
Nanotechnology at Our Service: Anti-Corrosion and the Impact of Paste Rheology on Production Efficiency

Recent Innovations with MOLECULAR REBAR[®] and its Mechanism of Action

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FENIBAT 2023

INTRODUCTION

Why Battery Makers Choose MOLECULAR REBAR®

- **A risk-free, supportive customer/supplier relationship**

- In-depth technical advice and product integration services provided
- We work with >190 manufacturers at various stages of commercialization or development
- We completed >500 industrial scale trials since 2013, where most trial batteries were shipped to the field
- Network our customers with our global contacts, technically and commercially



- **A precedence of adoption by trend-setting companies using MOLECULAR REBAR® to gain market share :**

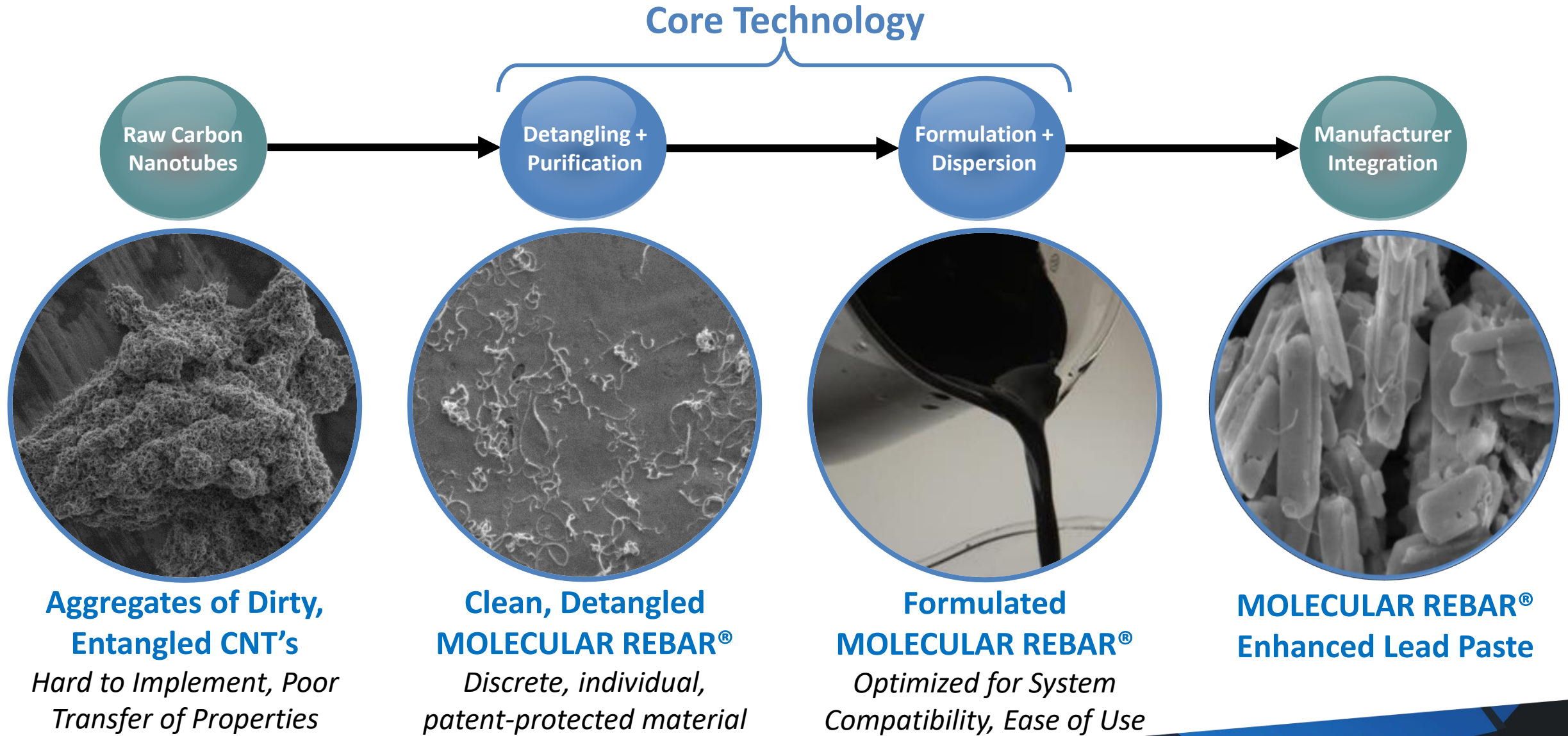
- MOLECULAR REBAR® batteries are available from automotive hardware stores in the USA
- OEM use MOLECULAR REBAR® for Automotive, Power Sports, and Deep Cycle batteries
- Batteries containing MOLECULAR REBAR® operates in London's Heathrow airport
- Thousands of E-rickshaw drivers uses MOLECULAR REBAR® batteries every day
- MOLECULAR REBAR® provides market-leading performance to EFB batteries in Africa and Europe



Low Investment, High Return

- **MOLECULAR REBAR®** adoption is extremely cost effective, adding <0.5-2% of total battery cost
 - % cost of adoption depends on application /battery size
 - Cost offset by reduced warranty returns, higher warranty products at premium prices, and direct cost reductions
 - Products are optimized to deliver required performance at low loading levels (<0.1% wrt PbO)
 - We have optimized the price over time to support expanding usage of **MOLECULAR REBAR®**

MOLECULAR REBAR[®] Technology



Structure/Function Relationship Review

MECHANISM OF MOLECULAR REBAR[®] ACTION

Increased Plate Durability (Impact Test)

- MOLECULAR REBAR® products increase the strength of the active material, reinforcing the lead matrix
- Impact tests on cured/dried plates containing Pb110N retain ~50% more of their material than controls

0 Impacts

1 Impact

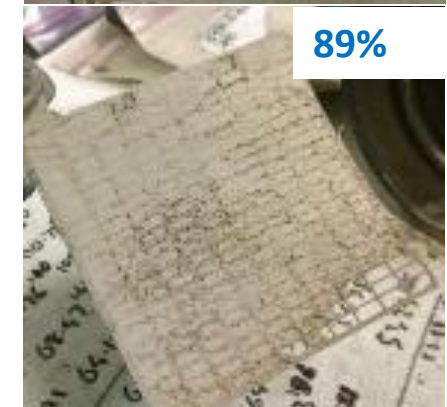
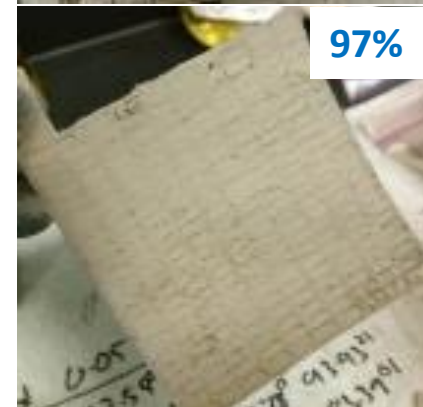
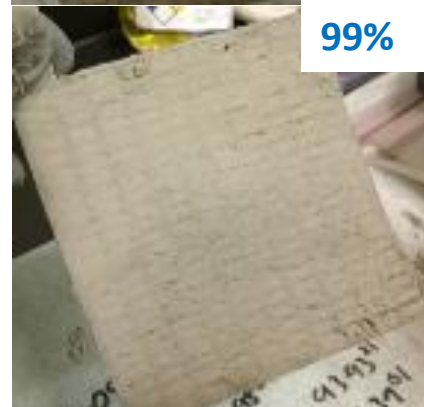
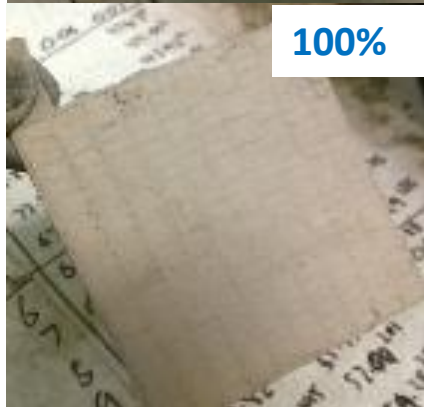
2 Impacts

