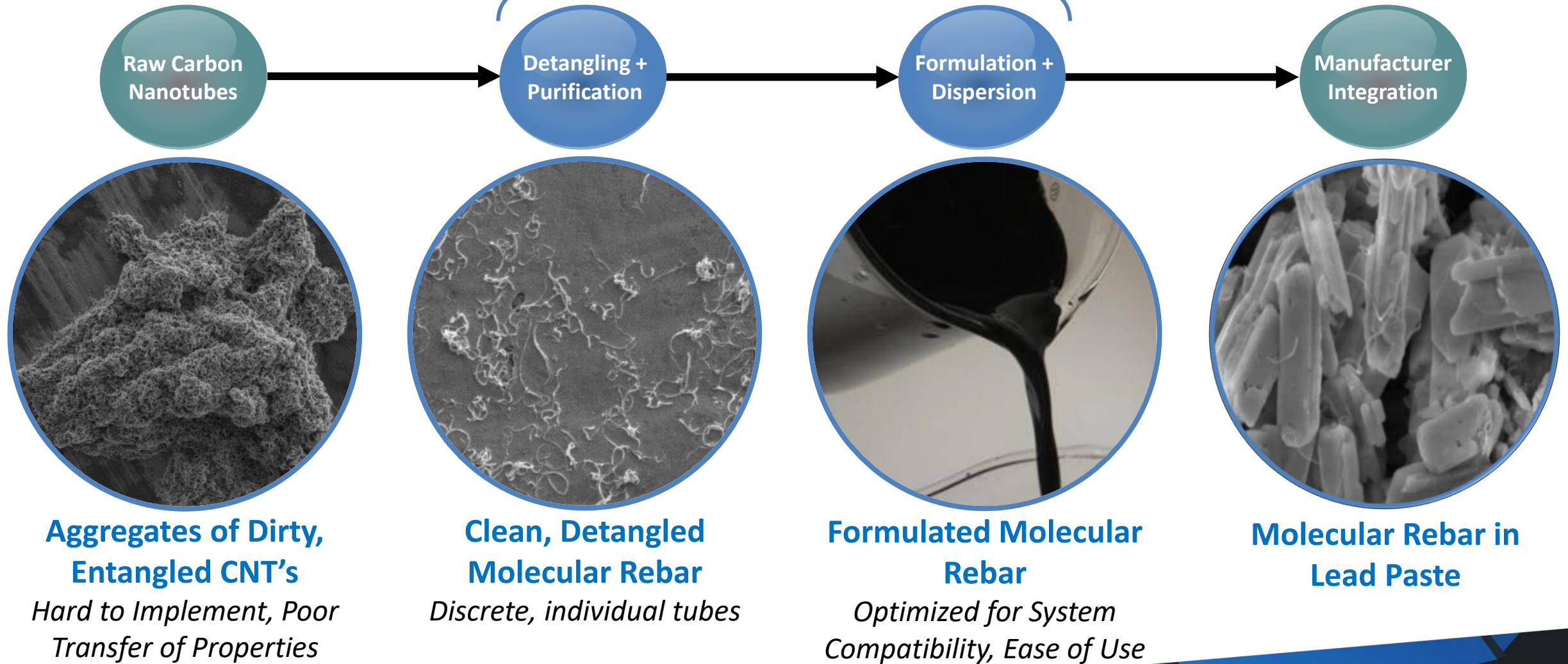

MOLECULAR REBAR® Enhances the Positive Plate Corrosion Layer to Improve High-Temperature Performance

Dr. Paul Everill, Dr. Rhet DeGuzman, Steven Swogger MBA, and Dr. Nanjan Sugumaran

