SolidPower

ADVANCES AND REMAINING CHALLENGES IN ELECTROLYTES FOR SOLID STATE BATTERIES

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SOLID STATE BATTERY OPPORTUNITY

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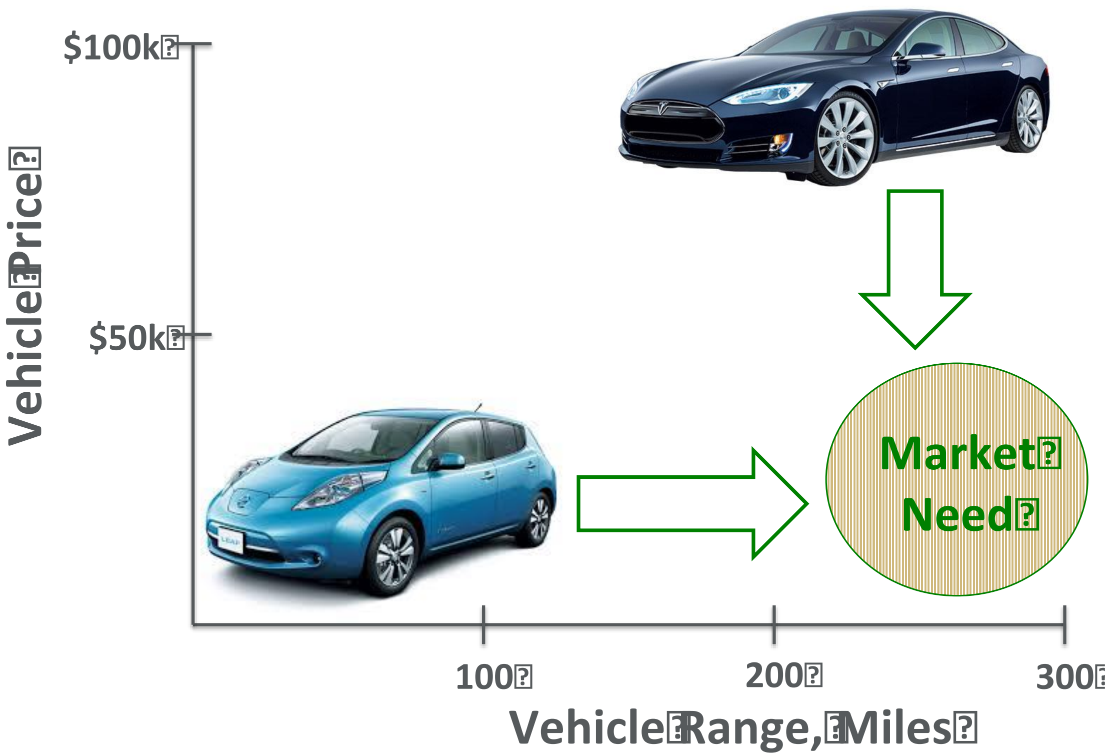
Solid-state batteries are a leading candidate to surpass Li-ion in energy, safety and cost:

Energy:
Greater vehicle range / device life

Safety:
Improved Product Reliability

Cost:
1. Eliminate battery cooling systems
2. Simplified cell- and pack-level designs
3. Abuse & manufacturing quality tolerance



> ***"With a solid-state battery you open up the field of metallic anodes, and make possible a big jump in energy density. That would be a game changer."****
>
> - Jeff Chamberlain, JCESR / ANL

> ***"Imagine batteries that do not catch fire and do not lose storage capacity. That is the promise of solid-state batteries"****
>
> - Gerbrand Ceder, MIT

Motavalli, J, "Technology: A Solid Future.," Nature* **526, S96–S97 (29 October 2015)

WHY SOLID-STATE?

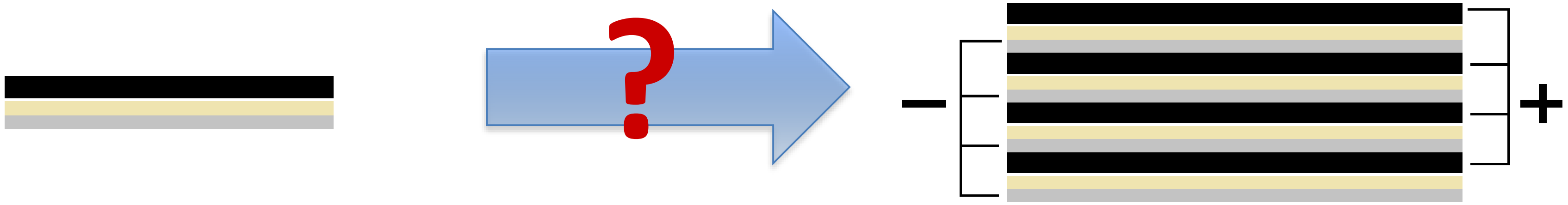
Solid-state allows for the parallel pursuit of high energy density and safety

- Non-flammable, high temperature stability
- Benign failure under abuse conditions (e.g., puncture, overcharge, etc.)
- 5V+ stable voltage window
- Long calendar life
- Enables entirely new classes of electrode materials
- Allows for more packaging options (bipolar designs, unpackaged cells, etc.)

SOLID-STATE BATTERY TYPES

Thin Film Batteries

- Several mAh or less
- Typically based on lithium phosphorus oxynitride (LiPON)
- Processing methods include magnetron sputtering, chemical vapor deposition (CVD), pulsed laser deposition (PLD), thermal evaporation, and various printing methods
- Ideal for microbatteries: sensors, smart cards, embedded electronics, medical devices, and RFID applications



High stack-level energy

But how do you scale?

SOLID-STATE BATTERY TYPES

Bulk Solid-State Batteries

- Higher areal cathode capacity loadings (mAh/cm^2) and current densities (mA/cm^2)
- Electrolyte/separator materials include poly(ethylene oxide) (PEO), glassy or ceramic Li-P-S, oxides and phosphates with garnet, perovskite, or NaSICON structures
- Materials produced as powders or melts and processed using extrusion, compaction or tape casting combined with sintering, or various coating techniques