3 Impacts

Control



Pb110N



Improved Crystal Structure Maintained Thru Life

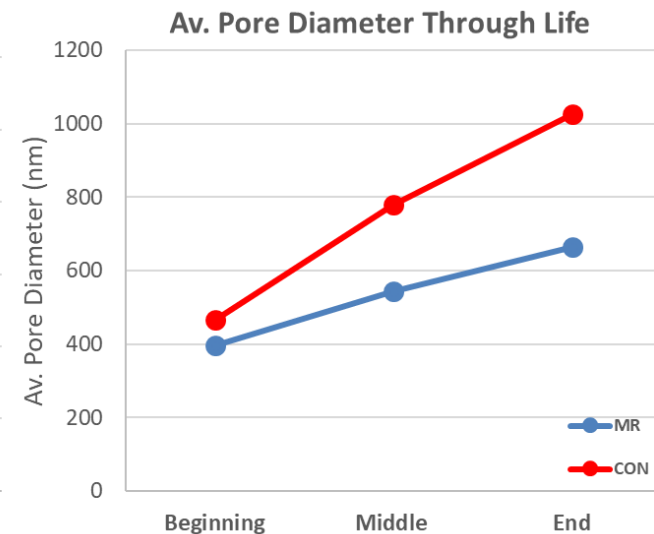
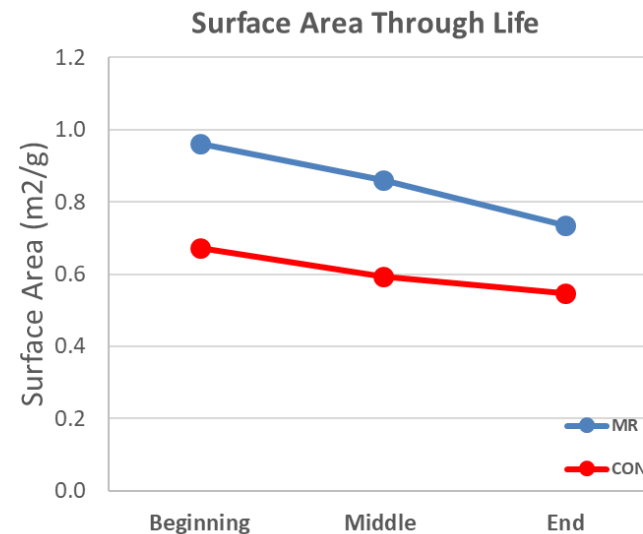
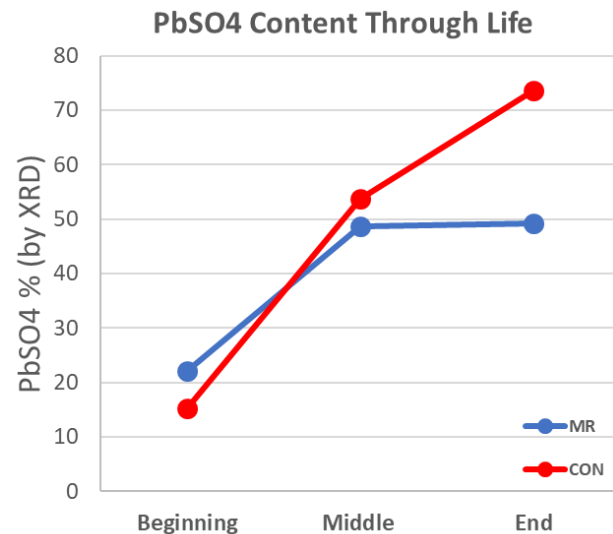
SLI Battery (Control)

PbSO₄ continues to grow in size, grow in number
Surface area decreases over cycling
Large cavities : pore diameter grow fast over cycling



MR Improved Battery

PbSO₄ crystals maintained smaller, fewer
Surface area higher for duration of cycling
Stable pore diameter: keeping tight crystal packing