MOLECULAR REBAR[®] Technology

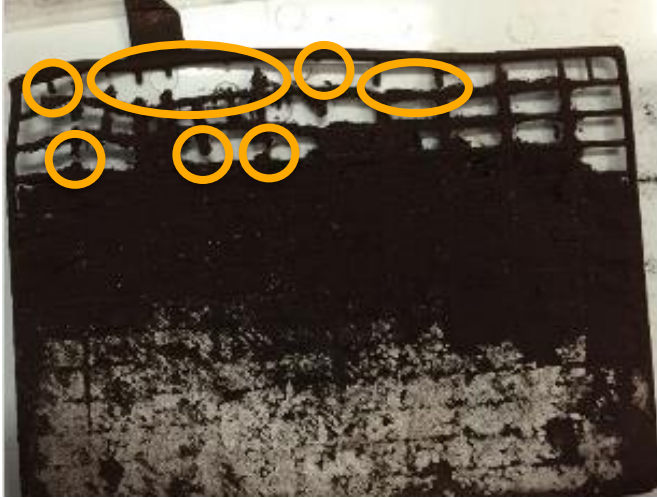
Core Technology



MOLECULAR REBAR® Provokes Corrosion Resistance

CONTROL

Failure Mode = NAM sulfation, Positive Plate Corrosion



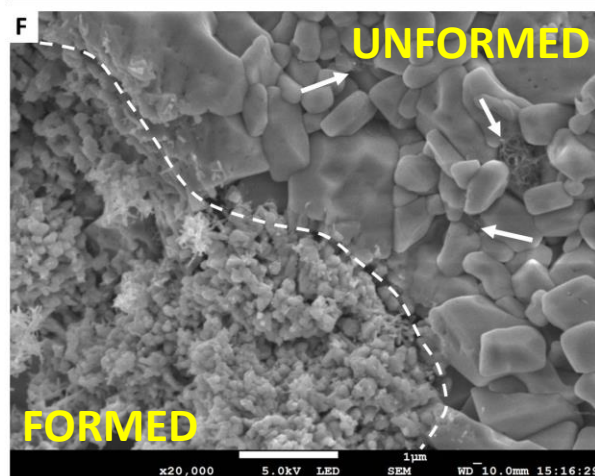
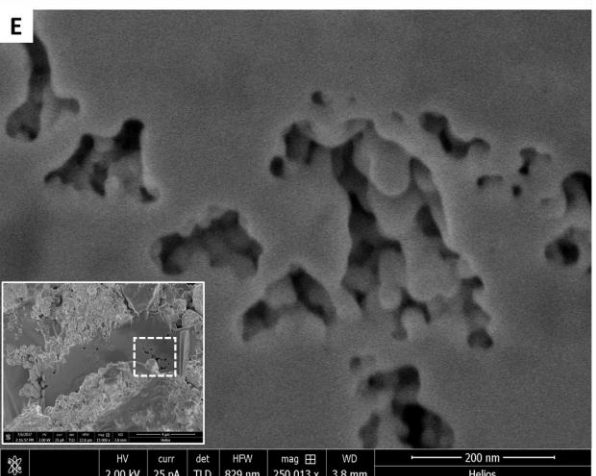
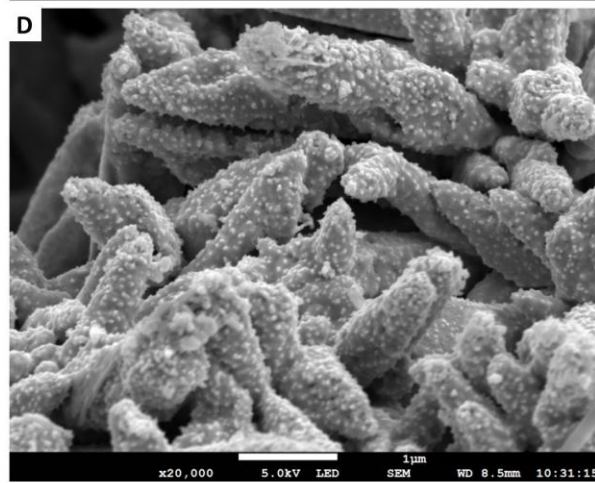
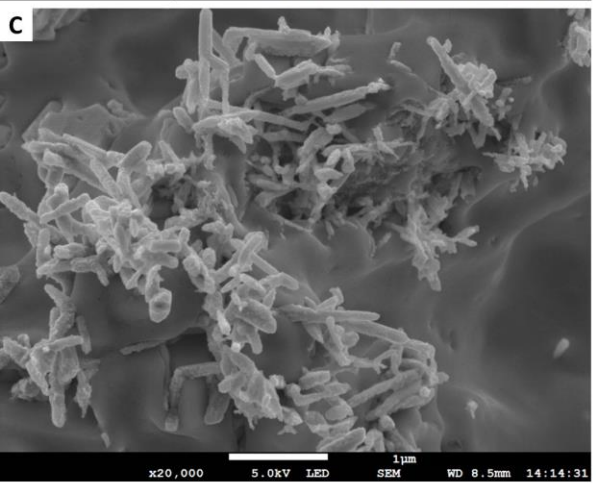
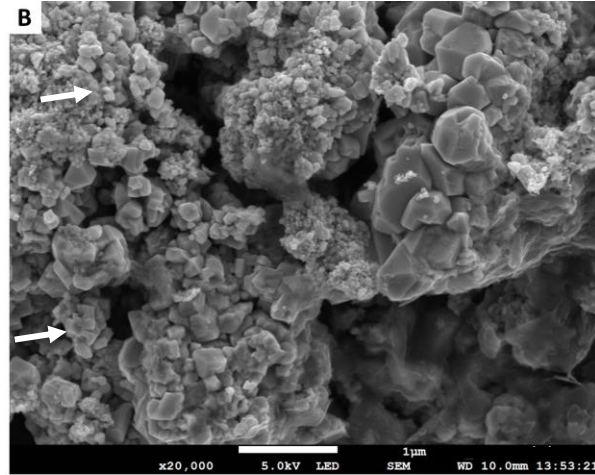
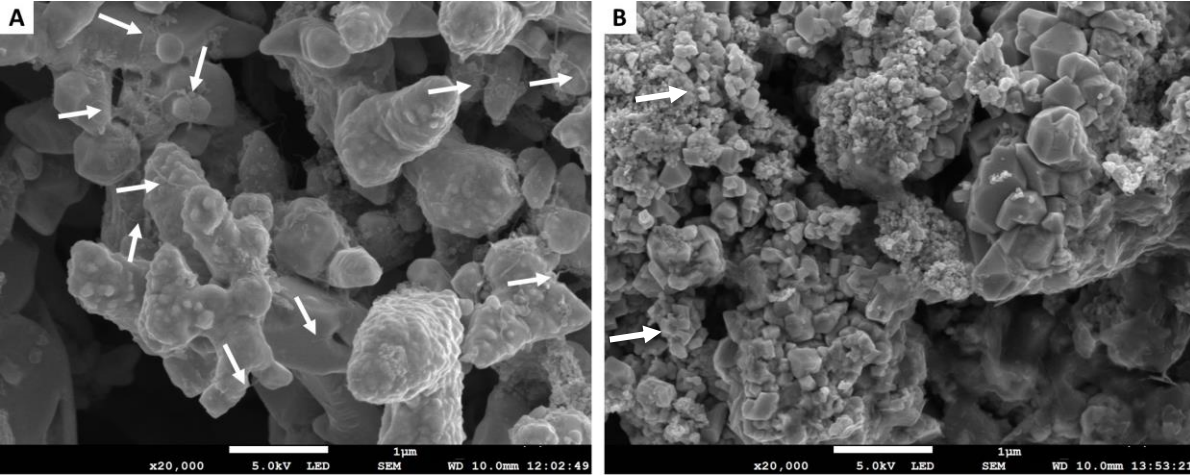
Pb2300N + Pb2300P

Life Cycle Improvement = +150%

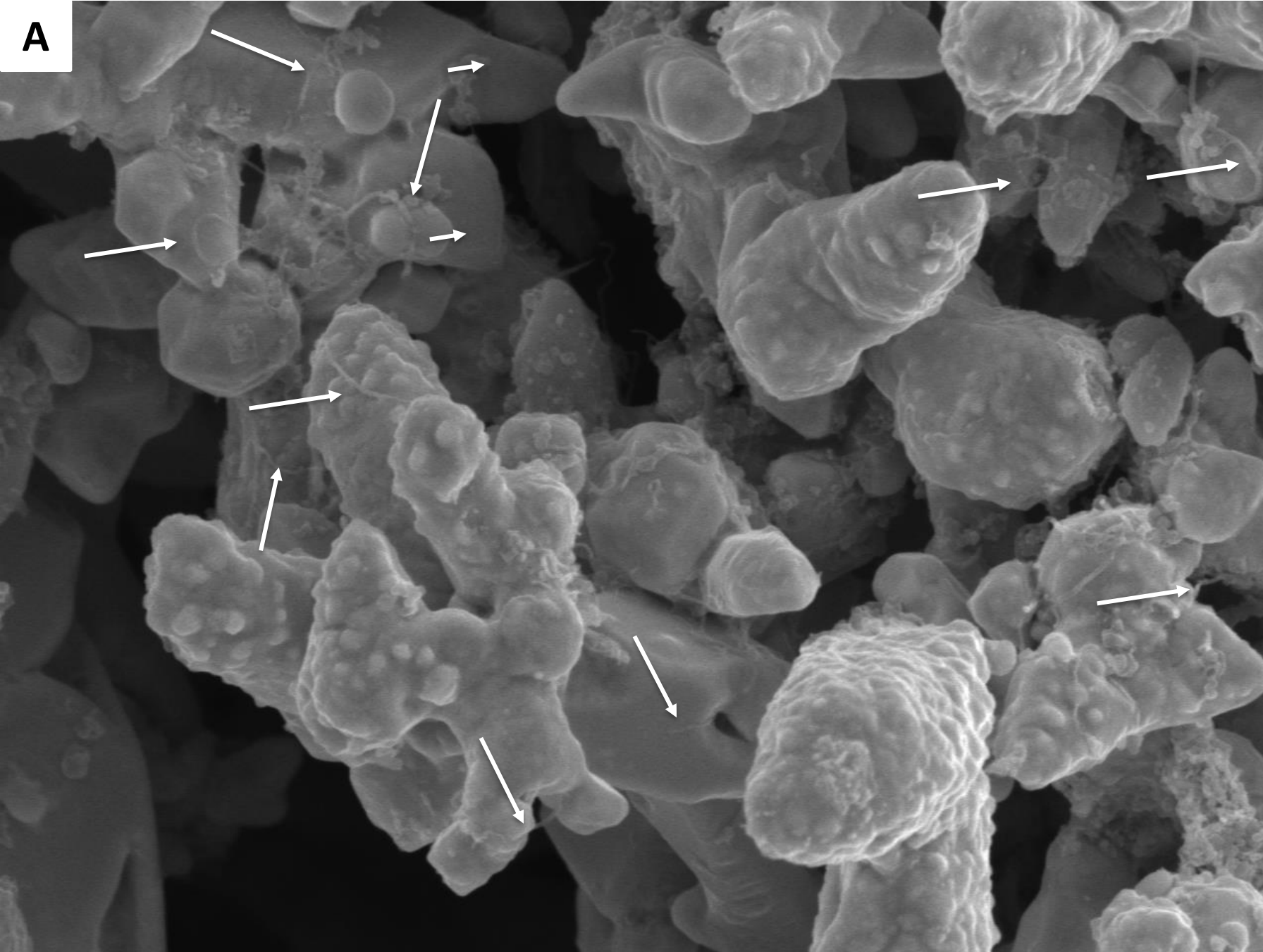


- **Previous Molecular Rebar PAM products:**
 - Commercially adopted mostly in Deep Cycle and AGM/VRLA applications
 - Some anti-corrosion properties are seen in Automotive and Flooded
- **BDS required better understanding to develop a targeted product:**
 - Tailored our AM-changing technology to focus on corrosion mitigation
 - Explored our own mechanism of action, using it to drive product development
 - Performed joint-development work on formation and curing impacts

Mechanism Unclear, Since...



