Enabling Solid State Batteries: Breakthrough Polymer Technology

April 2019

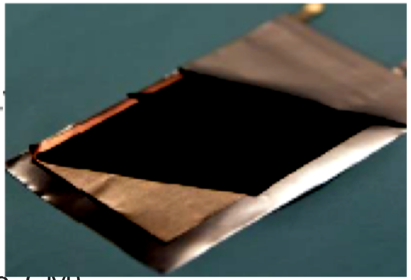
Presentation Overview

- The Challenge for Current Batteries
- Introduction to Ionic Materials
- Polymer Electrolyte Fundamental Properties
- Polymer Electrolyte Commercialization
- Next Generation: Lithium Metal Cycling
- Disruptive Chemistry: Rechargeable Alkaline

Who am I?

- Proven serial entrepreneur, 30+ years of polymer expertise
- iQLP (Founder), Tufts University (Professor), Bell Labs (Technical Staff for 14 yrs.)
- Expertise in polymer manufacturing and collaboration with commercial partners (Dupont, Nypro, GM)

World Class Team



- Mike Zimmerman Ph.D. (Founder/CEO)
  - Proven serial entrepreneur, 30+ years of polymer expertise
  - iQLP (Founder), Tufts University (Professor), Bell Labs (Technical Staff for 14 yrs.)
  - Expertise in polymer manufacturing and collaboration with commercial partners (Dupont, Nypro, GM)
- Proven Team
  - **Battery Team** including battery scientists and electrochemists, cell assembly engineers and technicians
  - **Materials Team** including materials scientists, polymer and process engineers and technicians
  - **Business Team** including business development, intellectual property, product management
- Technical Advisors and Collaborators Include:
  - Dr. Jay Whitacre, Carnegie Mellon University (Professor), Aquion Energy (Founder)
  - Dr. Steve Greenbaum, City University of New York (Professor)
  - Dr. Arthur Heuer, Case Western Reserve University (Professor)
  - Dr. Iryna Zenyuk, Tufts University (Professor)
  - Dr. William West, Jet Propulsion Lab (Staff Scientist)
  - John Dear, Imperial College London (Professor)
- Business Advisors Include:
  - Bill Joy (Founder, Sun Microsystems)
  - Jan van Dokkum (Former President, UTC Power, Siemens Power and Transmission, Inc.)
  - Jim Goldinger (Partner, Fairhaven Capital)
  - Mark Bertolami (Former President, Duracell)
  - David Wells (Partner, Water Street Capital)
  - Jeff Chamberlain (Argonne National Labs)
  - John Abele (Founder, Boston Scientific)

Ionic Materials has the skillsets and polymer expertise to build a world class materials company

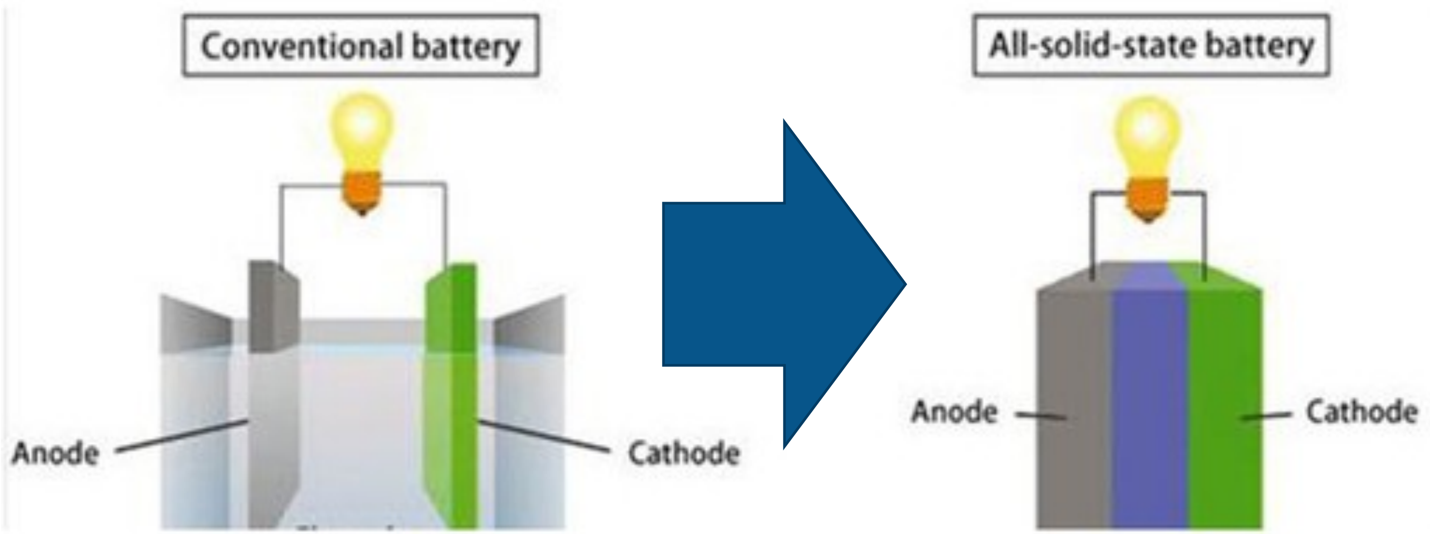
Ionic Materials Innovation

Our Scientific Breakthrough

- Our solid polymer is the first of its kind to conduct ions at room temperature, which can have profound benefits for electrochemistries.

Enabling the Next Generation of Batteries

- Our unique polymer enables the next generation of batteries to address these challenges.

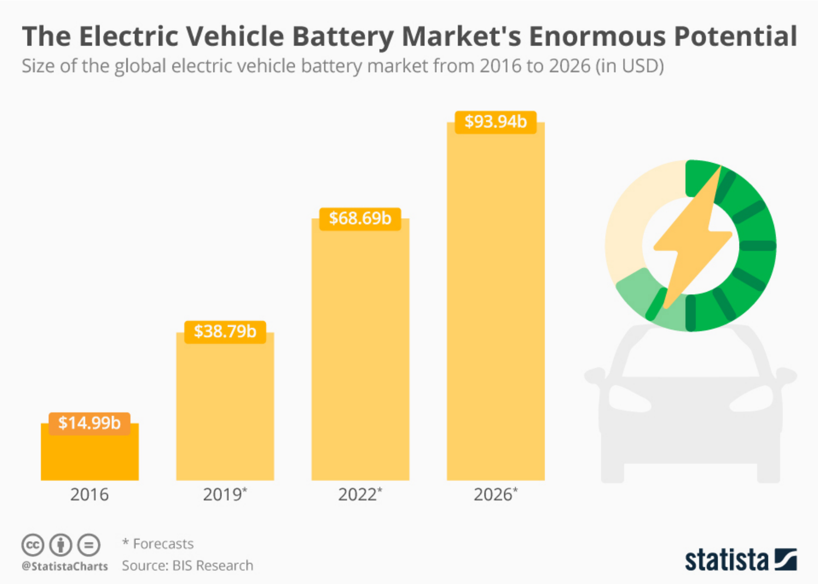


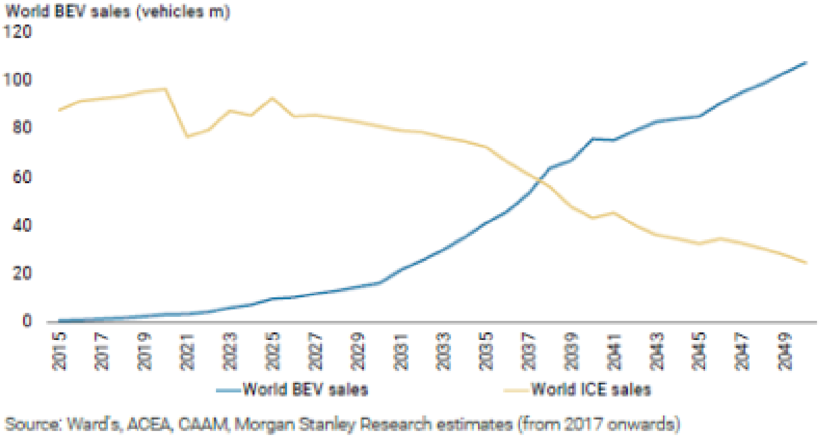
- **Conventional lithium-ion battery with liquid electrolyte**
- **Solid-state battery using the Ionic Materials polymer**

The Challenge for Current Batteries

The Context: A Revolution in Batteries

- Batteries are a key factor in enabling the electrification of transport
- Battery manufacturers are expanding production at a rapid pace to keep up with this demand
- The entry of mass market electric vehicles (EVs) will accelerate this trend dramatically over the next decade





Despite this growth trend, there is are still challenges for lithium ion batteries to meet key customer demands: safety, energy density and cost

The Challenge for Current Batteries

- Lithium-Ion battery technology has driven great advancements in consumer electronics and electric vehicles
- However, current batteries face a number of challenges that are holding them back

Safety

Flammable liquid electrolytes are dangerous

Energy Density

Lithium-ion is reaching the limits of its energy density

Cost

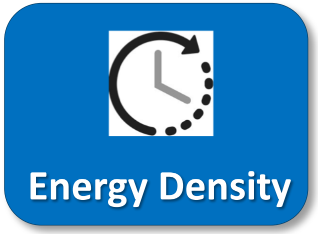
Expensive active materials prevent truly low cost batteries

The Challenge for Current Batteries

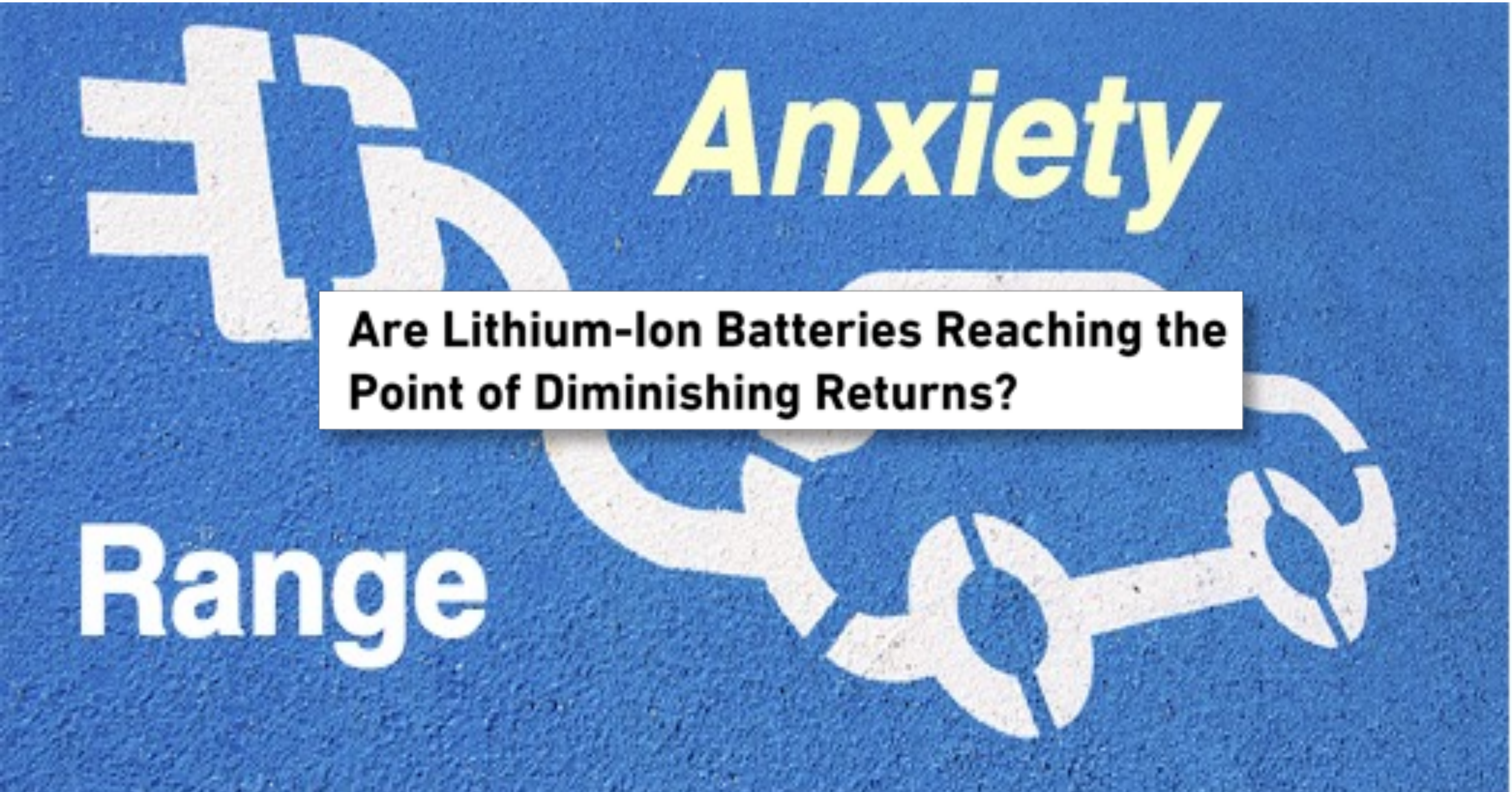
Safety

- Liquid electrolytes are necessary for current batteries but are toxic and highly combustible

The Challenge for Current Batteries



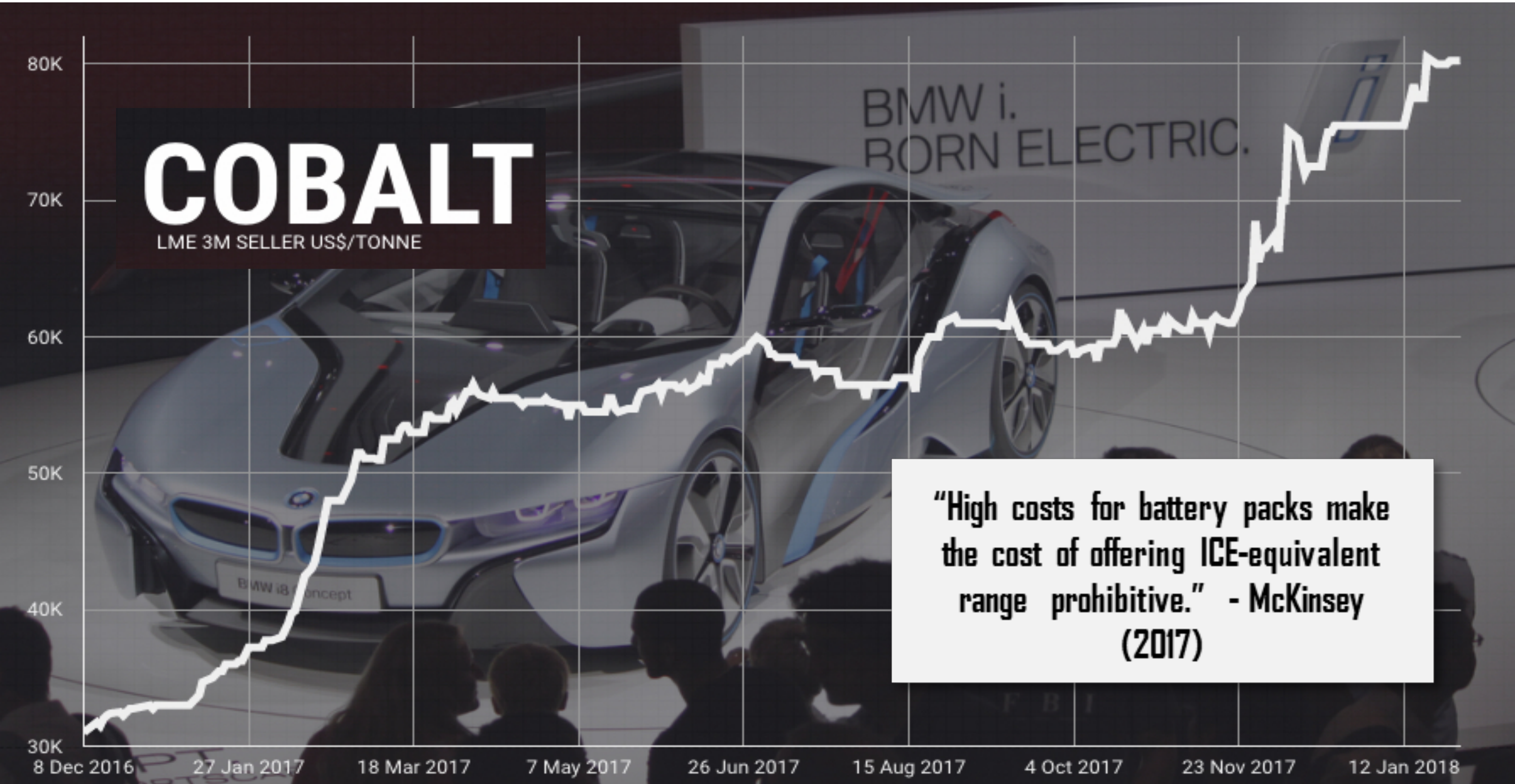
- Lithium ion energy density is plateauing, while demand increases



The Challenge for Current Batteries

Cost

- Electric vehicles and grid storage require vast quantities of low cost, high performance batteries



Introduction to Ionic Materials

Our Solution

Safety

- Our polymer creates a battery which is inherently safe

Ionic Materials Potential:
The first certified "safe to fly" lithium-ion battery

Energy Density

- Our polymer electrolyte is compatible with chemistries that have much higher performance limits

Ionic Materials Potential:
Energy density to enable 1000 mile EV range

Cost

- Compatible with next generation chemistries that can significantly reduce battery costs

Ionic Materials Potential:
Drive the cost per kWh to $50 or below

The Big Idea

Novel Polymer Electrolyte

Battery remains safe even under severe abuse

Inherent Battery Safety

Conventional liquid electrolyte and separator are top sources of all battery safety incidents.

