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Enabling Emerging Battery Technologies with Networked CNTs

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MIRALON® Carbon Materials

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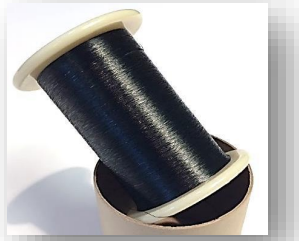
FC-CVD continuous production process

The Floating Catalyst Chemical Vapor Deposition (FC-CVD) process converts fuel into **long nanotubes which coalesce into a macro structure of branched bundles**

Yarn



- Hydrocarbon
- Catalyst
- Hydrogen

Sheet

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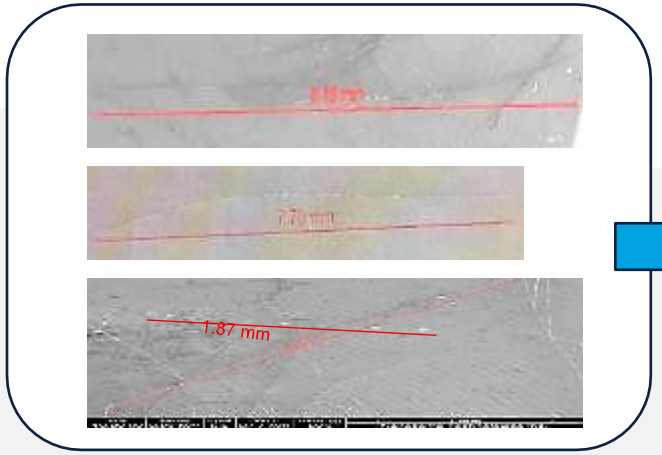
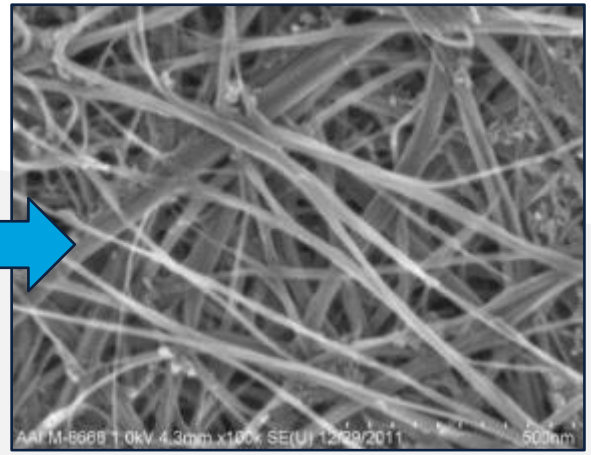
Differentiated from standard carbon nanotubes

The length and unique interconnection between bundles that make up MIRALON® translates into enhanced properties.

- Increased strength
- Increased conductivity
- Increased toughness
- Better thermal conductivity

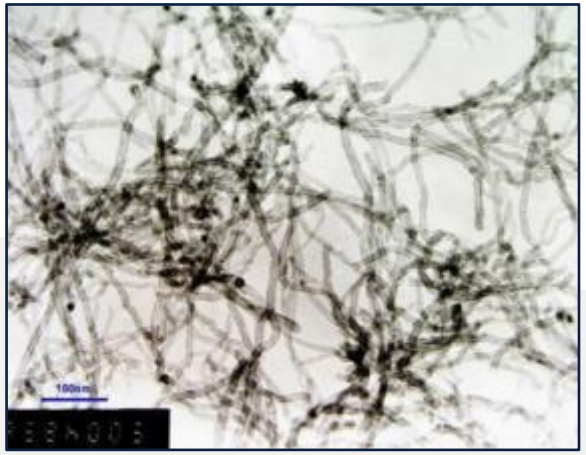


Many individual MIRALON® nanotubes are 1-10mm long



MIRALON® materials' structure: interconnected bundles

VS



Conventional nanotubes: powder form

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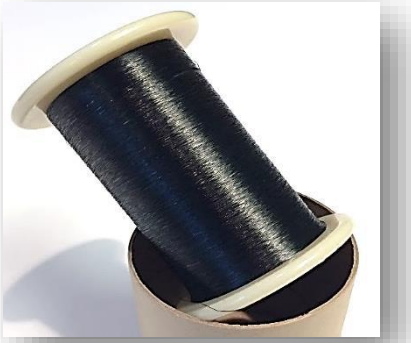
Enabling performance and design flexibility

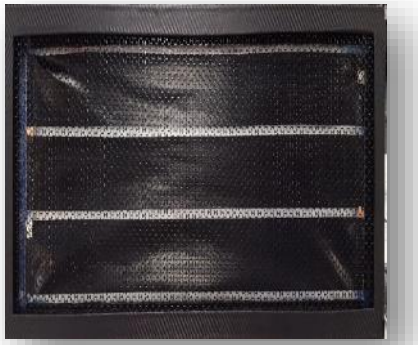
Sheets

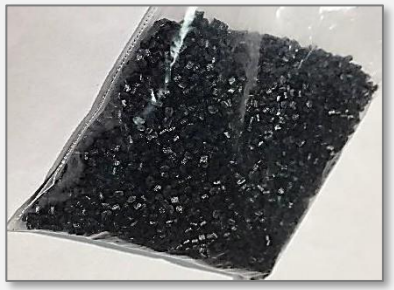
Yarns



Tapes

Heaters





Pulp

Compounds

Masterbatch

Formulations

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Key benefits compared to nanotube technologies

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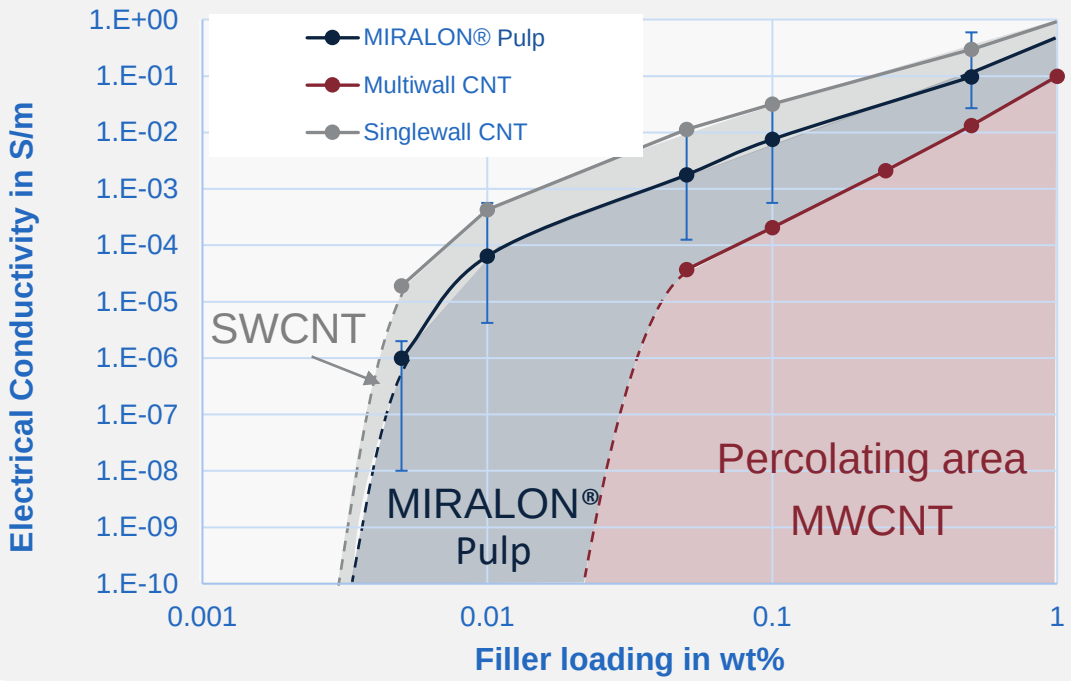
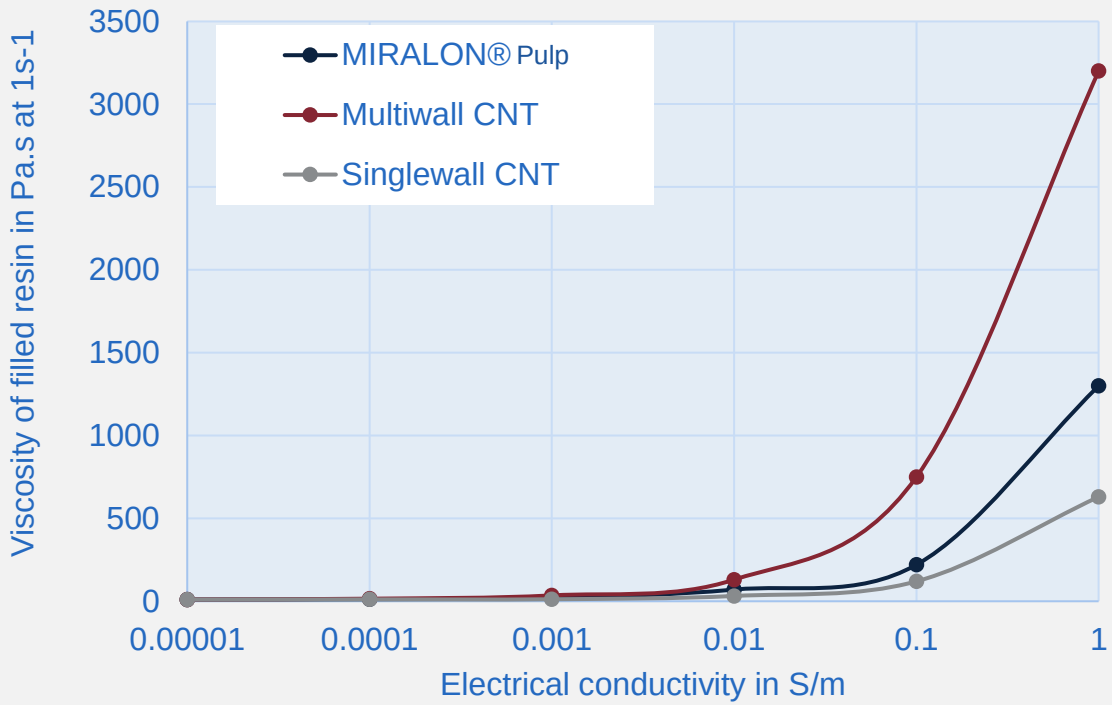
Electrical properties