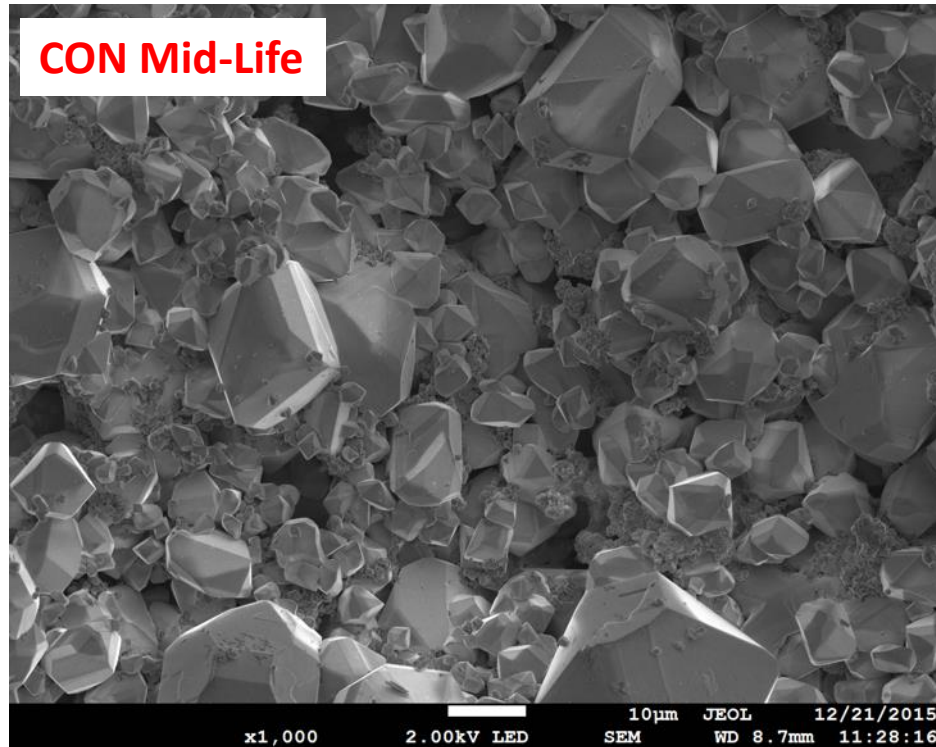


Molecular Rebar Improves the Fundamental Structure of your Battery

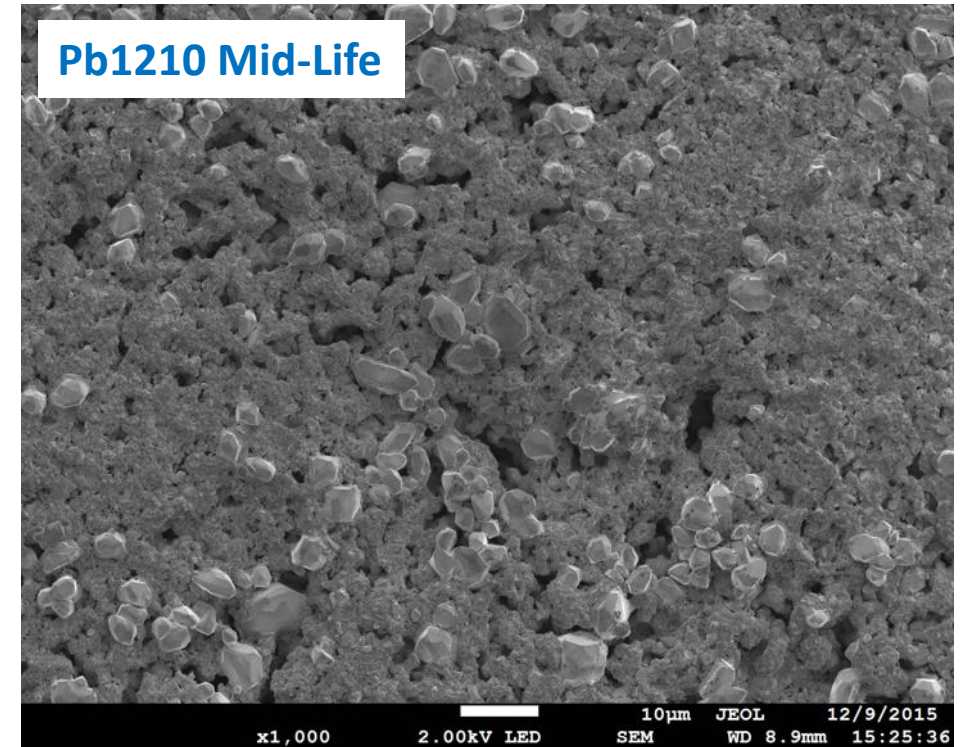
Improved Crystal Structure Maintained Thru Life

- After >4 Months of intensive PSoC cycling:

- CON plates indicate heavy, hard sulfation of various sizes and arrangements across the plate surface
- Pb1210N decreases sulfate crystal size and frequency to allow the majority of the plate to remain as active sponge lead
- Plates are noticeably stronger to the touch upon teardown; MR strength benefits retained through life

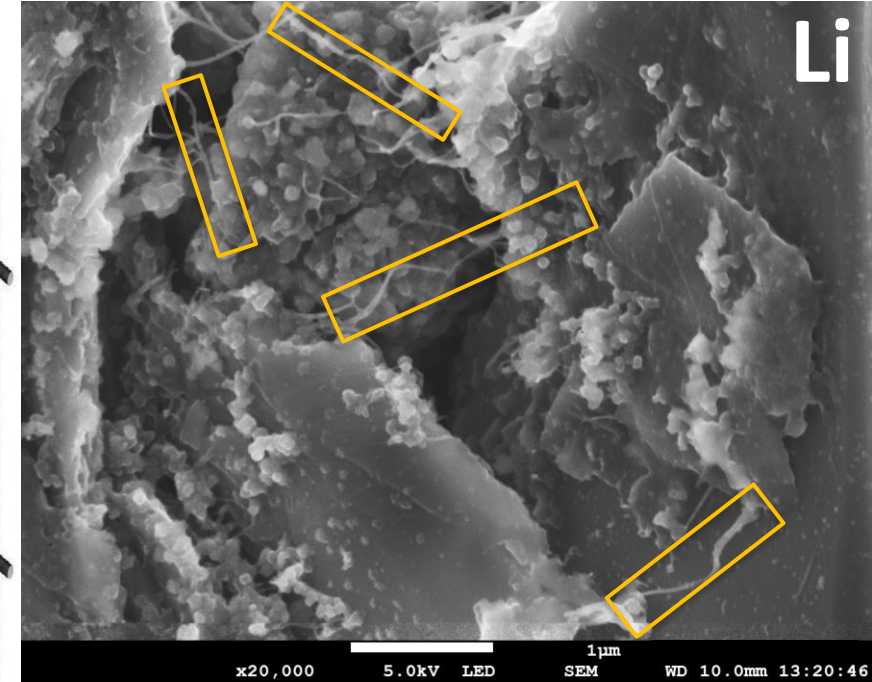
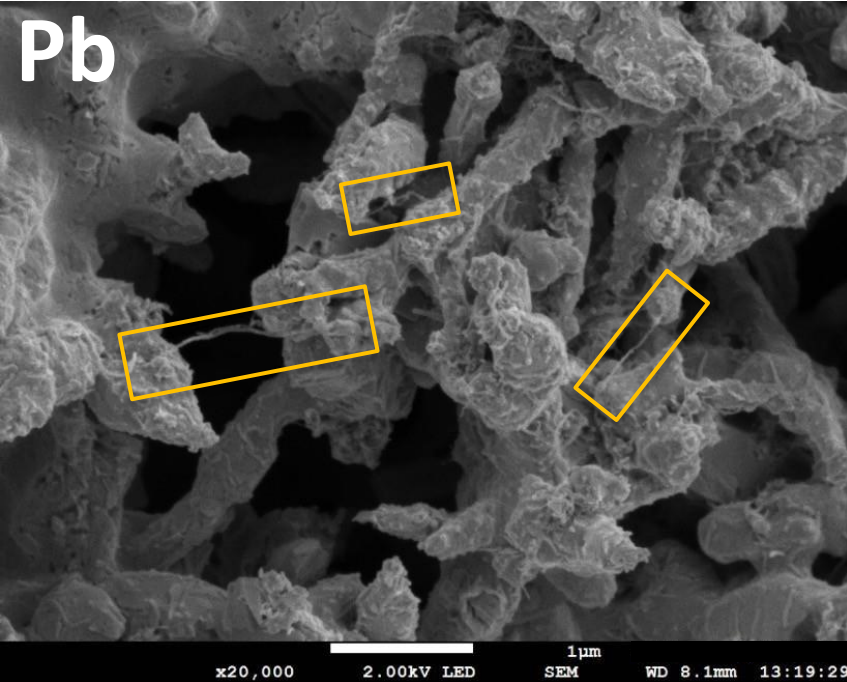


Micrographs at 1000x resolution illustrate Pb1210N's ability to ensure uniform NAM crystal structure even after > 4 Months of Cycling



Clear Structure / Function Relationships

- **MOLECULAR REBAR®-based products provide nanoscale, electroactive reinforcements which:**
 - Act to bring the active material together, reinforcing electrode structure → **Enhanced robustness and durability**
 - Alter interparticle connectivity and morphology to enhance active material structure → **Improved electrical performance**
 - Overcome structural and chemical limitations that induce failure → **Consistency of performance**