Ionic replaces both of these with an inherently safe, non flammable polymer electrolyte.

Lower Battery Cost

Ionic enables novel, low cost manufacturing techniques

Ionic enables very low cost anode and cathode chemistries, e.g. sulfur

Higher Battery Performance

Ionic Li/S battery powering tablet

Conventional liquid electrolytes are incompatible with many next generation anodes and cathodes.

Ionic enables use of lithium metal anodes, sulfur cathodes, and more. Result is much higher energy density and performance.

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Safety Demonstration: Ballistics Test

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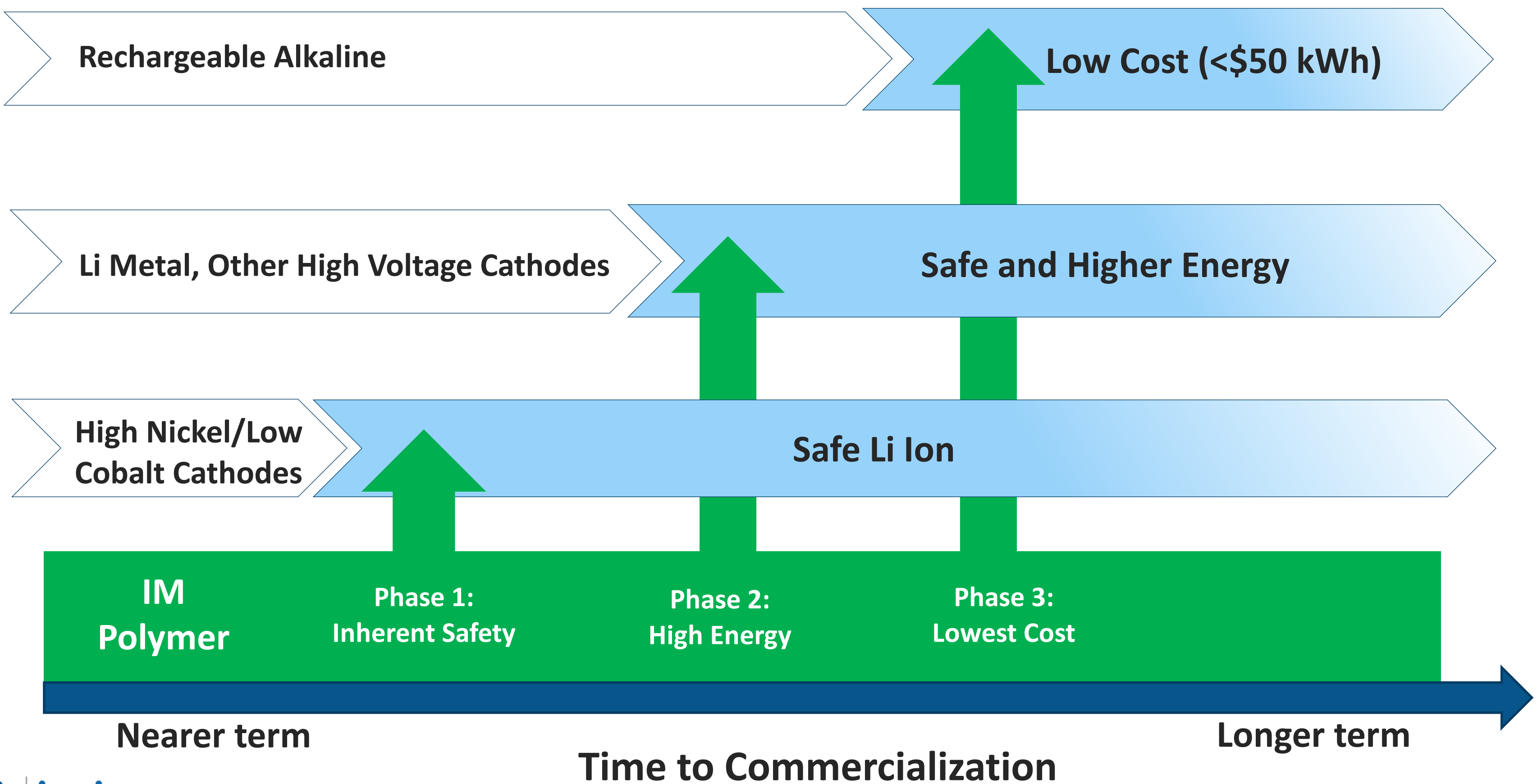
A True Platform Technology for Batteries

- Ionic Polymer is ready today to advantage multiple chemistries and as new chemistries are perfected, the polymer can uniquely enable those use cases



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Competitive Dynamics

- **“Because of your company, everyone is talking about polymers for solid state” – EV OEM Battery Research Lead**
- IM is recognized as a fundamentally new approach to solid state leveraging the manufacturability of polymers
- Other competition struggling to demonstrate that it can be brought to market in a cost effective and safe way

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Room temperature operation

Capable of high volume, low cost manufacturing

PEO Challenges

Can’t prove room temperature operation

Best in class works only above 60 Celsius

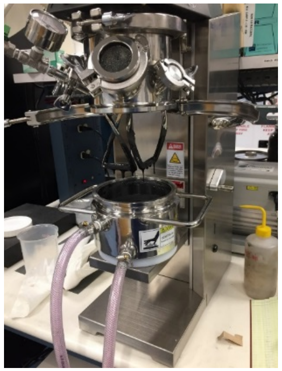
Sulfide Challenges

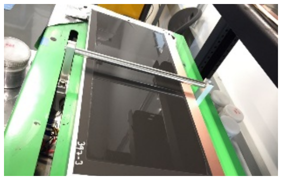
Costly and challenging to manufacture

Safety issues related to H_2S gas

Ionic Materials is uniquely positioned in the market, while competitors with less desirable approaches are facing challenges. We have the opportunity to lead the industry with our approach

The Big Idea – Improved Manufacturability





Ionic made electrode using standard planetary mixer + draw-down

Novel Polymer Electrolyte

Drop-in Electrode Mixing/ Coating

Ionic's polymer materials can be used with existing electrode manufacturing techniques such as: draw-down coater and slot-die.

Ionic can also enable next-generation electrode manufacturing techniques

Drop-in Cell Manufacturing

Other solid-state battery solutions are very costly and require high CAPEX expenditure for volume cell production

Ionic enables use of existing cell manufacturing lines that use technology such as Z-fold, stacking, or winding

Elimination of Process Steps

Use of Ionic's polymer materials in place of liquid electrolyte and separator eliminates process steps in cell manufacturing, such as the electrolyte filling process and degassing of liquid electrolyte pouch cells after formation.

Ionic NCM811/Graphite 10Ah Cell made w/ cell manufacturer Z-fold hybrid process

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Solid State: Coming Sooner Than Expected

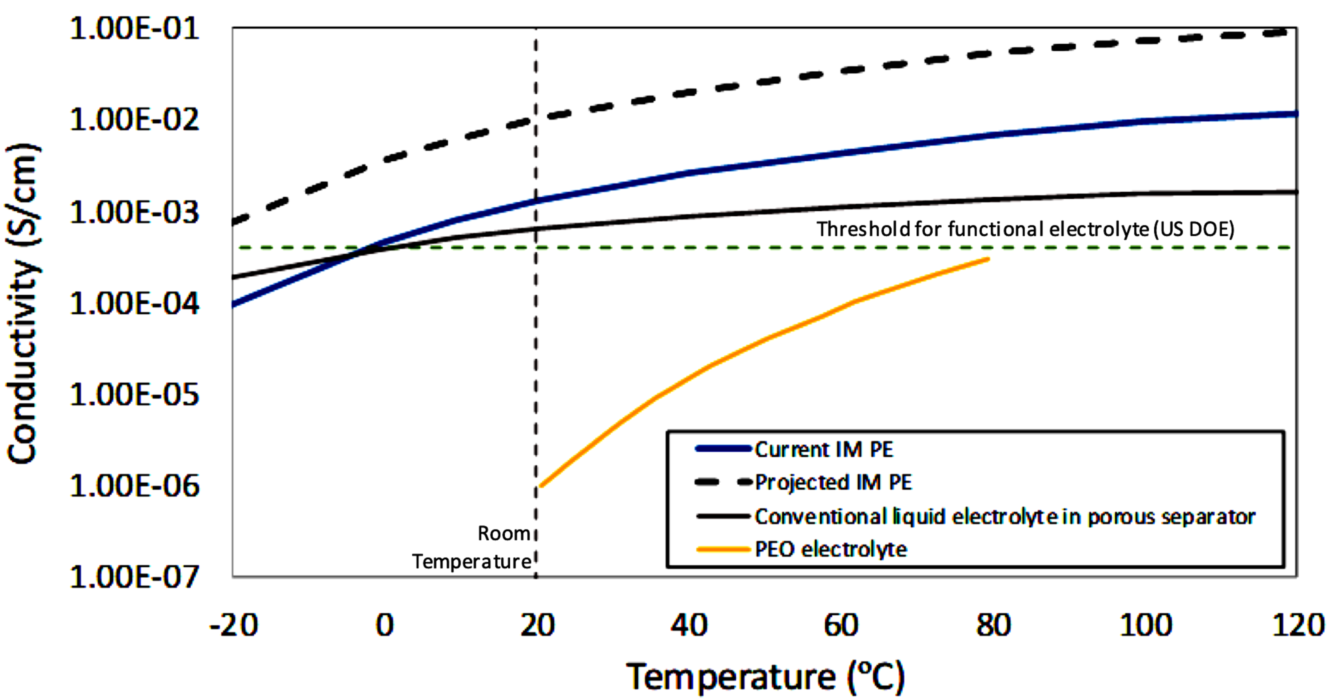
- Solid State cells have always been a “holy grail” technology for the battery industry
- Even with decades of research, viable solid state cells have still been seen as a 2030 and beyond opportunity
- Ionic Materials is accelerating the transition to solid state with its unique polymer
- The commercialization timeframe for solid state is now accelerated
  - CE applications in 2023
  - EV applications in 2024

Fundamental Properties of Our Polymer

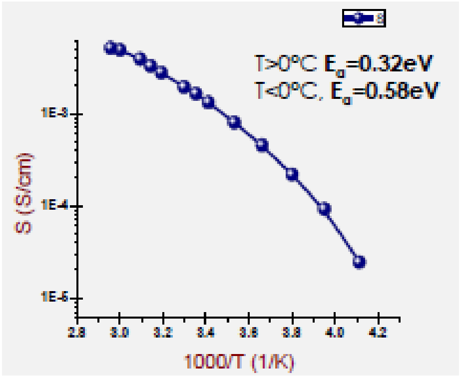
Ionic Materials Novel Polymer Electrolyte

Ionic is demonstrating that its polymer electrolyte has all of the necessary properties to replace conventional liquid electrolytes

- ✓ High conductivity across broad temperature range
- ✓ Up to 1.3 mS/cm at room temperature
- ✓ Lithium transference # >0.5
- ✓ Non-flammable
- ✓ Low cost manufacturing
- ✓ Low cost precursors
- ✓ Conducts multiple ions
- ✓ Compatible with next-gen Li-ion cathodes
- ✓ High Voltage (5V)



Ionic Conductivity measured at cell manufacturer – verified IM measurements



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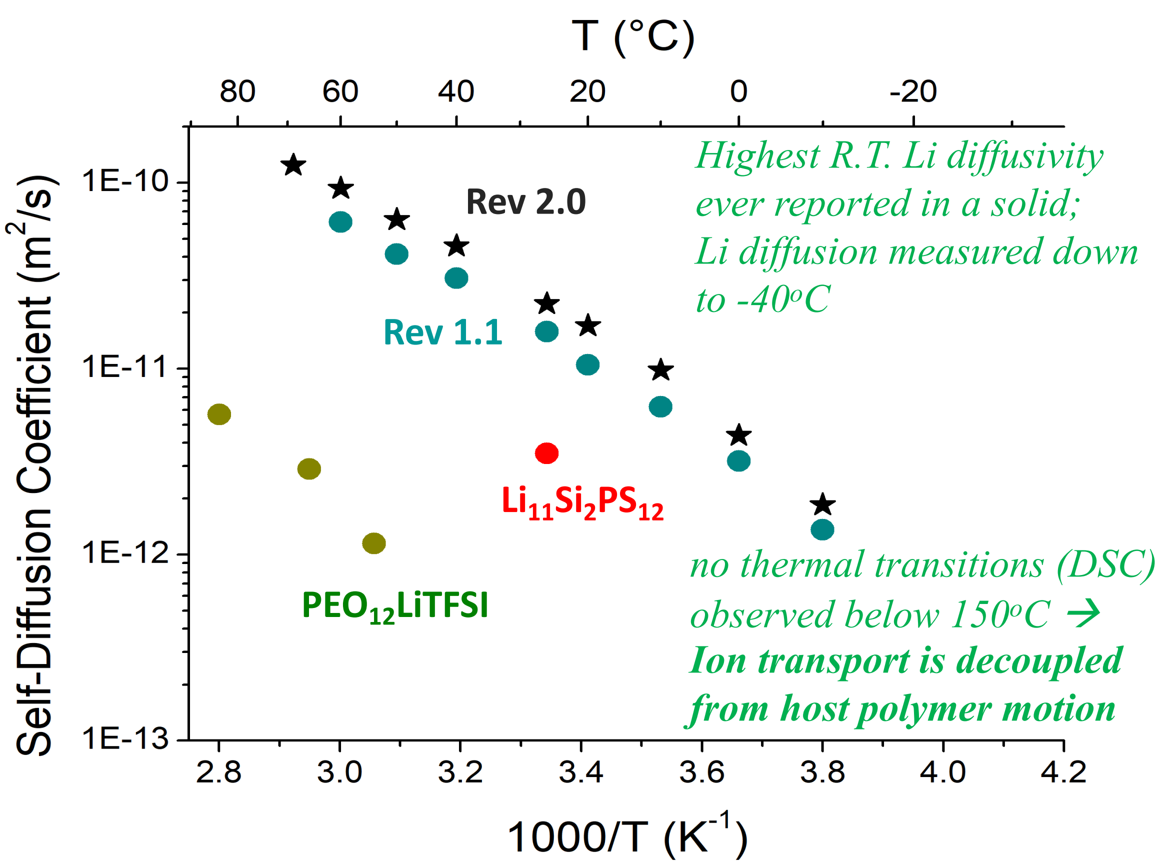
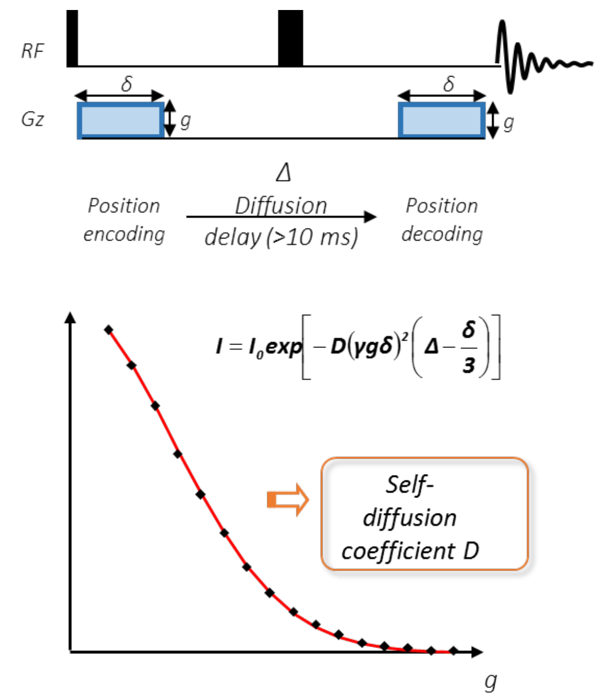
NMR Diffusivity Measurements