- ...MOLECULAR REBAR® is undetectable post-formation:
 - A. MR as it exists in formed NAM
 - B. Formed PAM previously containing MR (No MR found)
 - C. Chemically-exposed PbO₂ interior (No MR found)
 - D. Electrically-exposed PbO₂ interior (No MR found)
 - E. Focused Ion Beam-exposed PbO₂ interior (No MR found)
 - F. Partially formed PAM (MR only found in unformed region)

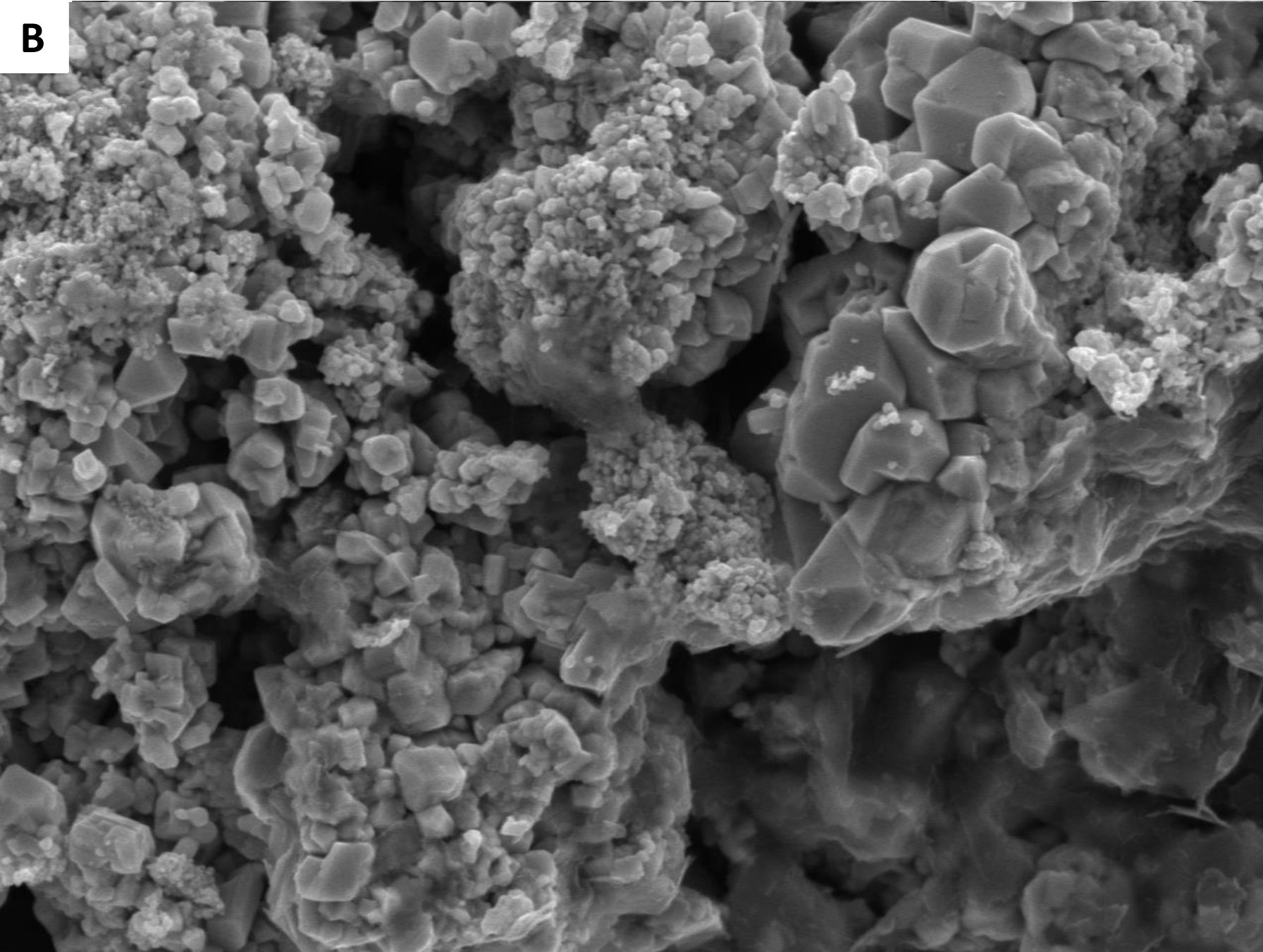


Unclear, Since...

is undetectable post-formation:

- formed NAM
- initially containing MR (No MR found)
- PbO₂ interior (No MR found)
- PbO₂ interior (No MR found)
- composed PbO₂ interior (No MR found)
- (MR only found in unformed region)

B



x20,000

5.0kV LED

SEM

WD 10.0mm 13:53:21

1 μm

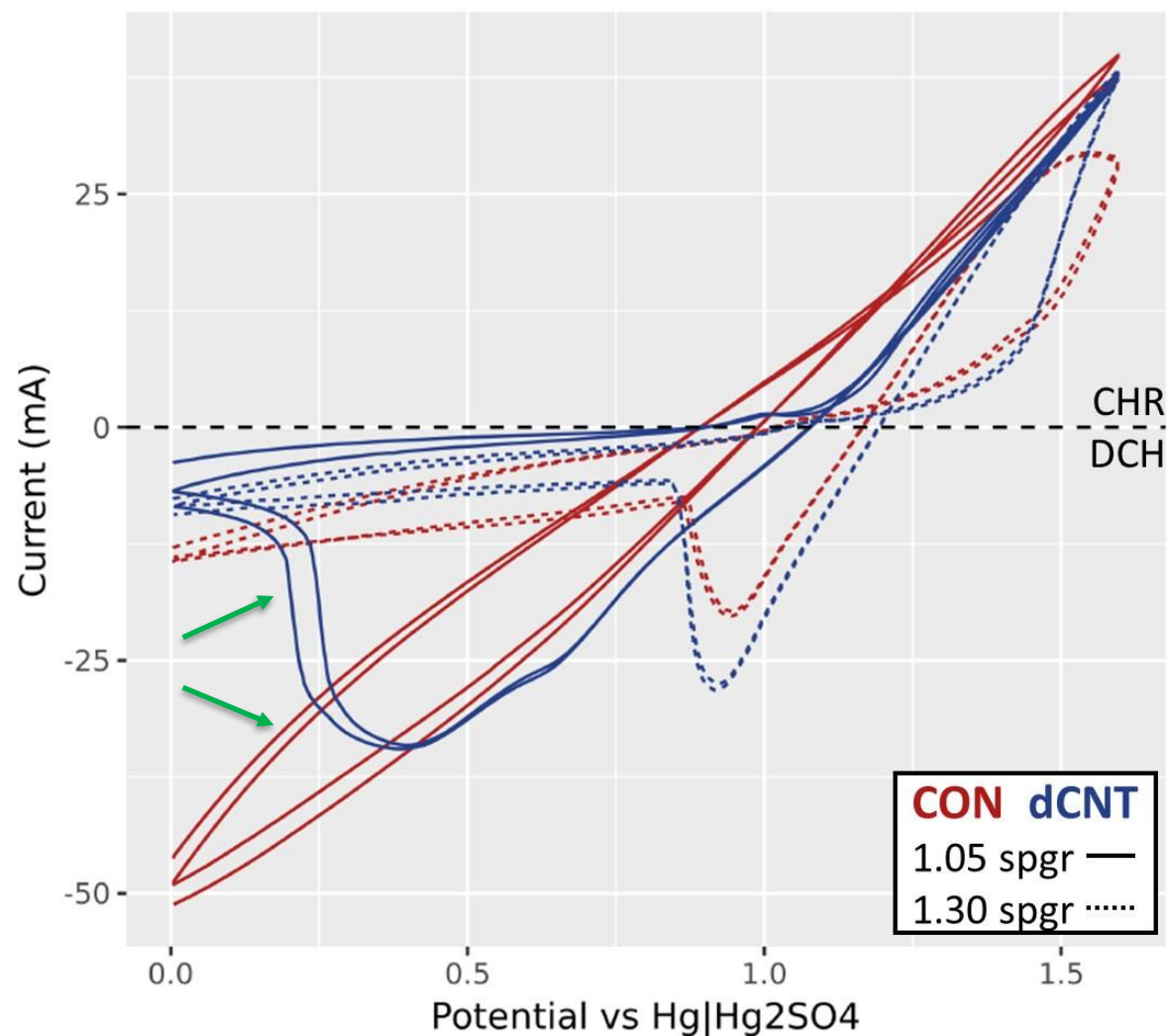
Unclear, Since...