Molecular Rebar Products Change the “DNA” of Your Battery

**BLACK DIAMOND
STRUCTURES™**

Our Relentless Pursuit of Science

Outside of our commercial pursuits, Black Diamond Structures is proud to push Lead-Acid Battery technology forward

- Co-authoring a journal article proposing a novel, in situ, electrochemical analytical tool capable of determining the state of PAM decay without the need for invasive chemical analysis
 - Lithium-Ion data analysis tools, applied to lead-acid chemistry for the 1st time
 - Under review at the Journal of Power Sources, expected publication date before End of Year
- Answered the U.S. Department of Energy's call to support AUX battery development
 - **MOLECULAR REBAR**® and complementary materials to increase service life and reduce costs
 - 12 V prototypes to be produced by East Penn Manufacturing under grant DE-FOA-0002893

PbLite, PbAC

RECENT INNOVATIONS

PbLite: Enhancing the Production Process

- **Key Features:**

- A new formulation; only 2.5 L per 1,000 kg PbO
- No changes to existing paste mixture, program, or H₂O; just add it!
- A “**Process Additive**” that improves battery consistency and output
- Provides key MOLECULAR REBAR® performance where it matters most, for your most economical battery products

- **PbLite provides:**

- Investment returned immediately from your production line:
 - Less waste from rejected plates and lost batches
 - More batteries per batch
- Enhanced battery-to-battery consistency
- Consistency of capacity and CCA through life
- 10-15% improved charge recovery



Meaningful Manufacturing Savings, Immediately

- For a decade, our customers have educated us on the unexpected benefits of manufacturing batteries with MR
 - **More “paste-able” paste**
 - A more mobile paste rheology (no density changes) which makes application to grids easier and more efficient
 - Ex. 95% of all customers
 - **~25-150 more plates per paste batch, depending on plate dimensions (Up to 25% reduction in waste)**
 - Reduction in manufacturing costs due to lost grids, wasted active material, and excess recycling costs
 - Ex. Pacific Batteries LTD, EU and LATAM development partners
 - **~1-5 additional batteries possible per paste batch**
 - Improvements in plate output allow manufacturers to build more batteries from a paste
 - Ex. Pacific Batteries LTD, EU and LATAM development partners
 - **Enhanced plate-to-plate and battery-to-battery consistency, with no risk to customers**
 - Less formation variability, less uneven performance between batteries, tighter error bars in lab testing
 - Ex. Slides 16-18

PbLite Pays for Itself, Rewards **You** from the Field

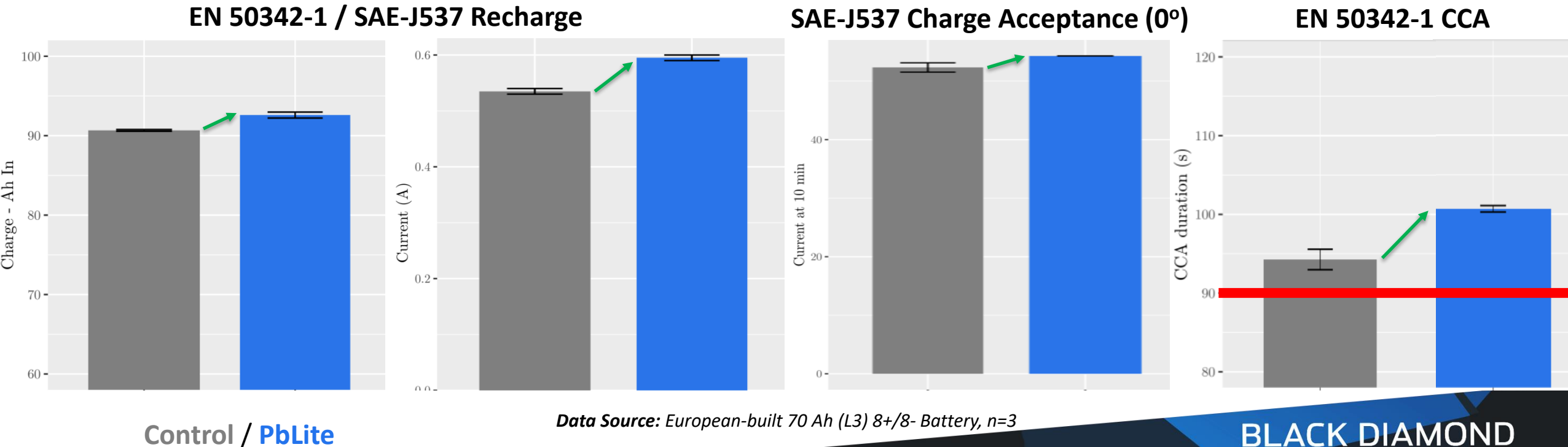
- Early development partners have reported 20-100 additional plates produced per batch, so far
 - Depending on a manufacturer's scale and the level of PbLite success, this results in 1-4 additional "batches" every month

Additional plates = Additional batteries = Additional Revenue

- We will work with you to ensure that your PbLite investment makes sense for your company
 - Ultra-low addition rates (2.5 L / 1000 kg PbO) help keep your per-batch cost low
- Manufacturing benefits:
 - Decrease in fixed costs (ex. Labor force productivity increases)
 - Decrease in waste (ex. Less scrap, less recycling)
 - Decrease in energy utilization (ex. 1-4 "free" mixer uses per month, fewer flash oven warm-ups)
- From the field:
 - You receive fewer warranty claims and a competitive, monetizable edge in the marketplace
 - Your customers will experience more consistent, durable products