Viscosity



MIRALON® Pulp competes with single-wall CNTs (SWCNTs)

Moderate impact on viscosity at equivalent electrical conductivity

examples based on mixtures in epoxy resin

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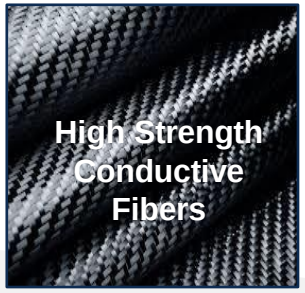
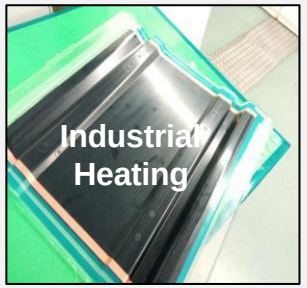
Enhancing products across multiple markets

The MIRALON® materials' technology is driving innovation in aerospace, coating, composites and automotive markets

- **Strength**
- **Electrical conductivity**
- **Thermal conductivity**
- **Corrosion resistance**
- **Mechanical damping**





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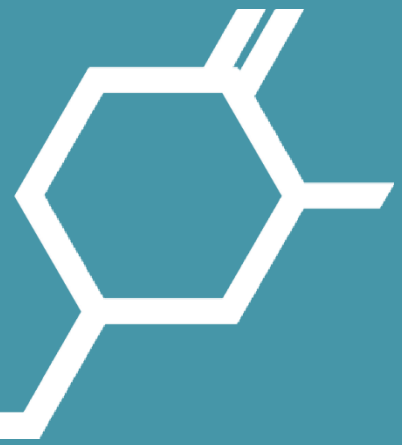
MIRALON® in Batteries



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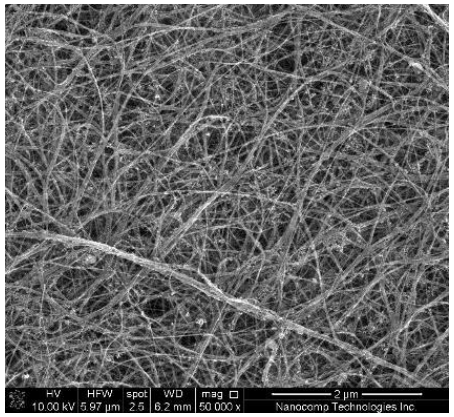
Sheet material is processed into pulp then dispersed and spread on current collector

MIRALON® sheets made FC-CVD

CVD).

Entangled Network of Bundles.

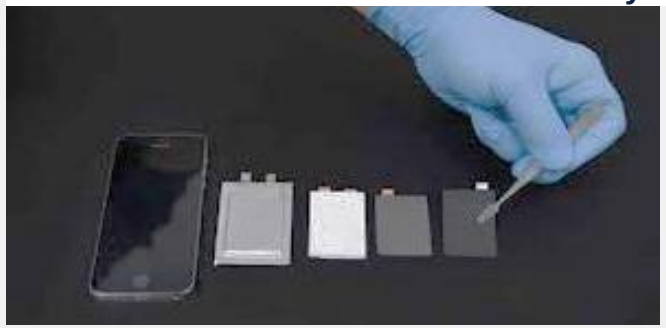


Dispersible Pulp made by standard paper processing methods

The pulp is combined with a binder and solvent to make a Masterbatch

The Masterbatch is dispersed with active material and spread onto a current collector.

Anode, cathode, separator, electrolyte and case are combined to make a battery



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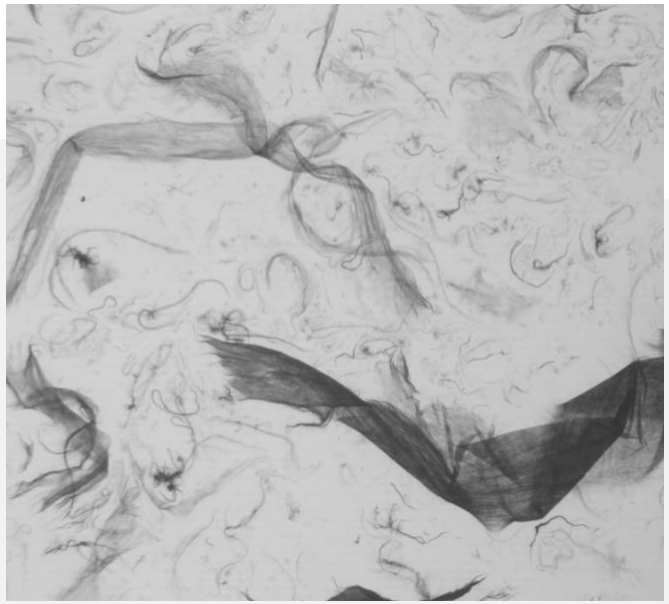
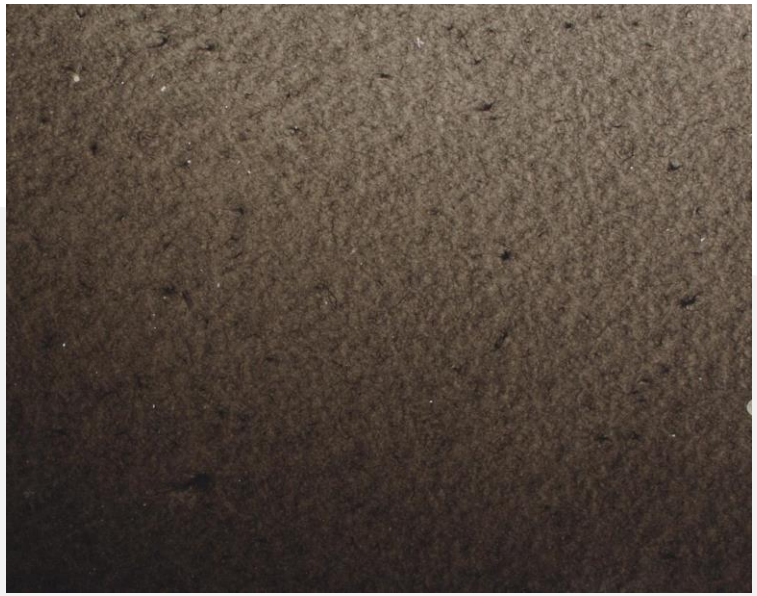
Interconnected bundles enhance connectivity

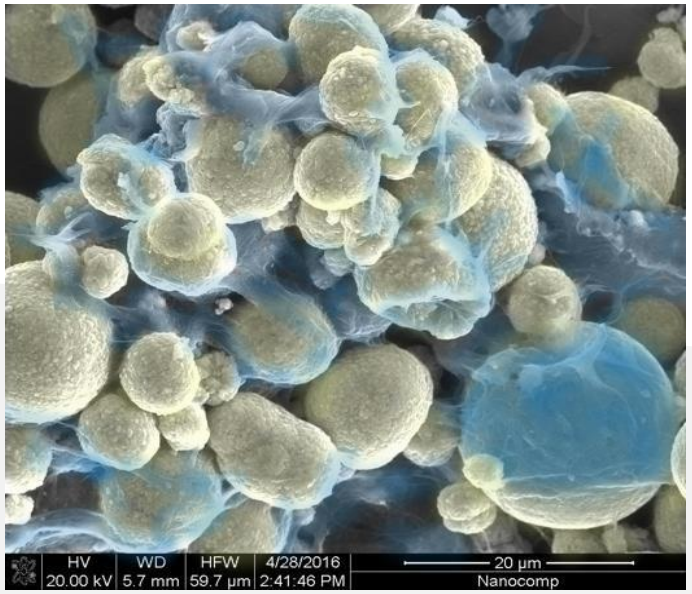
- Hierarchical structures unlike anything seen with powder CNT
- Long-range interconnections of branched bundles in the active material
- Wraps around particles & holds them together, making electrical and mechanical connection



Aqueous MIRALON® Pulp
Dispersion showing "Sheetlets"



NMP Masterbatch: 1.25% MIRALON® Pulp, 3.75% PVDF.