is undetectable post-formation:

- formed NAM
- possibly containing MR (No MR found)
- PbO₂ interior (No MR found)
- PbO₂ interior (No MR found)
- supposed PbO₂ interior (No MR found)
- (MR only found in unformed region)

Despite Lack of MR, Voltage Response Remains

- PAM uniformly modified by MR presents different voltammetry signatures at “Low SoC” (1.05 spgr)
 - “High SoC” (1.3 spgr) trace differences not as dramatic
- The MR plate exhibits different features during the discharge progression from 0.4 → 0.0 V (arrows)
 - More complete reaction, limiting current response?
 - Resistance to structural changes active in the CON?



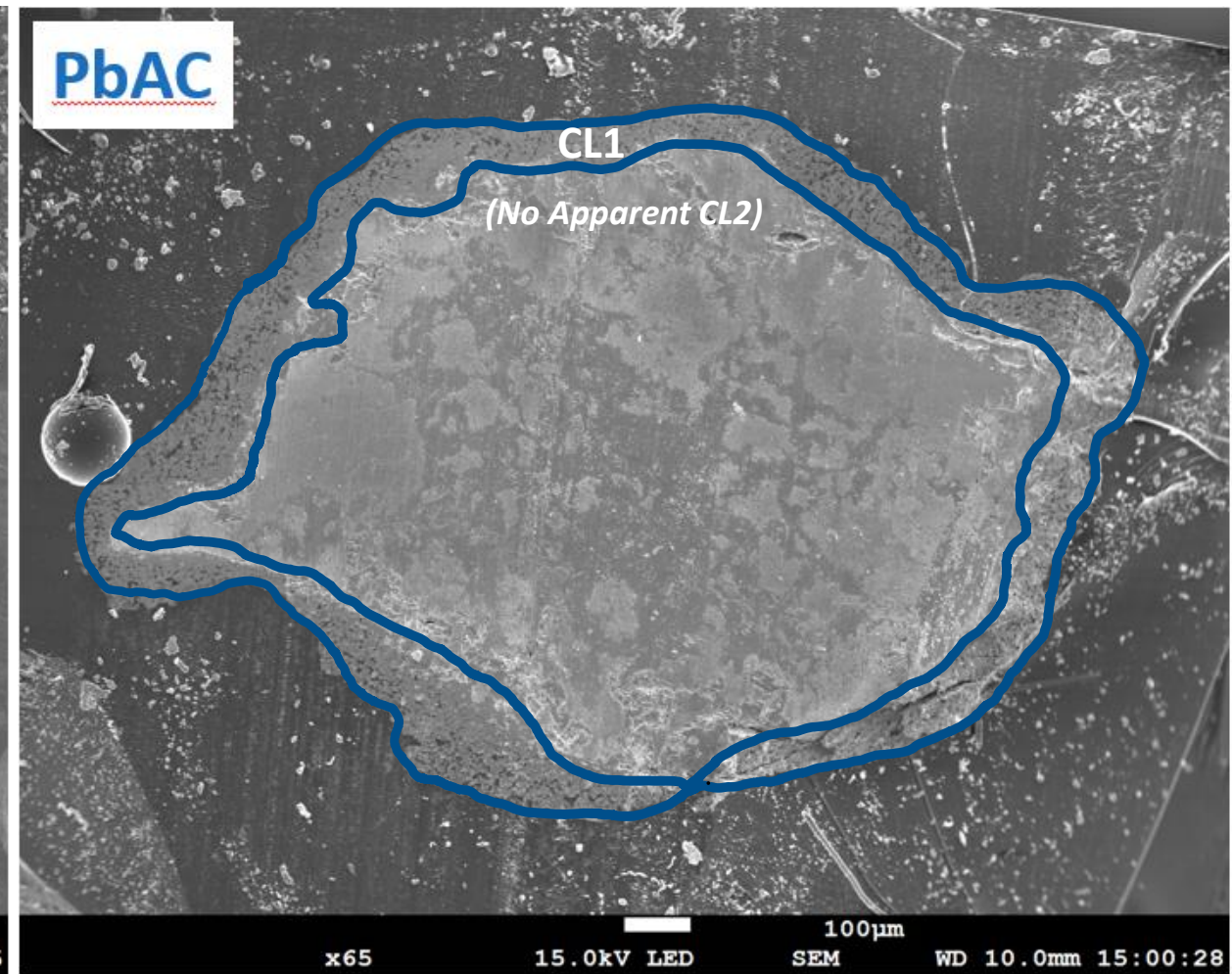
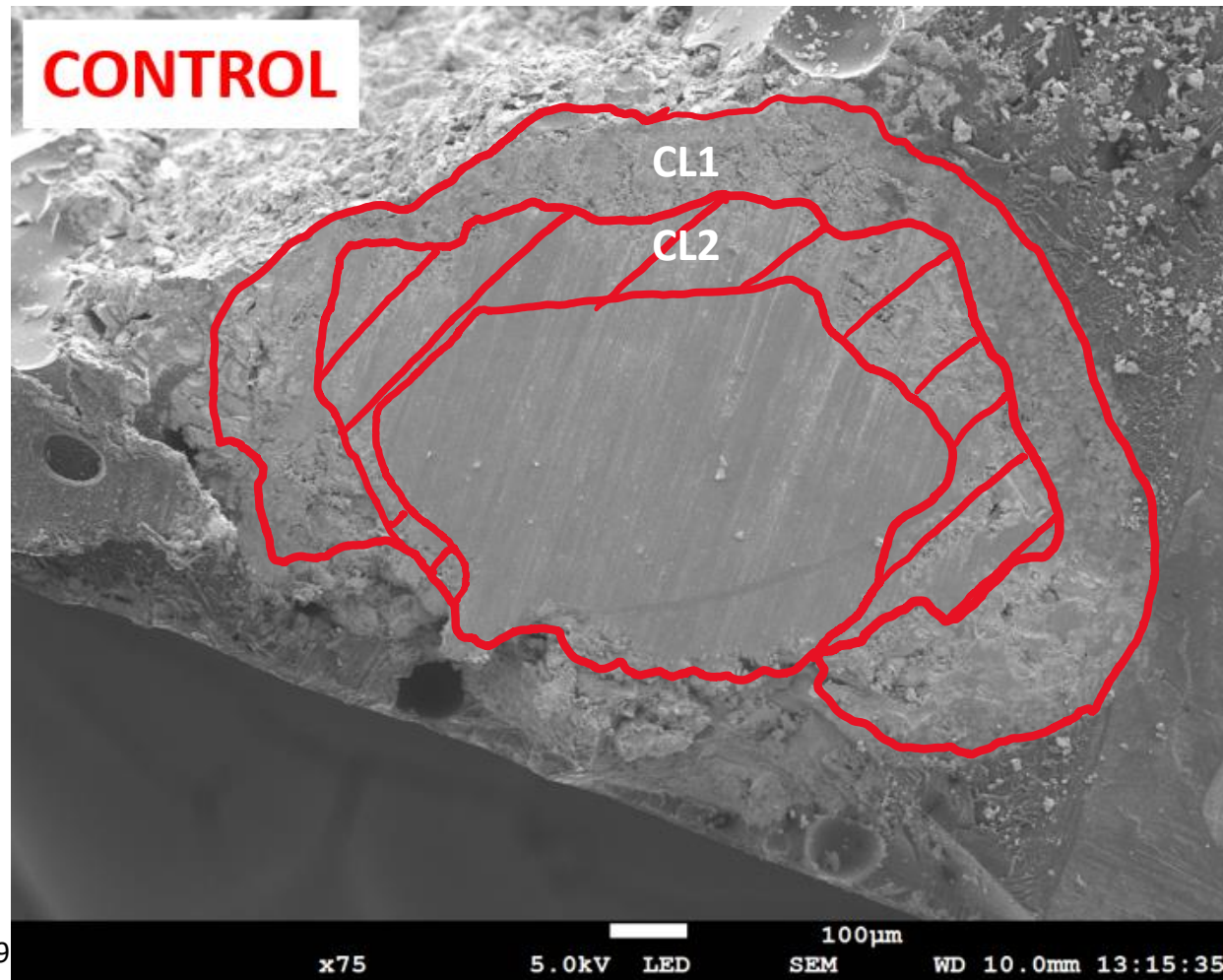
Hypothesis Generation