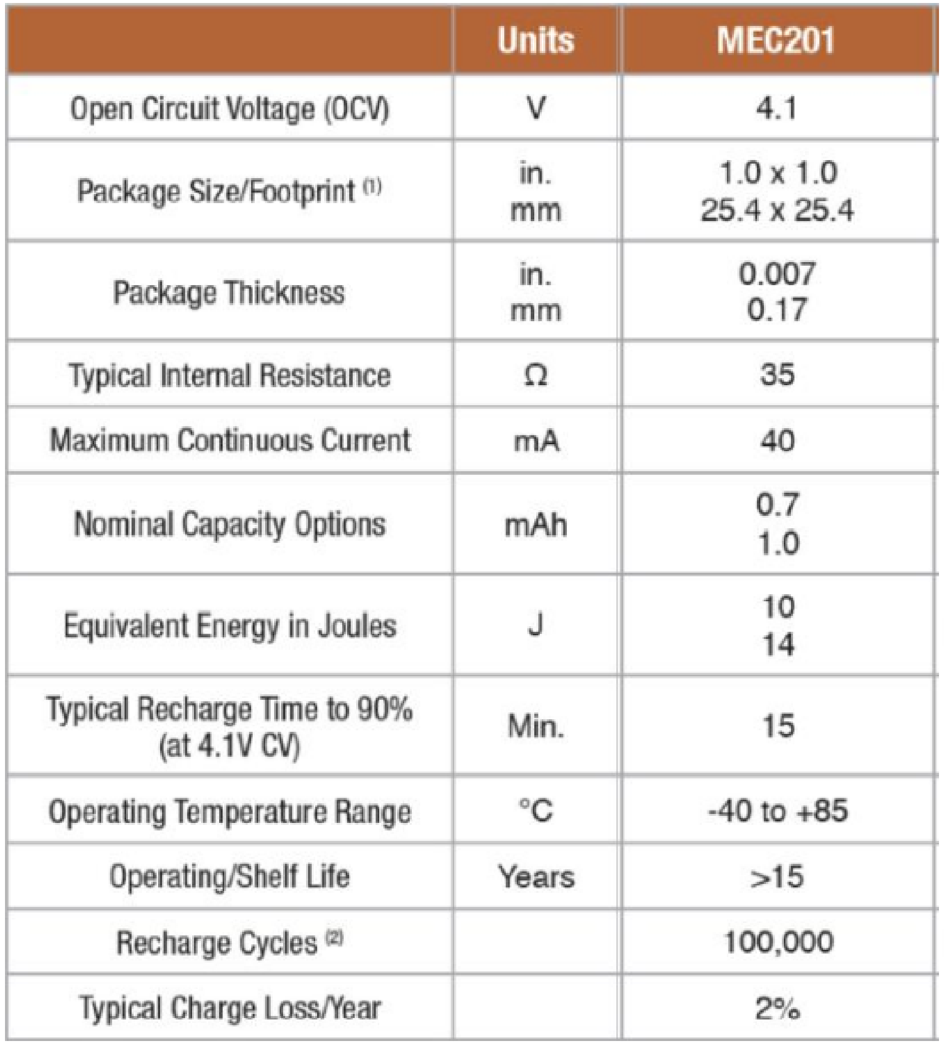
More scalable, but high current densities and non-ideal material layers pose issues

BULK SOLID-STATE CHALLENGES

- **Rate capability limitations**
  - Conductivity drops with temperature
  - No liquid to conform to interparticle and interlayer interfaces
  - High C-rates require higher current densities than for thin films
- **Cycling with Li metal anode**
  - Separator and/or any protection layers must be dense, stiff, Li^+-conductive, and chemically compatible
  - Lithium can propagate across open pores or grain boundaries
  - May require conservative charge rates and temperatures
- **Other miscellaneous**
  - Needs to approach cost parity with Li-ion
  - Higher stack pressure may be needed than for Li-ion
  - Layer thicknesses and material loadings must be appropriate for high energy density

SOLID-STATE EXISTS TODAY (WITH COMPROMISES)

Infinite Power Solutions



	Units	MEC201
Open Circuit Voltage (OCV)	V	4.1
Package Size/Footprint (1)	in. mm	1.0 x 1.0 25.4 x 25.4
Package Thickness	in. mm	0.007 0.17
Typical Internal Resistance	Ω	35
Maximum Continuous Current	mA	40
Nominal Capacity Options	mAh	0.7 1.0
Equivalent Energy in Joules	J	10 14
Typical Recharge Time to 90% (at 4.1V CV)	Min.	15
Operating Temperature Range	°C	-40 to +85
Operating/Shelf Life	Years	>15
Recharge Cycles (2)		100,000
Typical Charge Loss/Year		2%

- Based on thin film lithium phosphorus oxynitride (LiPON) electrolyte
- Low conductivity but stable against Li
- Processed using vacuum deposition

Thin film separator needed to reach moderate resistance

Limited to small form factors

Low 35 Wh/L due to thick substrate

Excellent cycling stability

http://www.cytech.com/products-ips

SOLID-STATE EXISTS TODAY (WITH COMPROMISES)

LMP Battery Characteristics

Battery	
Volume (L)	300
Weight (kg)	300
Electrical Specifications	
Energy	30KWh
Peak Power	45kW (30s)
Nominal Voltage	410V
Thermal Characteristics	
Internal Temperature	60˚C - 80˚C
Ambient Temperature	-20˚C - +160˚C

- Based on Poly(ethylene oxide) (PEO)
- Low conductivity requires high cell temperature
- Can safely use Li metal if charge and discharge conditions tightly controlled

→ **Modest 100 Wh/kg and 100 Wh/L**

→ **Scalable**

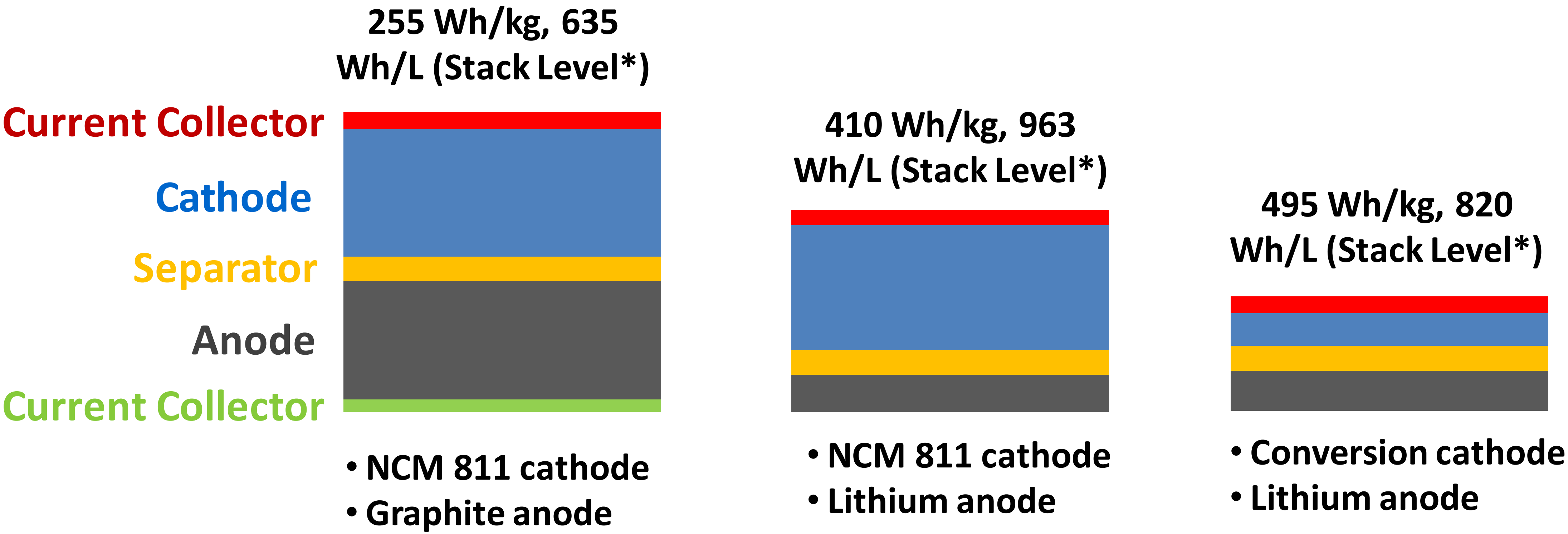
→ **Modest 150 W/L peak power**

→ **Narrow temperature window**

http://www.bluecar.fr/les-batteries-lmp-lithium-metal-polymere

ENERGY DENSITY IMPROVEMENT

Li metal anode is key to solid-state cells matching and surpassing Li-ion cell-level energy density



Current Collector

Cathode

Separator

Anode

Current Collector

255 Wh/kg, 635 Wh/L (Stack Level*)

- **NCM 811 cathode**
- **Graphite anode**

410 Wh/kg, 963 Wh/L (Stack Level*)

- **NCM 811 cathode**
- **Lithium anode**

495 Wh/kg, 820 Wh/L (Stack Level*)

- **Conversion cathode**
- **Lithium anode**

*Includes cathode, anode, separator, and current collectors. Assumes 20 micron separator and 4.0 mAh/cm^2 capacity loading