0.5% MIRALON® pulp
3% PVDF in NMC

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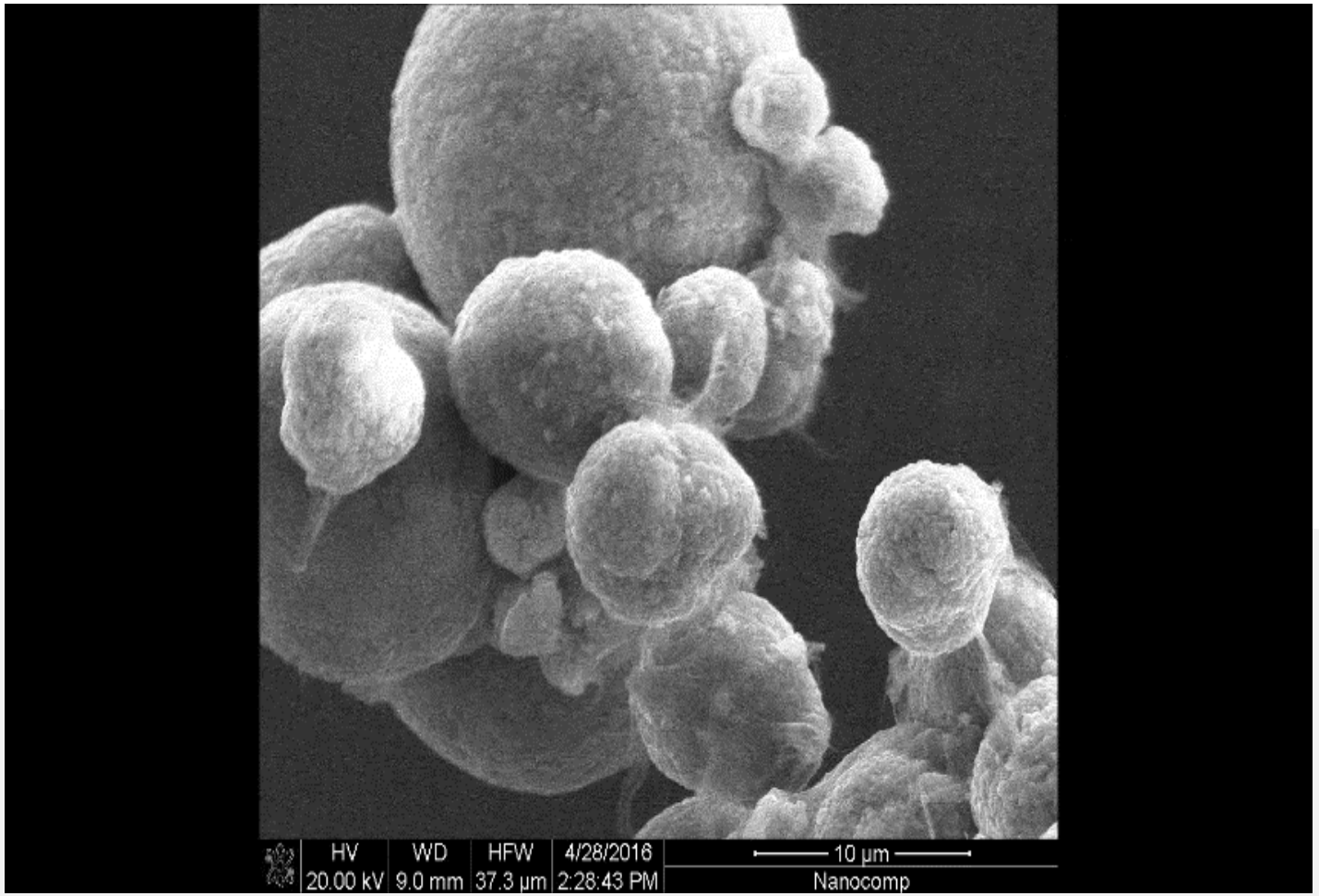
Interconnected bundles enhance connectivity



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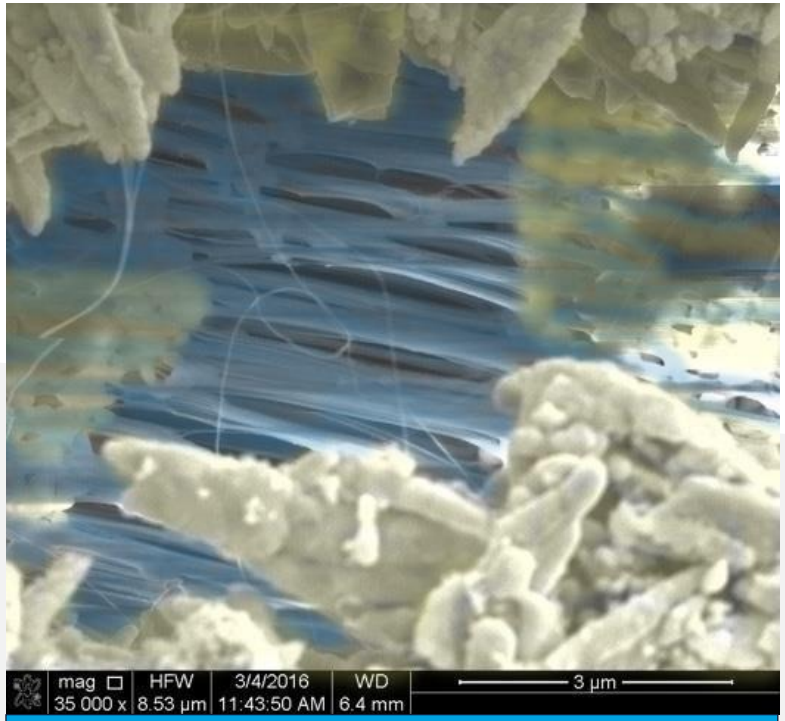
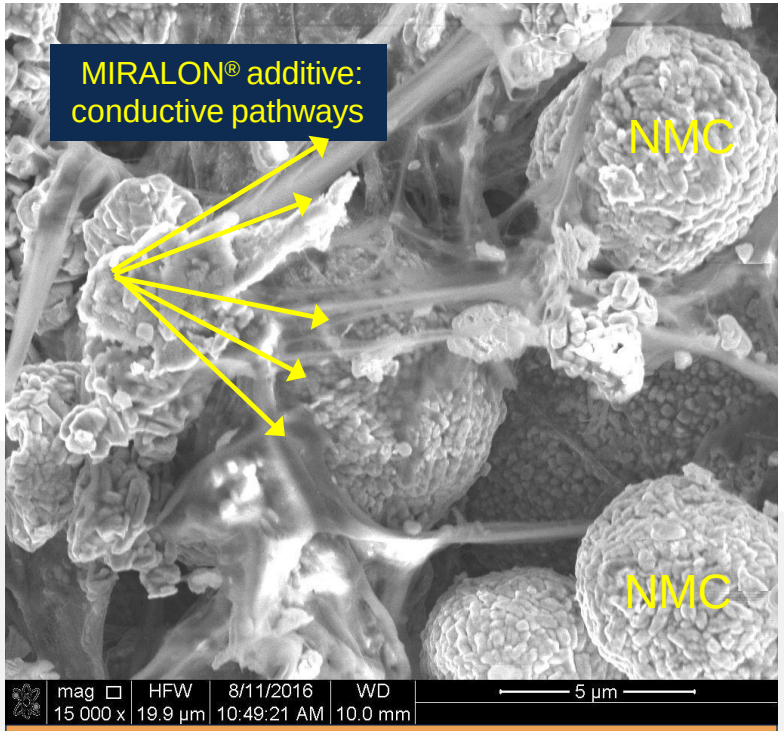
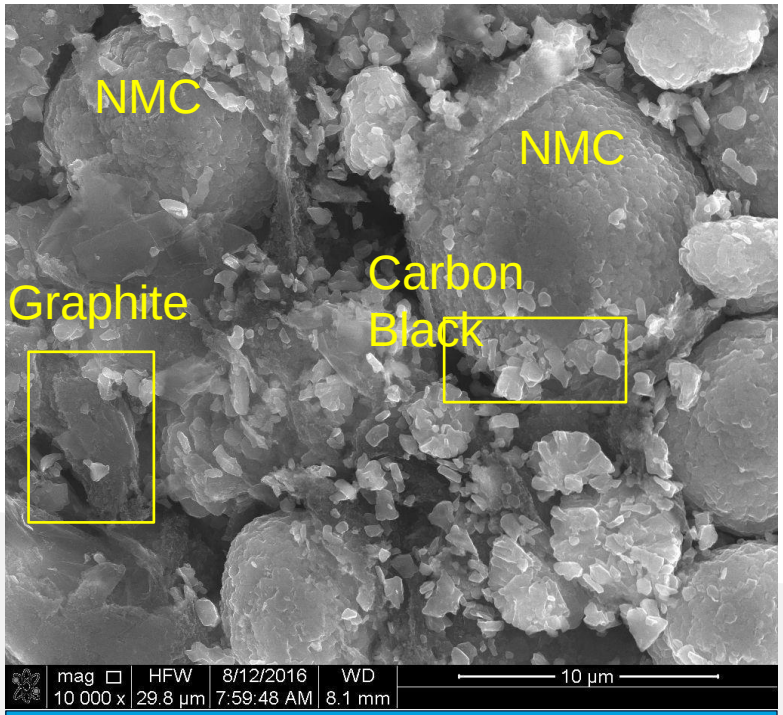
MIRALON® enables higher conductivity and more active material



0.5% Miralon® Pulp
3% PVDF
96.5% LFP



0.5% MIRALON® pulp
3% PVDF
96.5% NMC



2.5% Carbon Black & 1.5% Graphite
3% PVDF
93% NMC

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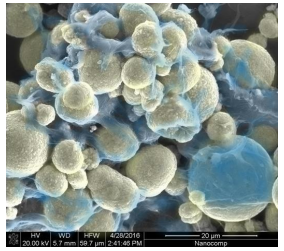
MIRALON® materials enable better battery performance and improved safety compared to carbon black