Progress in Li ion diffusivity since previous AABC meeting (Rev 1.1)

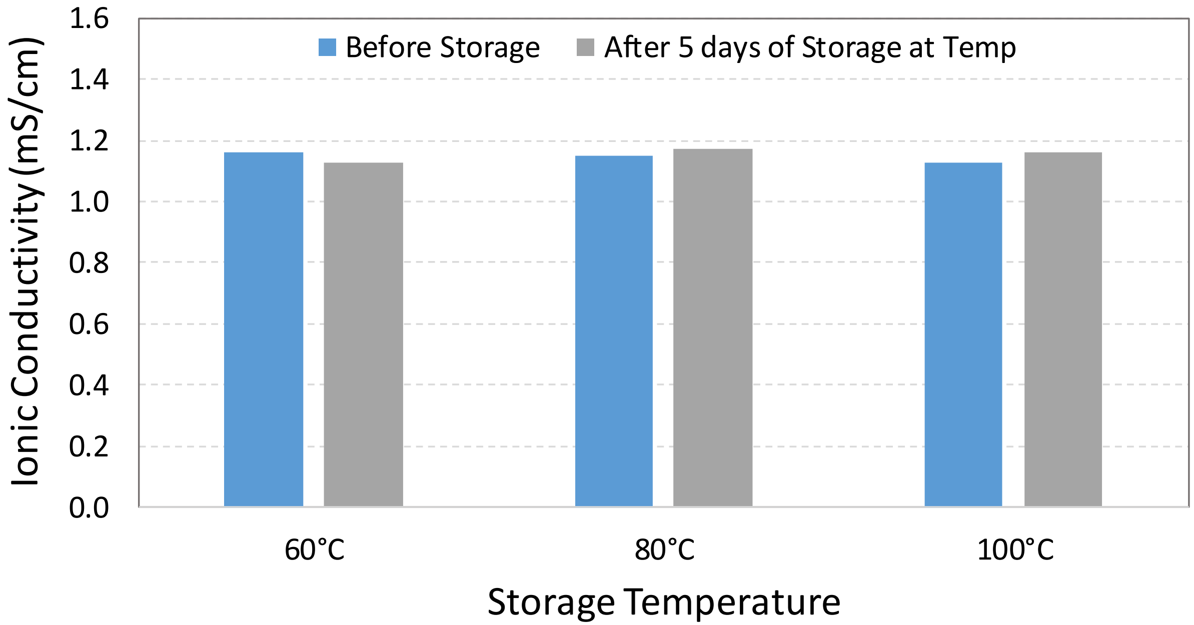




Nernst-Einstein analysis gives σ(NMR) ≈ σ(EIS): salt is well dissociated; t_{Li+} > 0.5, as high as 0.9 (NMR and Echem). High transference and "decoupling index" indicate new polymer electrolyte conductivity mechanism.

Stability of PE Film at High Temperature

Polymer Film demonstrates good stability to 100°C



Ionic conductivity measured at RT after high temp storage for several days

- Samples retained high conductivity after 60°C to 100°C storage – <u>demonstrating stability at high temperature</u>
- Temperature stability results are important for partners for manufacturing flexibility

Discharge HPPC Testing at Low Temperature

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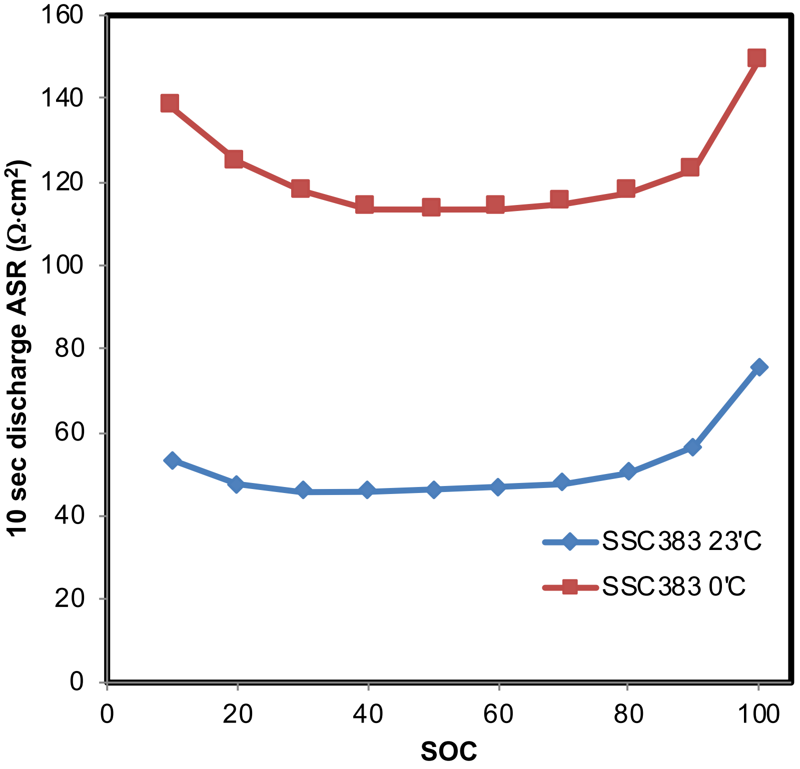
Gr/PE/NCM811 pouch cells displayed high rate (5C) performance at RT and 0°C



- High rate (5C), 10 second pulses
- ***Solid state cell showing ion conductivity at low temperature***

Cell maker: "Baseline measurements at 23°C and 0°C demonstrate appreciable ion conductivity which is exceptional for solid electrolyte materials"

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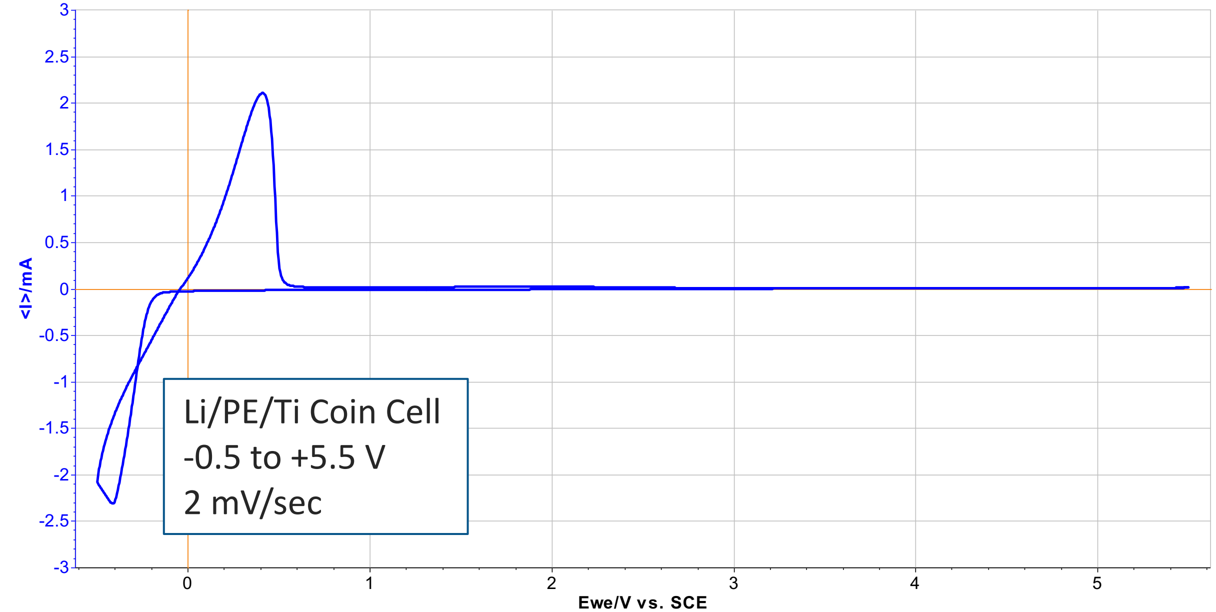
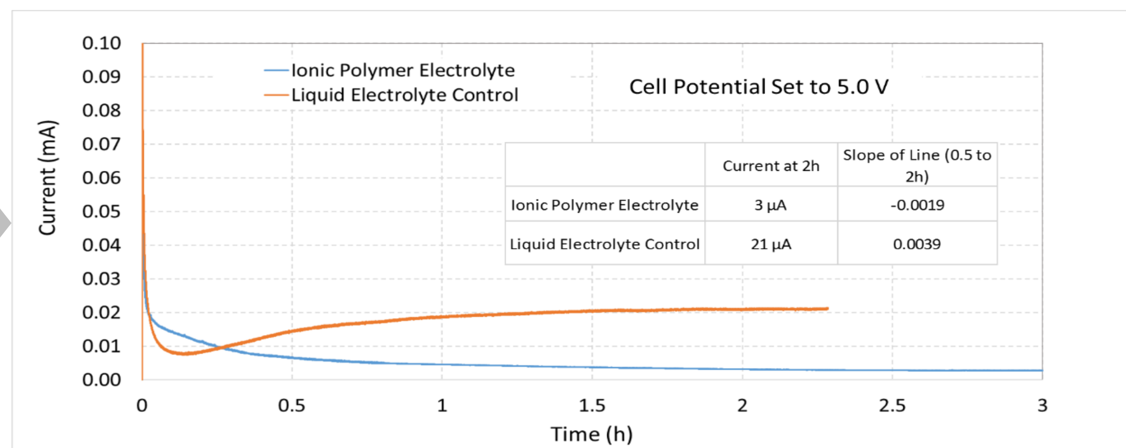
Voltage Stability

Ionic has shown high voltage stability with cyclic voltammetry, potentiostatic measurements, and in functional high voltage cells.



Cyclic Voltammetry shows stability to 5.5 V

Potentiostatic measurement confirms stability of polymer electrolyte



	Current at 2h	Slope of Line (0.5 to 2h)
Ionic Polymer Electrolyte	3 µA	-0.0019
Liquid Electrolyte Control	21 µA	0.0039

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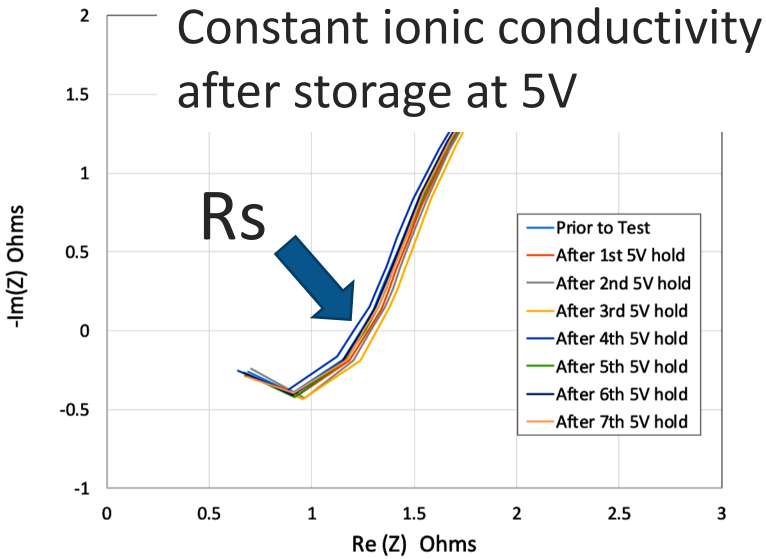
Fundamental Stability of Ionic PE at High Voltage (5V)

Impedance of Ionic's PE film after 5V hold demonstrates high voltage stability, along with theoretical capacity obtained for 5V LNMO cathode material

SS/PE/SS Test Conditions

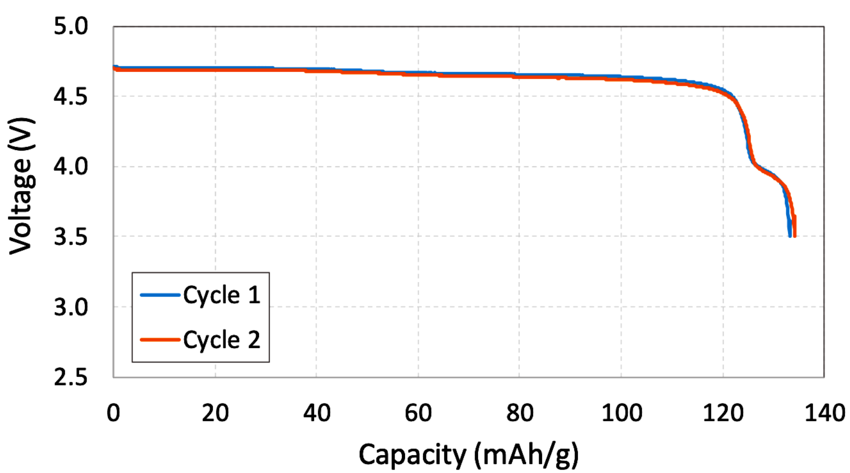
1. Cells tested at RT
2. Initial OCV ~ 3V
3. EIS
4. Li/PE/Ti mini-pouch cells (10.9 cm^2)
5. LSV to 5V
6. Hold at 5V for 2 h
7. LSV back to 3 V
8. OCV for 1 h
9. Repeat EIS

Constant ionic conductivity after storage at 5V



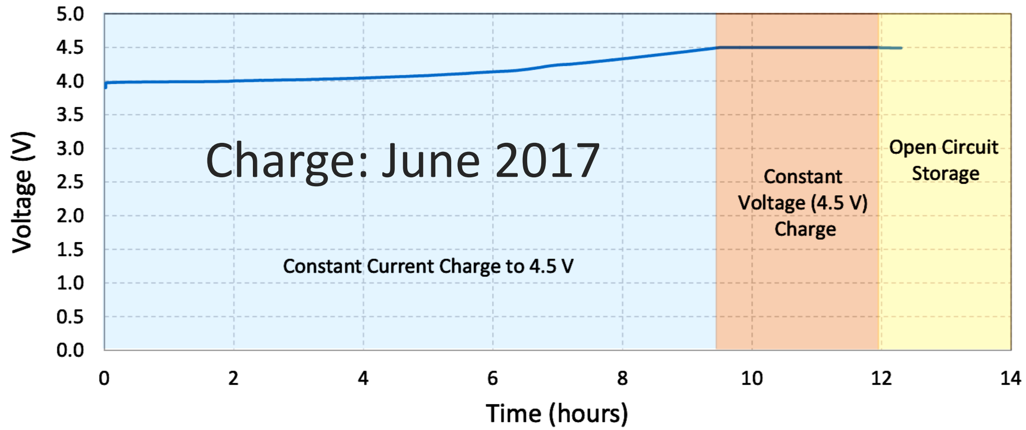
Theoretical capacity obtained for LNMO

- Pouch cells
- 20 µm Li foil anode
- C/10 at RT
- 4.9 V to 3.5 V



High Voltage Material Stability – Low Self Discharge

Li/PE/LCO charged to 4.5V and stored on Open Circuit for 18 months, confirming high stability of the polymer at > 4 V



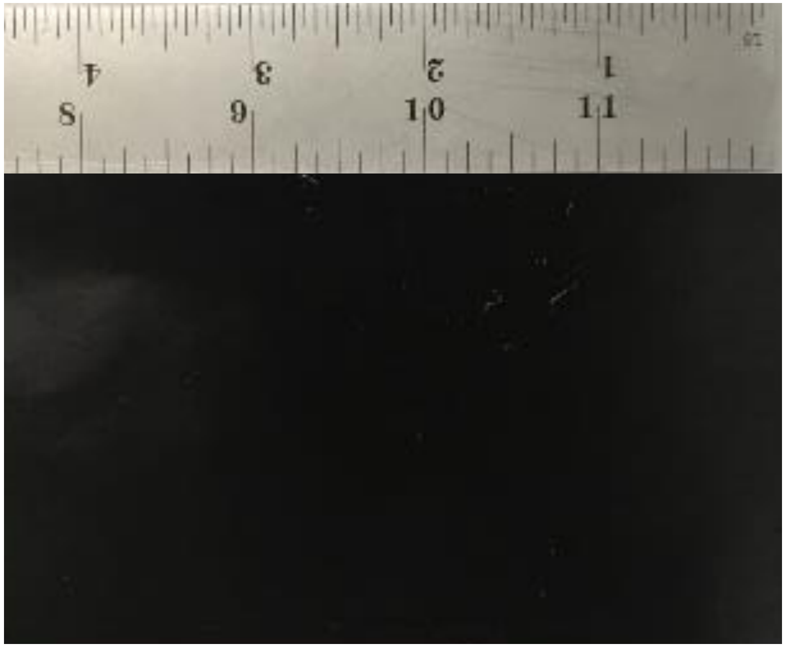
Cell charged to 4.5V, after **563 days** OCV is 4.36V

Cell discharged after 18 months of OCV storage

- Yielded 145 mAh/g for LCO
- **91% of charged capacity after 18 months**
- 0.5% self discharge/month

Electrolyte Thin Films

A year ago IM Polymer Electrolyte films were 125 microns thick – now films are as thin as 30 microns and will continue to be made thinner



- Thickness reduction and quality of film made possible by:
  - Reduction of particle size of ingredients.
  - Mixing DOE improved distribution and dispersion of ingredients.
  - Process improvements in the extrusion of film.