PREVENTING LI "DENDRITES"

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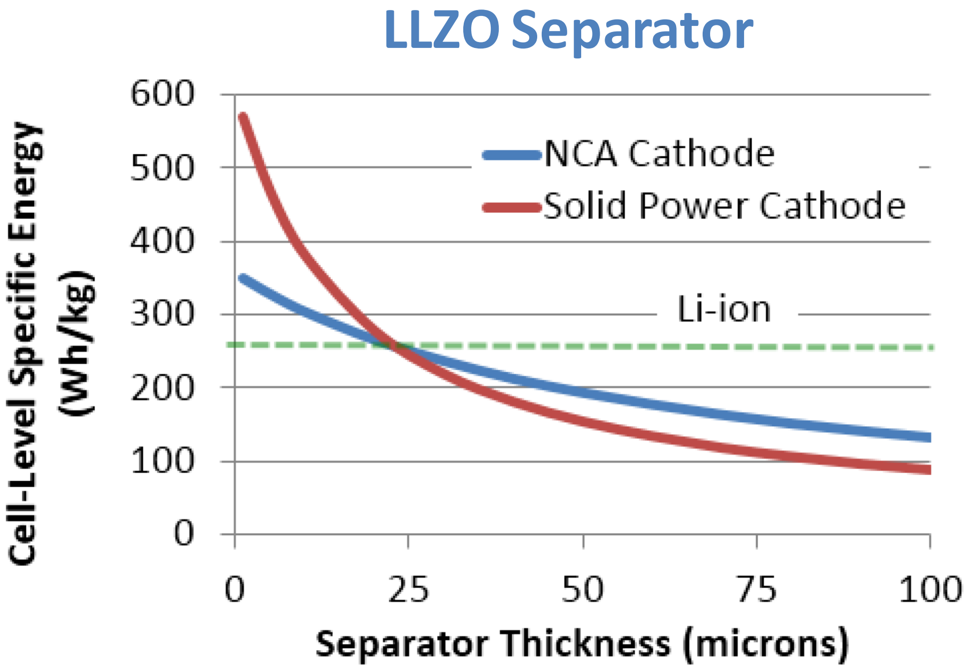
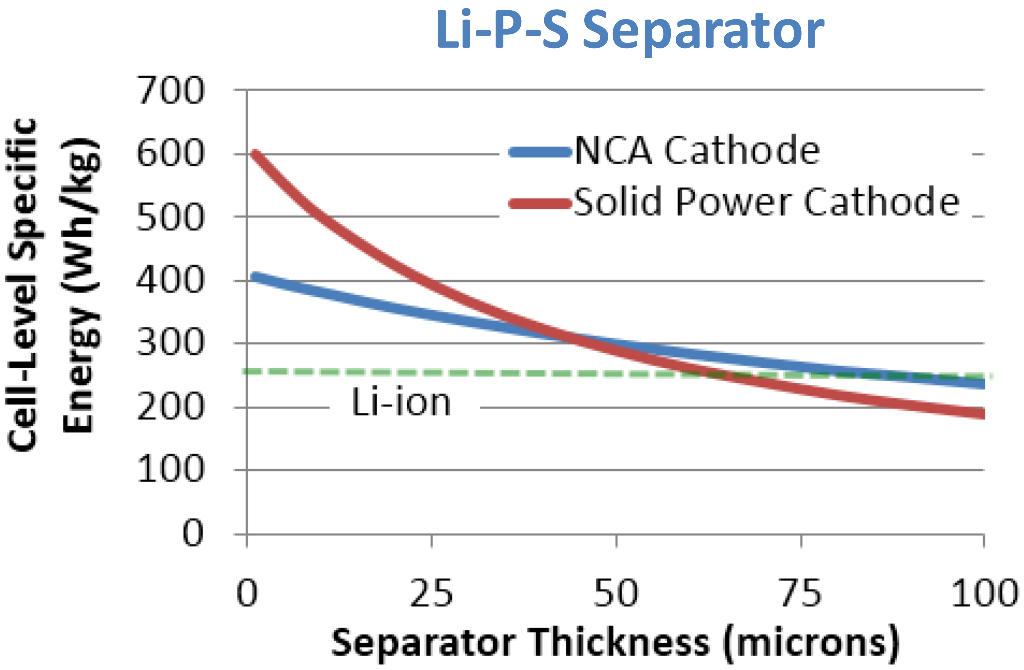
- **High proportion of current carried by Li^+ rather than anion (transference number)**
  - Prevents concentration effects that lead to onset of dendrites
- **Mechanically stiff separator**
  - Shear modulus ≥~2X that of Li predicted to promote smooth plating
- **Low current density**
  - More uniform current distribution and no concentration effects
- **Separator stable with Li metal**
  - Stable uniform interface promotes smooth plating
- **Thick separator**
  - Increases distance of Li propagation before shorting
- **High temperature**
  - Increases electrolyte and interface conductivity while decreasing Li shear modulus

SEPARATOR THICKNESS

- Thin separator needed to realize energy density gains
- Thickness more critical for dense electrolytes
- Thin separators more difficult to process and more susceptible to failure due to Li "dendrites"





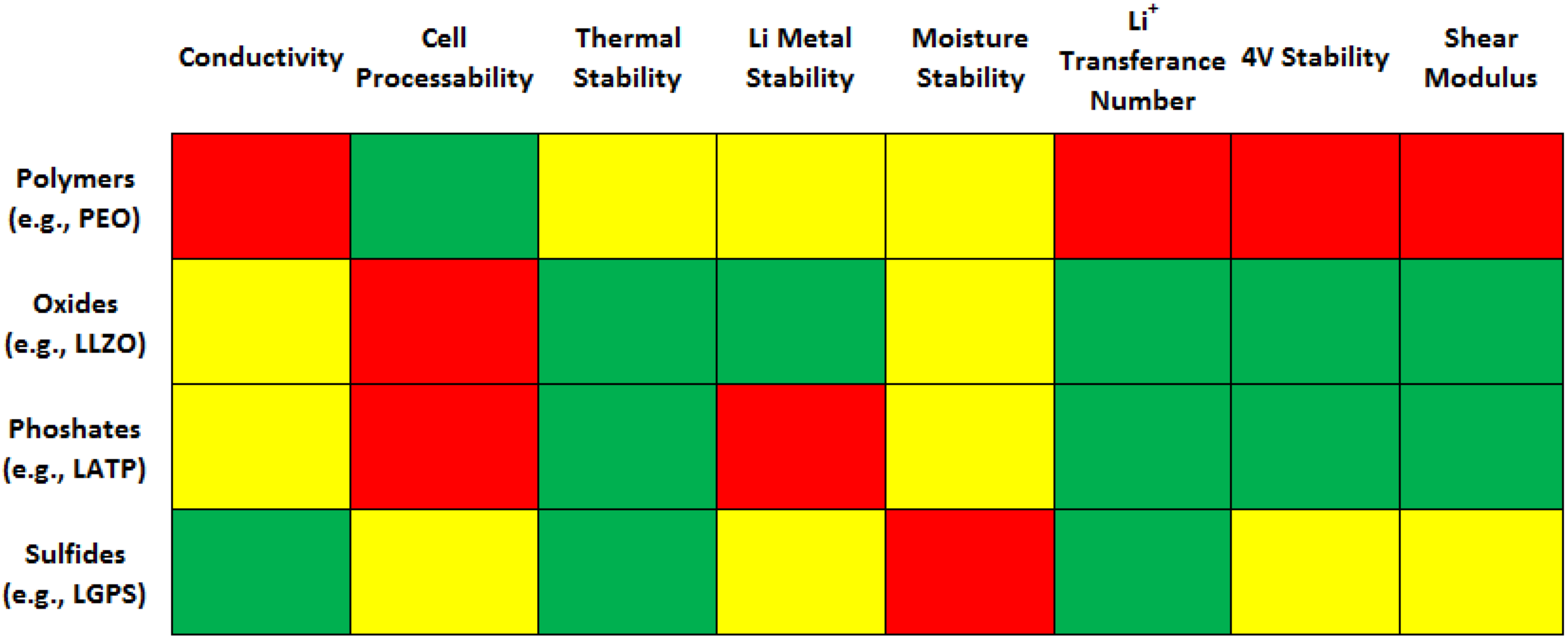
Assumes large-format pouch cell with 3.0 mAh/cm^2 cathode loading and 30µm Li anode doubling as current collector