MIRALON® Features

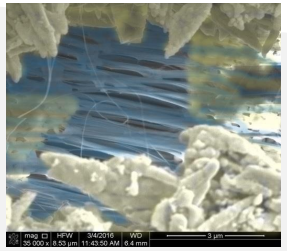
Electrically Conductive

- Miralon's long strands create conductive pathways that provide **16x better electrical conductivity** than carbon black



Thermally Conductive

- Interconnected bundles provide **enhanced ability to transfer heat** to reduce ohmic heating & thermal mgmt. issues



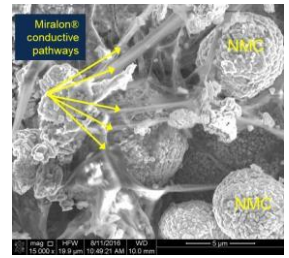
Strength & Flexibility

- **Improves mechanical properties and cohesion within coatings**. It also adds flexibility allowing for thicker media unlike brittle carbon black

MIRALON ® Benefits

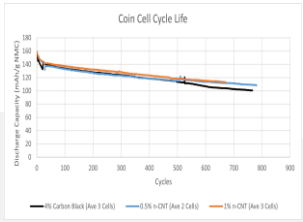
Mass Reduction & Increased Capacity

- 8Xs lower loading levels enables higher amounts of active material reducing non-active mass
- Strength and flexibility enables thicker cathodes increasing volumetric capacity up to 20%



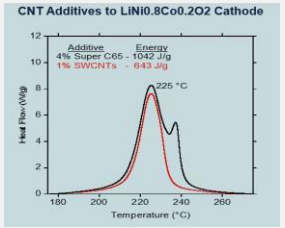
Longer Cycle Life

- Preliminary investigation indicates that lower carbon loading levels to lessen the potential of degradation of the electrolyte providing a longer cycle life



Improved Safety

- Safety expected to be improved by reducing exotherm by 40% based initial findings
- Lower internal resistance significantly reduces discharge heating



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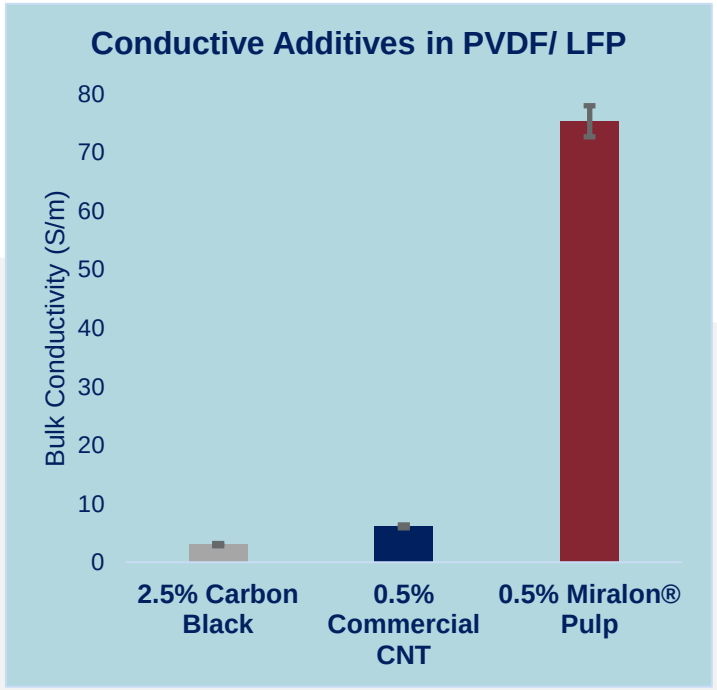
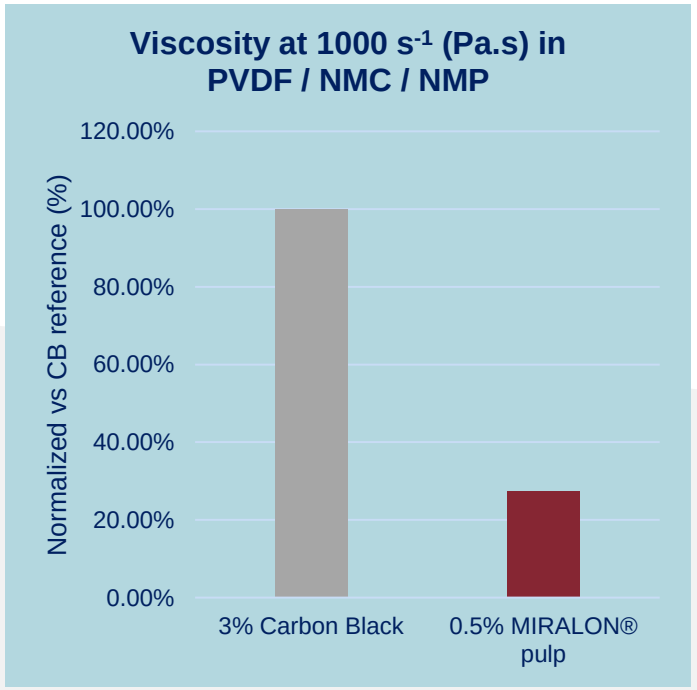
Better Conductivity, Processing & Mechanical Properties

Electrical Conductivity



Higher electrical conductivity at lower loadings

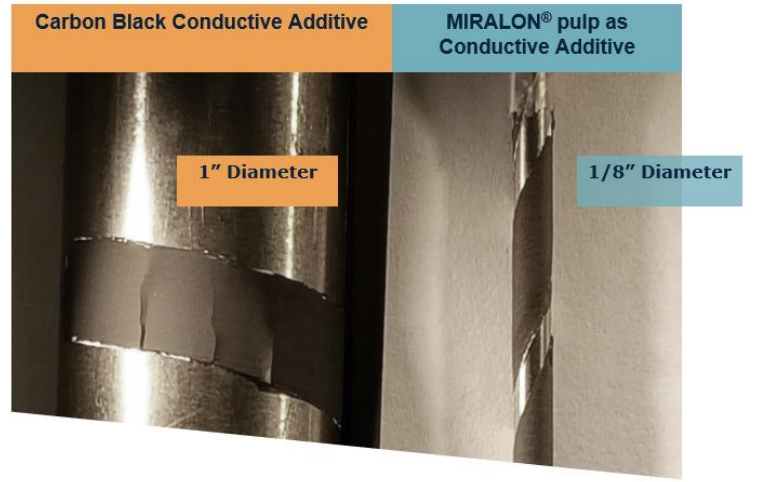
Improved Processing Performance



Lower viscosity enables use of less solvent

Mechanical Performance

Strength & Flexibility



Eliminates brittleness and cracking

SeNSE
This project received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 875548.

Note: Presented data has been verified using in-house and third-party labs. Additional testing programs underway

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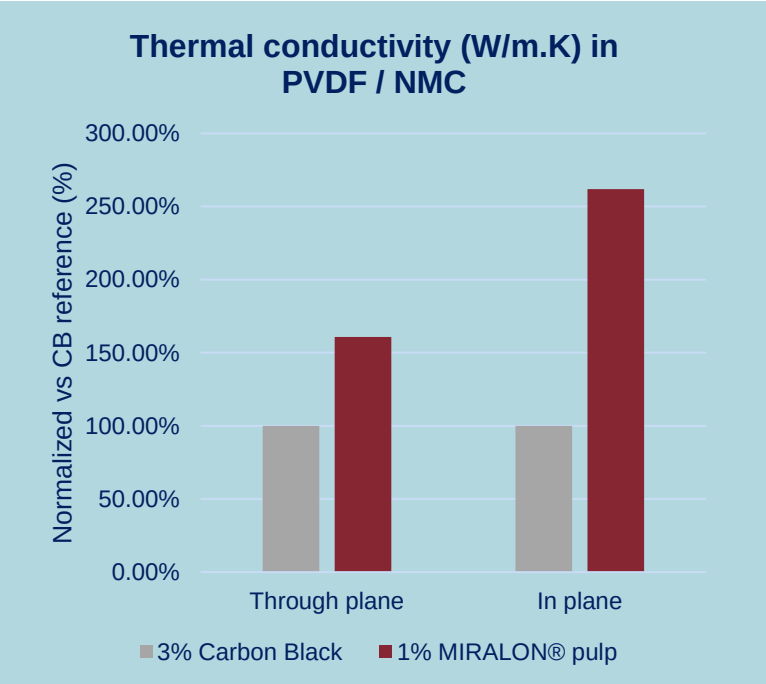
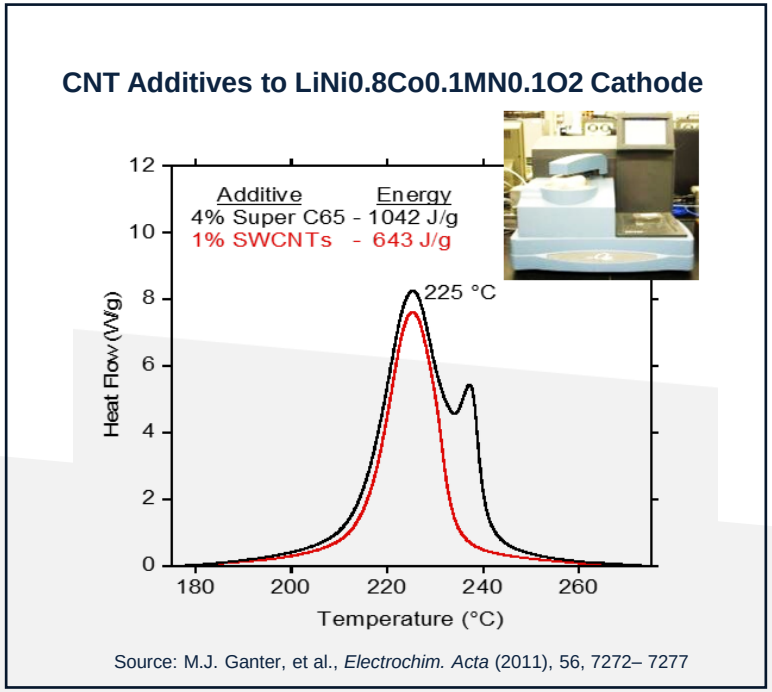
Better Thermal Management

