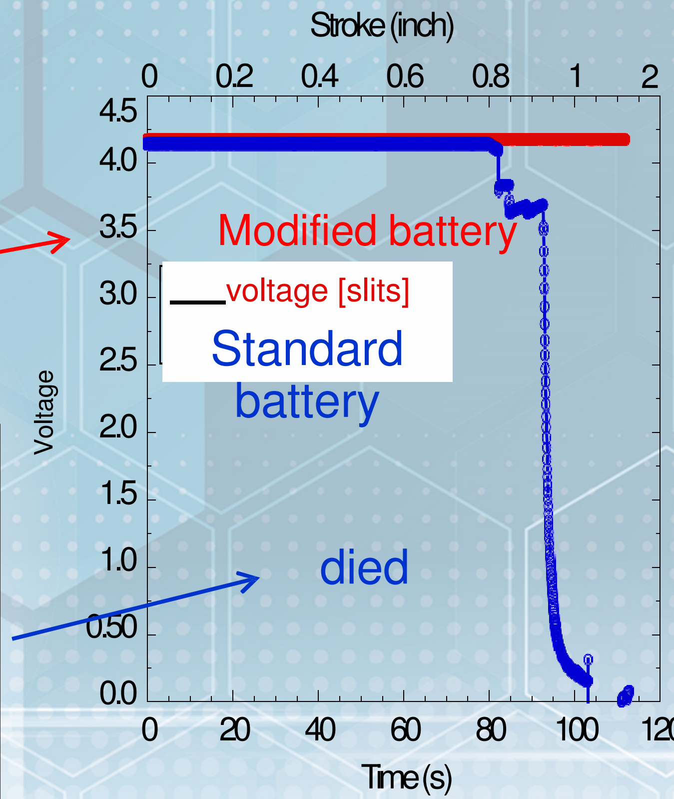
Modified battery

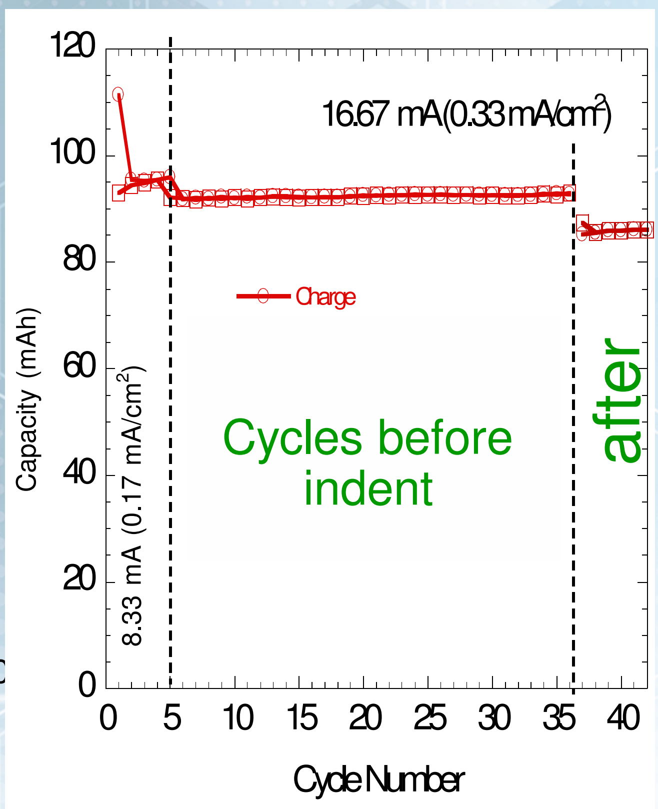


Standard battery

Success.