SOLID ELECTROLYTE REQUIREMENTS

1. **High ionic conductivity:** 0.2 – 10 mS/cm at room temperature depending on cell design
2. **Negligible electronic conductivity**
3. **Electrochemically stable against Li metal and cathode:** bi-layer separators decouple anode and cathode stability needs but also increase cost and complexity
4. **Processable into thin layers <50 µm across large areas**
5. **Promotes "dendrite-free" plating of Li metal**
6. **Non-prohibitive cost**

No reported solid electrolyte has satisfied every requirement

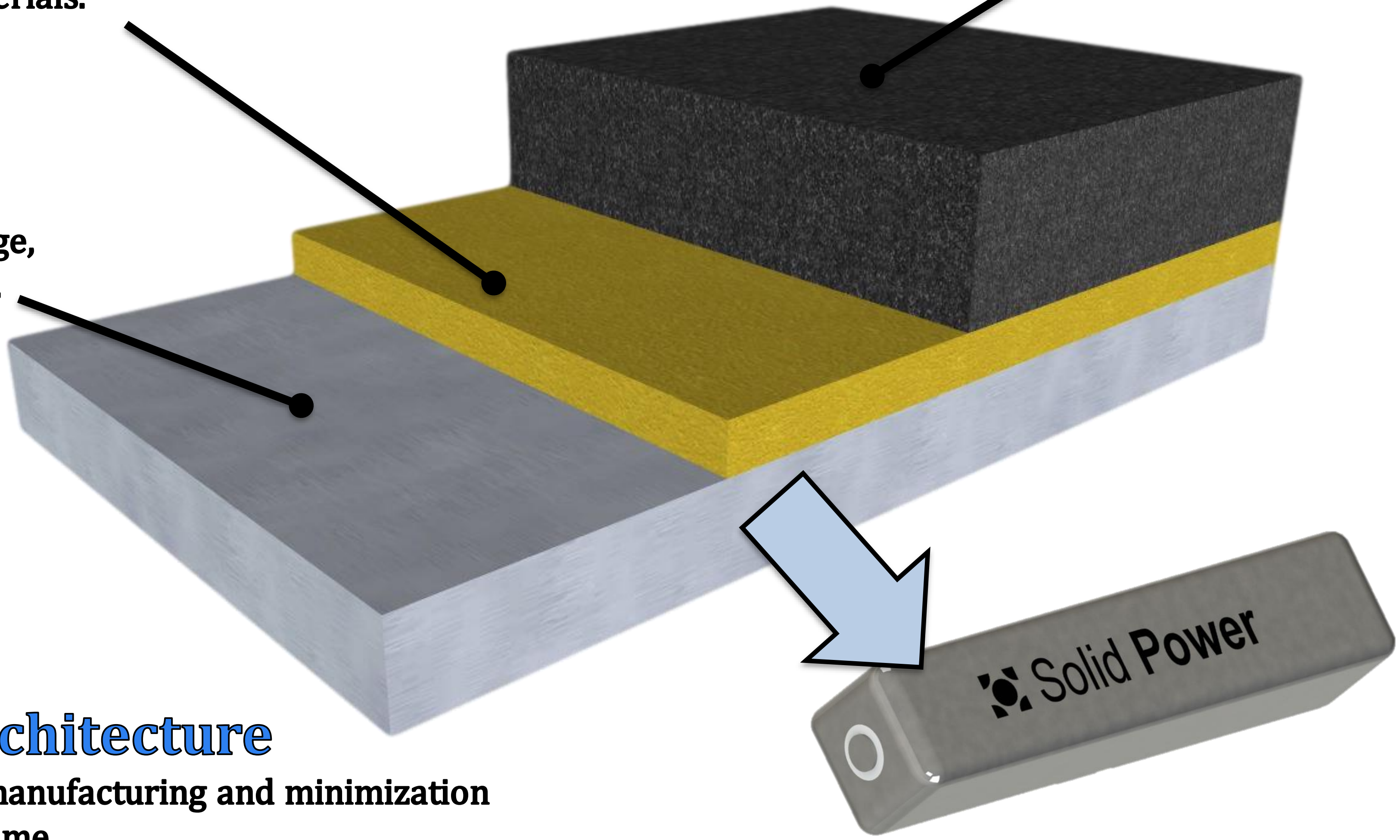
COMPARISON OF ELECTROLYTES



	Conductivity	Cell Processability	Thermal Stability	Li Metal Stability	Moisture Stability	Li^+ Transferance Number	4V Stability	Shear Modulus
Polymers (e.g., PEO)	🟥	🟩	🟨	🟨	🟨	🟥	🟥	🟥
Oxides (e.g., LLZO)	🟨	🟥	🟩	🟩	🟨	🟩	🟩	🟩
Phoshates (e.g., LATP)	🟨	🟥	🟩	🟥	🟨	🟩	🟩	🟩
Sulfides (e.g., LGPS)	🟩	🟨	🟩	🟨	🟥	🟩	🟨	🟨

🟩 Strength
🟨 Neutral
🟥 Weakness

SOLID POWER TECHNOLOGY



Robust Separator

Thin layer offers anode and cathode compatibility using scalable, non-flammable electrolyte materials.

Broad Cathode Compatibility

Compatible with conventional intercalation and more advanced conversion reaction cathode chemistries

Li Metal Anode

Provides high capacity, voltage, and discharge rate capability.

Simple Cell Architecture

Allows for inexpensive manufacturing and minimization of passive mass and volume.