Polymer Electrolyte Commercialization

Ionic Materials: Fundamental Polymer Innovation

- Ionic Materials has pioneered polymer formulations that can unlock new market opportunities
- Ionic's core value proposition is the ability to tailor polymers to have unique conductive properties, a world first

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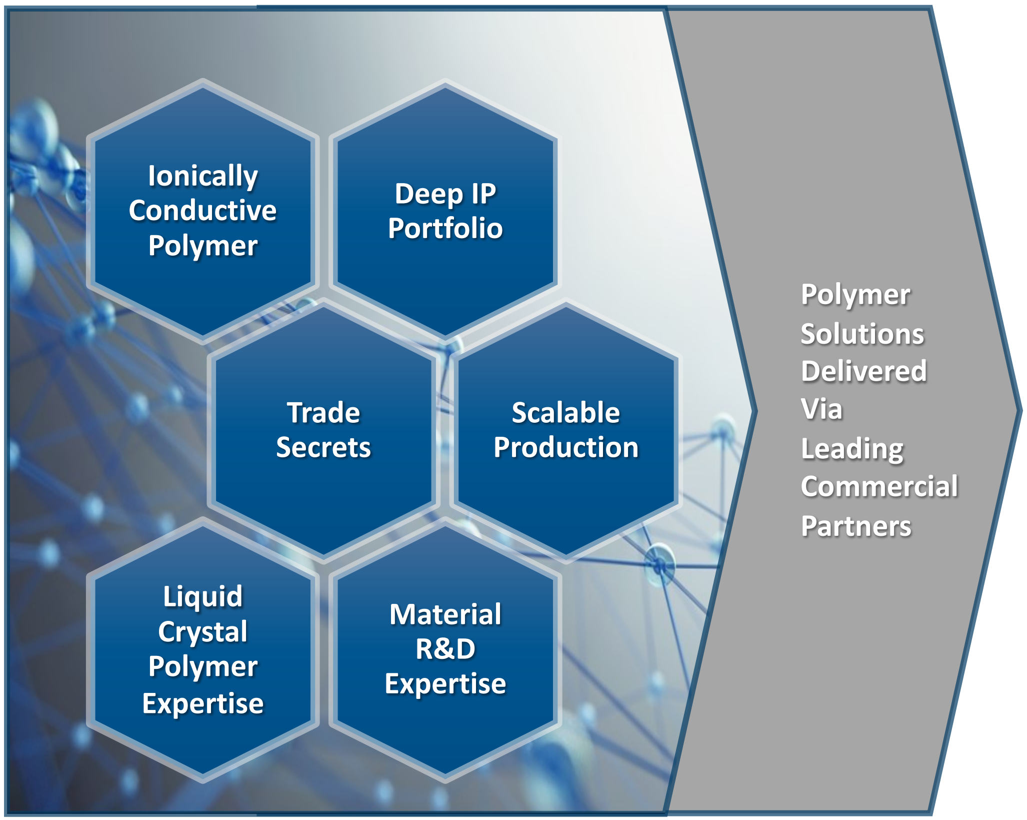
New class of conductive polymers tailored to address key market challenges, backed by IP and trade secrets

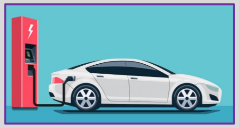
Ionic Materials: Addressing Key Markets

- Ionic Materials is a world expert in polymer science and materials processing
- Via our commercial partners, we are delivering these solutions to a range of large end markets as an advanced materials supplier

Innovative Polymer Capabilities



Attractive End Markets



EV Batteries $27B


Grid Storage and CE Batteries $20B

Source: Avicenne Li-Ion 2025 forecasts

Platform Technology: Multiple Product Offerings

- Ionic Materials offers a true platform technology, with our foundational polymer innovation yielding a range of differentiated product offerings

Innovative Polymer Capabilities

Differentiated Product Offerings

Lithium Ion Systems

- Polymers to enable first solid state batteries
- EVs and other applications benefit from inherent safety, improved energy density, lower cost

Rechargeable Alkaline Systems

- Polymers to create ultra low cost battery systems
- Grid storage and other markets accelerated by world's first rechargeable Zn Mn02 cells

Successful $65M Series C Fundraising in 2018

- Ionic Materials announced its $65M financing, raised from a combination of financial and strategic investors

RENAULT NISSAN MITSUBISHI

TOTAL

A123 SYSTEMS

HYUNDAI

+VOLTA ENERGY TECHNOLOGIES

FRANKLIN TEMPLETON INVESTMENTS

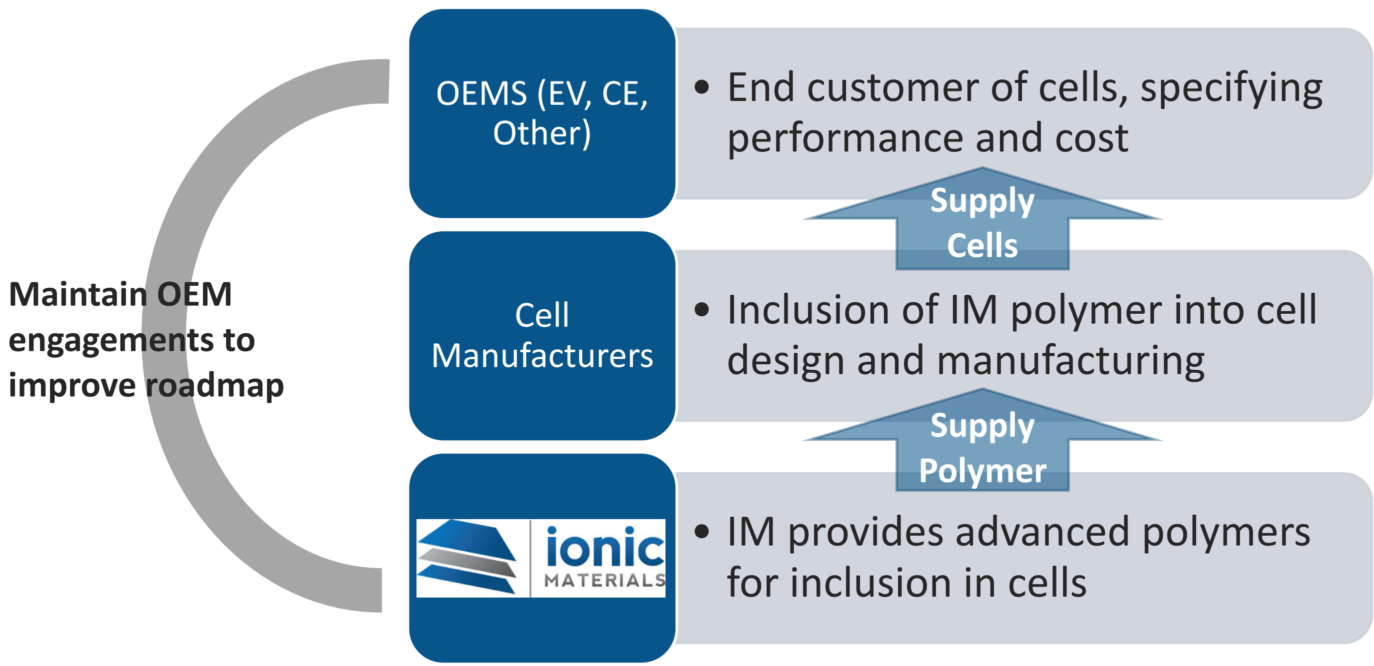
Hitachi Chemical

Two major undisclosed cell makers

- There are now numerous strategic corporate investors supporting the company, representing all elements of the supply chain, from end customer OEM to cell maker to material supplier

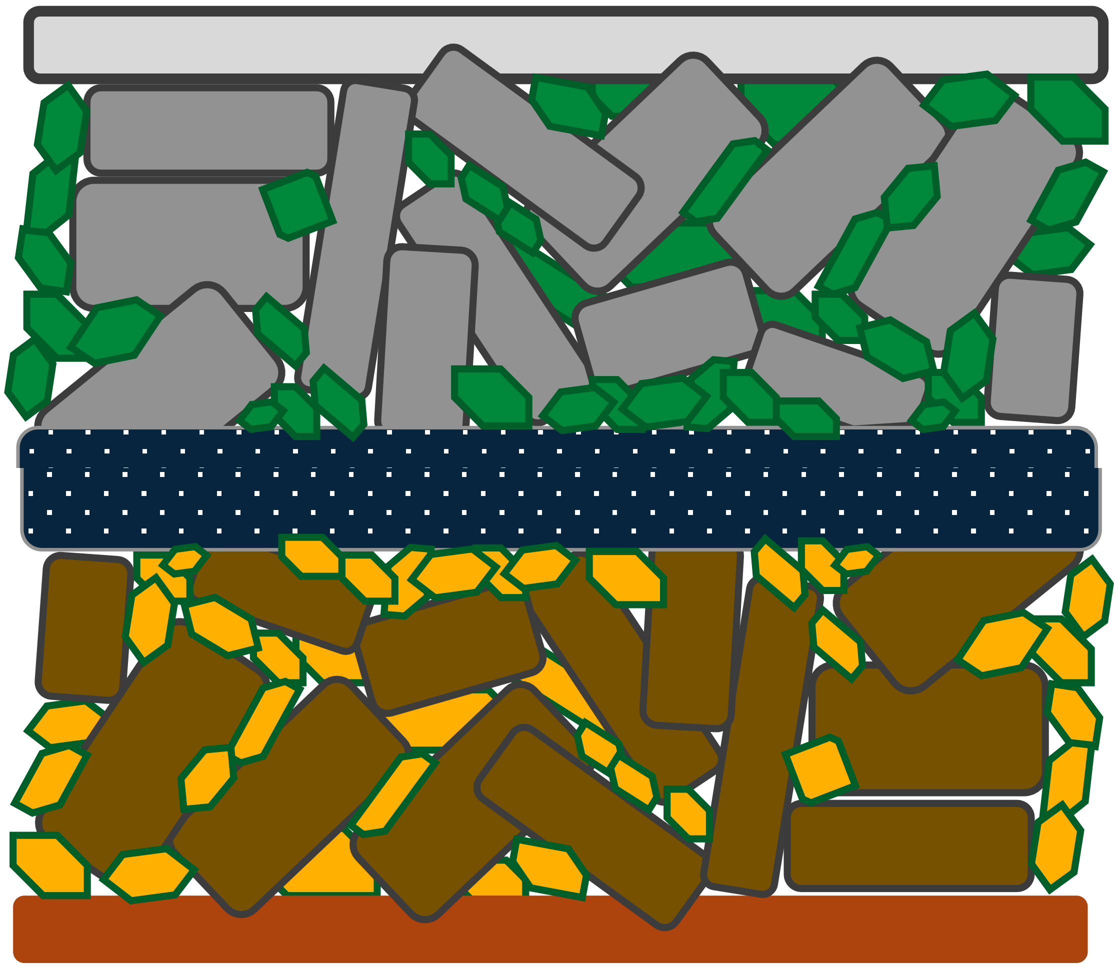
Our Path to Market

- Ionic Materials will go to market as an advanced materials supplier, leveraging our strengths in polymer design and manufacturing to enable the battery value chain.
- Cell manufacturers will be direct customers for our material
- IM will maintain close relationships with end customers to ensure that our material is fit for purpose

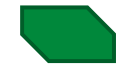


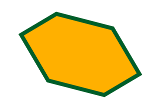
Polymer Electrolyte Commercialization

Commercialization is focused on **Three Products**:



Schematic of IM Li-ion Cell





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Polymer Electrolyte Commercialization

IM Li Polymer Products are tailored to work with:

- **Catholyte Powder** → NCM 811
- **Catholyte Powder** → 5V Cathode
- **Polymer Film** → Li Metal/Cathode
- **Polymer Film** → Graphite-Si/Cathode
- **Anolyte Powder** → Graphite-Si Anode

The strategy is to provide a different polymer product for both cathode and anode. Each is tailored to the specific properties of the cathode and anode.

This strategy further differentiates IM PE from a liquid electrolyte, since a liquid electrolyte can not be separated from cathode and anode, and must strike a compromise between each electrode

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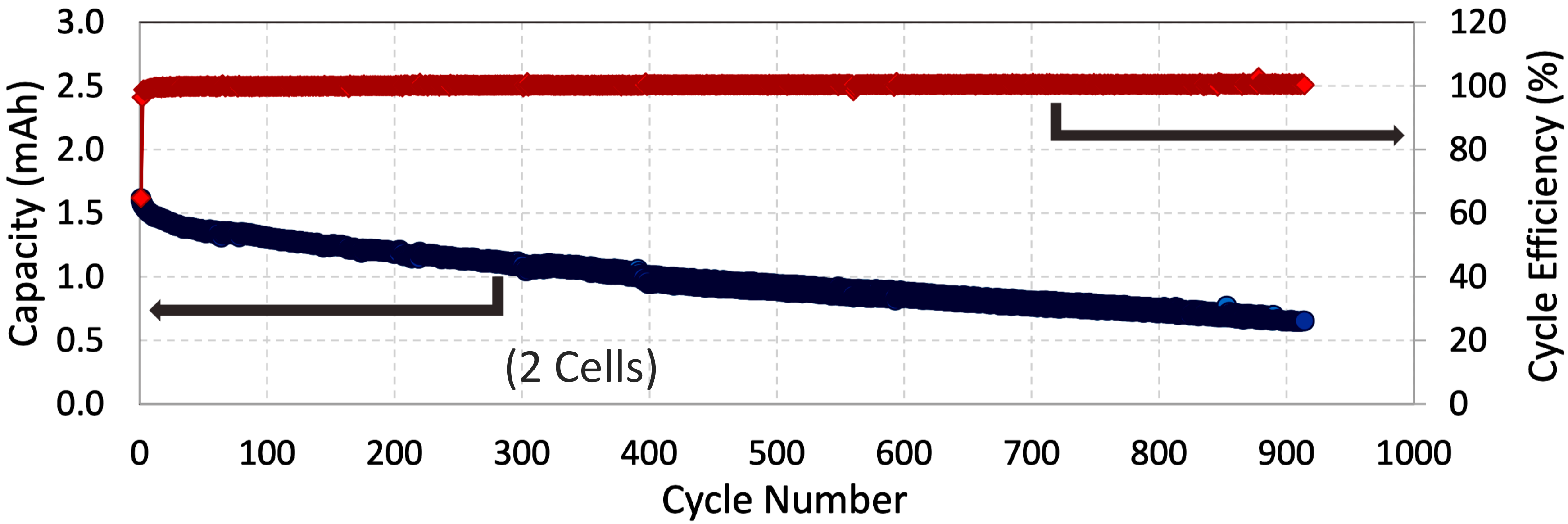
High Cycle Number - Graphite/PE/NCM811

Pouch cells built in R&D with low-Cobalt NCM-811 cathodes and graphite anodes demonstrate **> 900 cycles** at room temperature.

