PneumatiCoat
TECHNOLOGIES
Commercializing "nano"

Atomic Layer Deposition: Past, Present, and Future

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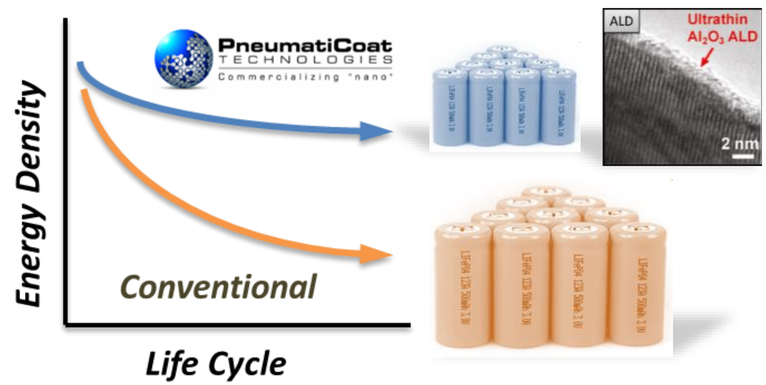
Company Overview – PneumatiCoat (PCT)

- Technology
  - Improve pack performance and cost using encapsulation coatings that deliver sustainable $/kWh advantages
- Value Proposition
  - Increased performance
  - Lower cost per kWh
- Atomic Layer Deposition (ALD)
  - Toll Coating
  - Service Contracts
  - Production Systems
  - Grant Opportunities

PCT's Impact: BRINGING VALUE TO CUSTOMERS AND OEMs

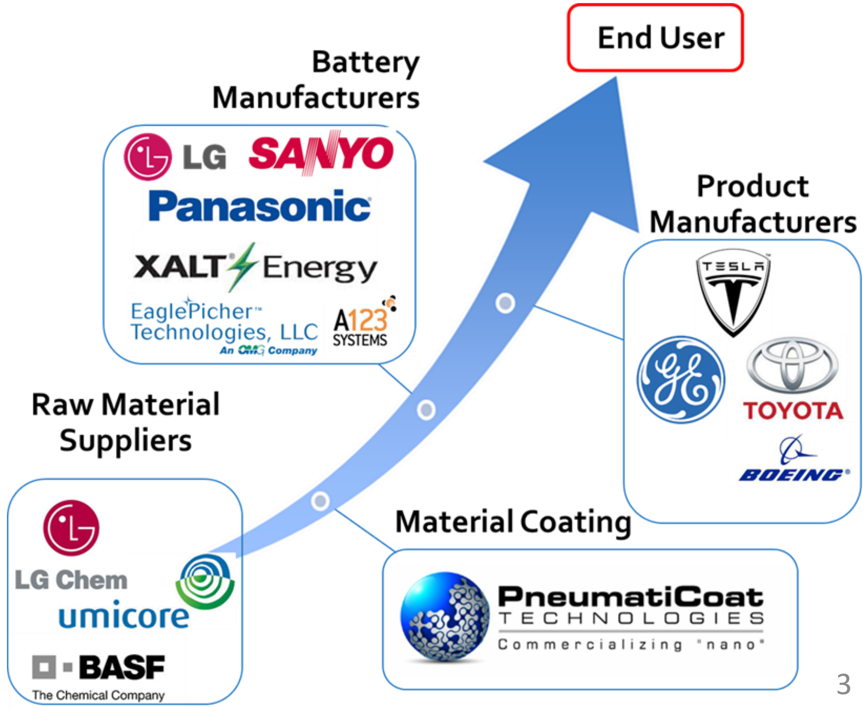
HELPING TO MAKE BATTERIES SMALLER, LIGHTER, SAFER AND CHEAPER



Vision Statement: To be the world leader in innovative materials solutions, and to create safer and more efficient products.

Outline

- Active Materials and Encapsulation Benefits
- Encapsulation Processes and ALD Background
- ALD processing: Current/Future Advantages and Historical Disadvantages
- Capabilities and Demonstrated Benefits of ALD
- ***Commercial*** ALD Solutions
- Summary and Recommendations

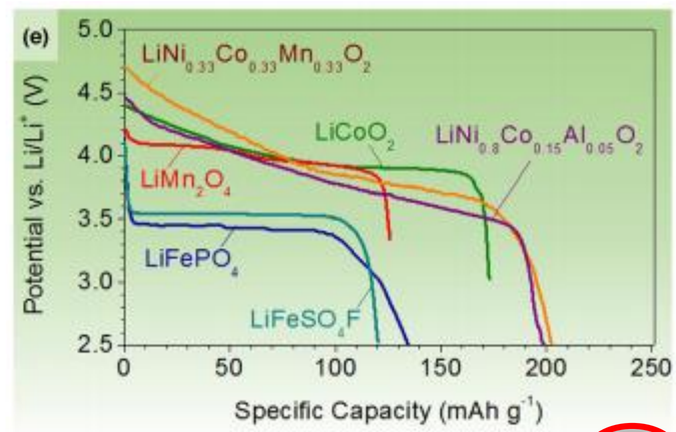


Active Materials

- Incremental improvements in quality, energy density over 30 years

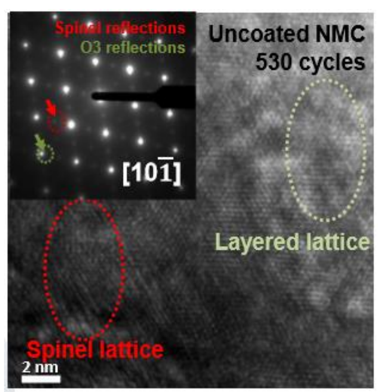
> The 1980s and 1990s recorded many successful discoveries and the commercialization of oxide-based cathode materials such as the layered compounds $LiCoO_2$, $LiNiO_2$, spinel $LiMn_2O_4$, and mixed oxides (e.g., $LiMn_{1.5}Ni_{0.5}O_4$, $LiMn_{0.33}Co_{0.33}Ni_{0.33}O_2$, and $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$) [6–10]. Among the massive research carried out on oxide insertion compounds, in 1997, Padhi et al. introduced the concept of polyanionic compounds as an alternative class of cathodes, $LiFePO_4$ being the first example [11,12]. In the lithium-battery field, the

B. Scrosati et al. Lithium Batteries: Advanced Technologies and Applications. 2013.



N. Nitta et al. Materials Today 18, 5, 2015.

- However materials still suffer from ***surface-driven degradation***:
  - Electrolyte Interactions
  - Phase Transitions
  - Oxygen Loss
  - Particle Fractionation
  - Conductivity Loss
  - SEI / Resistivity Build-up



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Next Gen Performance Requires Coated Particles

KEY PROBLEMS AT 4.5 V CHARGE

Degradation During High Temp Storage (60°C, 90°C)