Solid Power Focus: Sulfide Solid State

Sulfide-based solid electrolytes possess the best combination of performance and manufacturability

Solid Power's solid electrolyte exhibits one of the highest known conductivities in a highly processable, lithium-metal stable system

🟩 Strength
🟨 Neutral
🟥 Weakness

	Conductivity	Cell Processability	Thermal Stability	Li Metal Stability	Moisture Stability
Polymers (e.g., PEO)	🟥	🟩	🟨	🟨	🟨
Oxides (e.g., LLZO)	🟨	🟥	🟩	🟩	🟨
Phoshates (e.g., LATP)	🟨	🟥	🟩	🟥	🟨
Sulfides (e.g., LGPS)	🟩 **	🟩	🟩	🟩 **	🟥 **Requires Dry Room Processing**

Solid Power's Focus

**Unique to Solid Power

PERFORMANCE ROADMAP

Solid Power's all solid-state rechargeable batteries represent a higher energy, safer (& hence, lower cost at pack-level) alternative to current Lithium-ion batteries

Parameter	Lithium-Ion	Solid Power
Energy (Wh/kg)	150-260 → 2-3X Improvement →	250-500 (cathode dep.)
Energy (Wh/L)	400-600 → 1-1.5X Improvement →	650-1000 (cathode dep.)
Power (W/kg)	100-2000	>500 (temp. dependent)
Cycles	>1000	>1000
Safety	Acceptable w/ Features	Excellent
Shelf Life	2-8 years	10+ years
Temp. Operation	-20-60°C	-20 – 150°C

Cell Performance Roadmap

Focused on meeting or exceeding Li-ion in every performance metric by 2020

	2016	2017	2018	2019	2020
Energy Wh/kg	250	300	400	500	500
Energy Wh/L	500	600	800	1,000	1,000
Cycles	100	250	500	1,000	2,000
Temperature	60°C	25°C	25°C	-20°C	-20°C

SOLID POWER SULFIDE SOLID ELECTROLYTES

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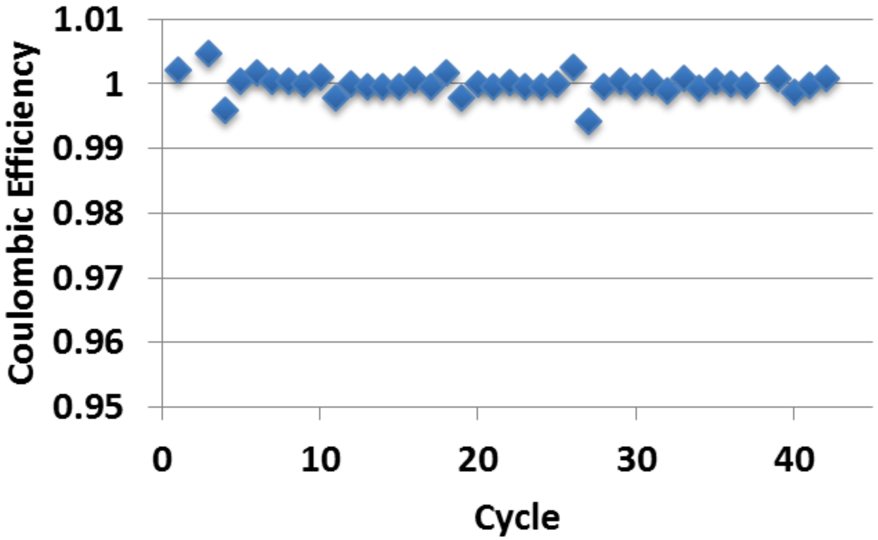
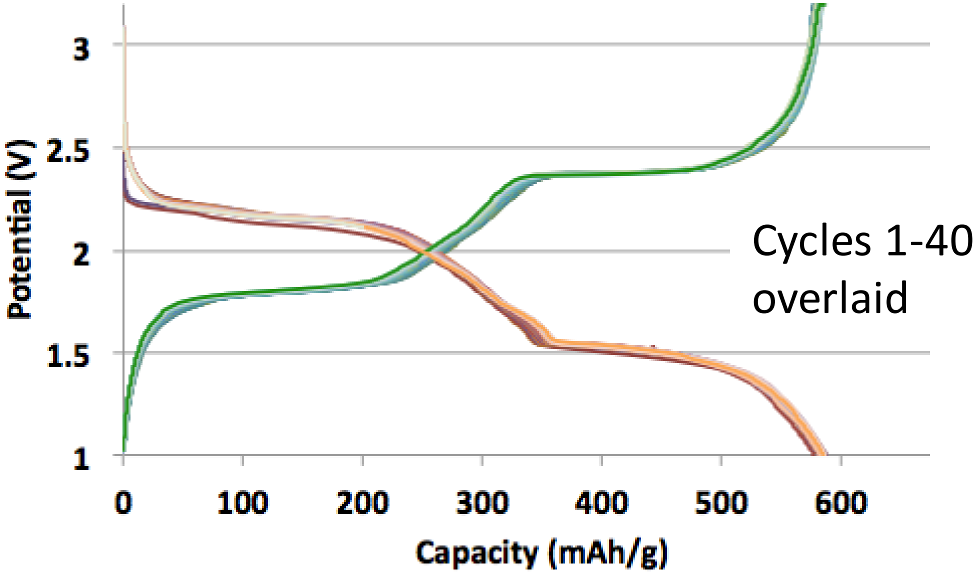
- ***Best known combination of electrolyte stability, conductivity and processibility***
- Room temperature conductivity up to 5 mS/cm (cold compacted) while retaining Li metal stability





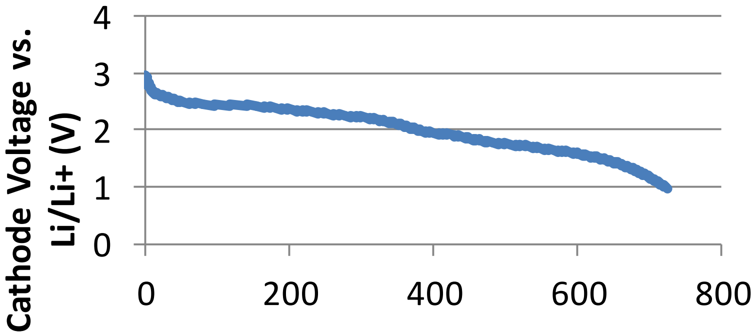
Test Conditions

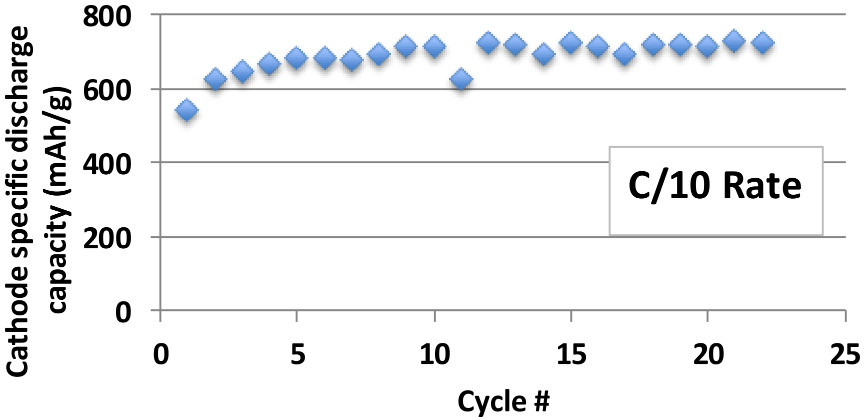
- *2 cm^2 diameter cell*
- *Li metal anode*
- *Tested at 60°C, C/10 rate*

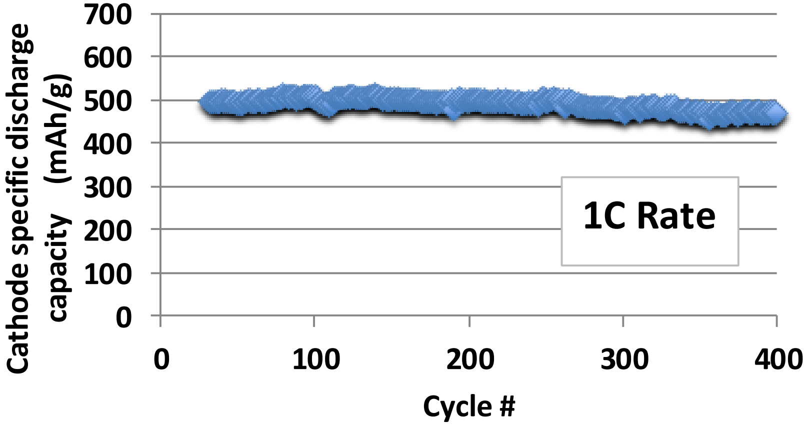
SOLID POWER HIGH CAPACITY CATHODES

- Early work focused on cathodes with specific capacities >600 mAh/g
- Excellent stability and cycle life at laboratory scale
- Long cycle life in 1+ Ah cells requires additional development