Cells display high cycling efficiency:
Average Cycle Efficiency > 99.9%



Cells cycled at C/2 rate (0.5 mA/cm^2) at room temperature

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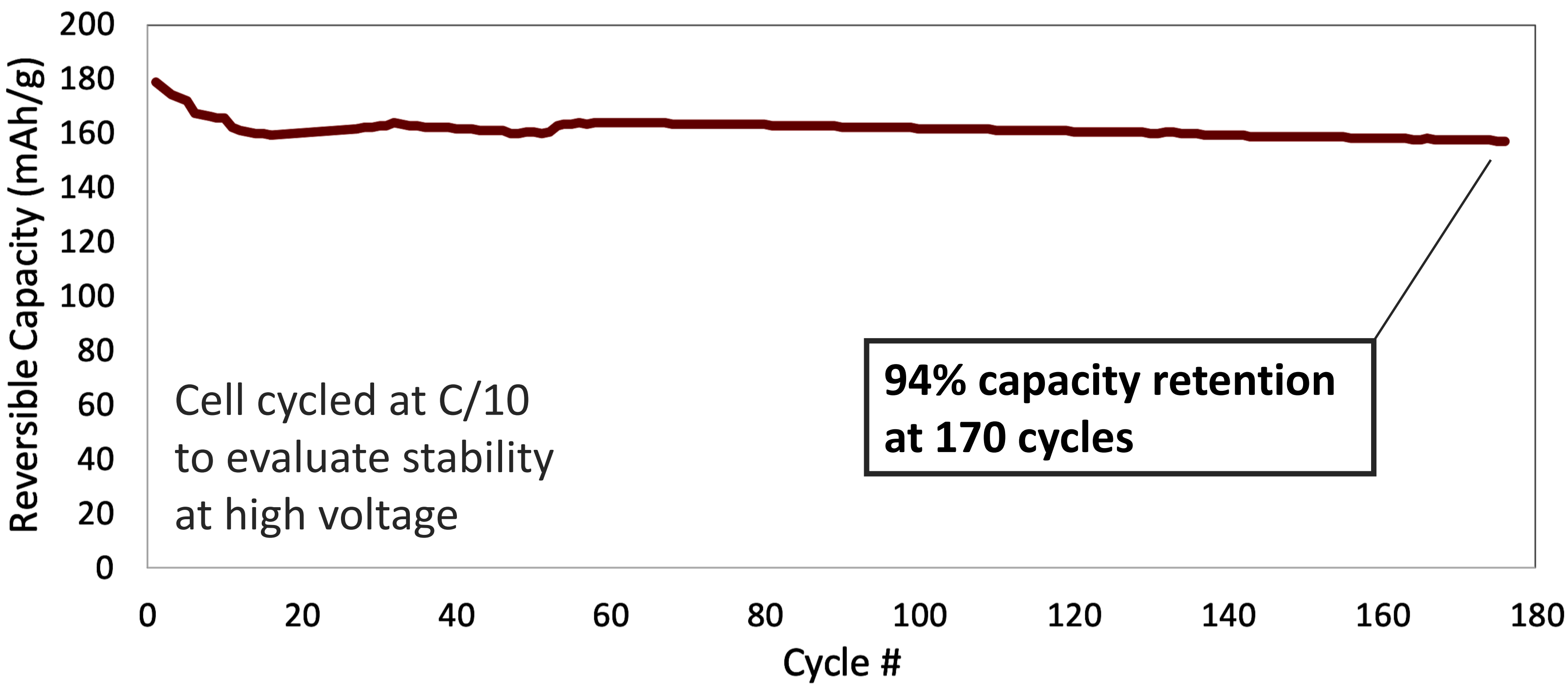
Solid State Battery Cycling with NCM811

Cells assembled by cell making partner exhibiting very stable cycling with 3 mAh/cm^2 areal capacity

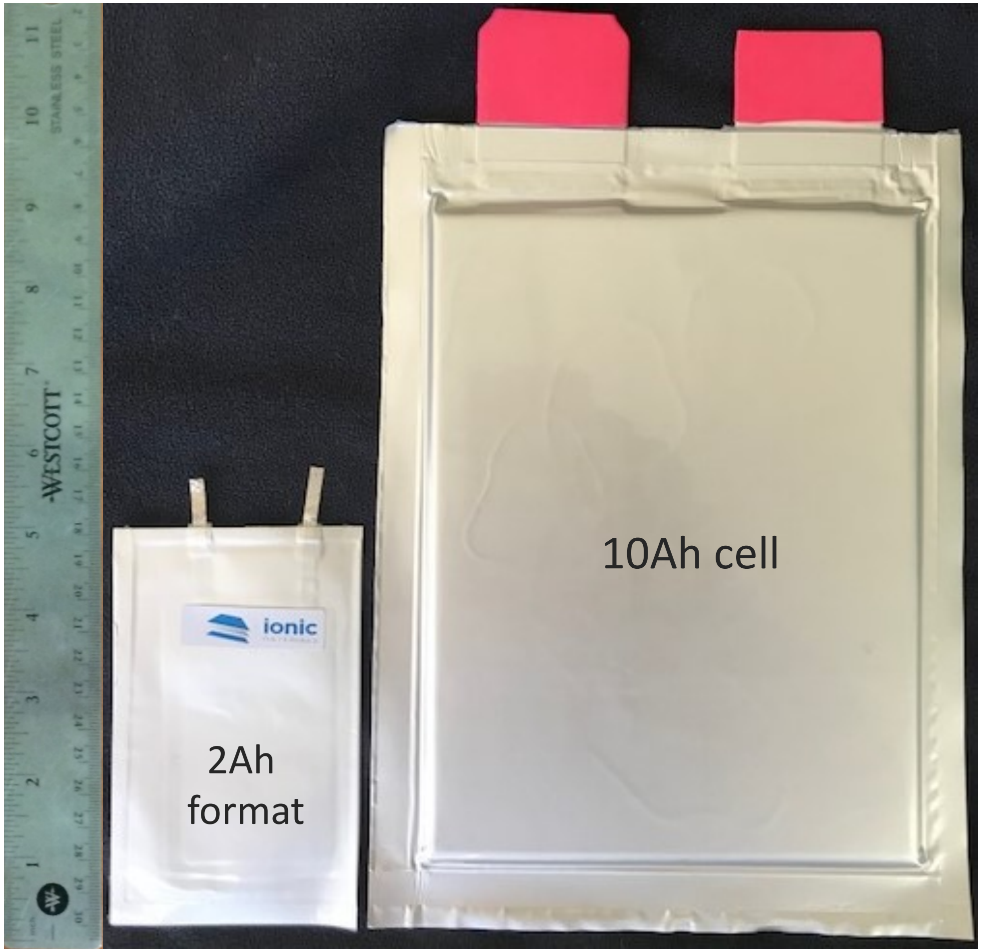
- Graphite/PE/NCM811 single layer pouch cells with 30 micron PE film
  - 94% capacity retention at 170 cycles at C/10 cycle rate at RT



10Ah Cells

10Ah cells with Graphite/PE/NCM811 have successfully been built!

Graphite/PE/NCM811, PE Film: 203mm x 155mm, ~3mAh/cm^2 electrodes



Making polymer electrolyte in commercially viable sizes

"10Ah" Cell#	First Cycle Discharge Ah
1	11.3
2	13.0
3	14.3
4	14.9

10 Ah Cell Cycling with Thin Polymer Separator

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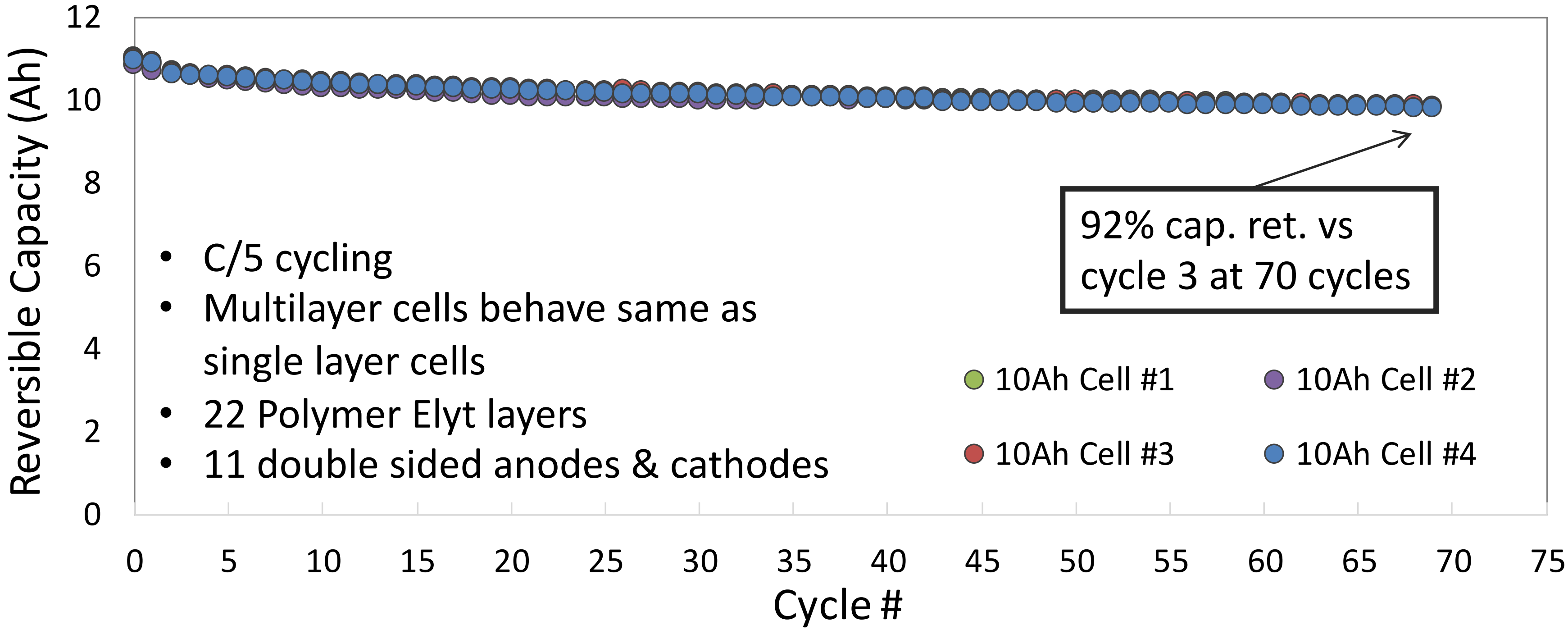
10 Ah pouch cells built via automated assembly exhibiting stable cycling with 30µm polymer separator

Graphite/PE/NCM811 **10Ah** cells built via automated assembly



10 Ah Cells displaying excellent capacity retention: 92% at 70 cycles

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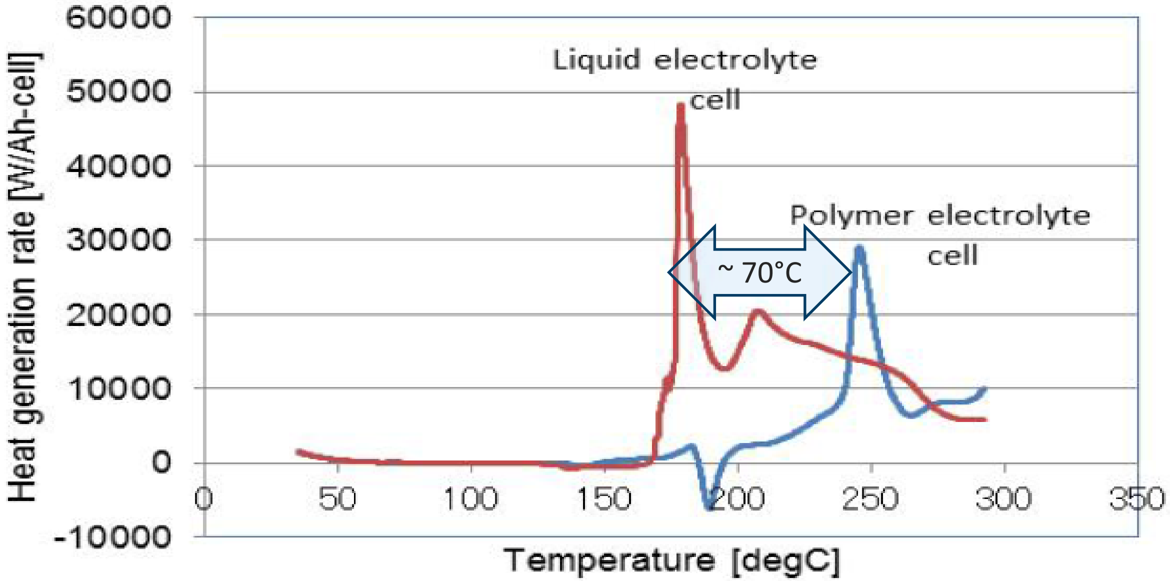
Thermal Analysis for All Solid Rechargeable Battery

MITSUBISHI CHEMICAL
Tomohiro Kawai, Dr. Eng

The onset temperature of thermal runaway for polymer electrolyte cells is much higher than liquid electrolyte cells and exhibited safer thermal behavior.
IM's polymer makes Li Anode safer.

IM's polymer electrolyte cells and components were tested by battery safety expert, Dr. Tomohiro Kawai from Mitsubishi Chemical Corporation



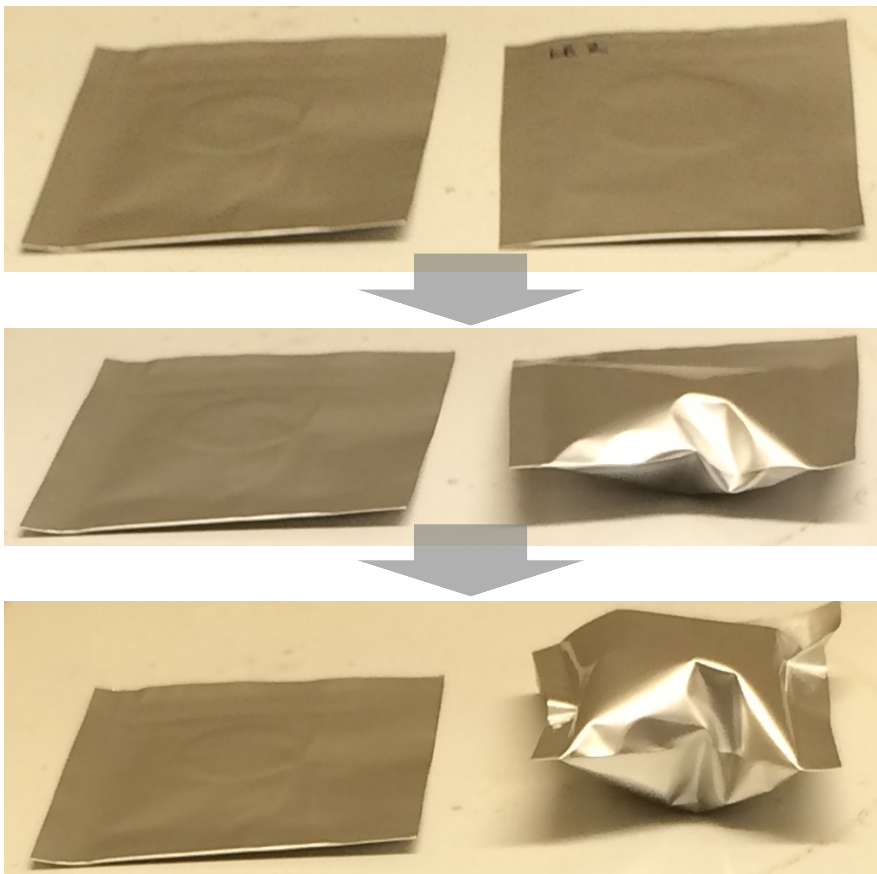
Conclusions by Dr. Kawai from the thermal analysis:

- Peak temperature of polymer electrolyte cell was higher.
- Peak height of highest peak of polymer electrolyte cell was smaller.
- The shape of highest peak of polymer electrolyte cell was more gradual.
- Heat generation rate from anode side was dominant for the one of full cell.
- **Polymer electrolyte seemed to suppress heat from lithium metal with electrolyte.**

Electrolyte + Lithium Reaction

Polymer electrolyte + Li at high temperature displays excellent stability- Polymer stabilizes lithium

Polymer Electrolyte   Liquid Electrolyte



Electrolyte + lithium metal sealed in laminate pouches

Heated on hot plate above 180°C (melting point of Li)

Liquid electrolyte pouch inflates with gas decomposition products

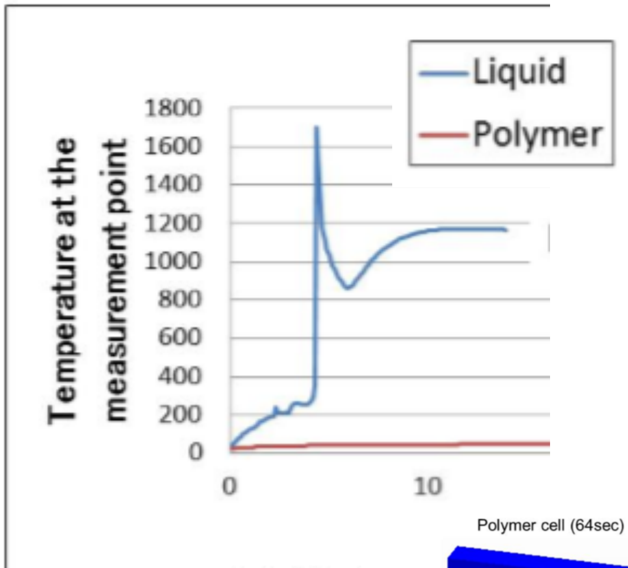
Ionic PE pouch has no change!