- Ni^{4+}, Co^{4+} dissolution
- Accelerated interfacial reactions with electrolytes

Degradation During Cycling

- Anisotropic volume expansion/contraction
- Ni^{4+}, Co^{4+} dissolution

Degraded Thermal Stability

- Oxygen extraction from lattice
- Exothermic reaction with electrolytes

SOLUTIONS AND CRITICAL TO QUALITY ATTRIBUTES

Surface Coatings

- CP coating
- ALD coating

Electrolyte Modification

- Electrolyte composition
- Additives

Bulk Material Modification

- Dopant selection
- Improved homogeneity

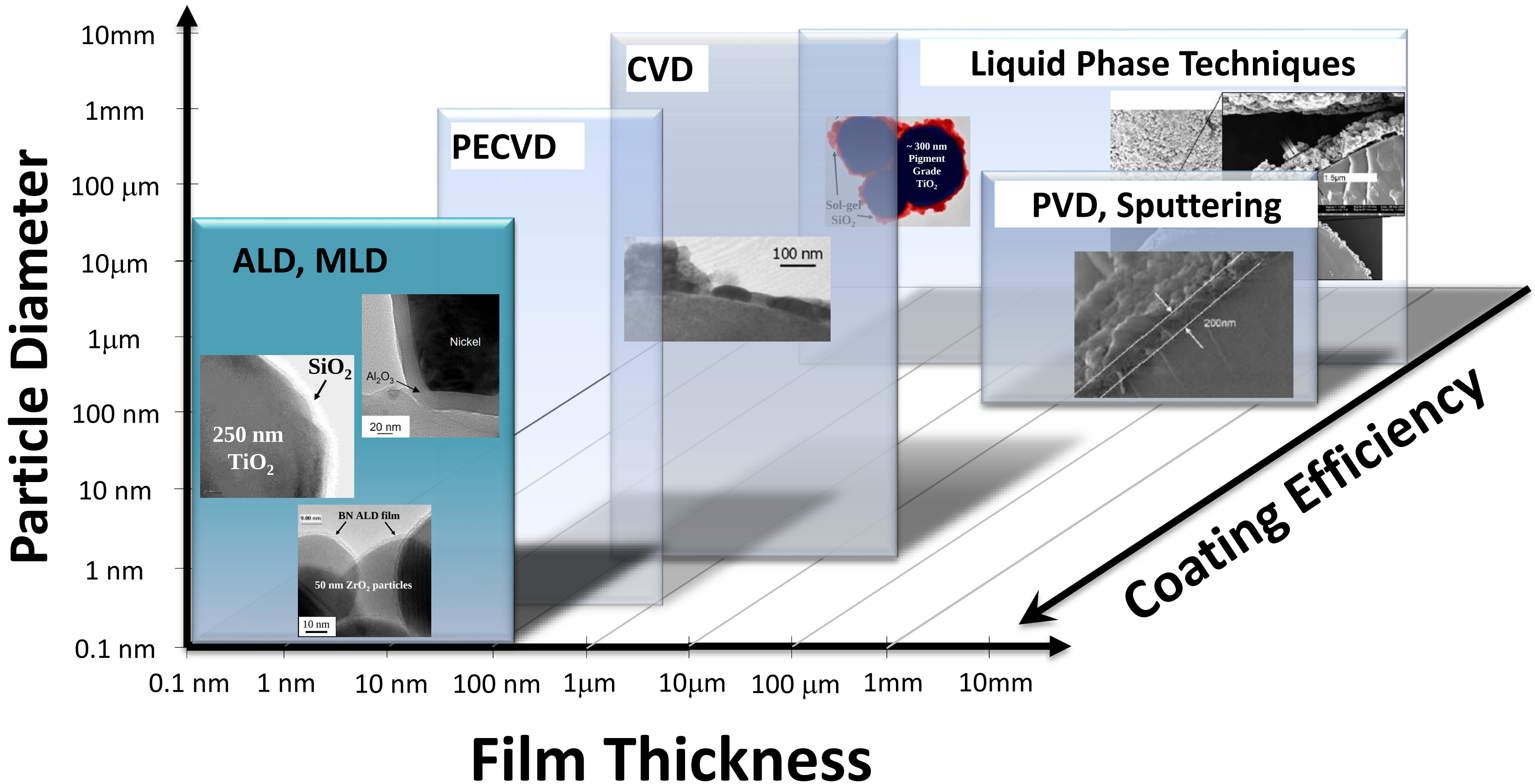
Critical to Quality

- Minimal Loading
- Homogenous Coating
- Homogenous Dispersion
- No Side Reactions
- Minimal Post-Treatment Steps
- Thin enough to not create resitivity
- Durable enough to provide integrity

Problems: capacity decrease, lack of improvement of structural instability

Adapted from Figure 3 of J. Cho, P.G. Bruce et al., Angew. Chem. Int. Ed. 2012, 51, 9994 – 10024.

Process Windows of Coating Techniques



ALD offers precision control required to prevent resistivity build-up due to coatings

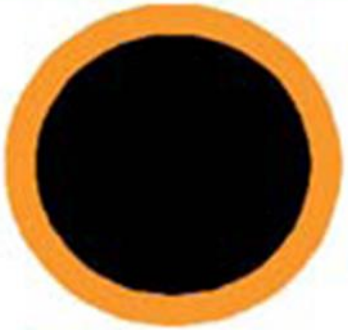
Next Gen Performance Requires Coated Particles

Rough Coating (Co-Precipitation)

- Lots of bared area.
- Protection was not maximized.

Improved performance deteriorates due to inconsistent coating

Core-Shell (Co-Precipitation)



- Coating shell composes of multiple layer of nano particles.
- Thick coating layer impede the transport of electron and Li^+.

Thick, consistent coating causes high resistivity

Ultrathin Film Coating (ALD)

- Tunable thickness.
- Complete coating.
- Precise control.
- Can be obtained by ALD,

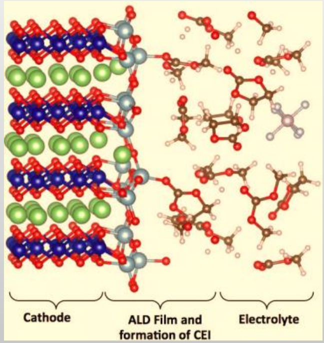
Ultrathin consistent coating has lasting performance with no resistivity impacts

Adapted from:
Z. Chen, Y. Qin, K. Amine, Y.-K. Sun
J. Mater. Chem. 2010, **20**, 7606-7612

Rational Design of Optimal Coatings

Quantum simulation of oxides:

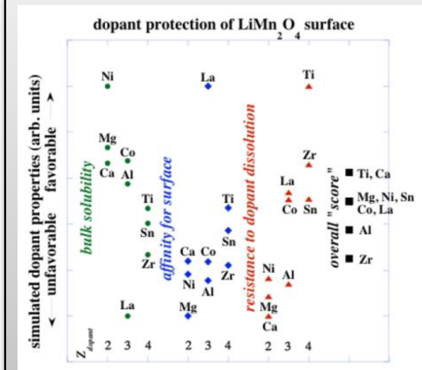
- Single non-porous monolayer is sufficient to mitigate electrolyte degradation



Courtesy of C. Musgrave
University of Colorado at Boulder

- Chemically bonded film (ALD) is the most durable solution

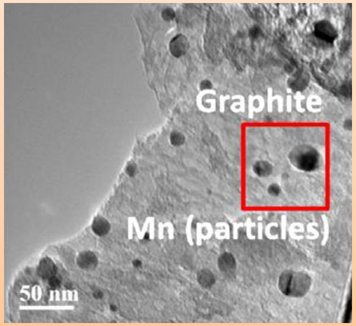
- Simple ALD coatings can lithiate and fluorinate in situ



Courtesy of M. Thackeray
Argonne National Laboratory

- Complex ALD coatings further enhance thermal, mechanical and electrochemical stability

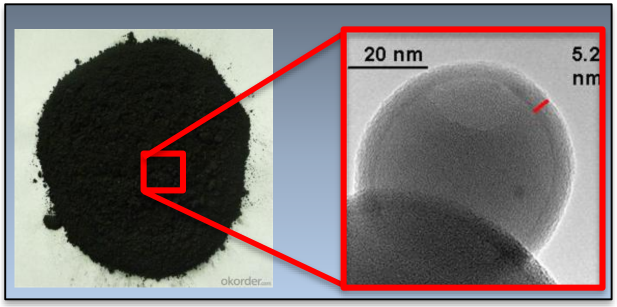
Failure Analysis from LNMO/Graphite Cell*

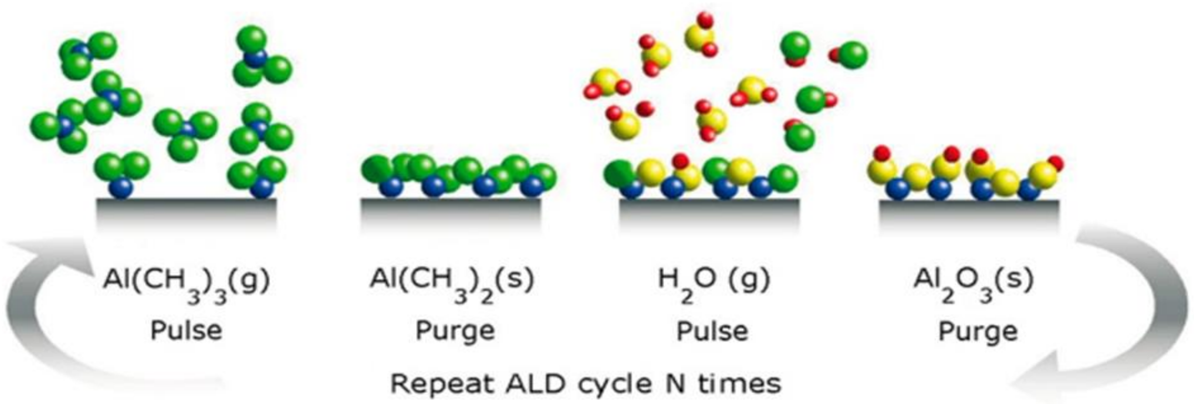


Mn from Cathode Deposits on Anode

* X. Xiao et al. Electrochemistry Communications 32 (2013) 31–34

Overview of ALD Process





- Gas phase process
- No line-of-sight restrictions
- Self limiting
- Sub-nanometer control
- Pinhole free

Particle ALD invented

1992

Historically: Slow, Expensive

Zero Manufacturing Innovation

Zero Commercial Adoption

2011 – PCT Tech Validation

2012 – 3 kg/hr Prototype

2013 – DOE SBIR Phase I & II

2014 – 200 kg/day Pilot Line

2015

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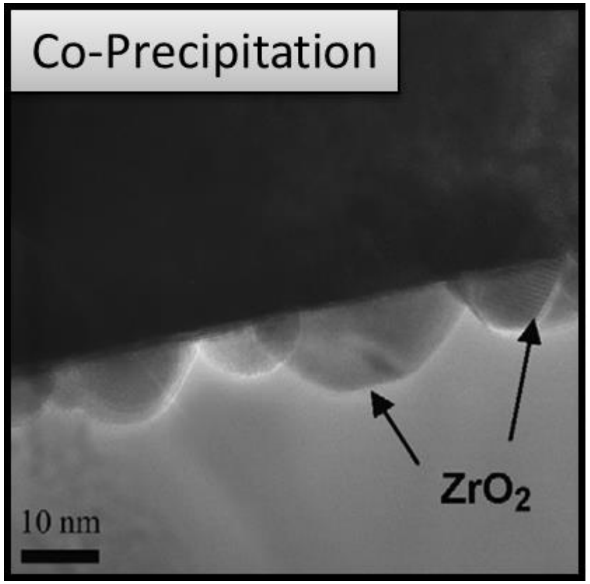
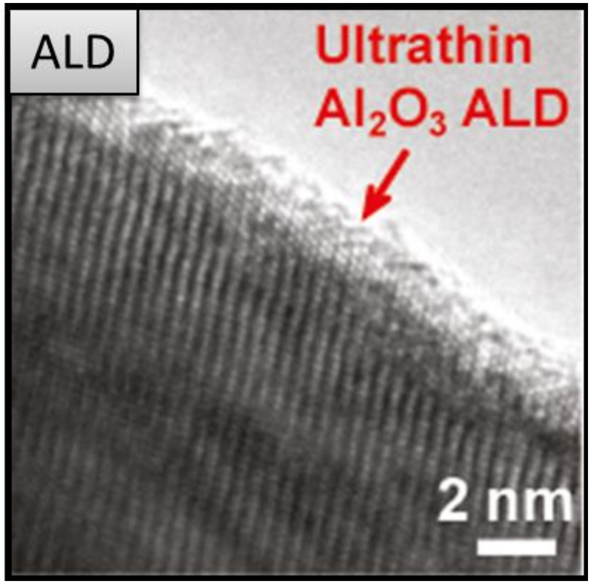
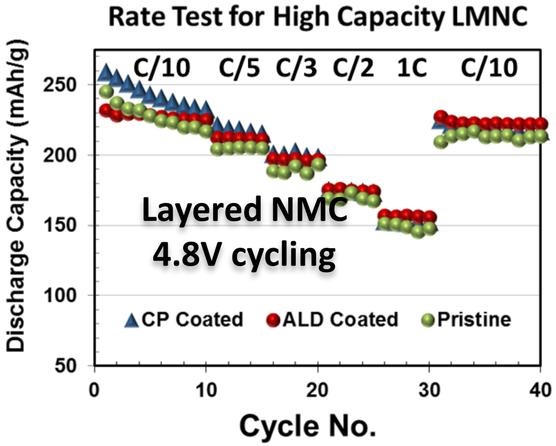
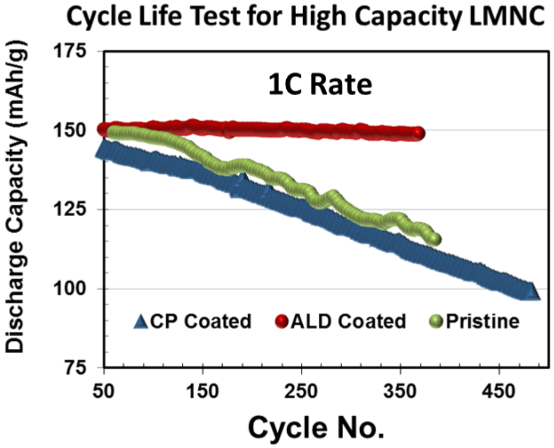
Direct technology comparison: Li-ion Batteries