- *Single-stack 1.27 cm diameter cell, InLi anode*
- *Capacities based on total cathode mass*
- *Tested at 60°C*



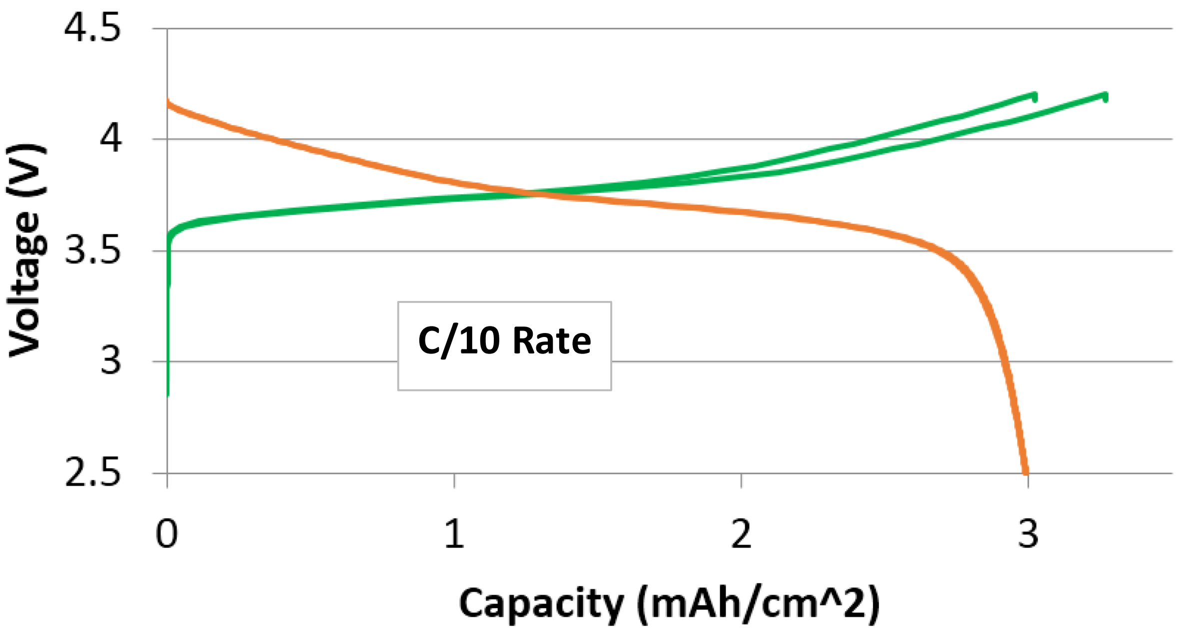




SOLID POWER – OXIDE CATHODES

- Electrolyte compatible with surface-treated 4V-class oxide cathodes
- High conductivity allows for practical cathode loading levels and a wide temperature range
- High coulombic efficiency from outset of cycling with Li anode

- *2 cm^2 diameter cell*
- *Li metal anode*
- *Gen 3 electrolyte*
- *NCM 622 cathode*
- *3.0 mAh/cm^2 loading*
- *Tested at 70°C*

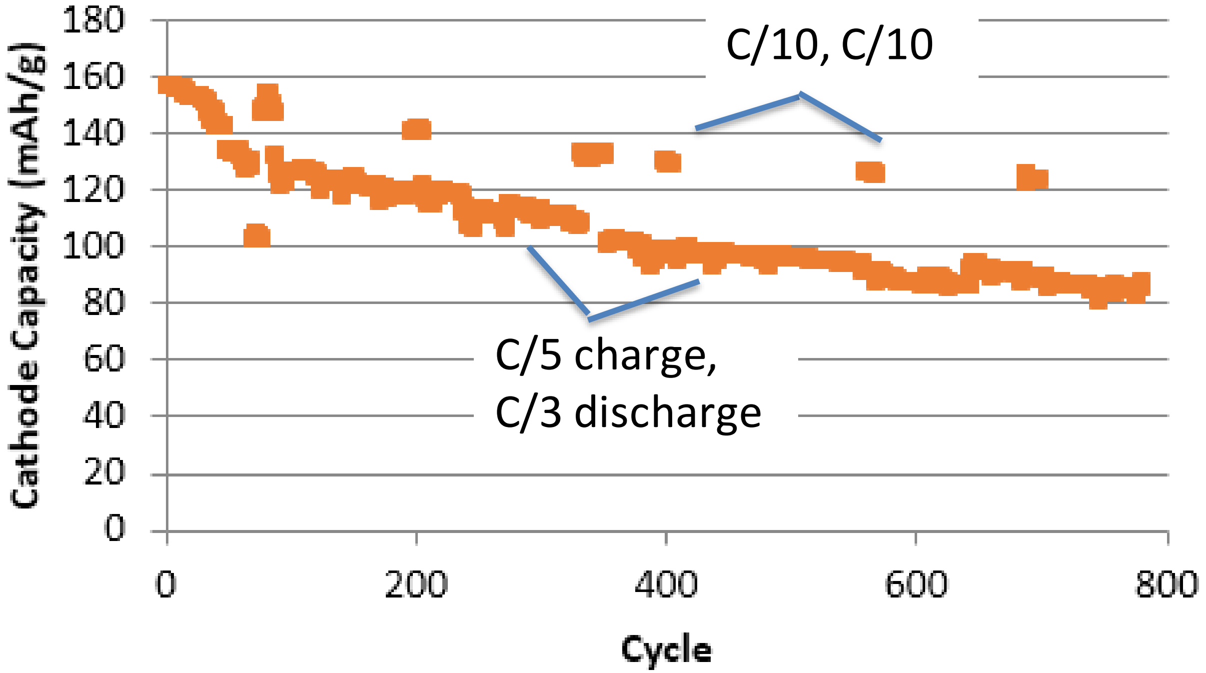


Coulombic Efficiency	
1st Cycle	91.5%
2nd Cycle	99.0%
3rd Cycle	99.5%
4th Cycle	>99.9%

LONG-TERM CYCLING

- Stable resistance and capacity for cells with Li metal anode and high-nickel NCM cathode
- 161 mAh/g based on NCM 622 mass with 4.2V charge voltage (92% utilization based on 175 mAh/g theoretical capacity)
- 90% capacity retention cycle 200, 85% retention cycle 350, 80% retention cycle 680