Simulations of Polymer Cell vs Liquid Cell

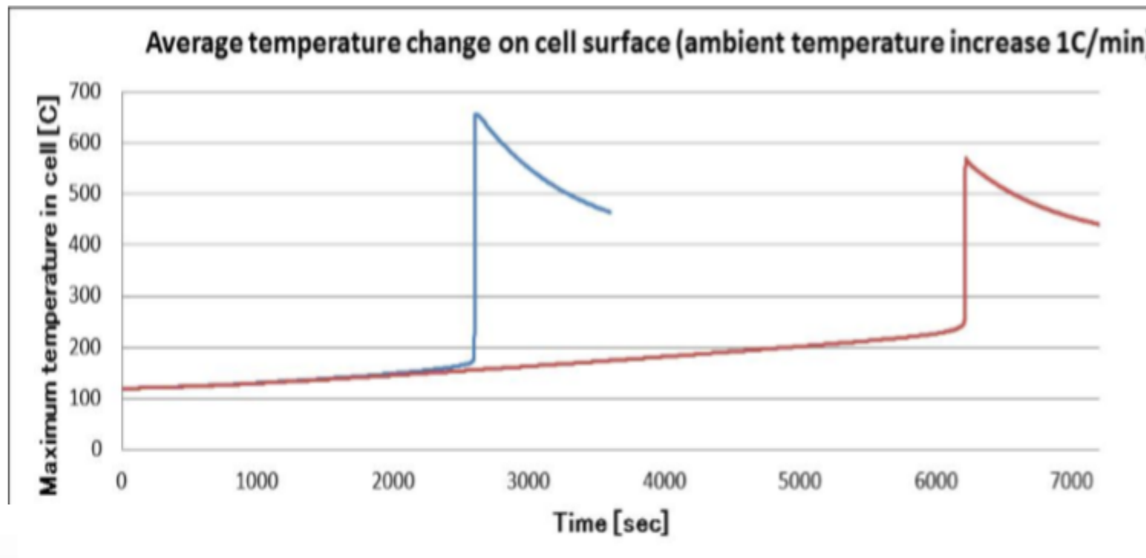
MITSUBISHI CHEMICAL
Tomohiro Kawai, Dr. Eng

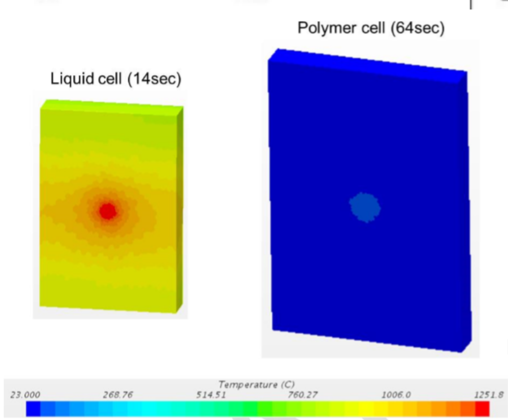
Calculated behavior for polymer electrolyte cell showed much safer performance for nail pen and oven test than liquid electrolyte cell

Nail Penetration



High Temperature Oven Test





Thermal simulation for nail pen of liquid electrolyte cell (>1000°C) compared to polymer cell (< 50°C) from finite element analysis

Propagation Model of Polymer Cell vs Liquid Cell

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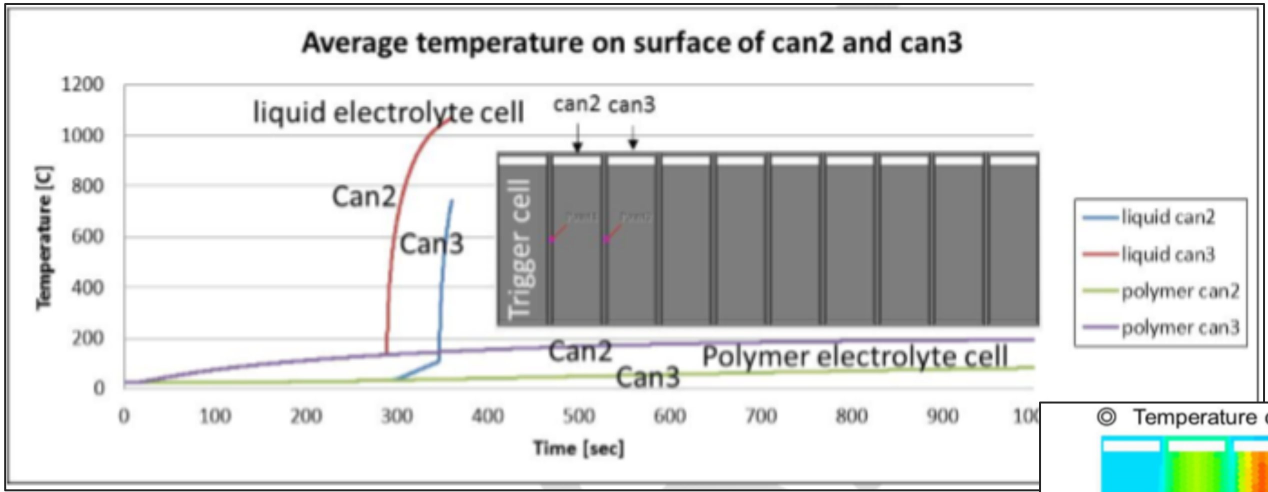
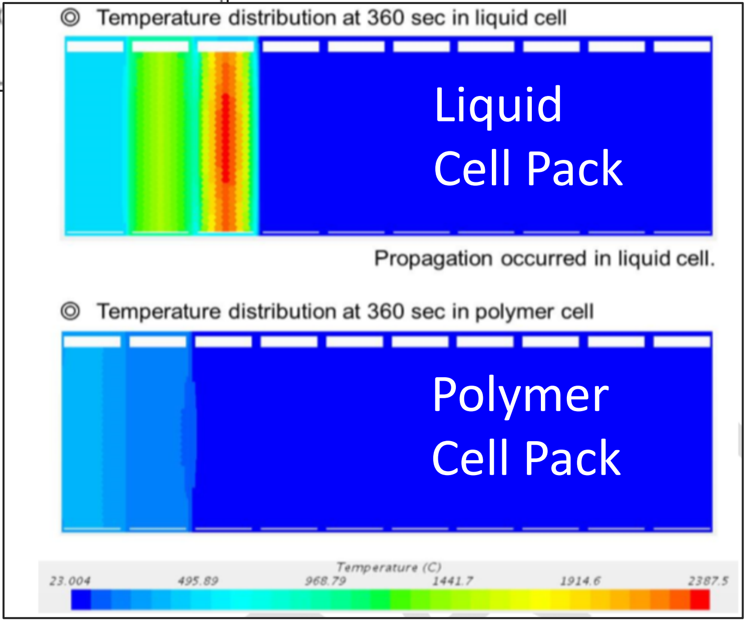
Tomohiro Kawai, Dr. Eng

Modeling of pack shows that thermal propagation occurred only for the battery module of liquid electrolyte cells



Max temp for liquid cell #2 > 1000°C

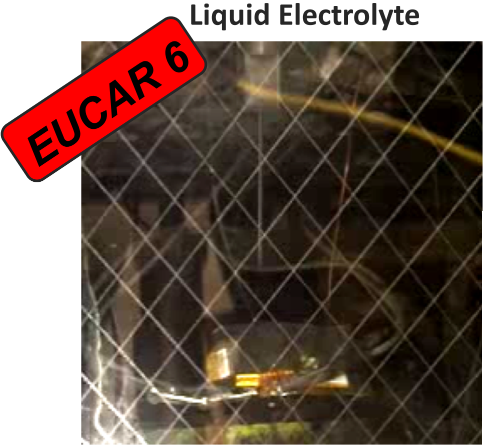
Max temp for polymer cell #2 < 200°C



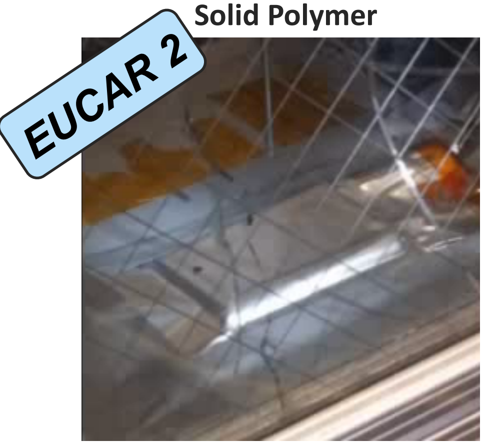
- Trigger cells were set at left end in the module and modeled to reach 800°C
- Modeling shows that cells with liquid electrolyte have propagation of thermal event to cells 2 and 3 in the battery pack, polymer cells show no propagation

1.5-2Ah Nail Pen Results: 125µm and 30µm Polymer Elyt

Liquid Electrolyte

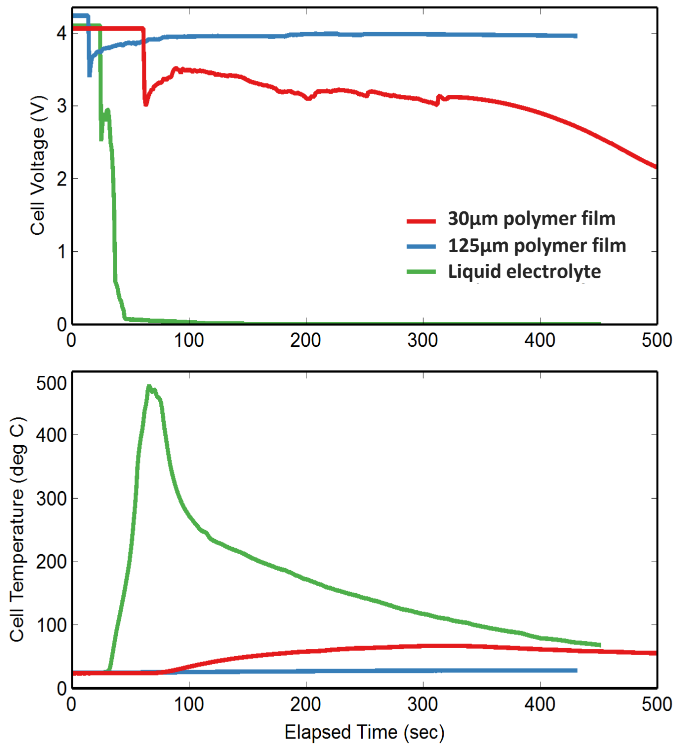


Solid Polymer



Nail Penetration Test:

Voltage and Temperature Data



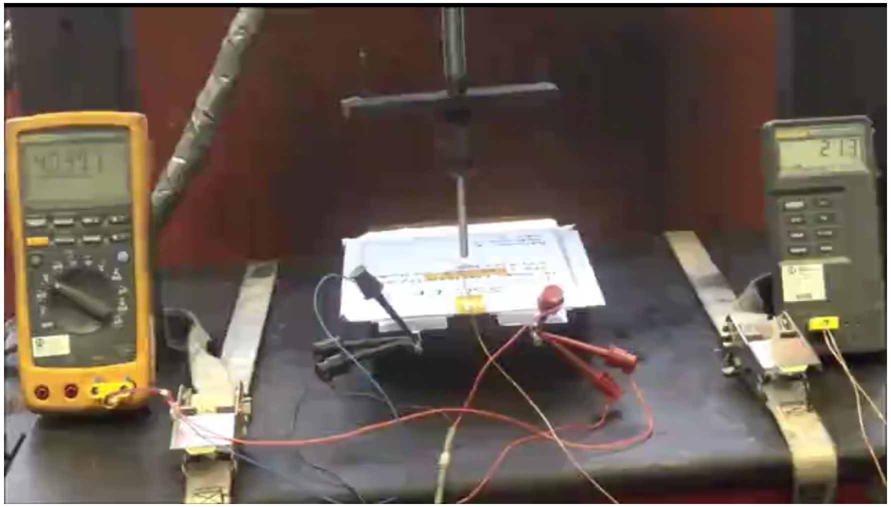
- NMC811 Cathode with Graphite Anode.
- 1.5-2.0 Ah Prismatic Cells at 100% SOC.
- Separator thickness was reduced to 30 microns
- First demonstration of a automated manufacturing process.
- Eurcar 2 performance for Solid Polymer (Pass).
- Superior Voltage and Temperature profiles for Solid Polymer.

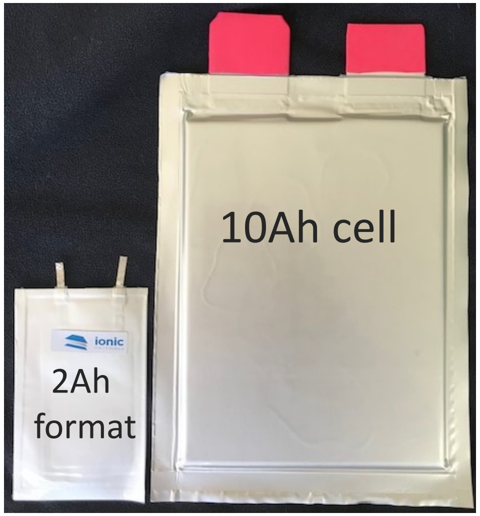
Cells with 30µm polymer film passed with EUCAR 2!

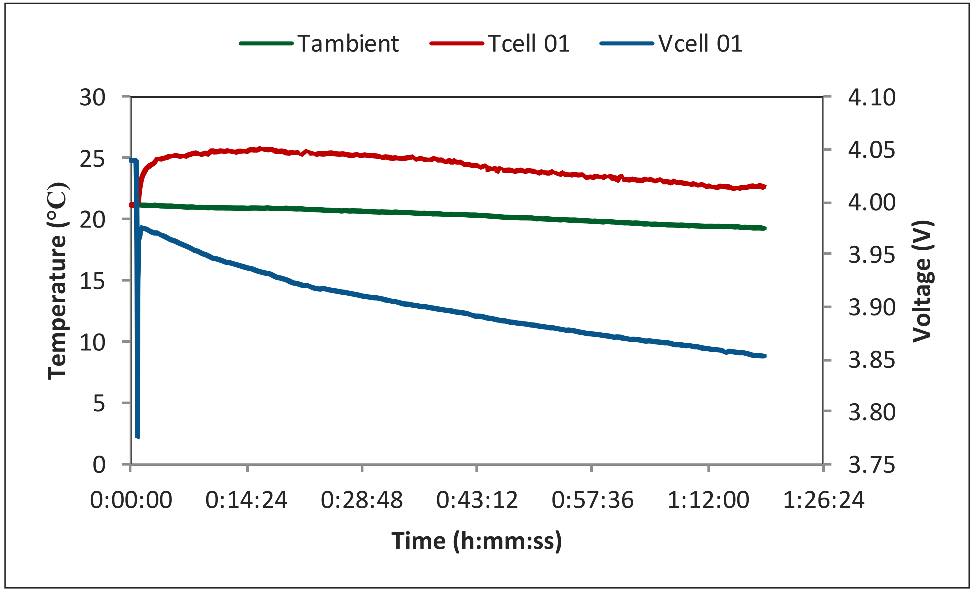
10Ah Nail Penetration Test Results

10Ah solid state cell passes nail pen test with EUCAR 2 rating!