Material efficiency is the difference









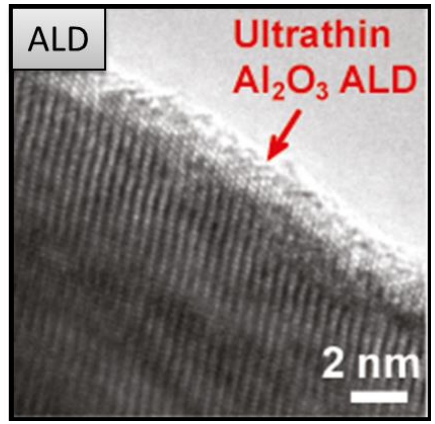
ALD delivers improved long-term performance at reduced material costs

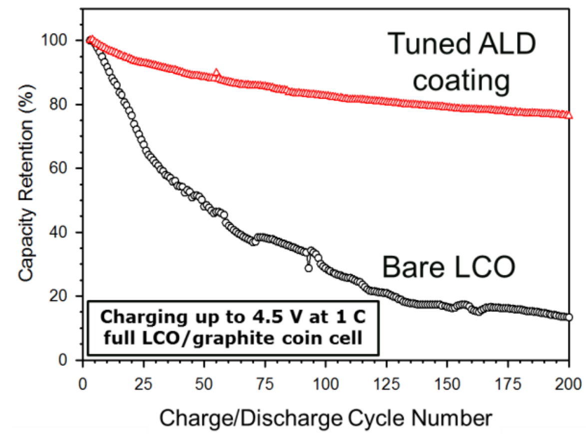
US Patent 8,993,051

ALD provides enhancements to ALL chemistries

Particle ALD delivers clear, low-cost value propositions for all market applications

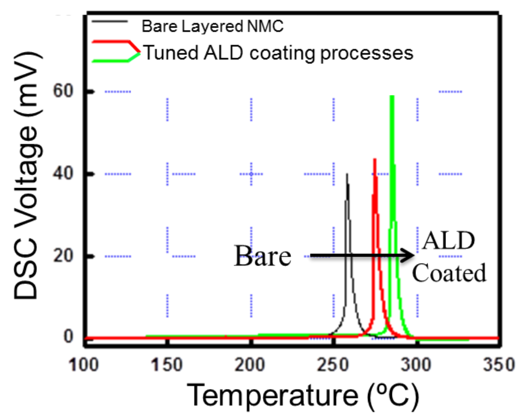
- Increased capacity retention
- Higher temperature stability
- Greater over-voltage protection
- Faster charge/discharge rates
- Reduced Cost of Ownership

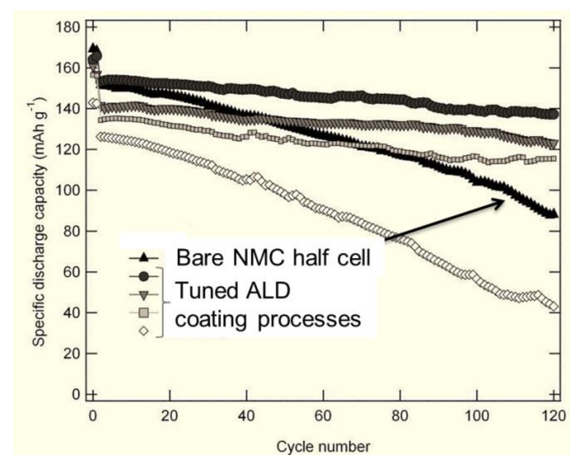




Clear scale-up roadmap:
High throughput spatial ALD processing system for particles