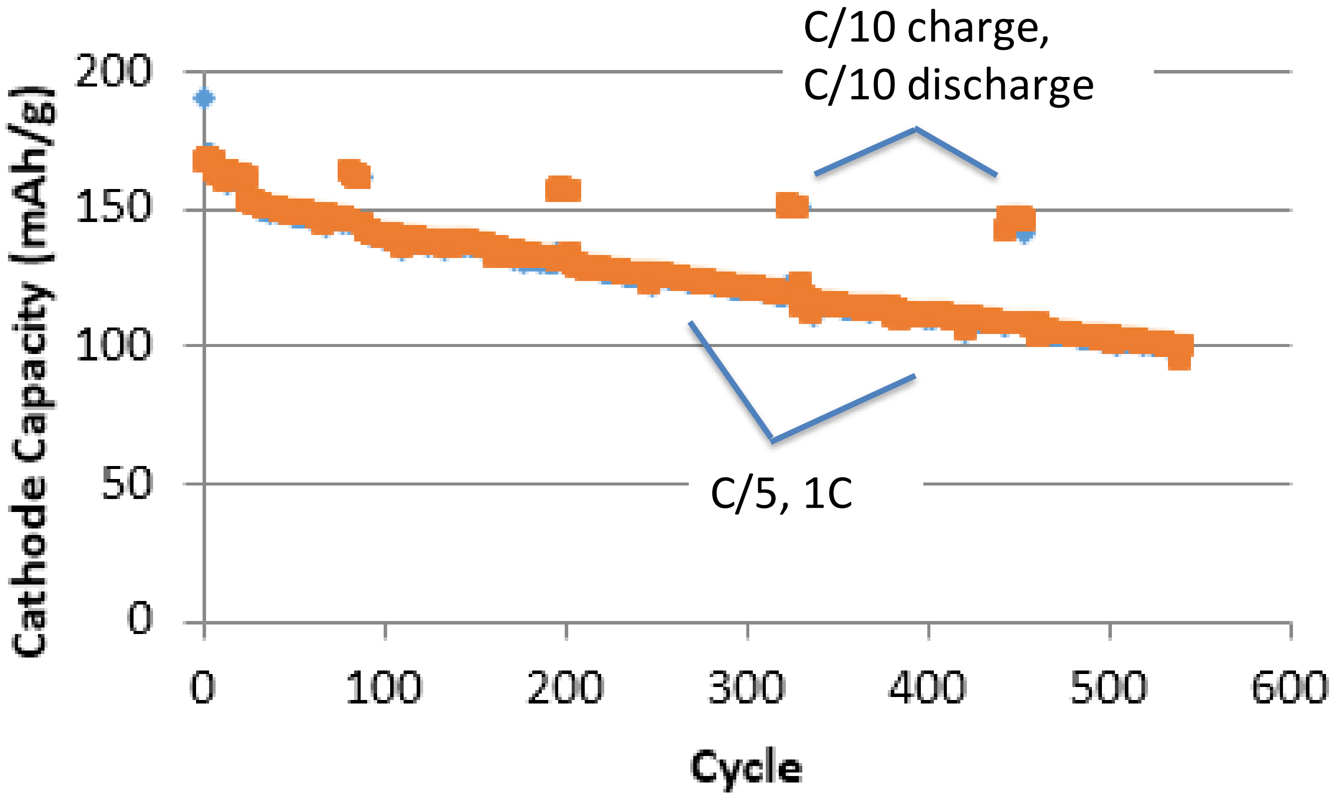
- *2 cm^2 diameter cell*
- *Li metal anode*
- *Gen 3 electrolyte*
- *NCM 622 cathode*
- *3.0 mAh/cm^2 loading*
- *Tested at 70°C*
- *100% DOD*
- *4.2V – 2.5V*



1C DISCHARGE RATE CYCLING

- 168 mAh/g based on NCM 622 mass at C/10 rate with 4.2V charge voltage
- 1C rate discharge capacity retention of 86% compared to C/10 capacity
- 96% capacity retention through 85 cycles, 87% through 450 cycles

- *2 cm^2 diameter cell*
- *Li metal anode*
- *Gen 3 electrolyte*
- *NCM 622 cathode*
- *2.8 mAh/cm^2 loading*
- *Tested at 70°C*
- *100% DOD*
- *4.2V – 2.5V*



ROOM TEMPERATURE CYCLING

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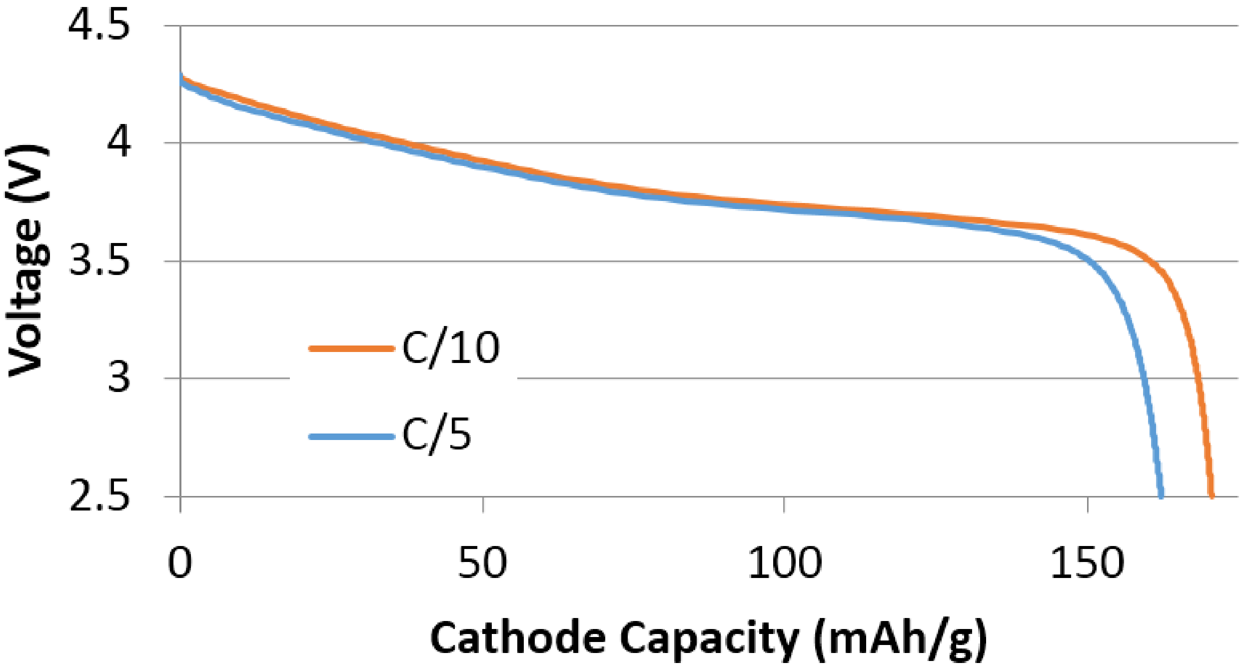
- 170 mAh/g based on NCM 622 mass with 4.3V charge voltage
- Practical cathode loading of 2.9 mAh/cm^2
- Total cell ASR of 40 ohm*cm^2

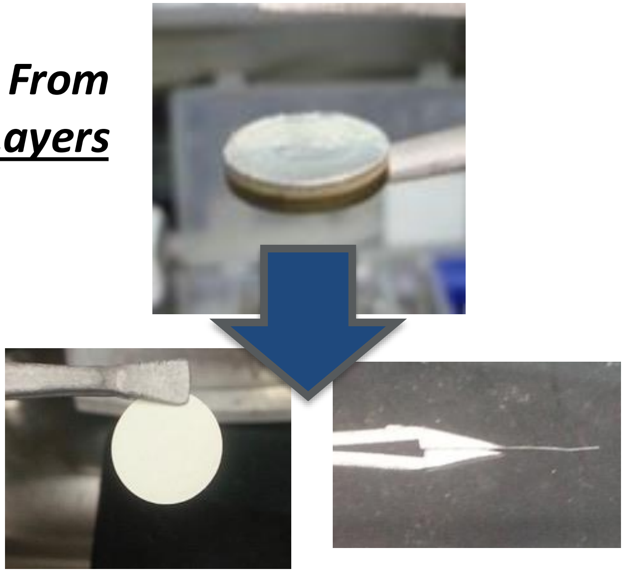
- *2 cm^2 diameter cell*
- *Li metal anode*
- *Gen 3 electrolyte*
- *NCM 622 cathode*
- *Tested at room temp.*
- *C/10 charge rate*
- *2.9 mAh/cm^2 loading*