- NMC811 Cathode with Graphite Anode.
- EUCAR 2 nail pen results!
    - No venting, rupture, or flame
    - No explosion or thermal runaway
- Voltage still at 3.8V after 1.5 hours after nail pen.
- Max temperature 26°C (5 degrees above ambient).







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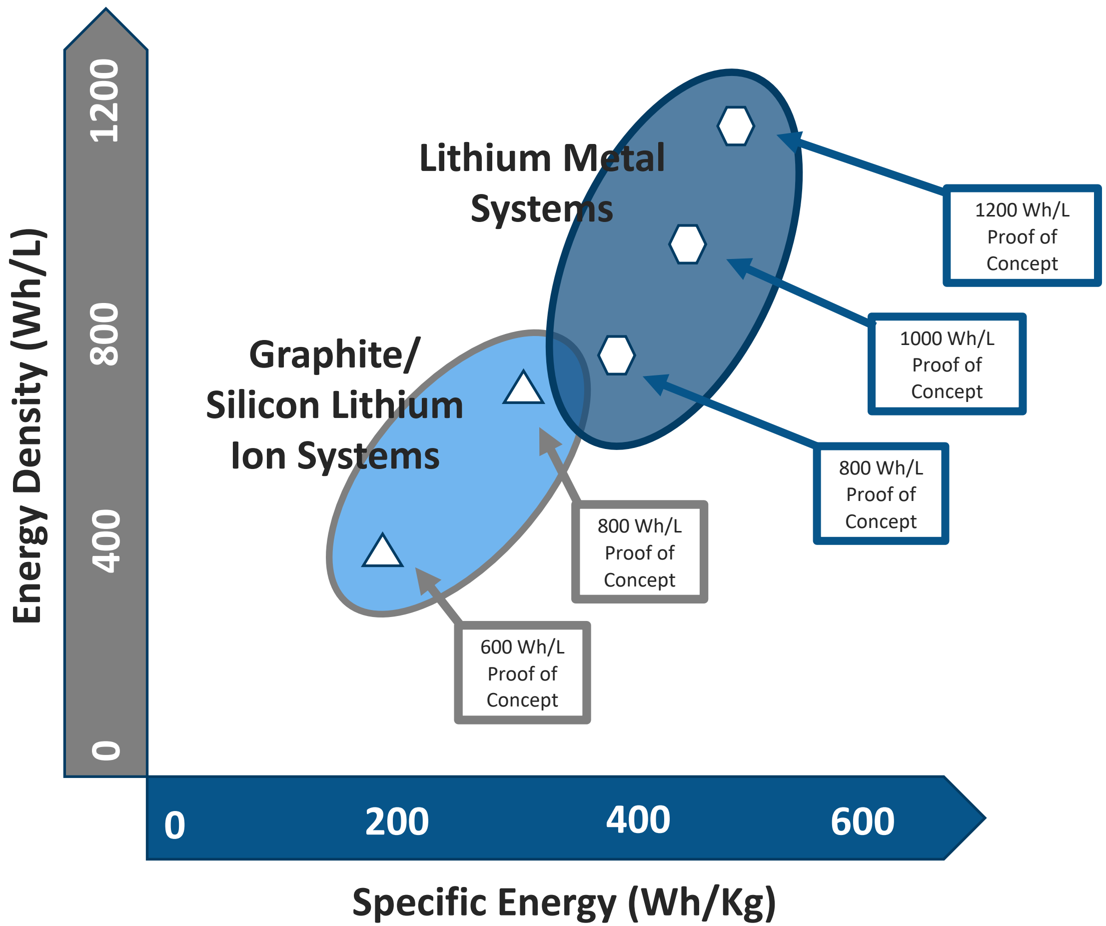
Next Generation: Lithium Metal Cycling

Ionic Materials: Chemistries of Interest

- Ionic Materials is partnering with key customers to develop leading edge chemistries
- Particular focus on Graphite/Silicon Lithium Ion and Lithium Metal



ARPA-e: Follow-on Funding

Approval received for additional two years for ARPA-e contract

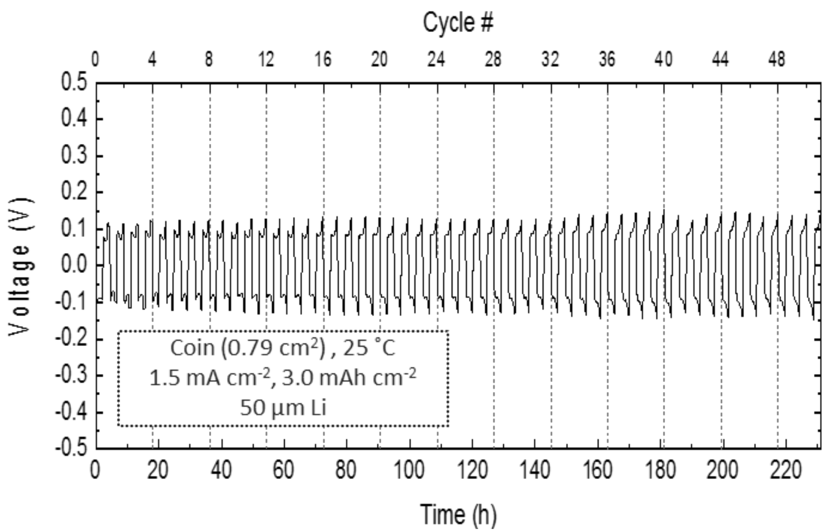
- Key technical focus areas for follow-on contract are:
  - Lithium polymer interface
    - Develop techniques to characterize surface of PE and Li, investigate Li metal coatings optimized for Ionic polymer.
  - Bulk property optimization
    - Dendrite suppression based on physical and mechanical properties of polymer electrolyte, conductivity optimization for Li cycling
  - Cathode optimization
    - Focus on developing higher areal capacity cathodes (> 3 mAh cm^{-2})
- Phase 2 milestones have been finalized
- Current projected contract time for Phase 2 is May, 2019.

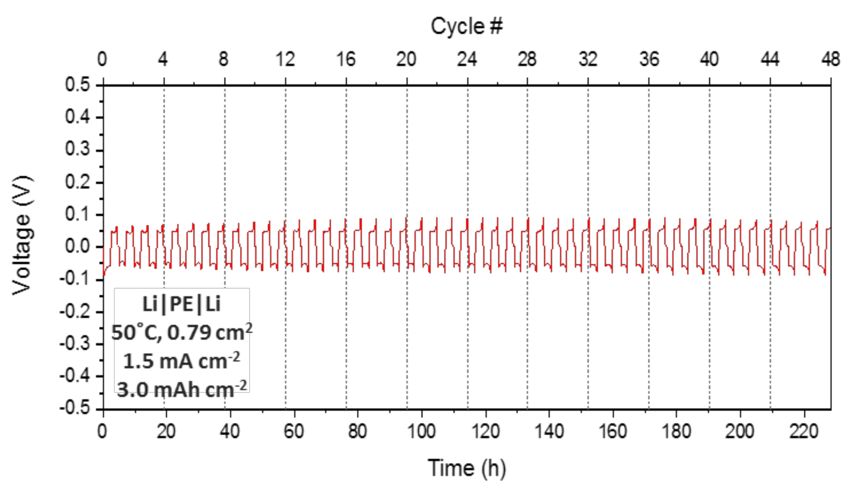
CHANGING WHAT'S POSSIBLE

Li/PE/Li Cycling

IM has demonstrated ability to reversibly cycle Li at high current densities and areal capacities.

- In addition to full cells, IM uses Li/PE/Li cells as a test vehicle to focus on Li anode and Li/PE interface development.
- IM's polymer enables reversible cycling of lithium at high current densities and areal capacities at both room temperature and elevated temperatures.

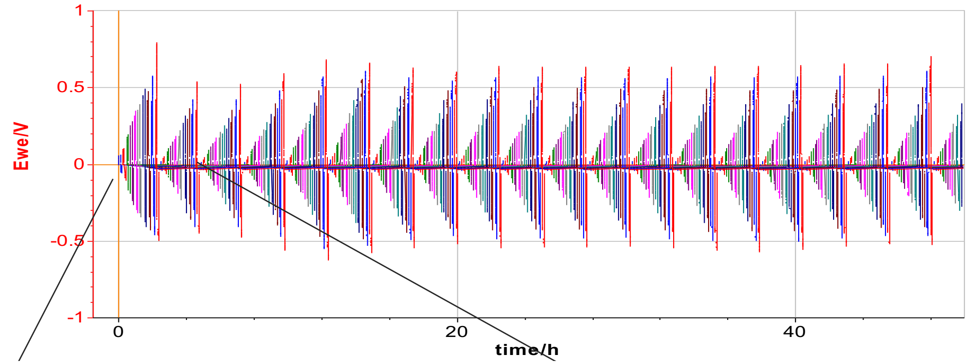




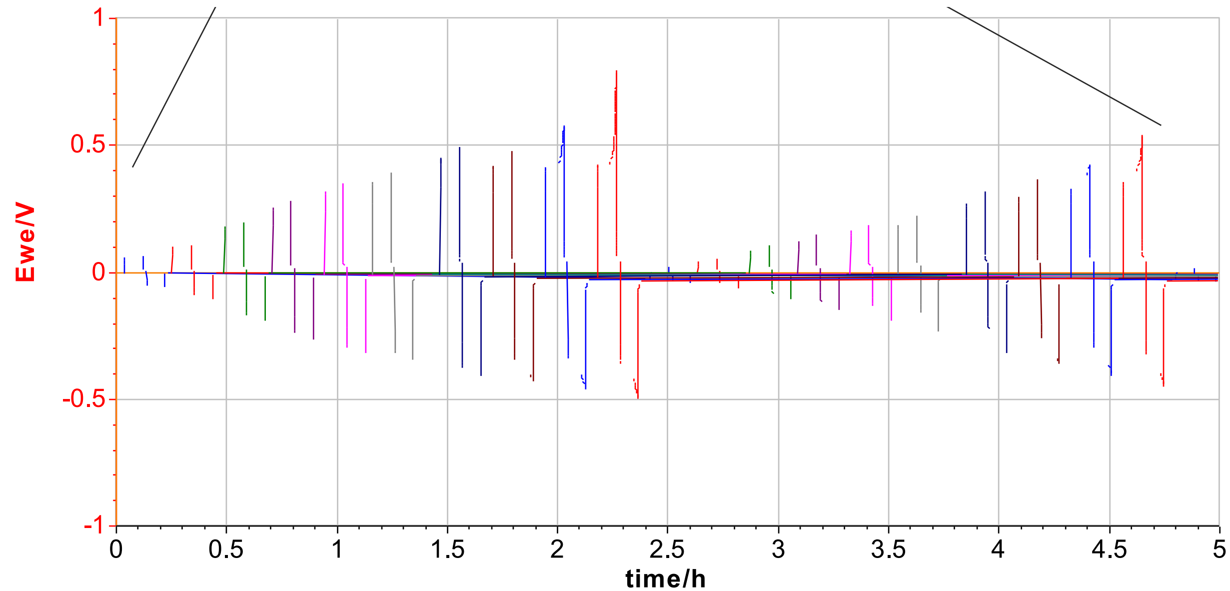
High Rate Cycling of Li Metal Cells

Li cycled at current density up to 10 mA cm^{-2} in “staircase” cycling test.

Test demonstrated ability of PE to handle high current densities up to 10 mA/cm^2 for many cycles, equivalent to > 2C-rate



“Staircase” test: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 mA/cm^2



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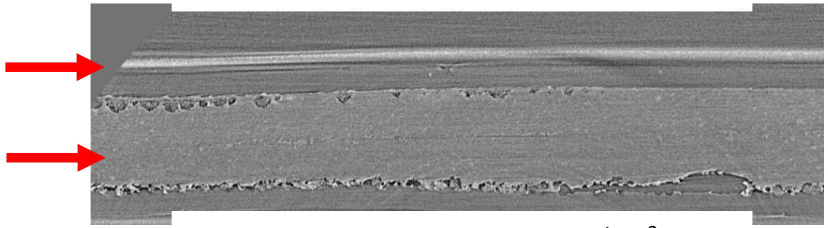
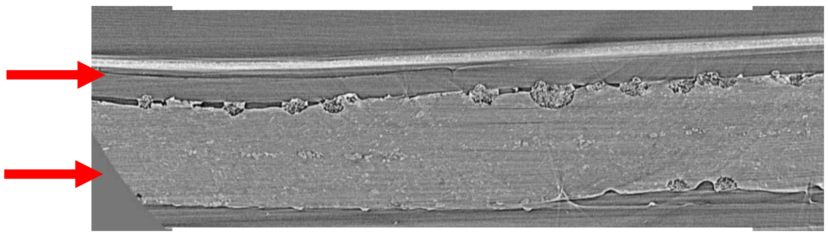
CT Imaging of Li/Polymer Interface – Tuning for Li Metal Cycling

Micro CT imaging of Li/PE/Li cells shows that new Ionic Materials Polymer demonstrates resistance to dendritic Li formation

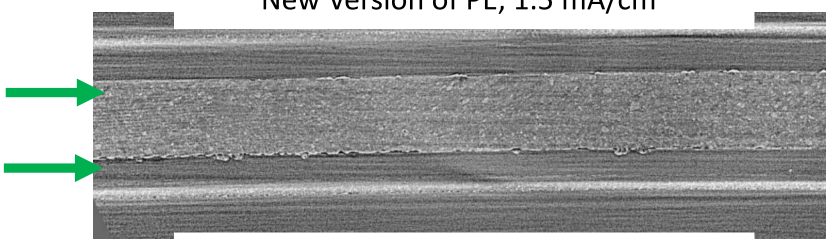
Old Version of PE, 1.5 mA/cm^2



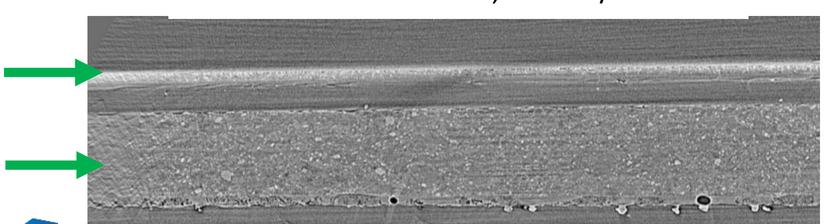
Old Version of PE, 0.5 mA/cm^2



New Version of PE, 1.5 mA/cm^2



New Version of PE, 0.5 mA/cm^2



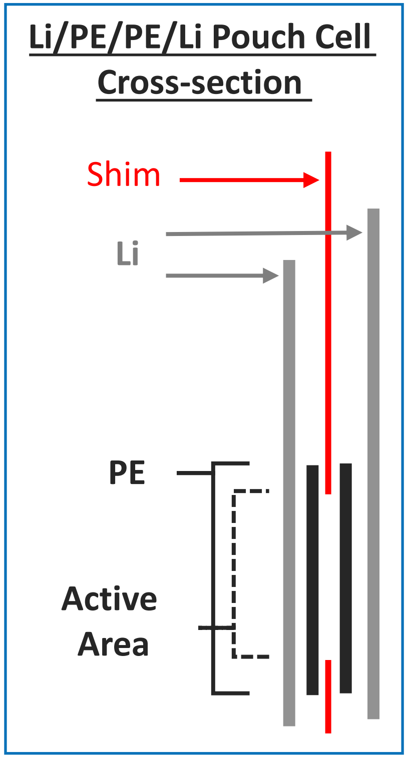
Significant improvement in PE film since AABC talk last year