The Challenge:
No silver bullet coating, all must be optimized by type

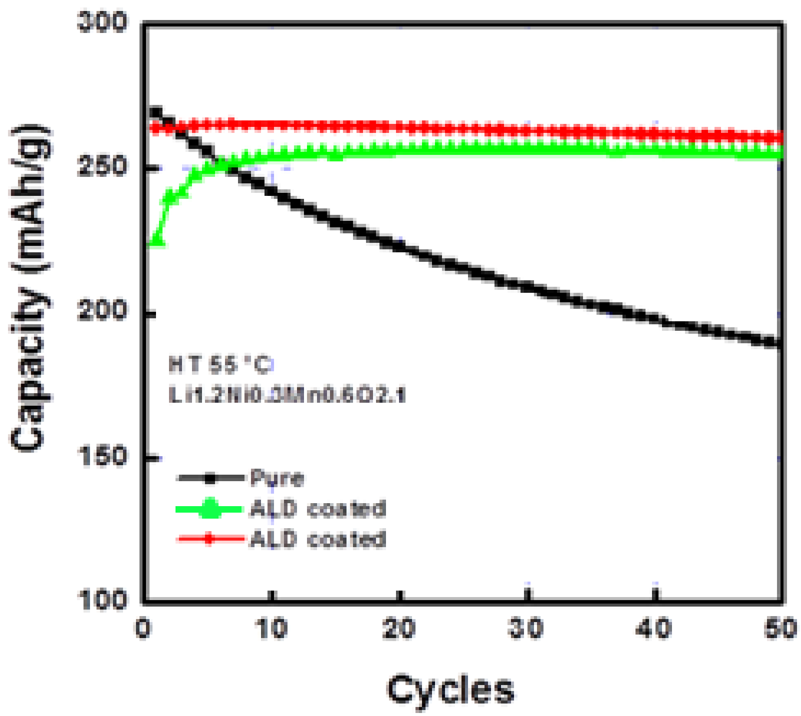


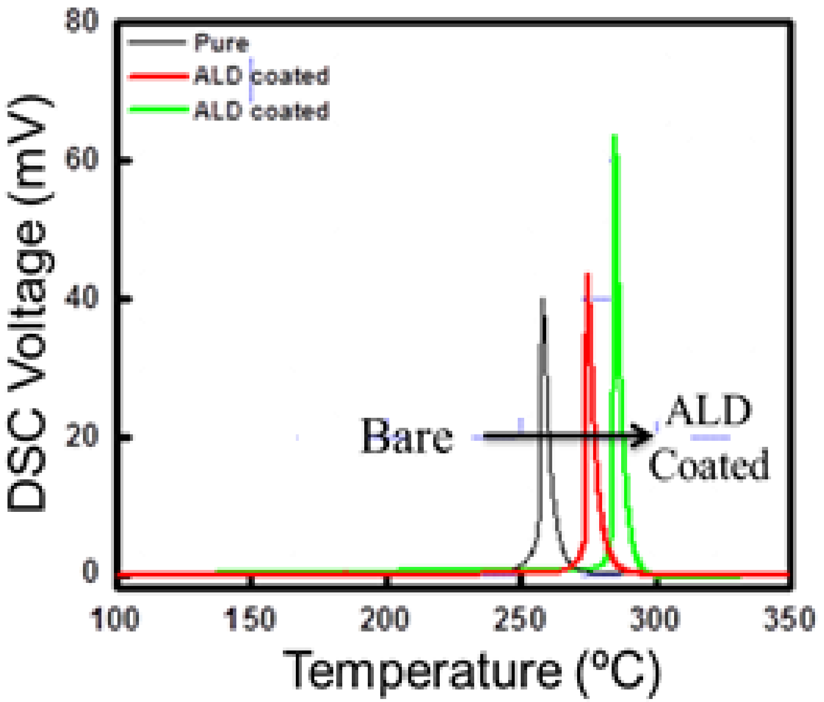


References for Scott et al, Jung et al., Riley et al., available upon request

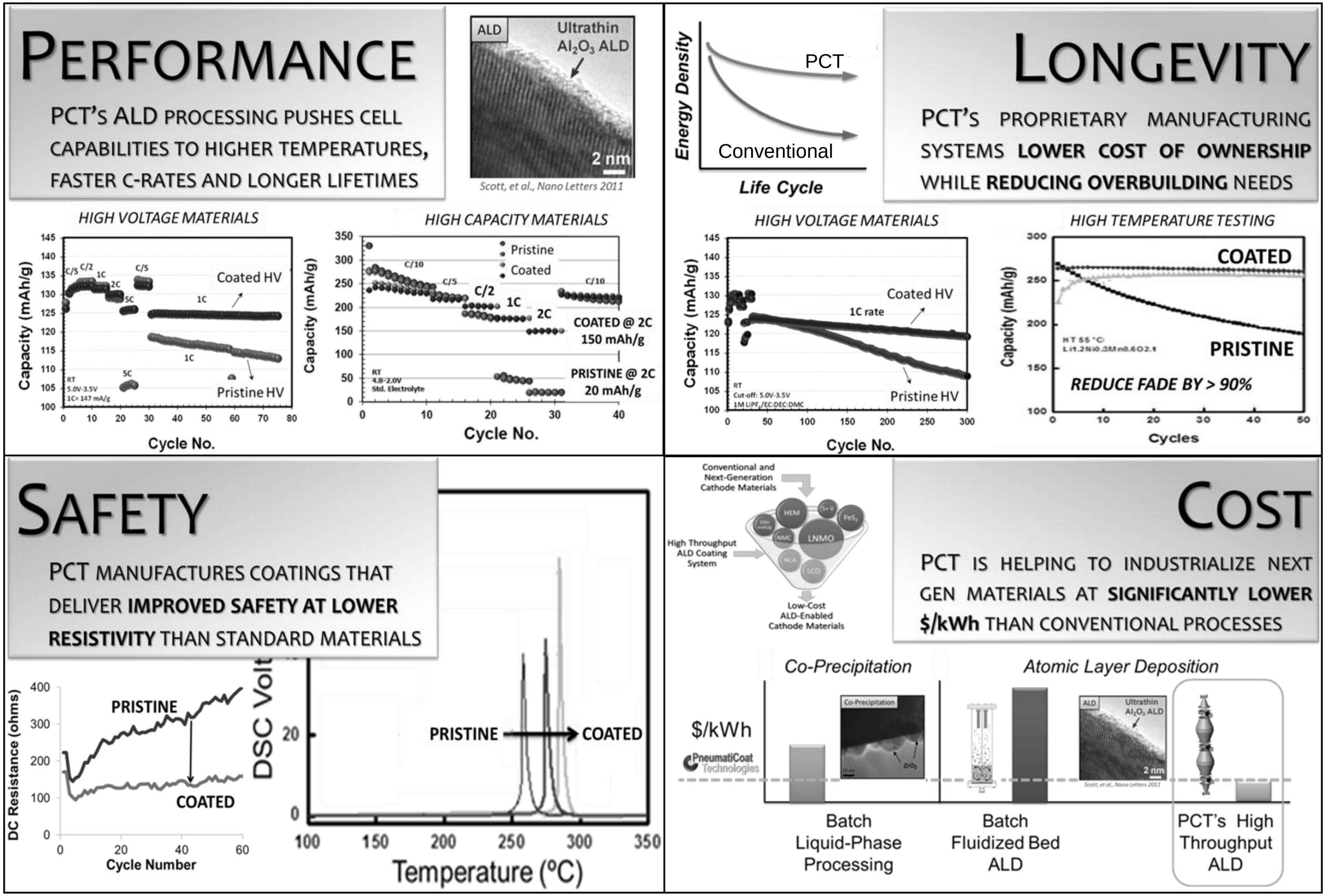
High Temperature Performance and Safety

- High temperature performance
  - Demanding applications
  - Reduced cooling requirements
- Safety Improvements
  - Exothermal reaction temperature increased by 40°C





Energy Storage Benefits of ALD



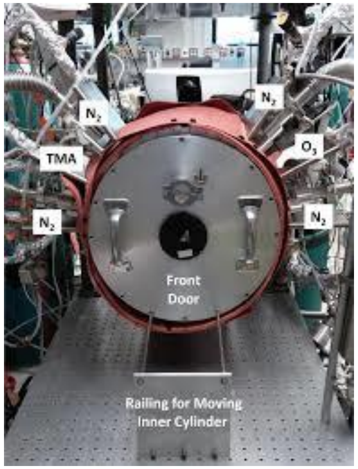
Common ALD Techniques

- Lithium-ion Batteries
  - Particle vs. Electrode
- Particle ALD
- Electrode ALD