Small, Critical Performance Improvements

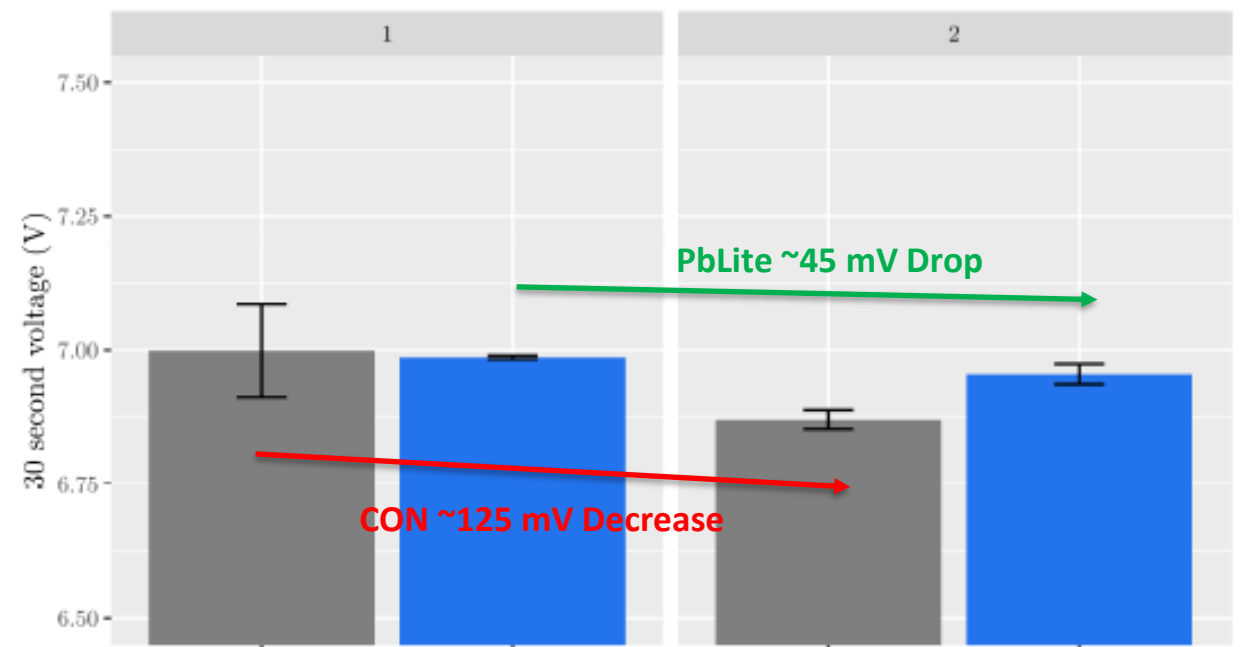
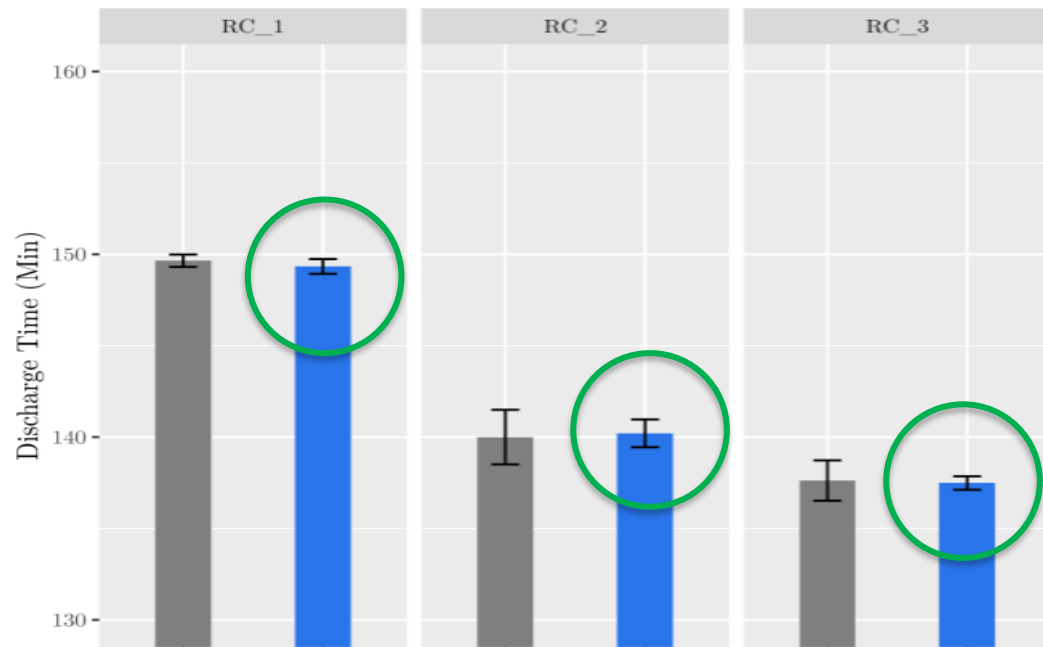
- Not all battery designs need game-changing performance enhancements, some just need a little boost
- PbLite offers many of the benefits that our customers have come to expect from MOLECULAR REBAR®
 - 10-15% improved charge return at automotive charging voltages = *higher Ah return, more effective recharge in the field*
 - A small increase in charge acceptance, with lower variability = *enhanced active material structure, more consistent*
 - A ~7% increase in cold crank duration (t_{6V}), with lower variability = *increased cranking energy output, more consistent*



More Consistent Products = Happier Customers

Paste consistency = Plate consistency = Battery consistency

- As a Process Additive, PbLite makes your paste more useable / pliable / consistent
- It increases the uniformity of the PbO mixture and helps to keep your Plate #1 more similar to Plate #5001
- Uniformity enhancements translate to tighter performance (smaller error bars) and more enduring CCA (V_{10s})



Control / PbLite

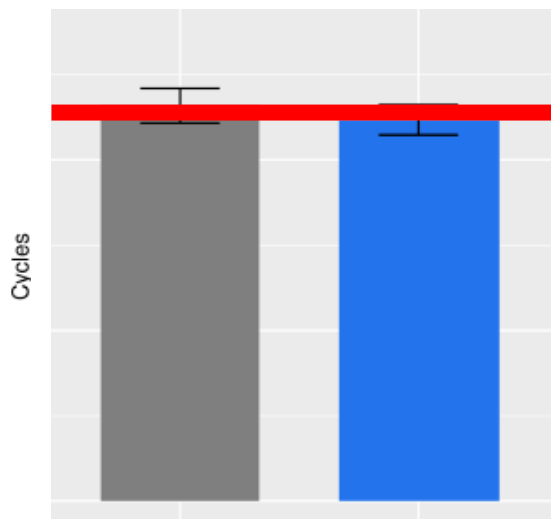
Data Source: European-built 70 Ah (L3) 8+/8- Battery, n=3

BLACK DIAMOND
STRUCTURES™

No Down Sides. No Risk.

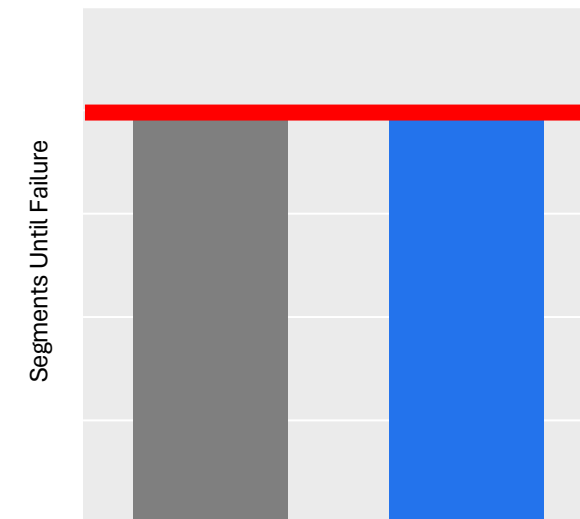
Endurance Cycling (EN 50342-1)

- *No risk to customers*
- No statistically-relevant detriment in lab-based cycle life tests
- Batteries made during evaluation period can be sold to market



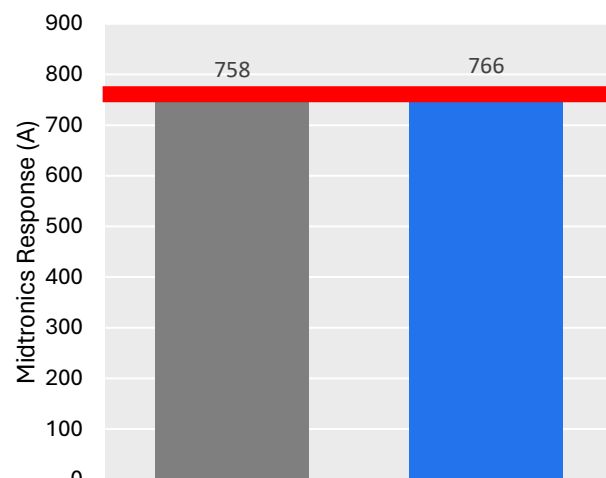
High-Temperature Durability (SAE-J240)