- Which enduring property might alter voltammetry and full-scale durability even after MR's disappearance?
 - Literature suggested the Corrosion Layer (“CL”) – the grid/active material interface
 - Formed during curing / formation
 - Persists during life of battery
 - Influenced by a variety of factors (alloy, active material, additives, acid access)

We hypothesized that MOLECULAR REBAR[®] would not alter the CL when incorporated into the positive active mass, and sought to falsify that hypothesis

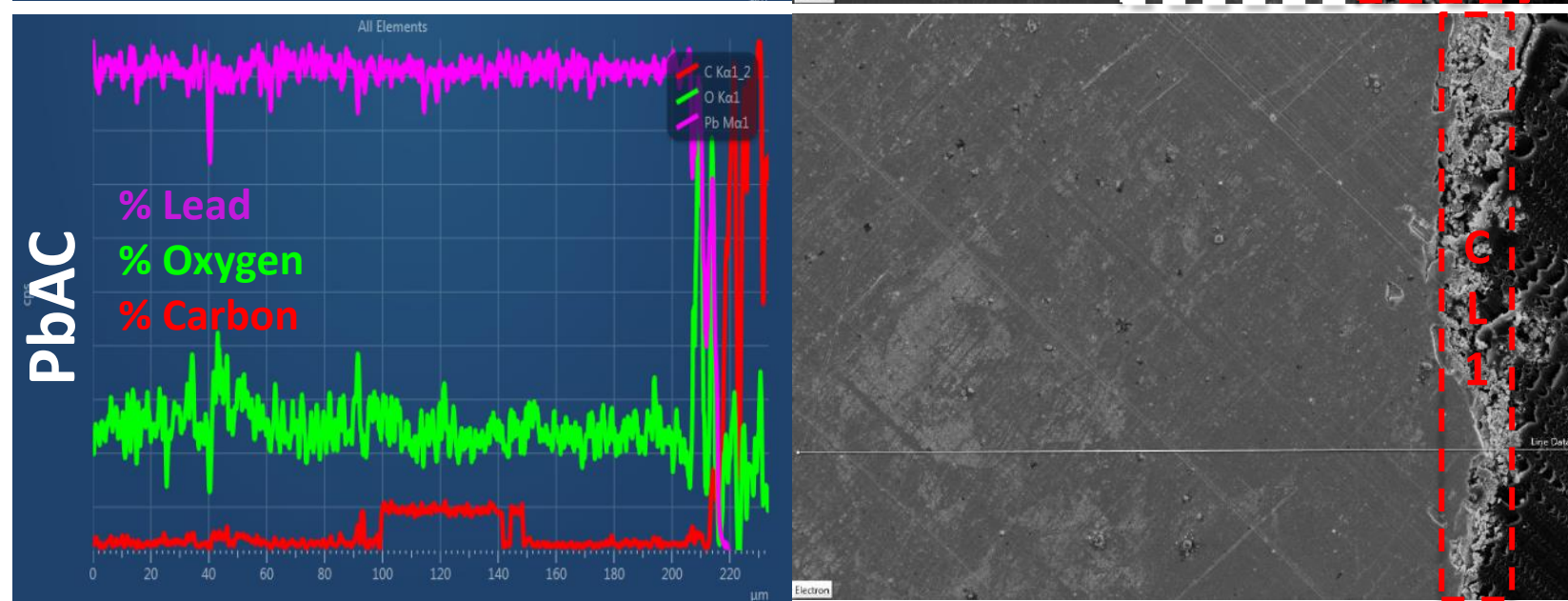
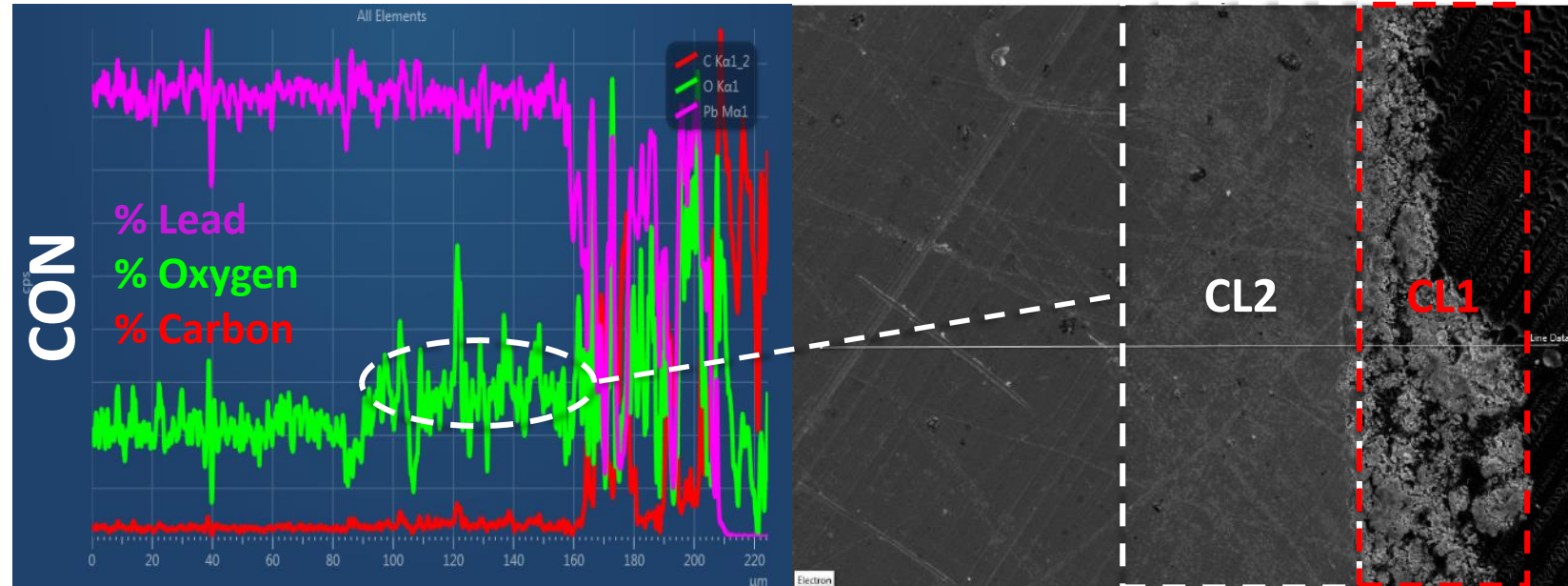
Hypothesis: MR Can Modify the Corrosion Layer

- PbAC generates a different corrosion layer morphology, improve J2185 cycle life >25% (post-life image below)
 - PbAC layer is thinner, denser, more uniform, and as a monolayer instead of a bilayer