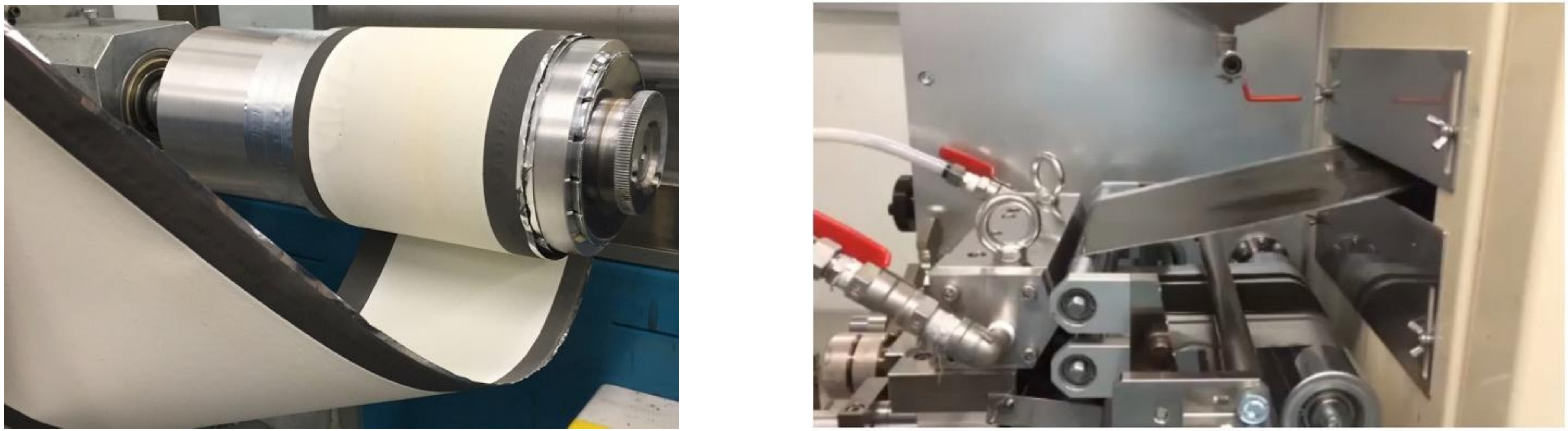
CELL PROCESSING

- Early work focused on “pelletized” cells – an un-scalable format
- Cathode and separator materials particles optimized for slurry-based roll-to-roll coatings

Cells Produced From “Pelletized” Layers



Cells Produced from Thin, Coated Layers



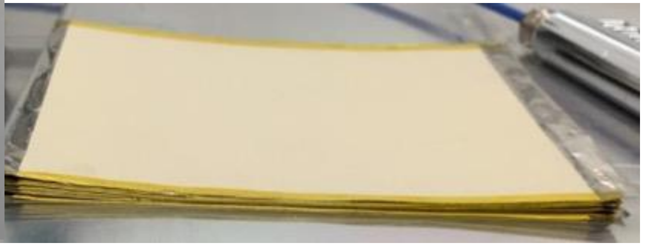
Continuous Roll-To-Roll Solid State Cell Layer Production

LARGE-FORMAT CELL DEVELOPMENT & TESTING

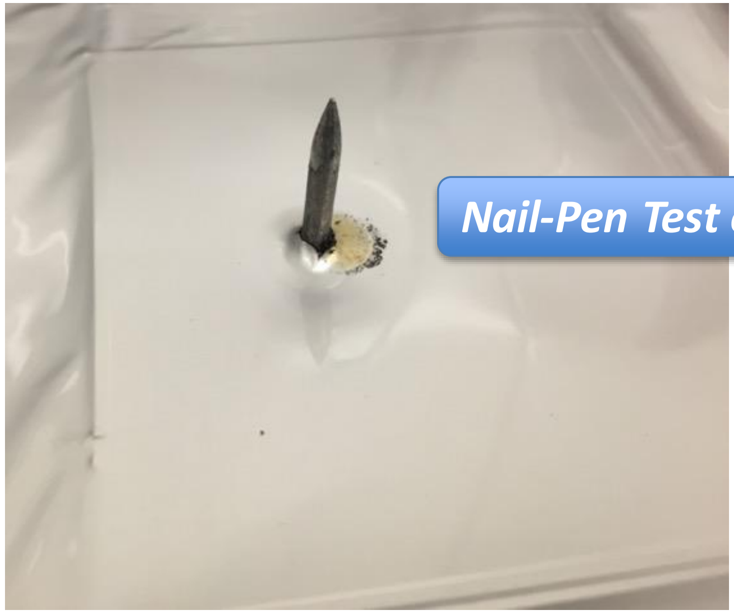
- FeS_2 – Li-metal cells produced up to 5Ah in size
  - Preliminary Abuse Testing (nail-pen, overcharge & external short) performed with Benign Failure
- NMC– Li-metal Cells up to 1Ah Produced & Tested
  - Early prototypes produce an as-measured 250 Wh/kg cell-level specific energy

Packaged Pouch Cell

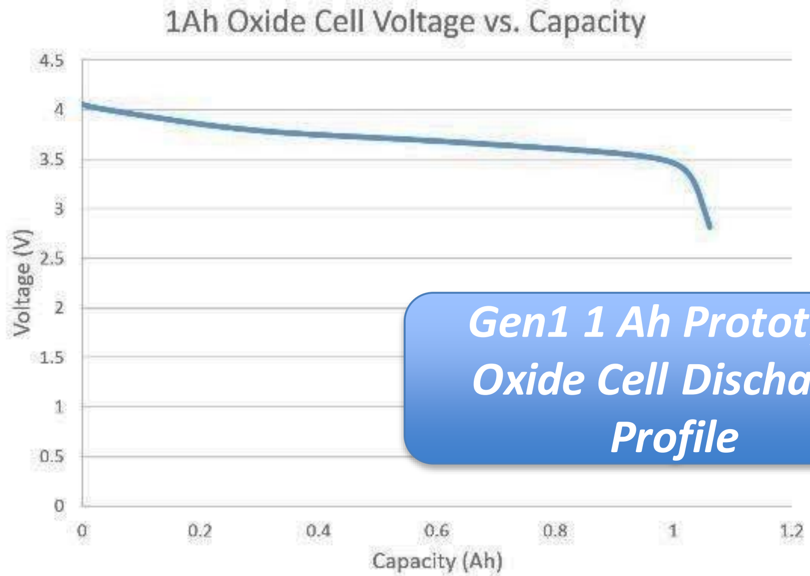
"Naked" Cell Prior to Lamination



Gen1 1 Ah Prototype Oxide Cell



Nail-Pen Test of FeS2 Cell



Gen1 1 Ah Prototype Oxide Cell Discharge Profile

OUTLOOK

- Solid-state is a practical approach to improving energy density and safety in parallel
- Enabling Li metal is key to enabling high energy density
- Major challenges remain in resistance/temperature, Li metal compatibility, and manufacturability
- Opens up the design space with new materials and cell and battery concepts
- Solid-state batteries are coming to electric vehicles – not a matter of if, but when