Improved Thermal Management



Higher thermal conductivity at lower loadings

Improved Thermal Management



Indications in literature of reduced exothermic energy released (J/g)

SeNSE *This project received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 875548.*

"Differential scanning calorimetry analysis of an enhanced LiNi0.8Co0.2O2 cathode with single wall carbon nanotube conductive additives" Matthew J. Ganter, Roberta A. DiLeo, Christopher M. Schauerman, Reginald E. Rogers, Ryne P. Raffaelle, Brian J. Landi. **Electrochimica Acta** 56 (2011) 7272– 7277

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Note: Presented data has been verified using in-house and third-party labs. Additional testing programs underway

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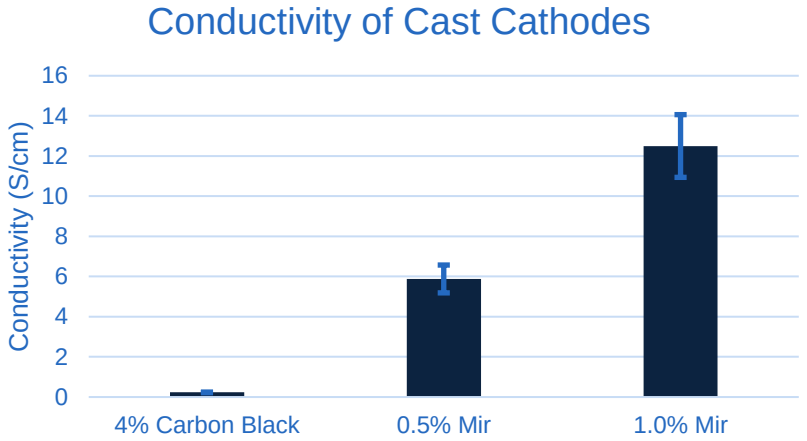
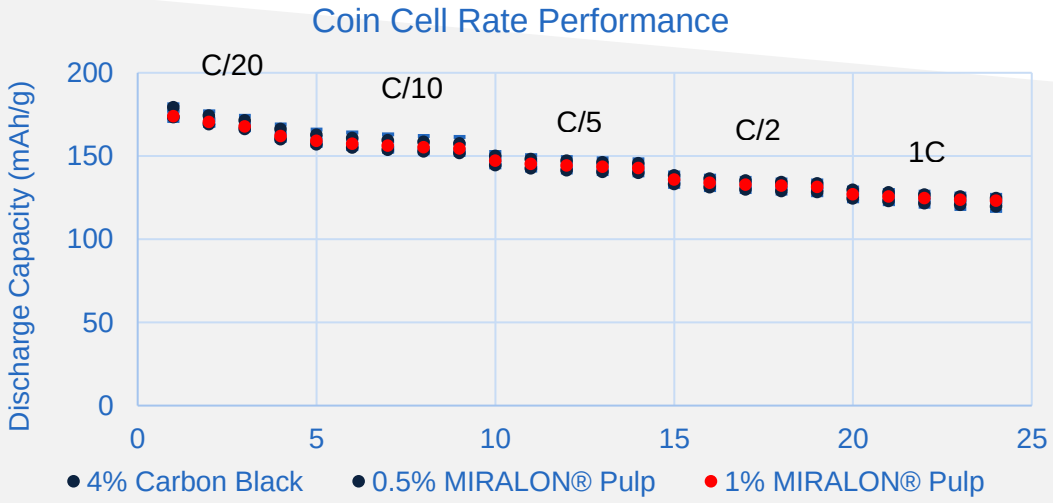
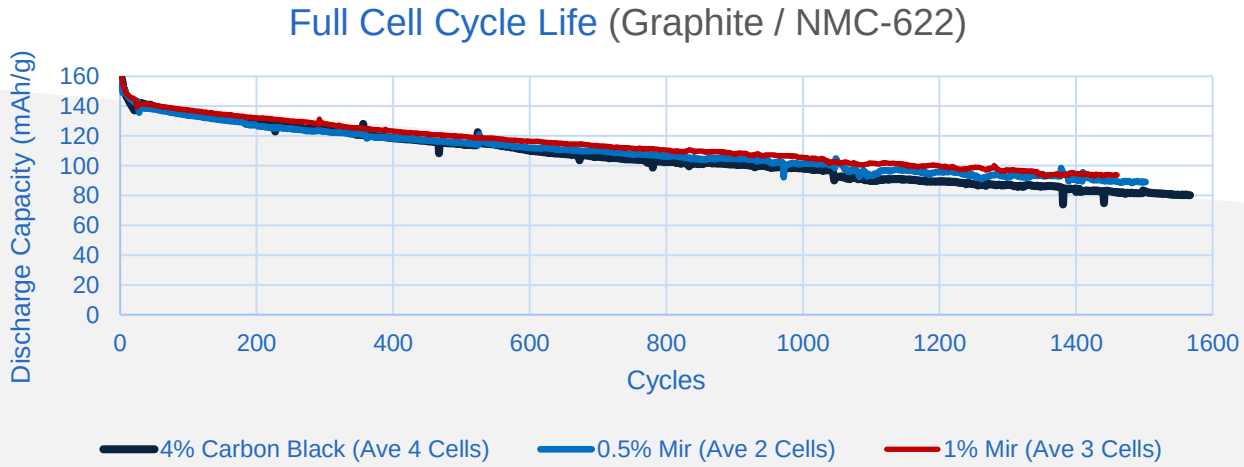
MIRALON® Pulp and JEFFSPERSE™ Dispersion Aid in LiBs

Sample #	Dispersion Aid	Conductive Additive	Active Material	Resistivity (Ω-cm)
C1	None	4% Carbon Black	92% NMC-622	4.40 (+/- 0.30)
C3	0.5% Jeff	0.5% Mir	95% NMC-622	0.17 (+/- 0.02)
C4	1.0% Jeff	1.0% Mir	94% NMC-622	0.08 (+/- 0.01)
Full coin cells fabricated and tested at RIT. Mir = MIRALON® Pulp. Jeff = JEFFSPERSE™ X-3200.				







JEFFSPERSE™ X-3200 as a dispersion aid enables **MIRALON® Pulp** as a conductive additive in NMP. Graphite anode, 4% HSV-900 binder, 2 mAh/cm2 loading.

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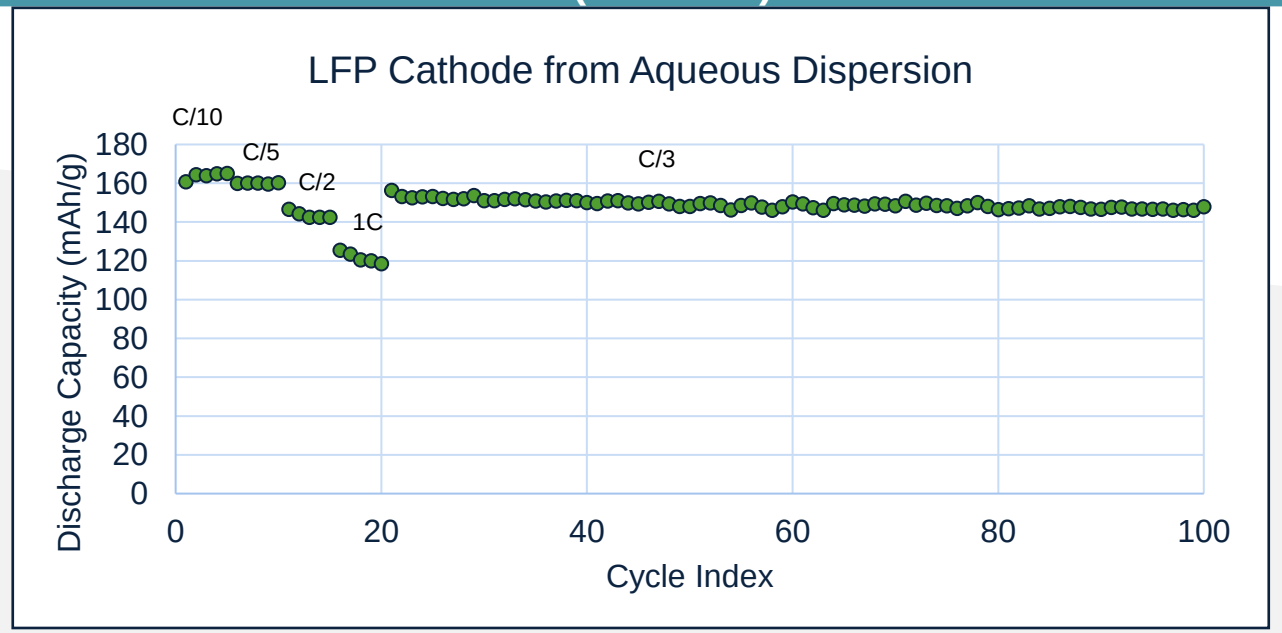
MIRALON® Pulp and JEFFSPERSE™ Dispersion Aid in LiBs

Sample #	Solvent	Dispersion Aid	Conductive Additive	Binder	Active Material	Resistivity (Ω-cm)	Loading
NB218-60-4	Water	0.5% Jeff	0.5% Mir	4% HSV-1800	95% LFP	1.01 (+/- 0.11)	2 mAh/cm^2

Aqueous dispersion used to make the cathodes for half-coin cells fabricated and tested at Huntsman-Merrimack. Mir = MIRALON® Pulp. Jeff = JEFFSPERSE™ X-3202 (% solids).