Electrode - Batch

US Patent 9,284,643

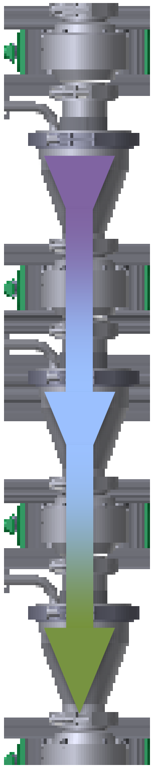
Particle - Fluidized Bed



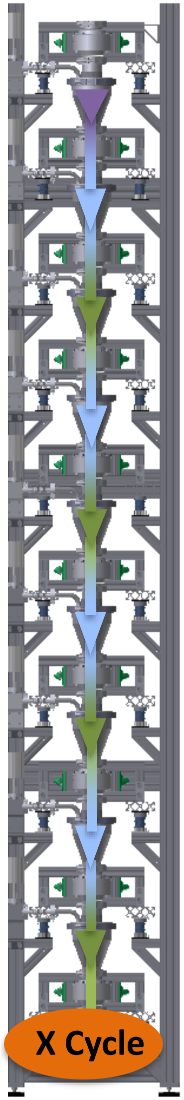
Electrode – R2R

Particle – Semi-continuous

High Throughput Spatial ALD (Particle)

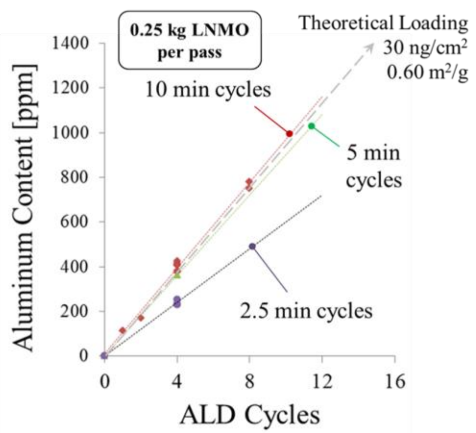


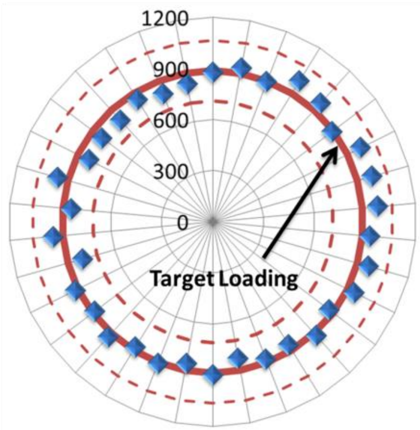
- Excellent process control
- Throughput independent of number of cycle
- Scalable



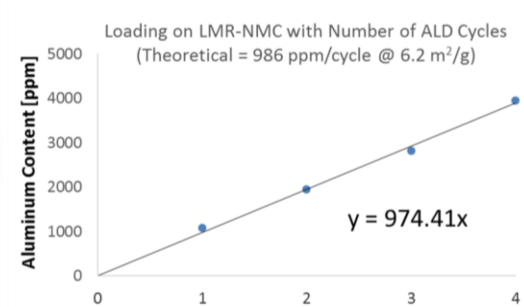
High Throughput Spatial ALD (Particle)

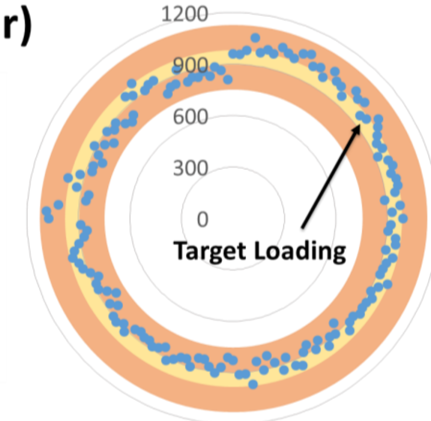
PROTOTYPE SCALE (3 kg/hr)





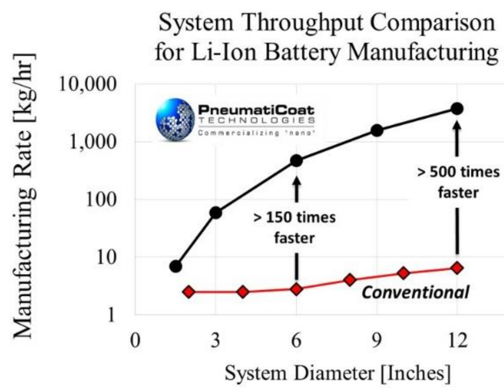
PILOT SCALE (15-25 kg/hr)



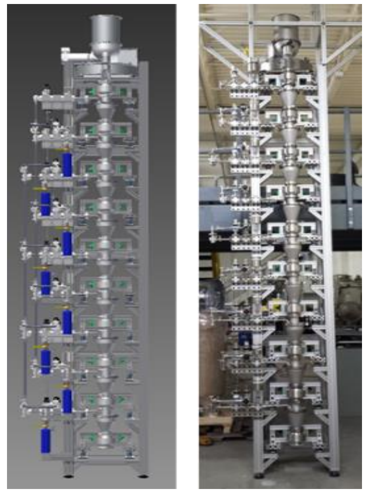


Particle Advantages

- Cost Effective
- Drop in (front-end or back-end)
- Excellent quality control
- Near-Zero waste
- Demonstrated throughput
- Robust coatings



Particle ALD Commercial Roadmap



To Be Installed at Production Facilities

2012	April 2015	2016/2017	2018
1.5 in.	3 in.	6 in.	9-12 in.
$1,000’s/kg	$100’s/kg	$10’s/kg	$1’s/kg

Example Business Case

ALD Improvement Comparison – Tesla Battery Cost Reduction in $/kWh/cycle			
	Target	Base Technology	Proven ALD improvement
$/kWh/cycle	Tesla 80 kWh of 4.8 Ah NCA cells	Pack Level: $120/kWh @ **300 cycles = $0.40/kWh/cycle**	Pack Level: $120/kWh @ **625 cycles** = **$0.19/kWh/cycle**
		Cathode Level: Sumitomo NCA (195 mAh/g, 3.7V nom., $25?/kg), 300 cycles = **$0.116/kWh/cycle**	Cathode Level: ALD-coated NCA (190 mAh/g, 3.7V nom., $31/kg], **625 cycles at 4.3V = $0.071/kWh/cycle** ***Additional energy gain anticipated using higher purity Sumitomo NCA.***

- ALD-enabled cathodes show lifetime benefit and higher capacity (range)
- Can reduce Tesla's $/kWh/cycle by > 50%

Summary

- Raw materials can be significantly improved with surface coatings
- ALD is an ideal tool for improving and optimizing raw materials
- Particle ALD is only viable means towards commercialization
  - Demonstrated 200kg/day
  - Excellent nail penetration data in 40Ah packs
  - Excellent electrochemical performance in 95Ah packs
  - Overall pack cost reduced, at scale
- ALD also has many applications outside of batteries