Atomic Evidence of Corrosion Mitigation with MR

- PbAC enhancements are obvious even directly after Formation
- CON grid
 - Shows 2 distinct corrosion layers
 - Thick, less uniform than PbAC
 - Less dense, “fluffier”
 - EDS shows corrosion layer as slowly increasing **O%**, slowly dropping **Pb%**
- PbAC grid
 - Shows 1 corrosion layer
 - Thin, more uniform than CON
 - More dense, tighter, more robust
 - EDS shows corrosion layer as quickly increasing **O%**, quickly dropping **Pb%**

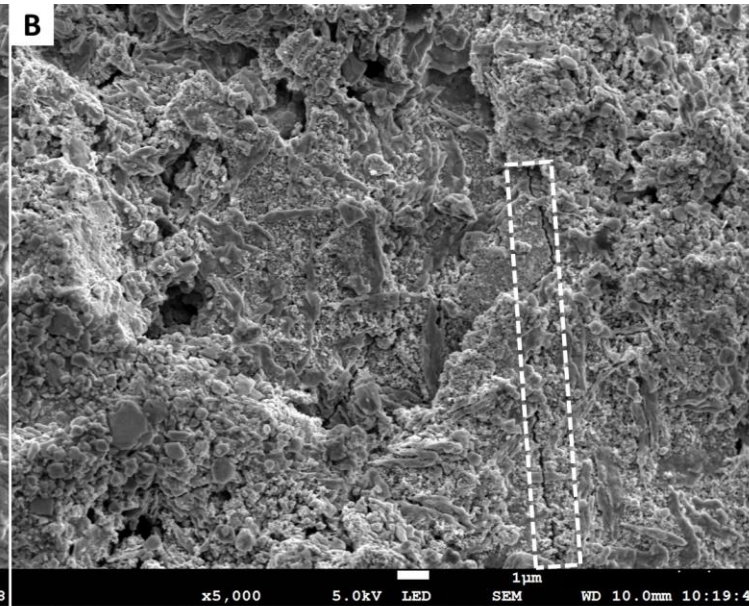
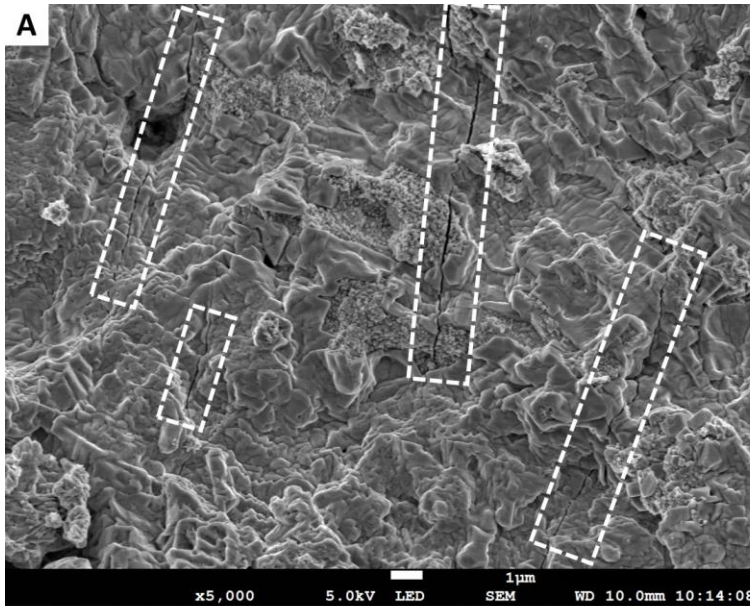


MOLECULAR REBAR Changes Grid Topography

12 V Reference PAM Grid

12 V MR PAM Grid

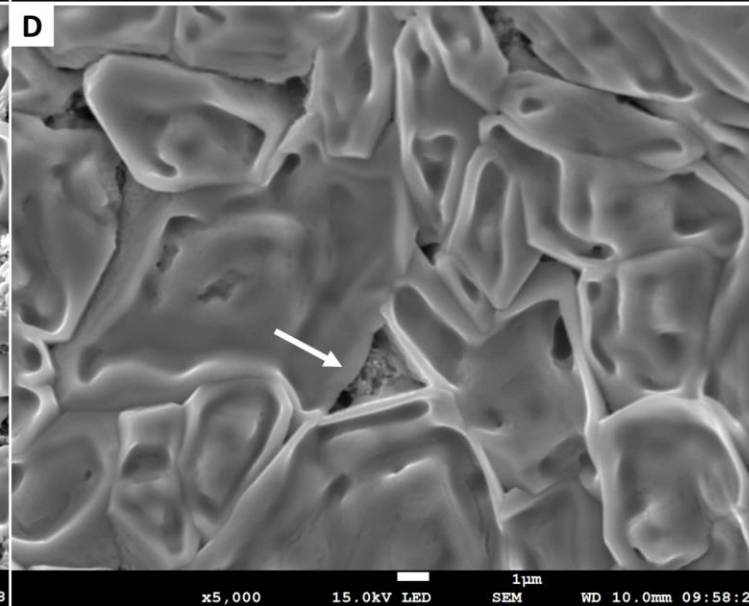
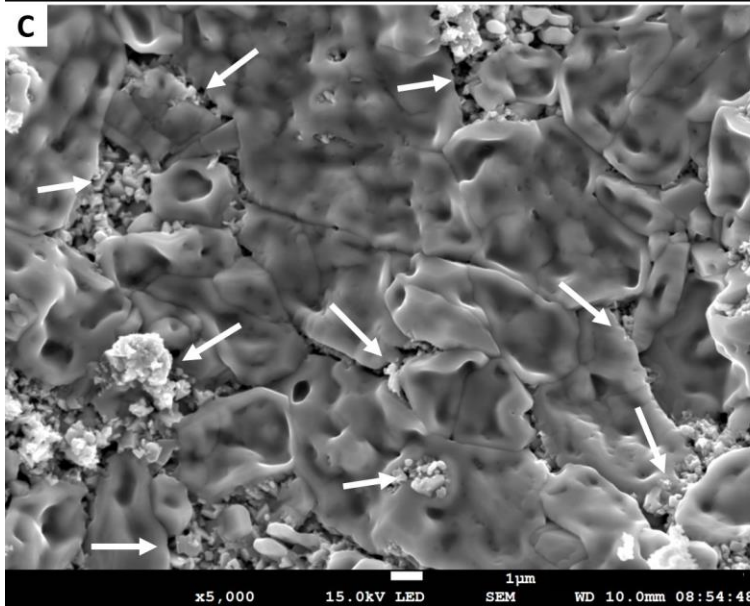
Post-Formation



← Post-Formation (12V SLI, Custom)

- A. CON grid retains less PAM, shows more hairline fractures (white boxes)
- B. MR grid retains more PAM, shows less hairline fractures (white box)