LFP Cathode slurries containing **JEFFSPERSE™ X-3202** and **MIRALON® Pulp** enable the use of PVDF binders in Aqueous Dispersions (with post-casting treatment).

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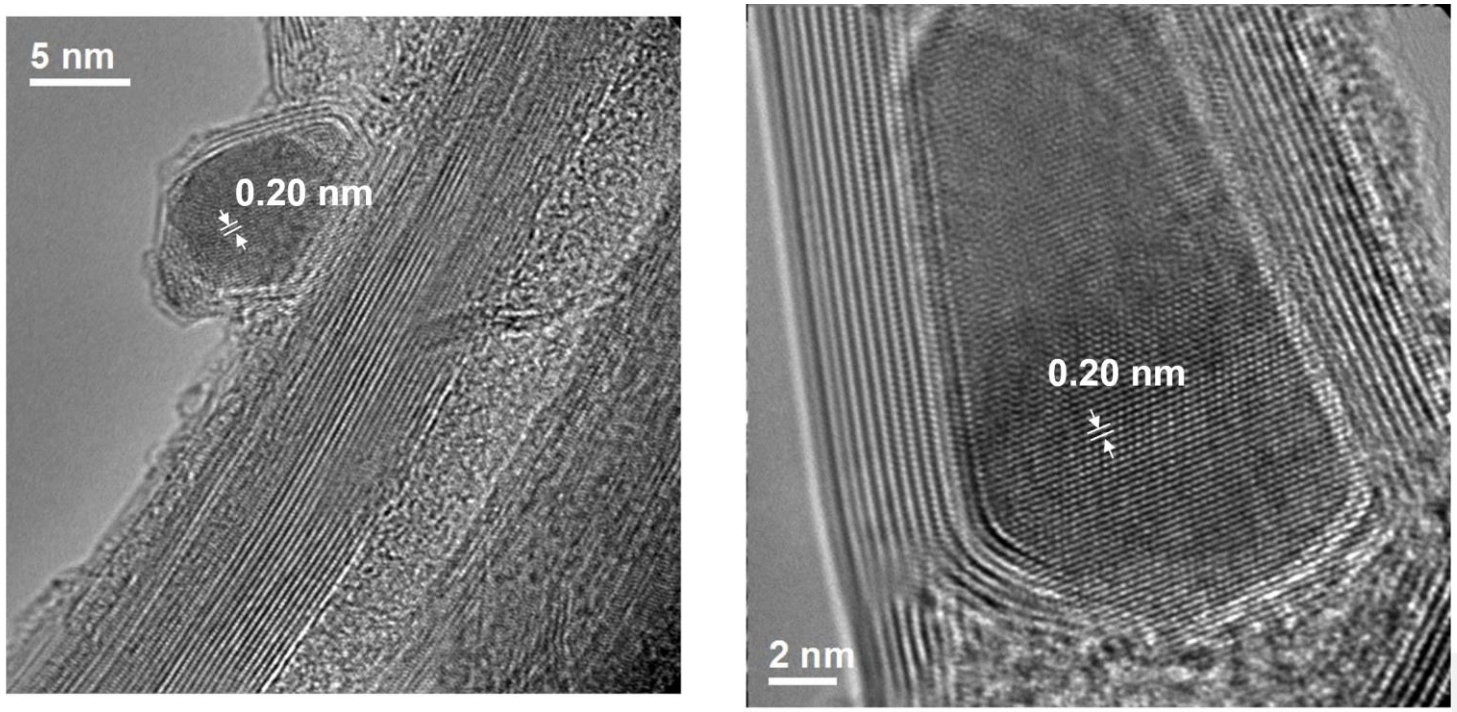
Floating Catalyst CVD means the Fe is still in there….



Layers of graphitic carbon nanotubes surround the nanoparticles. Lattice fringes are separated by 0.20 nm spacing which could be correspond to lattice plane of Fe_3C.

… encased in multiple layers of graphene, rendering the Iron chemically inert and having no effect on battery performance.

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Equivalent stability and higher capacity of NMC532/graphite full cells with MIRALON®

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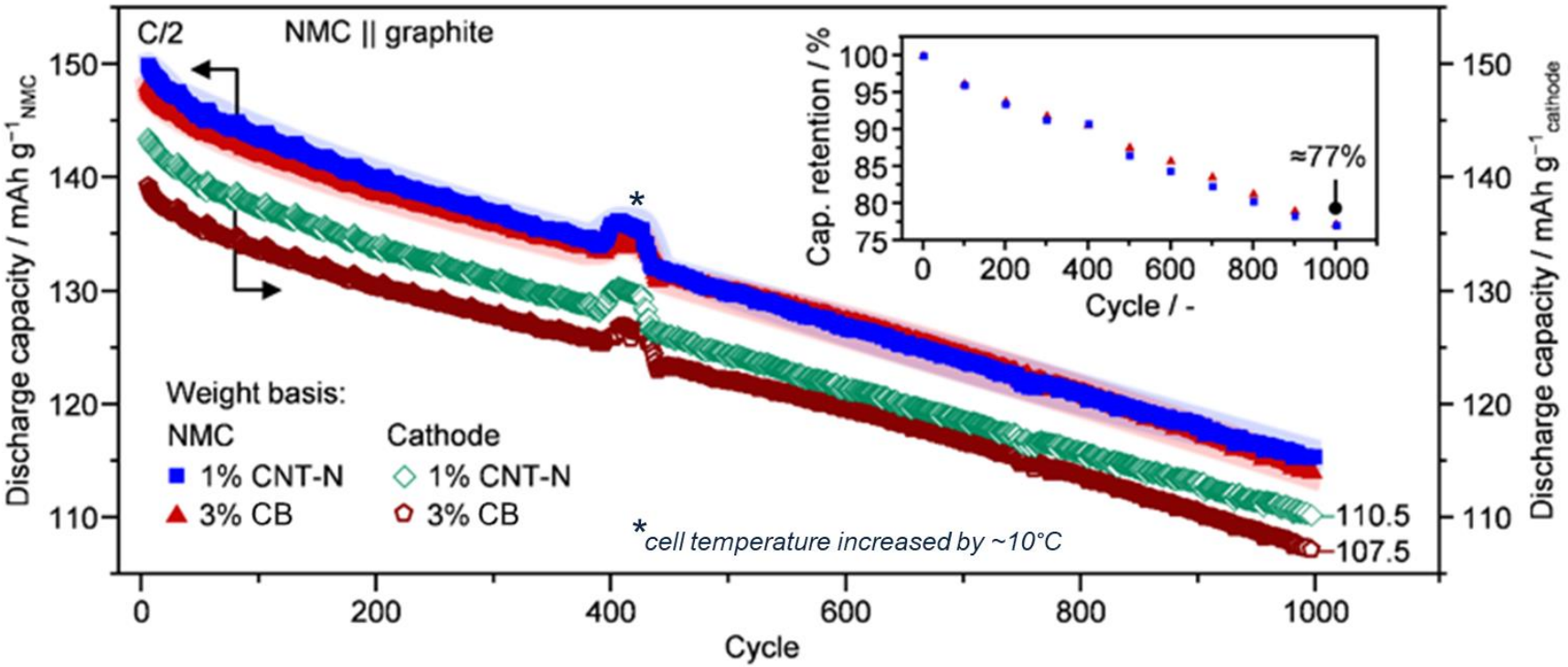
- **1% MIRALON® (CNT-N) cells outperform 3% CB cells** when cycled at C/2 charge-discharge rates:
  - comparable capacity retention after 1000 cycles
  - higher capacity both per NMC and particularly per cathode mass



Cycled from 2.8-4.2 V vs. Li/Li+

→ if Fe redox occurs, we would not see similar capacity retention to C65 cathode over 1000 cycles

Note: 1wt% MIRALON® in cathode means that 0.25wt% is Fe-based species

*all data with 3% PVDF binder

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 875548.