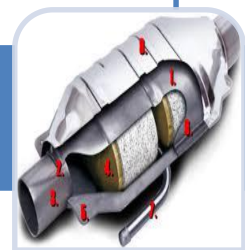
Particle ALD Products and R&D Opportunities

- Improved dispersion
- Oxidation Resistance

Materials

- Better catalysts
- Fouling protection
- Bimetallics

Metal Islands



- Better performance
- Longer lifetime
- Safety

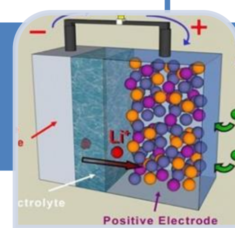
Li-Ion Batteries

- Precious metal replacement
- Improved lifetime

Fuel Cells

- NiMH
- MLCC
- Metal-Air
- Super-capacitors

Other Energy Storage



- Broadband UV protection
- Multifunctional additives

Pigments and Personal Care

Thank you

- Special thanks to the Vehicle Technologies Office (VTO) SBIR Phase I/II program DE-SC0010230 for supporting ALD cathode scale-up efforts

- New DOE (VTO) SBIR Phase I program for ALD-enabled anodes

- Other DOE, Navy, Air Force SBIR programs through additional primary or subcontract awards

Questions

PneumatiCoat TECHNOLOGIES
Commercializing "nano"

Systems and Technology

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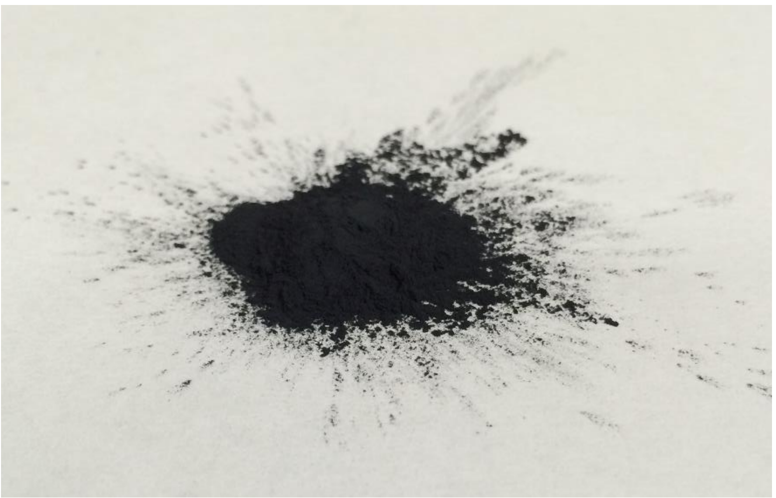
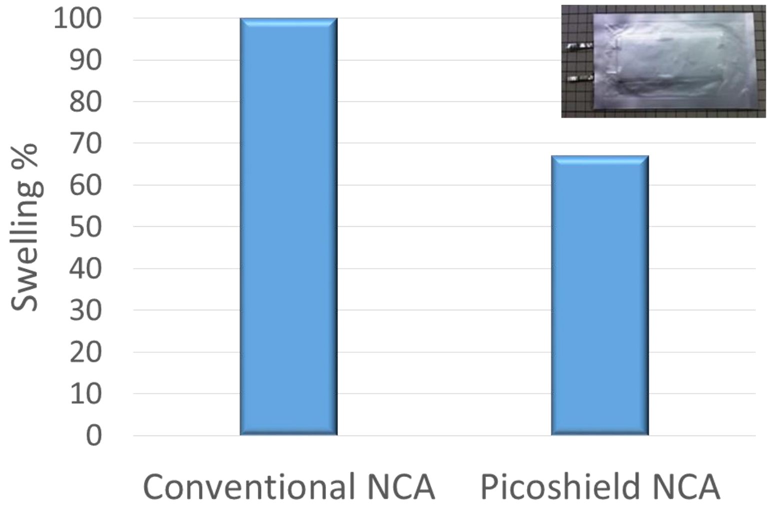
Battery Example 1 : NCA