Post-Cycling

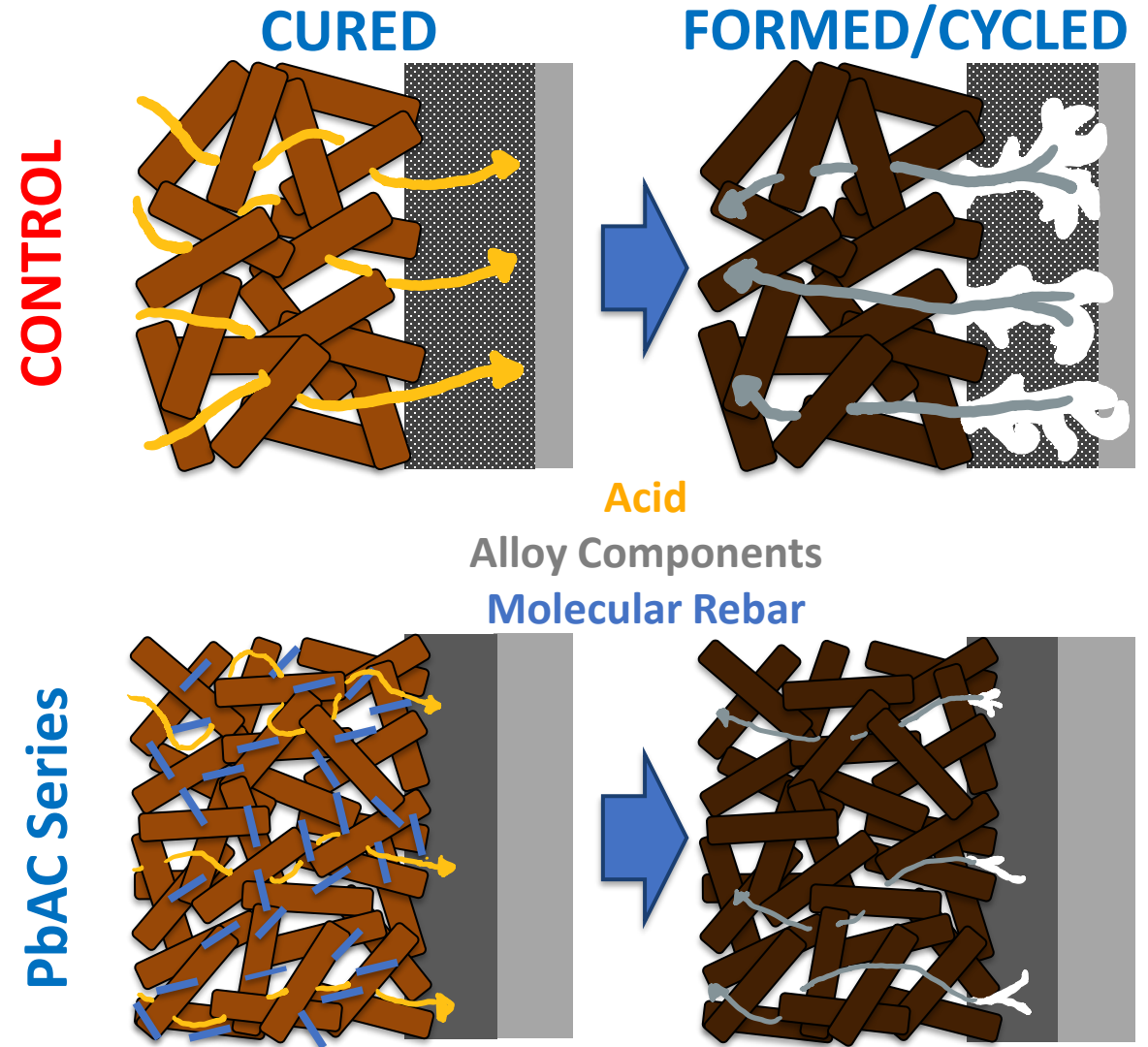


← Post-Cycling (12V VRLA, EN50342-1)

- C. CON grid shows many imperfections, pockets of PbO_2 (arrows)
- D. MR grid shows larger, agglomerated morphology, less PbO_2 pockets (arrows)

THEORY: MR Builds An Improved Corrosion Layer

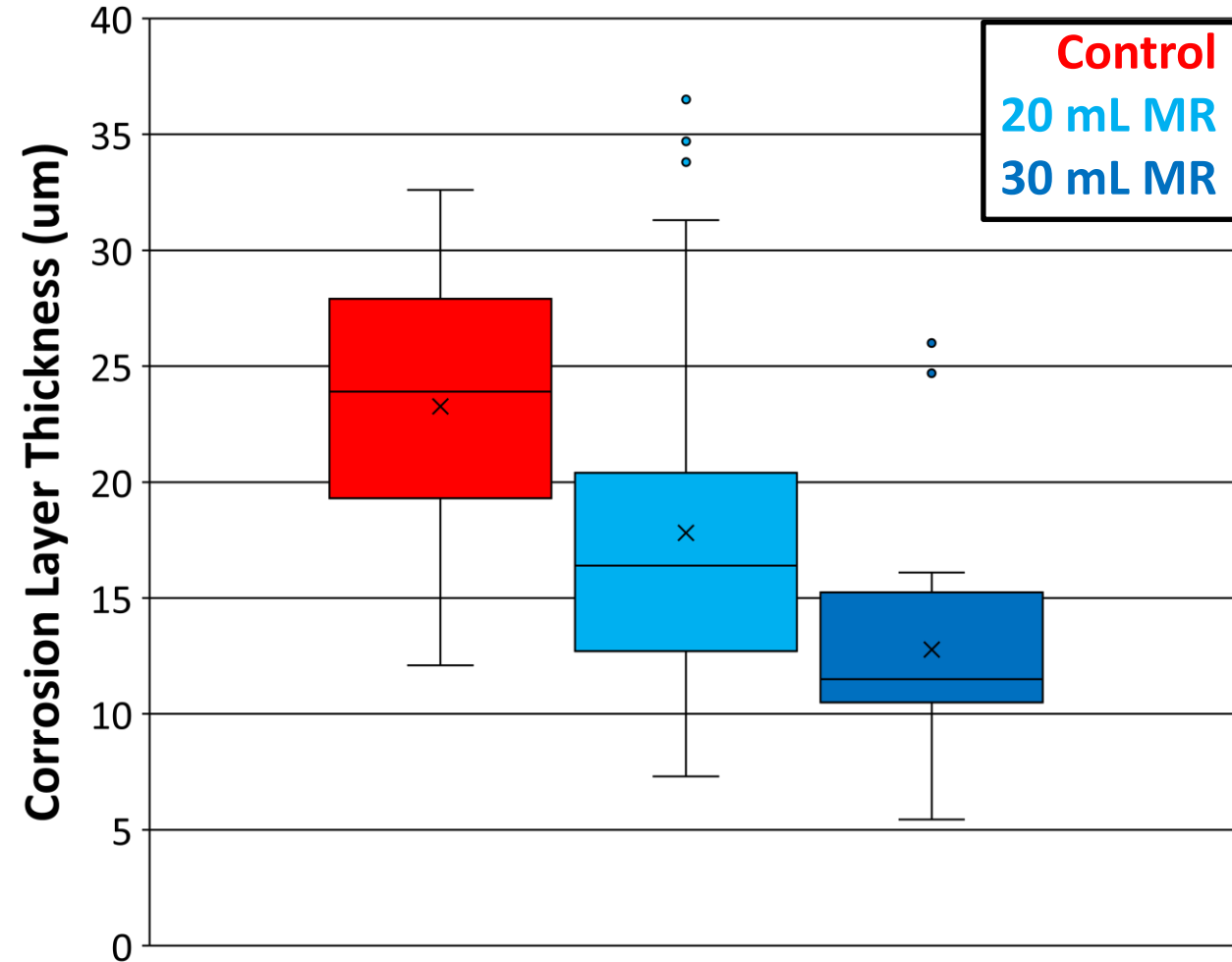
- **PbAC technology changes cured PAM “DNA”**
 - Uniformity of Action throughout active material
 - **KEY TO ENABLEMENT**
 - Discrete, nanoscale, uniformly-distributed MR
 - Alters crystal packing, changes water/acid access to grid
- **During formation, PbAC is a sacrificial agent**
 - Initially, energy 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