- *No risk to customers*
- No statistically-relevant detriment in lab-based cycle life tests
- Batteries made during evaluation period can be sold to market



Midtronics Response

- *No negative effect*
- 1% (8 A) improvement
- Batteries made during evaluation period can be sold to market



Control / PbLite

Water Loss (EN 50342-1)

- *No dramatic effect on H₂O consumption*
- <15% increase vs control
 - EU L3 design
- Addresses stratification in taller battery designs

W4

(<4g/Ah @ 42d)

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STRUCTURES™**

Customer Testimonial: PbLite Economics

- A European partner who helped us develop PbLite later adopted the product based on these economics
 - Inputs: 1000 kg batch, L3 battery (70Ah), 5% transportation costs, 3.7% duties/tax, 97 additional plates, 30 batches/day

“Bottom-Up” Model

- Approaches economics based on the material waste and recycling costs which are **SAVED** by PbLite
- Manufacturer disclosed a \$0.27 COGS per plate
- 97 extra plates were “worth” \$26.19
 - $97 \text{ extra plates} * \$0.27 / \text{plate} = \$26.19 \text{ saved per batch}$

“Top-Down” Model

- Approaches economics based on additional revenue **GENERATED** by PbLite’s increased battery output
- Manufacturer disclosed a 60% profit per battery
- 97 plates/batch = 54 extra batteries = \$1617/d profit
 - $[(97 \text{ extra plates} * 30 \text{ batches per day}) / 54 \text{ plates per battery}] * \$30 \text{ profit} = \$1617/\text{d}$

- Based on each manufacturer’s level of success with PbLite, cost is adjusted to make adoption “free”
 - Our development partners report between 20 and 100 extra plates captured per batch
 - Battery size and application also determine how many additional plates can be captured
 - Grid type also determines how many additional plates can be captured
 - Typically, PbLite increases batch cost <1.5%, and this is immediately recouped by extra plates

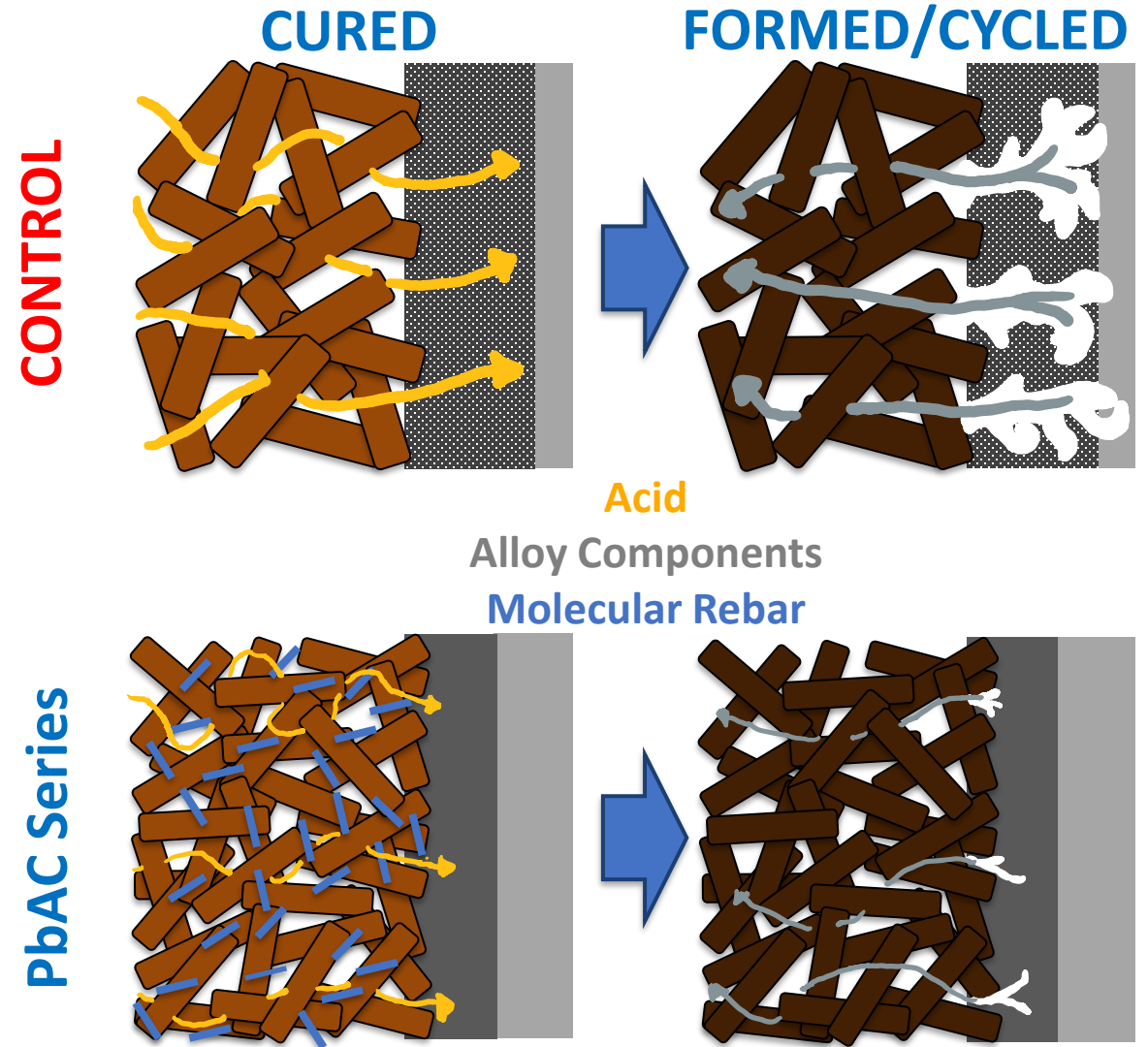
PbAC: Fighting Corrosion at its Source

- **Key Features:**
 - Use in Positive Electrode
 - Grow a designed Corrosion Layer
 - Enhance grid-to-mass adhesion
 - Delay grid corrosion
 - Meet challenging OEM specifications
 - Rebalance Advanced Carbon detriments to Corrosion/Water Loss
- **PbAC Series provides performance increases across the following key tests:**
 - SAE J2801, J2185, J240
 - JIS 5301 D LLE
 - VW 17.5% DOD @ 60C
 - EN 50342-1 Water Consumption