Low-Gassing *PICOSHIELD*® NCA – coarse and fine grades





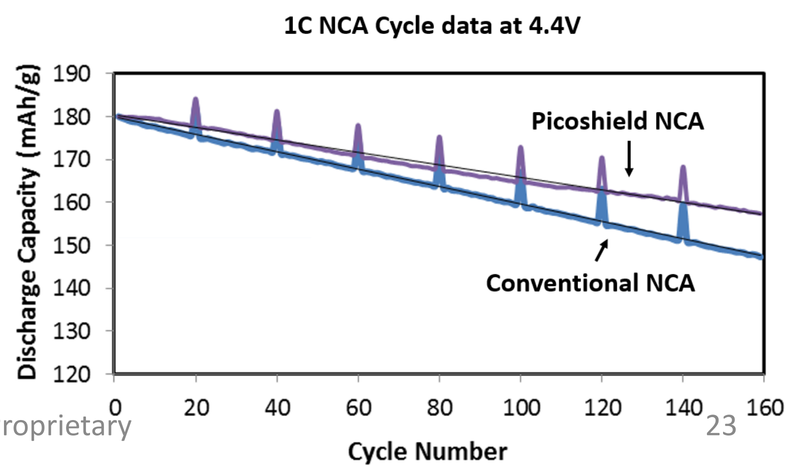
<u>Benefits include:</u>

Reduced gassing

Longer lifetime

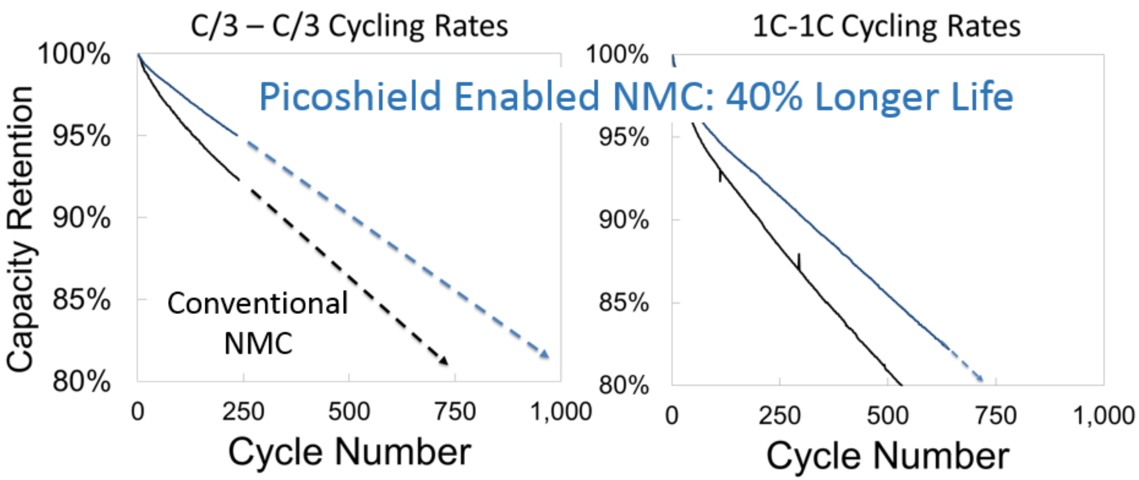
Higher stability at higher voltages

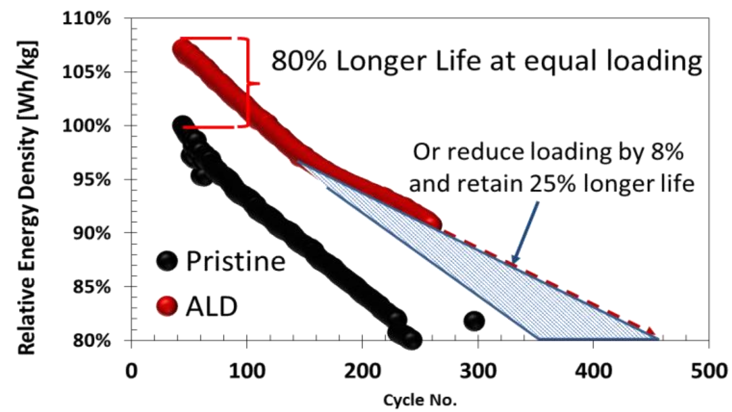
Drop-in ready

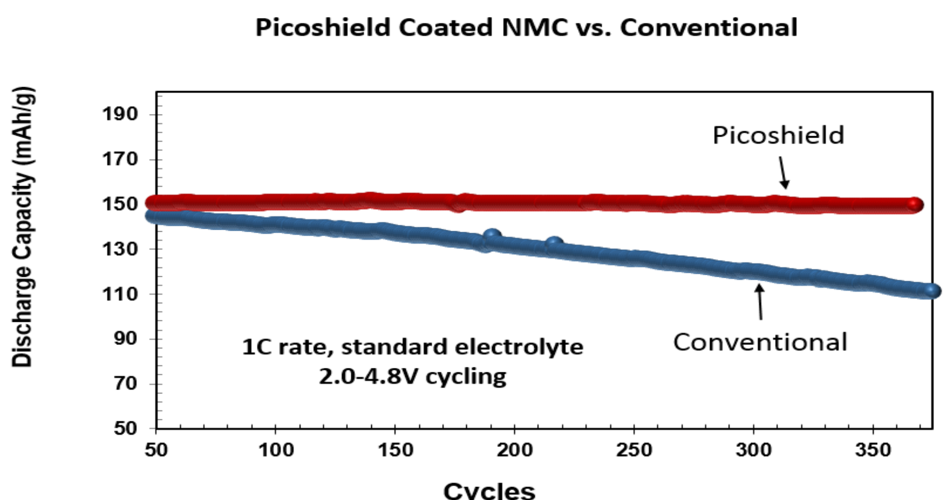


Battery Example 2 : NMC

Long-Life *PICOSHIELD®* NMC – many compositions







<u>Benefits include:</u>

Longer lifetime

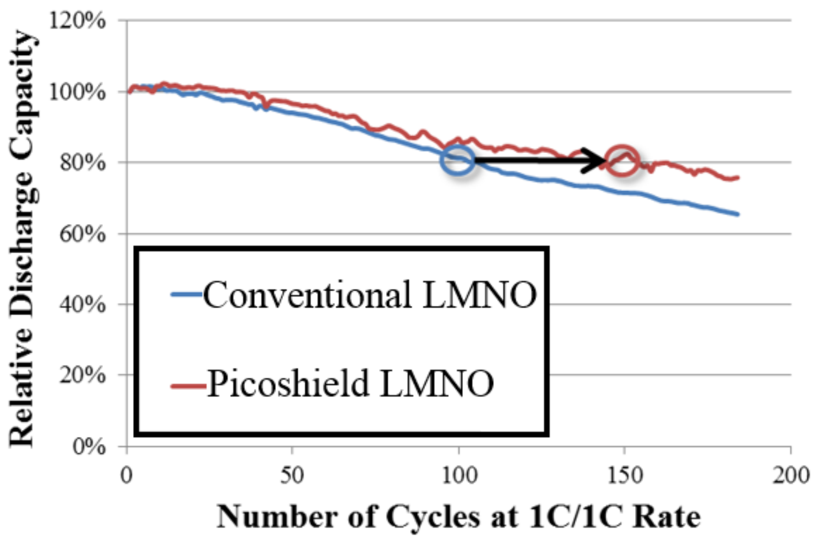
Increased Safety

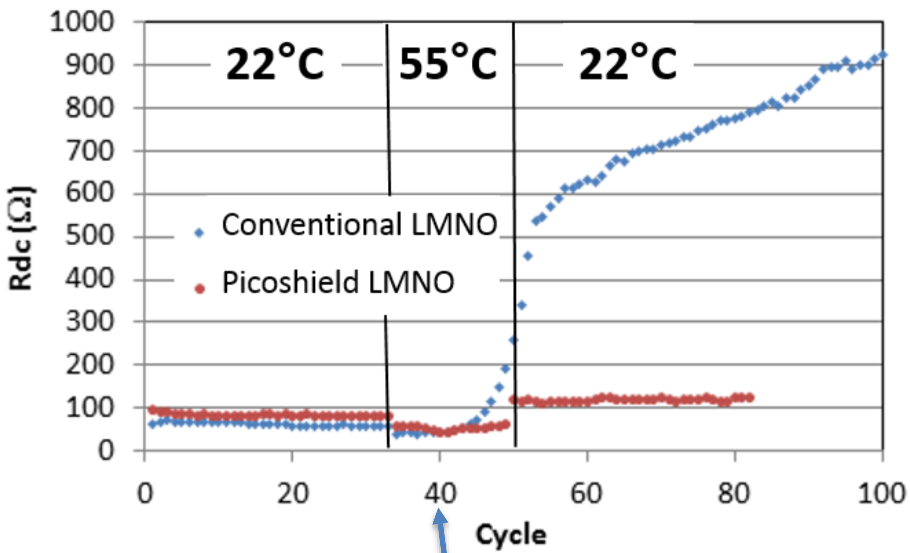
Higher voltage stability

PneumatiCoat TECHNOLOGIES Commercializing "nano"

Battery Example 3 : LMNO

Long-Life *PICOSHIELD*® MNO – many compositions





Negligible Resistance Buildup at High Temperatures.
Dramatic Safety Improvement!

<u>Benefits include:</u>

Longer lifetime

Increased Safety

Higher voltage stability