Old Version of IM PE: large number of Li structures at interface

Arrows indicate Li/PE interface
- Red arrow: Old IM PE
- Green arrow: New IM PE

New Version of IM PE: much more resistant to mossy Li formation

Specialized pouch cells designed for micro-CT imaging



Disruptive Chemistry: Rechargeable Alkaline

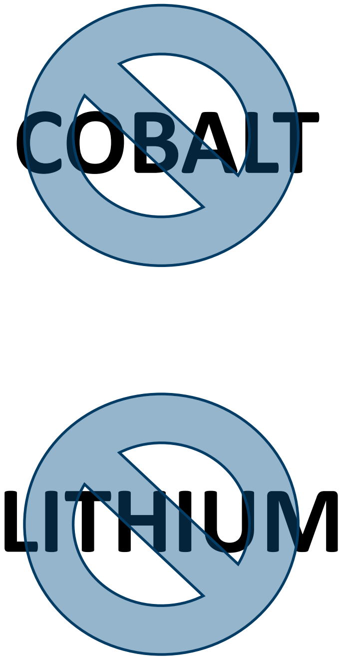
Rechargeable Alkaline: A World First

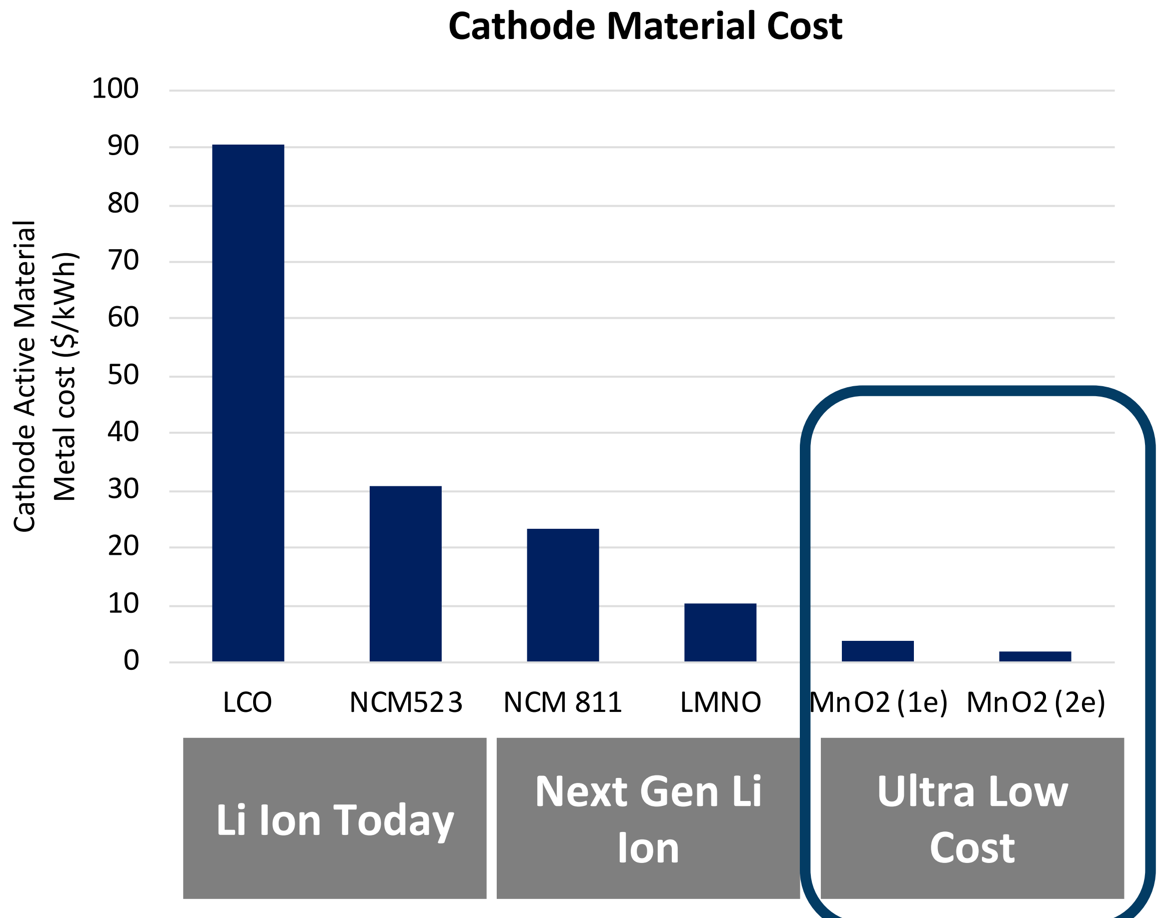
- Ionic Materials is the first company in the world to prove that Rechargeable Alkaline can be made viable
  - Unlocks tremendous potential for EV and grid storage applications

- Alkaline chemistries have the potential to match or exceed Li -Ion performance at a cost of **$50 kWh or lower**
  - Lower cost cathode materials
  - Lower cost anode materials
  - Lower cost of inactive materials
  - Lower cell processing costs
  - Trouble free supply chains

Ultra Low Cost Rechargeable Battery

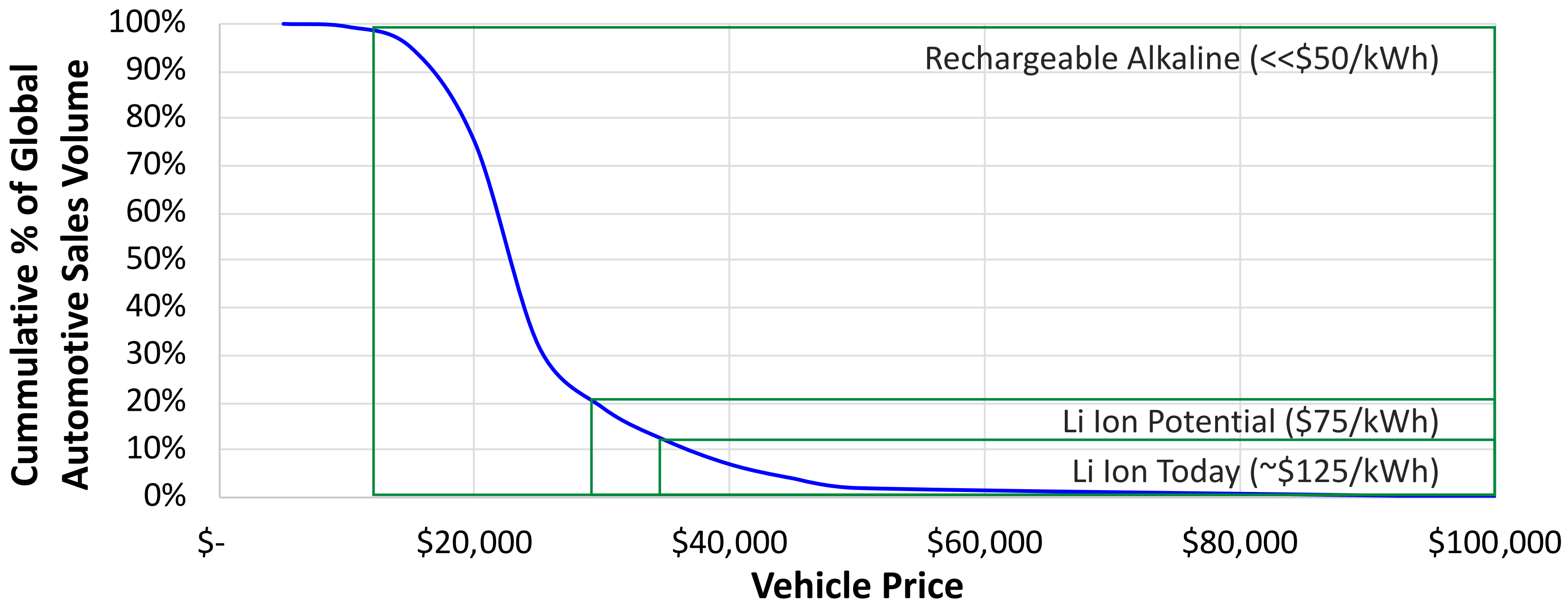
- Our polymer has the ability to enable ultra low cost rechargeable batteries
- These batteries eliminate expensive cobalt and lithium, replacing them with **cheap and abundant zinc and manganese**





Low Cost Opens New Markets

- Low cost of alkaline enables the creation of new markets
  - EVs for entry-level auto segments
  - Stationary storage – opportunity to rethink the grid
- Pathway to sub $50/kWh cell price point



- Sales data from Green Car Reports
- Cell costs listed here, assume pack cost adds 30%
- Assume 60kWh needed to meet range requirements & that pack cost cannot be >20% total vehicle price

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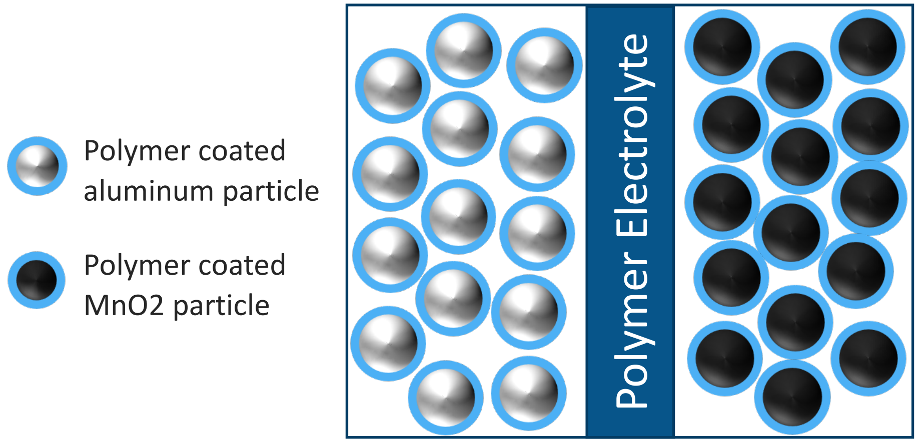
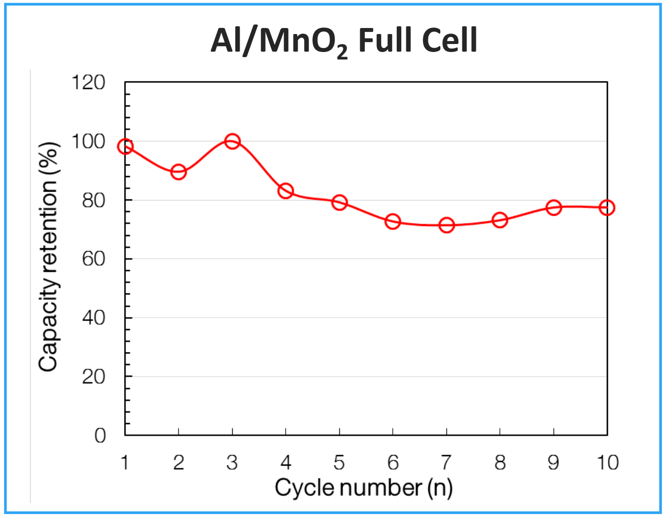
Next Generation Anode - Aluminum

ARPA-E has awarded IM *$2M* for development of a 1000 Wh/L rechargeable aluminum cell utilizing IM's polymer





- Ionic has demonstrated encouraging initial results with Al/MnO_2 cells, stable cycling with **80% capacity retention** over 10 cycles
- Aluminum utilization proven to date: **1200mAh/g** specific capacity (>40% higher than the theoretical max of zinc)
- To our knowledge, this is the **FIRST** in the field, rechargeable Al/MnO_2 with OH ion based polymer electrolyte!

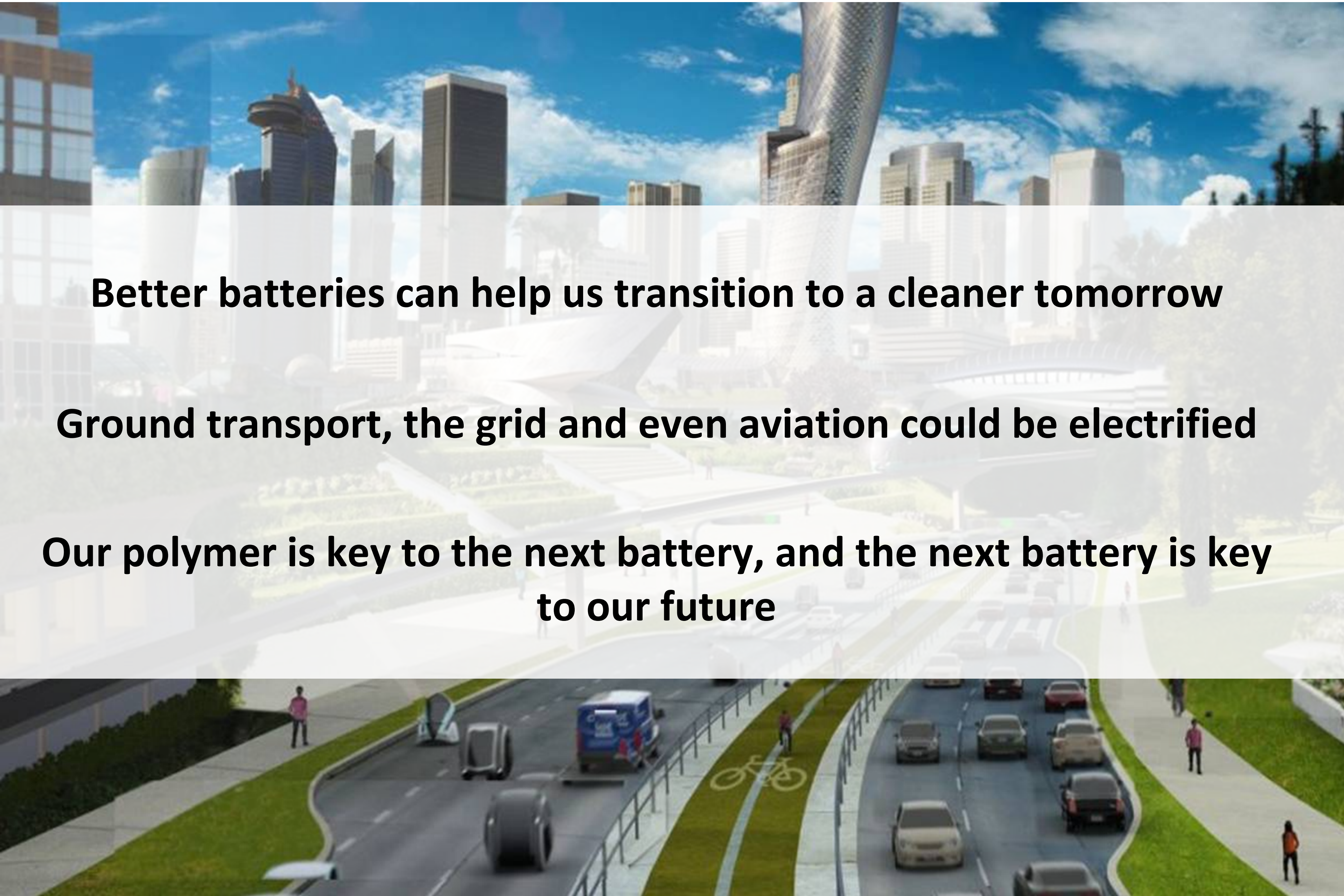
2021 Goal – 1000 Wh/L, 100 cycles to 80% capacity retention, 2 Ah cell capacity

Conclusions

Summary

- IM is working with cell makers to develop all solid state battery for EV industry.
- Initial products will be NCM811/Gr-Si with eventual goal of Li metal.
- We have shown significant safety results with cells in 1.5 – 10 Ah.
- 10Ah cells are being fabricated automatically with existing battery manufacturing equipment/lines.
- Cycling results in 10 Ah cells show promising results in 0°C-60°C range.
- IM roadmap is to further improve Ionic conductivity from 1 mS/cm to 10mS/cm at room temperature.
- Goal: Cell companies to scale to 65Ah cells in 2019, and characterize as A sample. IM to create a pilot line in 2019 to demonstrate high volume manufacturing of polymer.

Our Vision: Enabling Electrification



Better batteries can help us transition to a cleaner tomorrow

Ground transport, the grid and even aviation could be electrified

Our polymer is key to the next battery, and the next battery is key to our future