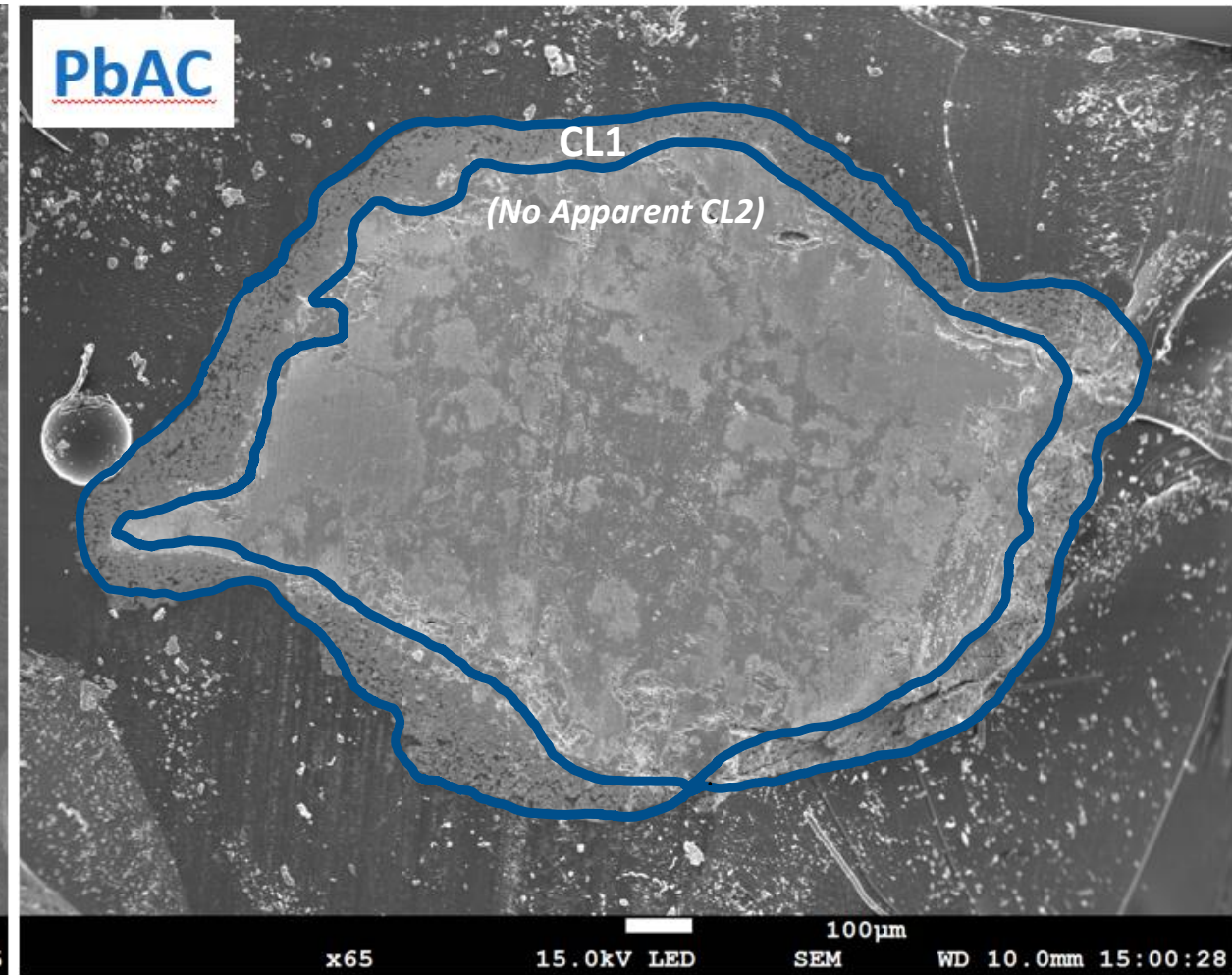
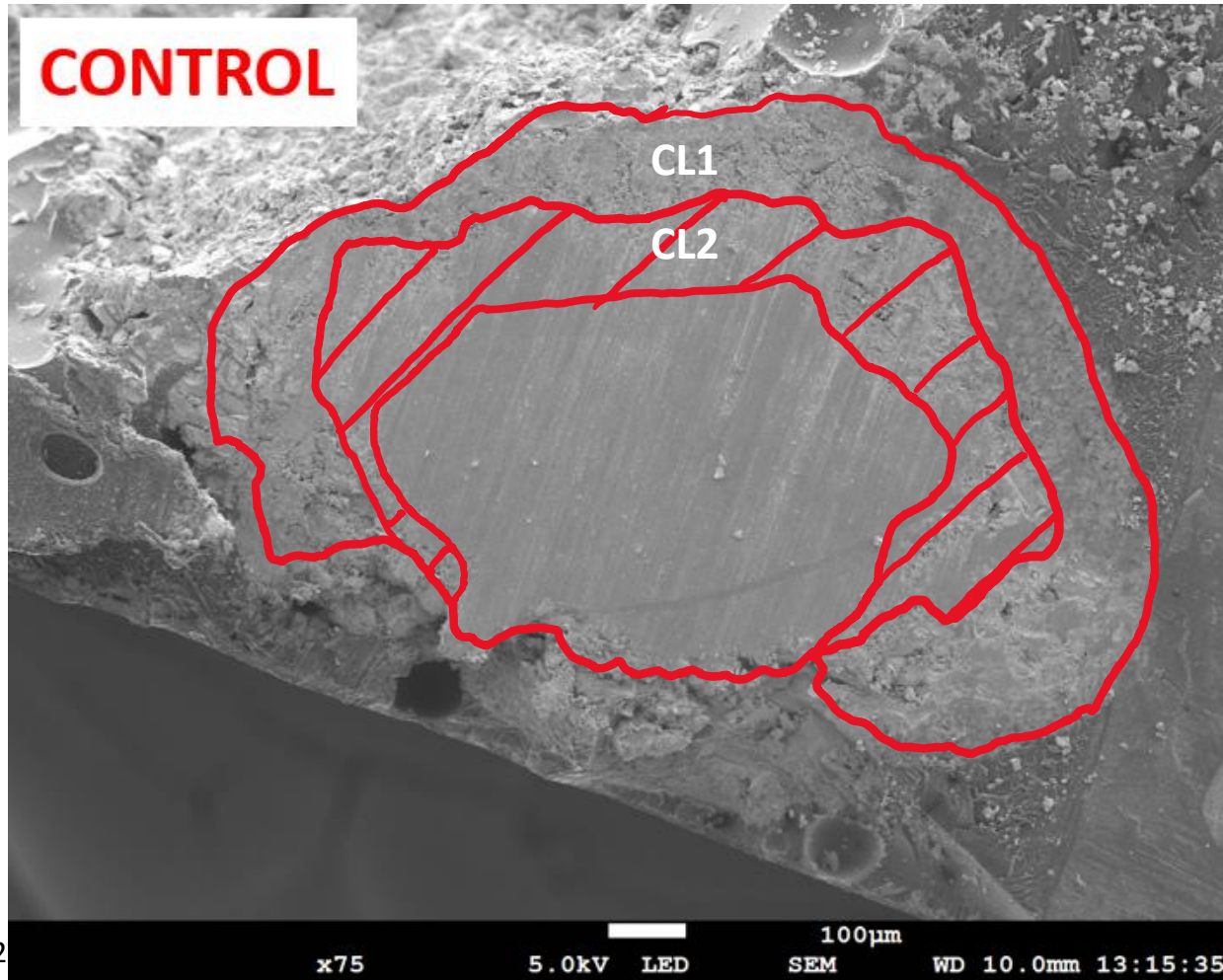
Our Approach: Build An Improved Corrosion Barrier