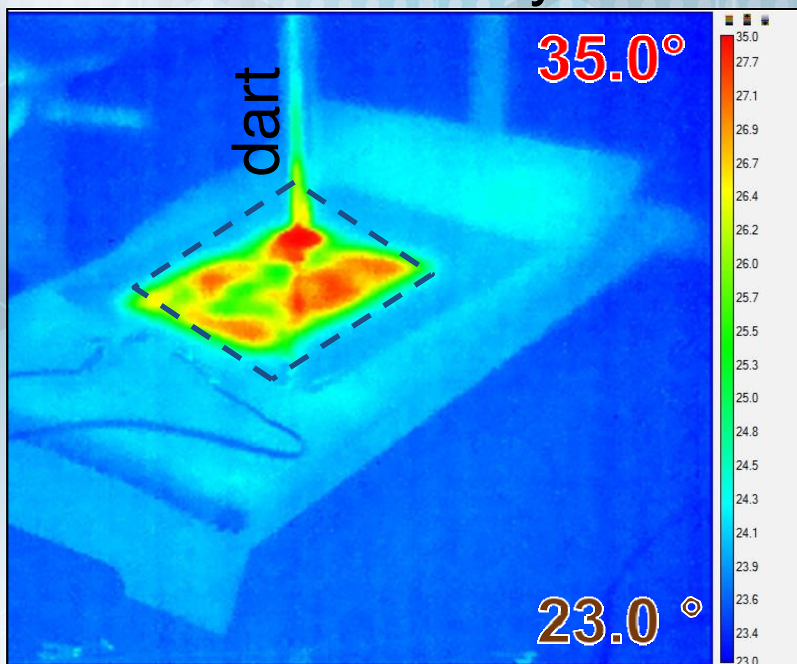
When greatly deformed, our modified battery continues to cycle, while a standard battery died. No self discharge for > 1 m



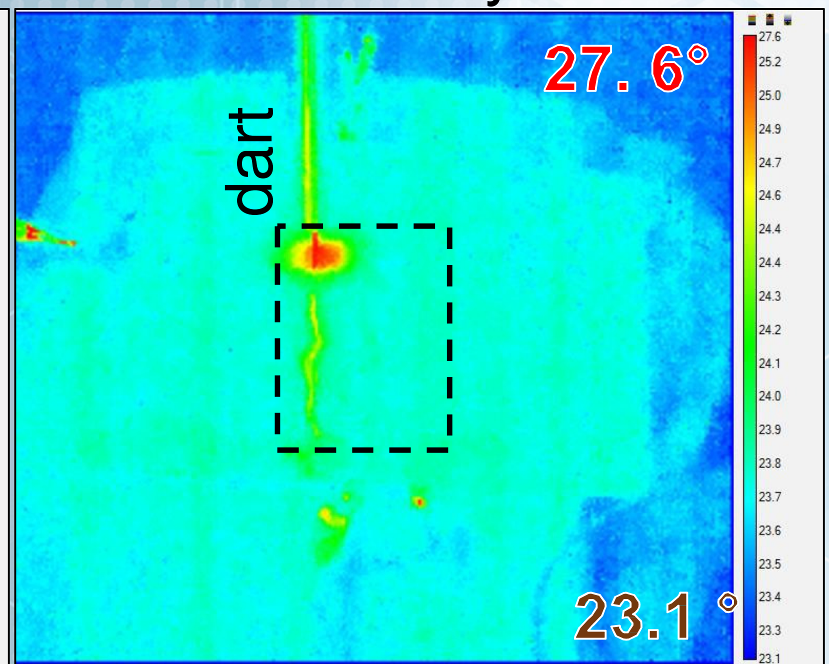


Shorting with Steel Dart

Standard battery



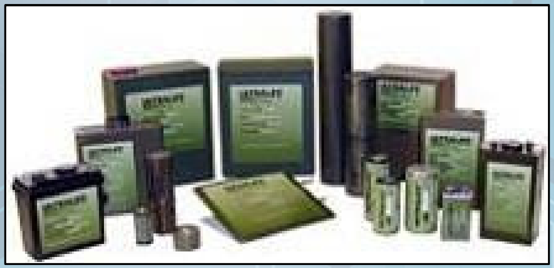
Modified battery



Reaching: + 19 °C at 3 sec +2 °C at 4 sec Max.

Control current flow and heating

Current collector and electrolyte compatible with standard battery chemistries



+

16+ lb weight savings; Enhanced mobility; Higher power; Simplified platform

- Demonstrated scale up-process
- Could be incorporated in body armor, introducing multifunctionality, or other applications
- Next steps include ballistic testing

Conclusion

Homeland Defense & Security Information Analysis Center

HDIAC Services

Technical Inquiry Service

- HDIAC provides up to 4 free hours of information services:
  - Literature searches
  - Document/bibliography requests
  - Analysis within our eight focus areas – Alternative Energy, Biometrics, CBRN Defense, Critical Infrastructure Protection, Cultural Studies, Homeland Defense and Security, Medical, Weapons of Mass Destruction

Core Analysis Task (CAT)

- Challenging technical problems requiring more than 4 hours of research can be solved by initiating a CAT:
  - Pre-competed and pre-awarded
  - Work can begin on a project approximately two months after the statement of work has been approved
  - Cap of $1,000,000 (on or after September 1, 2018)
  - Must be completed within 12 months

For more information: https://www.hdiac.org/technical_services

Questions?