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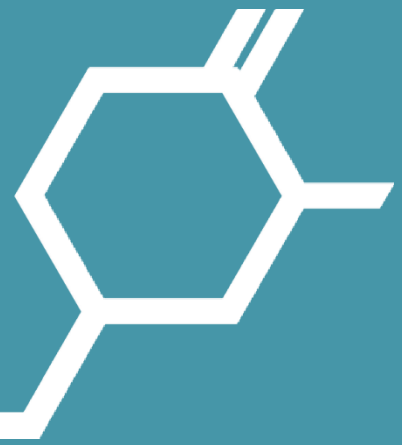
MIRALON® Additives for Anodes



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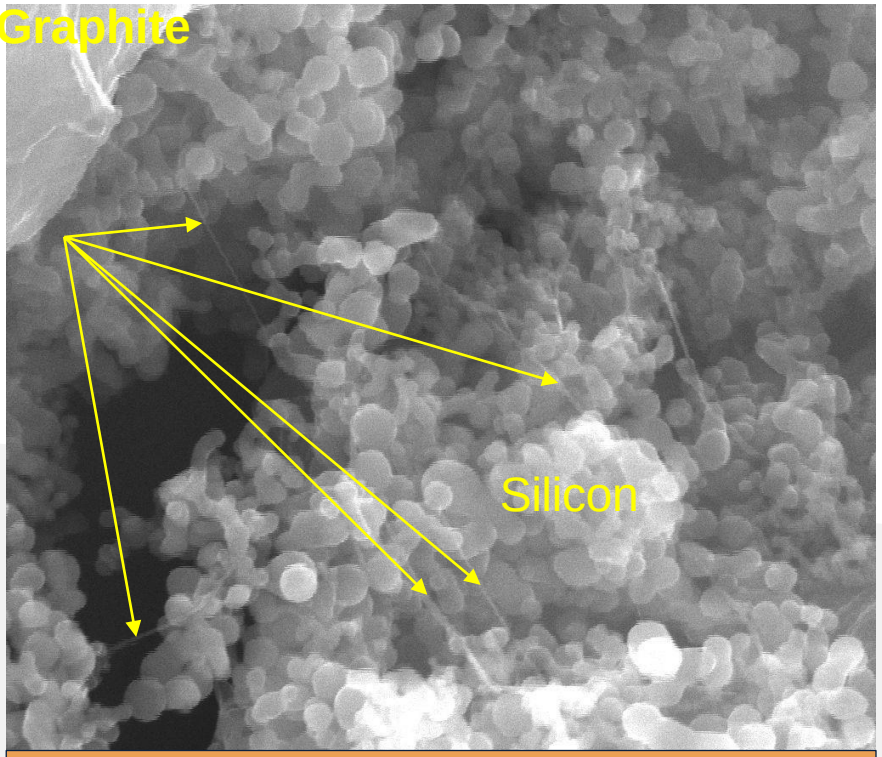
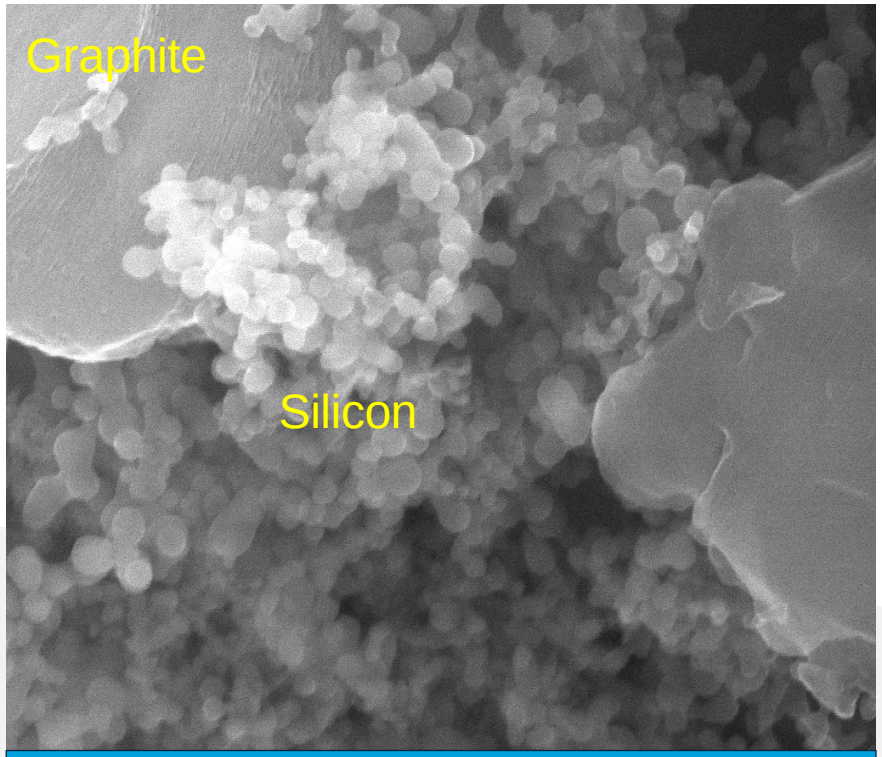
MIRALON® materials connect Silicon particles to the current collector increasing the number of working Silicon particles

MIRALON® additive: conductive pathways



4.5% CMC
10% Si
In Graphite
1% MIRALON® Pulp



4.5% CMC
10% Si
In Graphite

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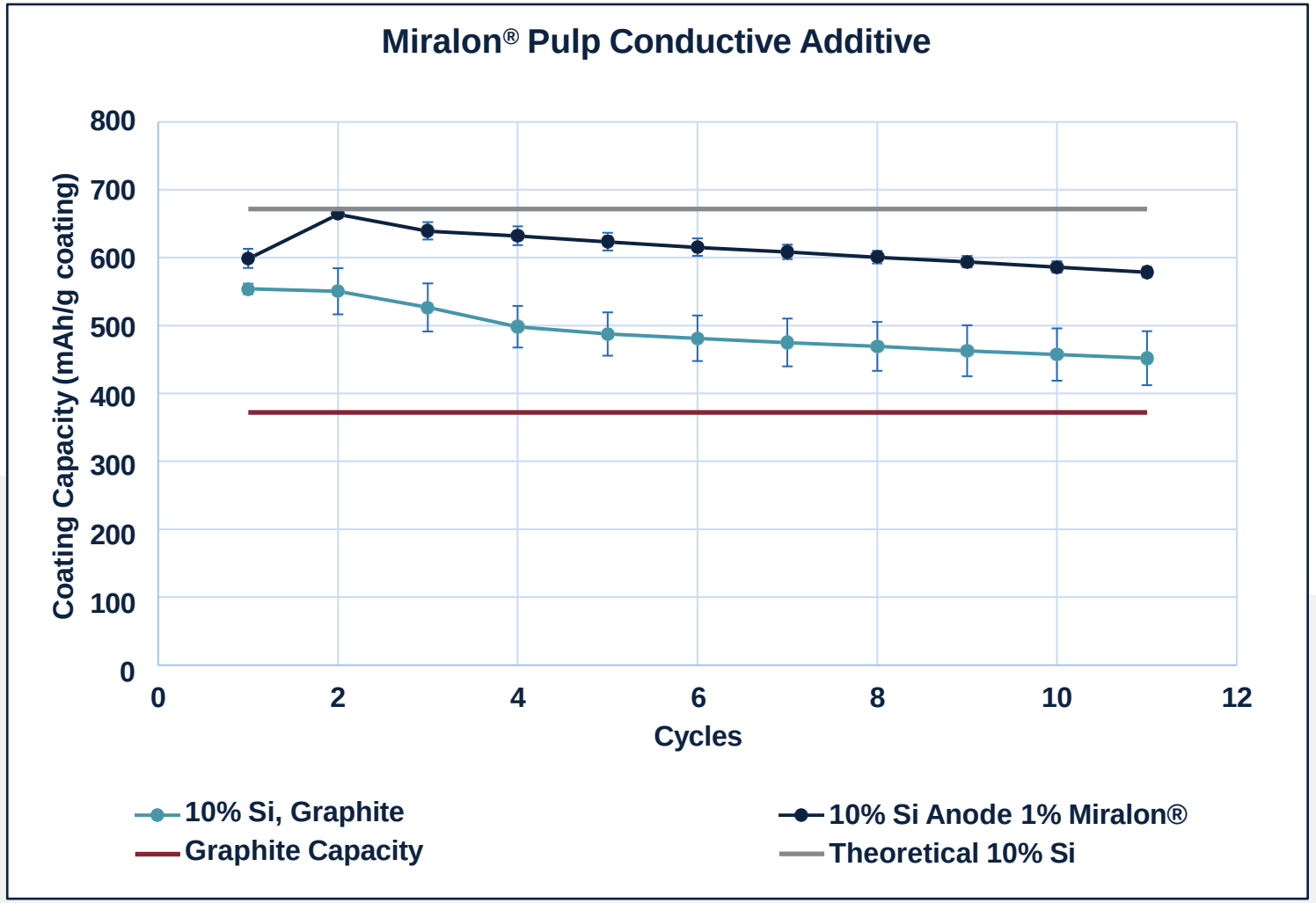
10% Si tests indicate >25% capacity increase

- Aqueous CMC dispersion interconnects Si nanoparticles electrically and mechanically
- With MIRALON® additive, achieved Theoretical Capacity (Li15Si4) on 2nd cycle
- Better cycle performance is expected with better Nano-Si



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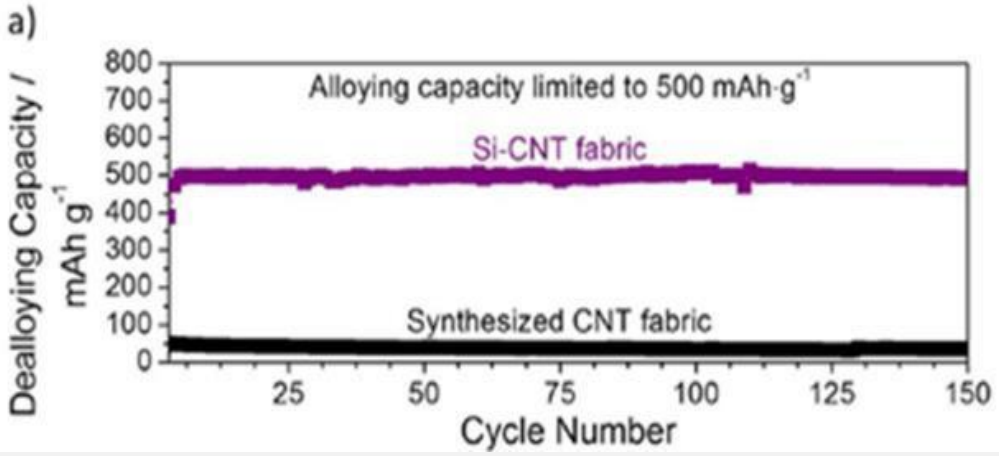
Independent University Studies show dramatically improved capacity with good cycle life.