MR Effect on Corrosion Layer is Dose Responsive

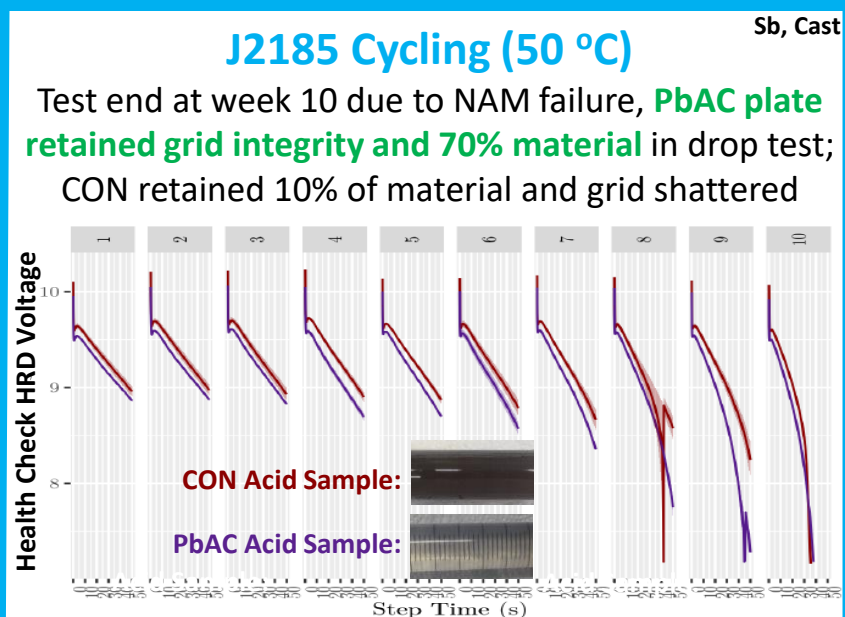
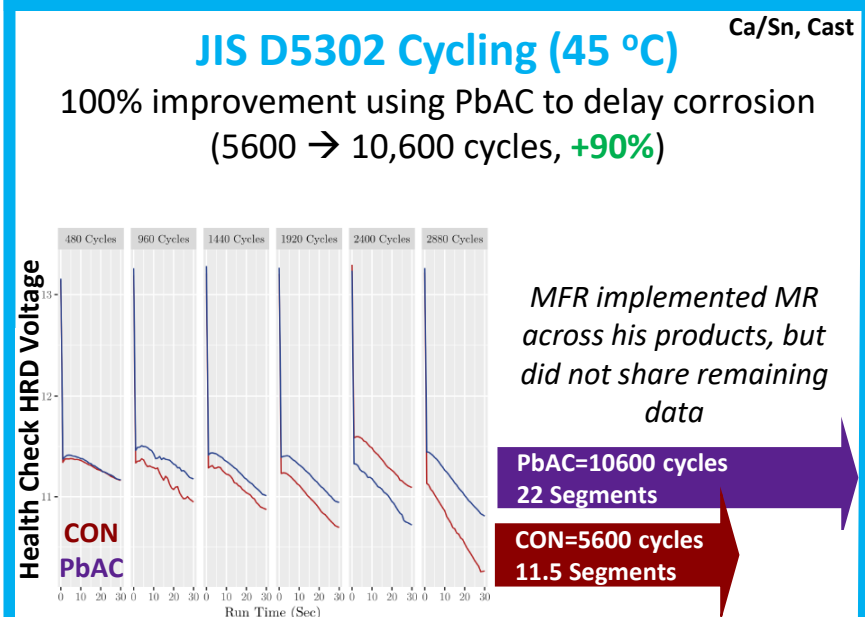
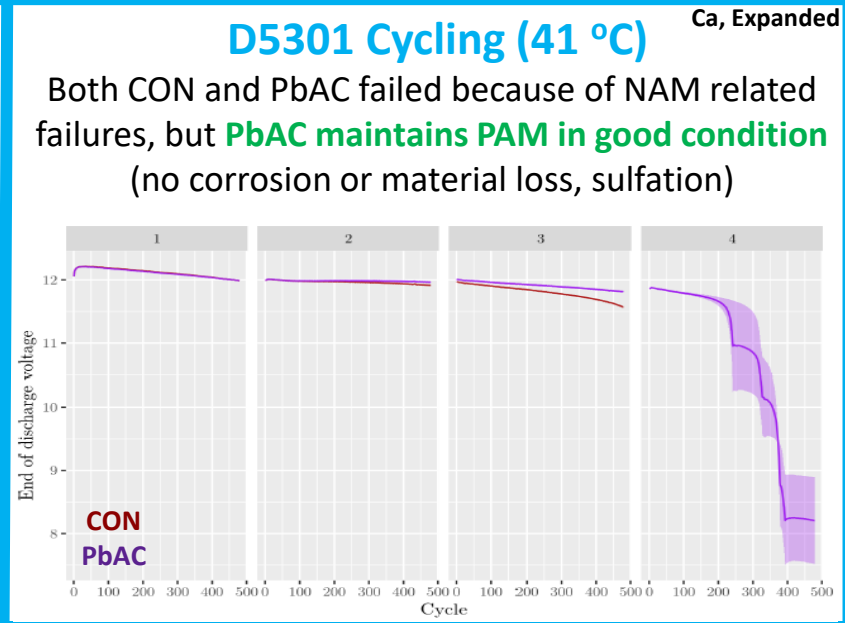
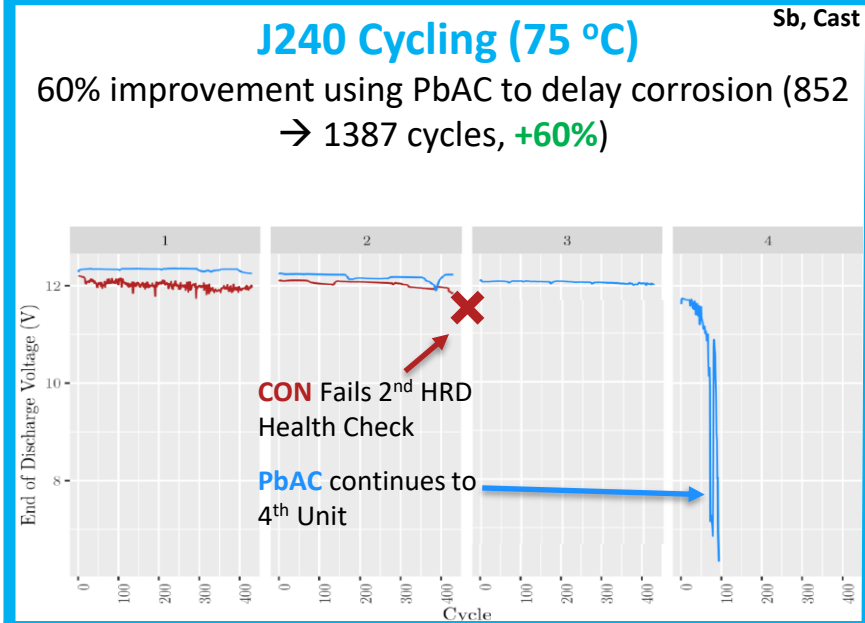
- To build evidence for our theory, we sought to confirm our observations with a dose response
- 2 V Cell Experiment**
 - Positive pastes with various volumes of MR were made
 - Plates were produced, cured, and dried
 - Plates were formed as 2P/2N, 5 Ah, EFB-styled batteries
 - Positive plates were extracted and washed in IPA
 - Grid samples were removed, epoxied, cross-sectioned
 - CL thickness from polished cross-sections were measured by SEM

MOLECULAR REBAR® changes the thickness and morphology of the Corrosion Layer in a dose-responsive fashion



CL Enhancements Translate to 12 V Performance

- MR-modified corrosion layer protects grid from further degradation and improves battery life where corrosion is the failure mode
- Effects confirmed with:
 - Grid Alloys
 - Sb, Ca/Sn (<2% Sn), Ca, Pb
 - Grid Types
 - Cast, Expanded, Punched
 - Various High-Temperature Tests
 - J240, J2185, JIS-D5301/2, nKLT



Review

- **MOLECULAR REBAR®-Promoted Corrosion Resistance**
 - Improved high-temperature cycling achievable with PbAC
 - Mechanism of Action based upon alterations induced by MR upon the grid-material interface (Corrosion Layer)
 - CL is modified due to altered active material packing and construction which changes acid/water path to the grid

Thank-You For Your Time!

Dr. Paul Everill

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