- New PbAC Products are designed to modify the Corrosion Layer to improve plate robustness
- PbAC technology changes cured PAM “DNA”
 - Uniformly affects the active material
 - **KEY TO ENABLEMENT**
 - Discrete, uniformly distributed MR
- During formation, PbAC is a sacrificial agent
 - Initially, energy goes to PbO/PbSO_4 and MR oxidation
 - Tempers energy delivery to system
- A lasting effect on Corrosion Layer after formation
 - Thinner, denser, more uniform
 - Improved Grid-to-Mass Adhesion
 - Changes persists through life
 - Shield grid from acid to prolong life



Enhanced Corrosion Layer Delays Corrosive Failure

- PbAC generates a superior corrosion layer to improve cycle life >25% (SAE J2185 post life image below)
 - PbAC layer is thinner, denser, more uniform, and as a monolayer instead of a bilayer
 - An effect of altered acid access, improved grid/mass adhesion, likely changed electrochemistry

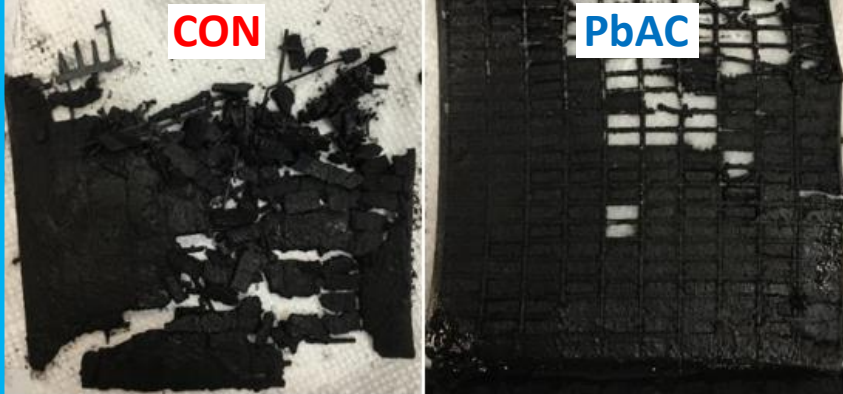


Dramatic Improvements Seen in Full-scale Testing

- Implementation of PbAC results in a modified corrosion layer
- This new corrosion layer protects grid from further degradation and improves battery life where corrosion is the failure mode
- Effects confirmed with:
 - Grid Alloys
 - Ca/Sn, Ca, Sb
 - Grid Types
 - Cast, Expanded, Punched
 - *...and counting!!*

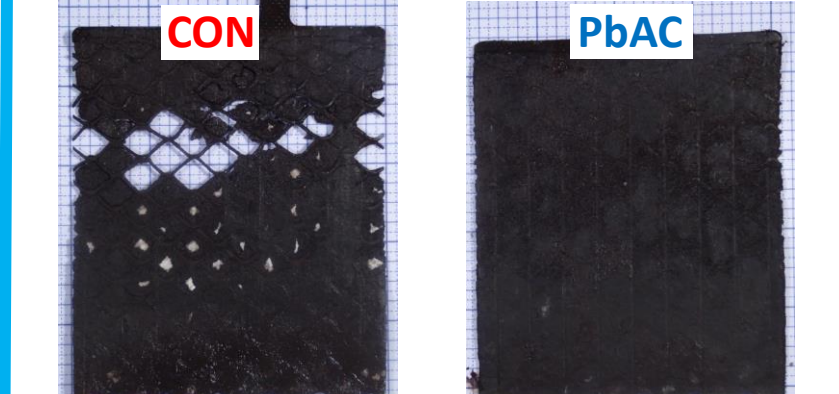
J240 Cycling (75 °C) Sb, Cast

60% improvement using PbAC to delay corrosion (852 → 1387 cycles, **+60%**)



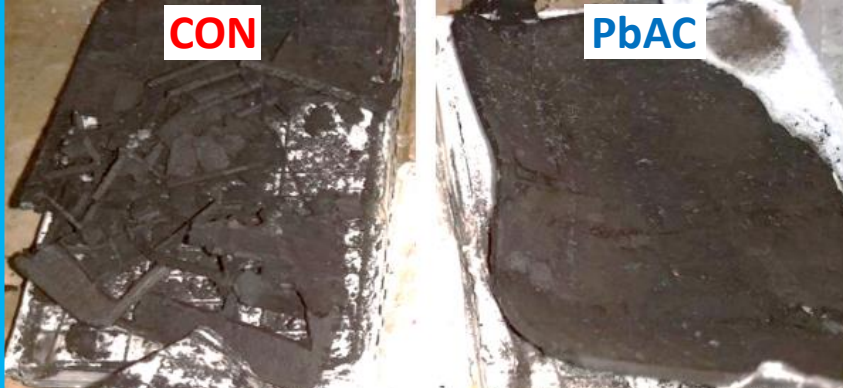
D5301 Cycling (41 °C) Ca, Expanded

Both CON and PbAC failed because of NAM related failures, but **PbAC maintains PAM in good condition** (no corrosion or material loss, sulfation)



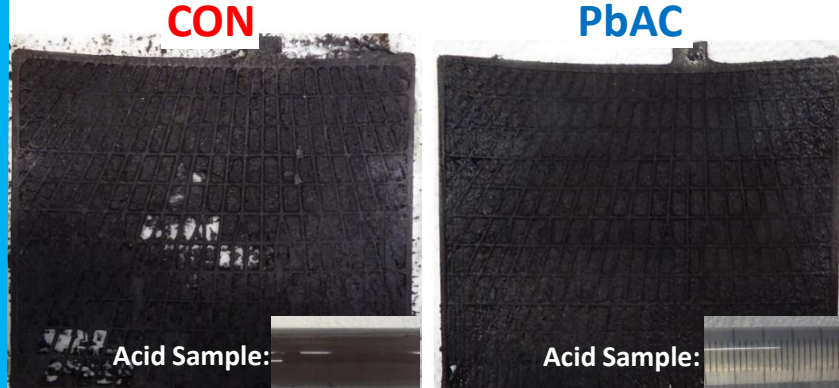
JIS D5302 Cycling (45 °C) Ca/Sn, Cast

100% improvement using PbAC to delay corrosion (5600 → 10,600 cycles, **+90%**)



J2185 Cycling (50 °C) Sb, Cast

Test end at week 10 due to NAM failure, **PbAC plate retained grid integrity and 70% material** in drop test; CON retained 10% of material and grid shattered



CONCLUSION

Parting Thoughts + Contact Information

- **MOLECULAR REBAR®** is a nanostructured component with well-described structure/function relationships
 - Strengthens active material (NAM + PAM)
 - Modifies crystal arrangement for enhanced activity
 - Improves product consistency through optimal paste incorporation vs. other carbons
- **Continued innovation:**
 - Sharing novel analysis tools with the world, through publication
 - Attacking the AUX problem (eVehicles) with US Department of Energy support, hopefully, and East Penn Manufacturing
 - Tackling corrosion and positive plate shedding at the source: **PbAC**
 - Improving production quality and output: **PbLite**

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