Silicon coated MIRALON® Sheet Material by the Gleb Yushin Group at Georgia Tech

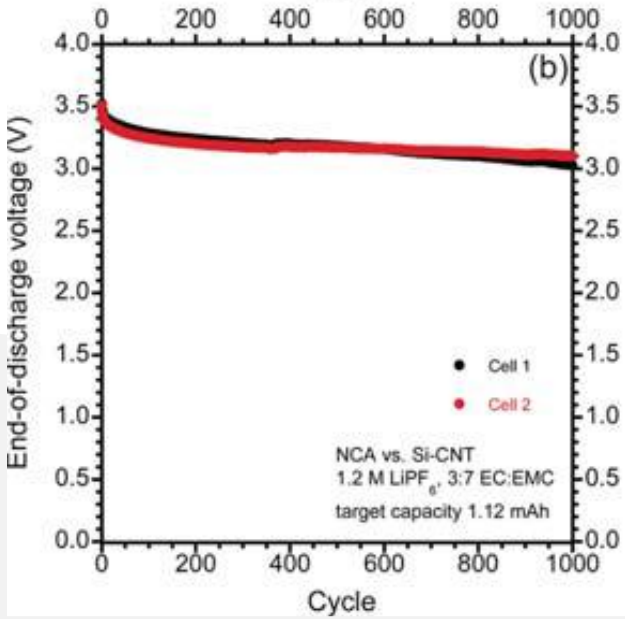
Silicon coating on MIRALON® sheets was limited to about 50% loading, and ~30% depth-of-discharge, which resulted in ~ 2X improvement over graphite with no fading at 150 cycles



Source: "Ultra Strong Silicon-Coated Carbon Nanotube Nonwoven Fabric as a Multifunctional Lithium-Ion Battery Anode" Kara Evanoff, Jim Benson, Mark Schauer, Igor Kovalenko, David Lashmore, W. Jud Ready, and Gleb Yushin. *ACS Nano*, **2012**, 6 (11), pp. 9837-9845

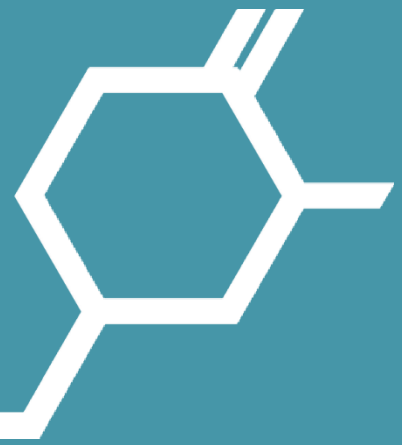
Silicon coated MIRALON® Sheet Material by the Brian Landi Group at RIT

Twenty percent depth-of-discharge cycling of a coin cell with NCA versus Si-CNT (p-SLMP prelithiation) electrodes at C/4 charge, C/3 discharge after 10 cycles at C/10.



Source: " Prelithiation of Silicon−Carbon Nanotube Anodes for Lithium Ion Batteries by Stabilized Lithium Metal Powder (SLMP)" Michael W. Forney, Matthew J. Ganter, Jason W. Staub, Richard D. Ridgley, and Brian J. Landi. *ACS Nano*, **2012**, 6 (11), pp. 9837-9845

MIRALON® Products Available



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HUNTSMAN
Enriching lives through innovation

MIRALON® products available to enhance your battery solutions

MIRALON® Pulp

CNT for conductive additives

Low carbon footprint

Scale up on-going in USA

MIRALON® Aqueous Dispersions

Aqueous Conductive Additive

Solvent free solution

Dispersions made in Europe

MIRALON® NMP Dispersions

Conductive additive in NMP

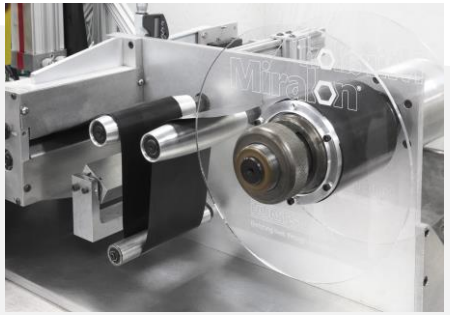
Replacement of CB in existing applications / formulations

Dispersions made in Europe

MIRALON® current collector

Available currently in seamed tape spools, 100-150 mm wide

Continuous roll-to-roll tape in development



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Masterbatch Products for Sampling

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Product	Solvent	Conductive Additive	Dispersion Aid	Binder
MIRALON D NMP 125	NMP	1.25% Mir	0.375% Jeff-3200	3.75% PVDF
MIRALON D AQU 100	Water	1% Mir	1% Jeff-3202	1% CMC
MIRALON D AQU 200	Water	2% Mir	2% Jeff-3202	None
MIRALON D AQU PAA	Water	0.75% Mir	0.25% PSS	2.5% PAA
MIRALON D AQU PSS	Water	1.5% Mir	0.5% PSS	None

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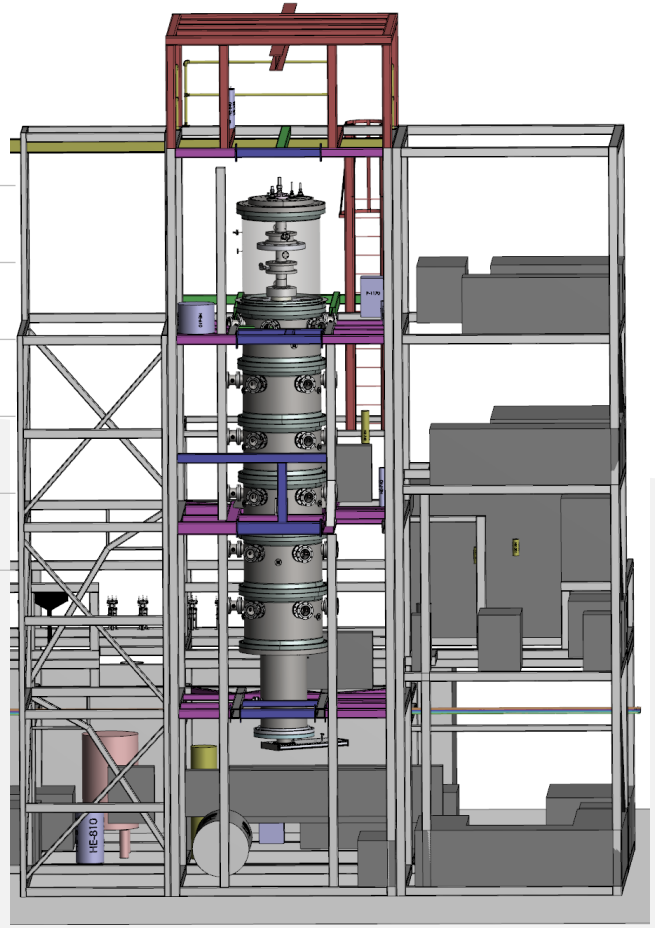
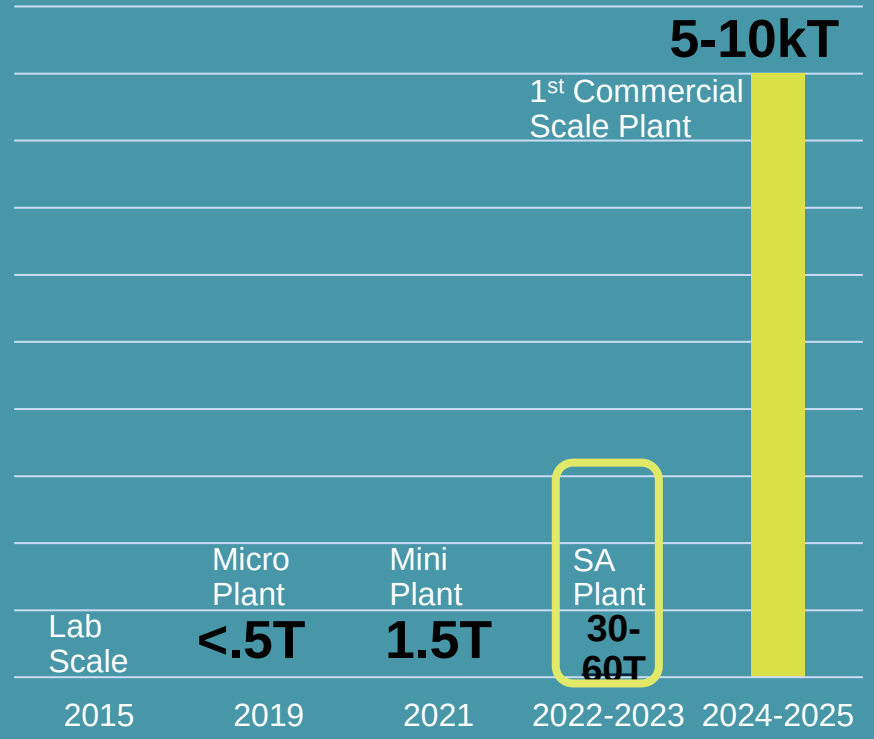
MIRALON® Capacity Expansion Plans

2010	Technology development
2015	Lab scale production
2018	Nanocomp acquired by Huntsman
2019	Microplant production
2021	Miniplant production
2023	30-60T SA plant production
2024	5-10kT Commercial scale plant





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