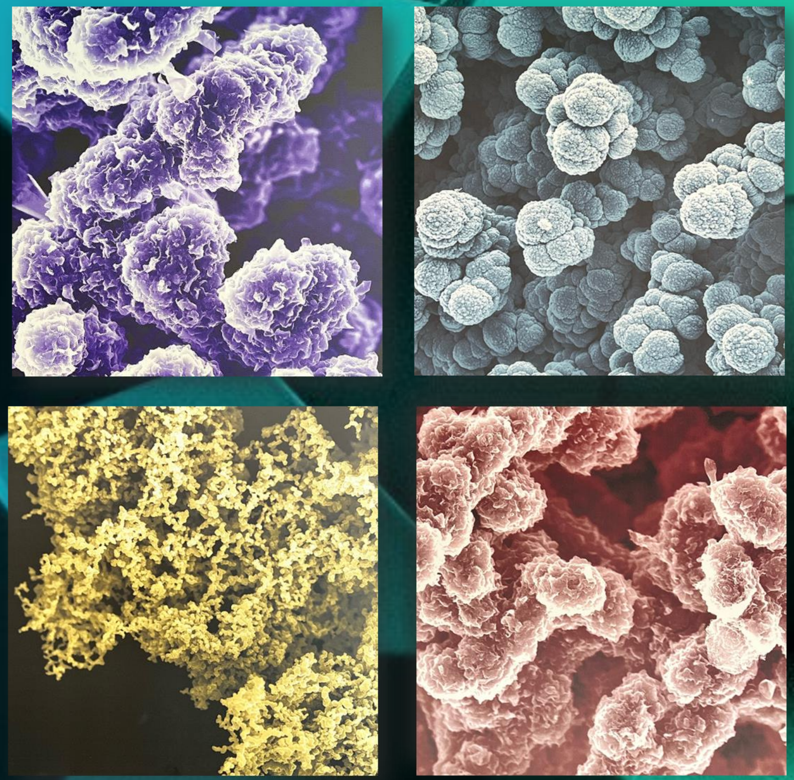
Performance and Safety Behavior of Lyten's Li-S Pouch and Cylindrical 18650 Cells

Babu Ganguli, Celina Mikolajczak, Zach Favors, Ratnakumar Bugga, Yongtao Meng, Arjun Mendiratta, Jefferey Bell and Dan Cook



LYTEN

2023 NASA Aerospace Battery Workshop
Huntsville, AL
November 14-16, 2023

LYTEN OVERVIEW

- Founded 2015 – Produce Lyten 3D Graphene™
- Leader in 3D Graphene Patents (>370 patent matters)
- >$410M Raised Through Series A; finishing Series B
- Initial Applications of Lyten 3D Graphene™
  - Lithium-Sulfur Batteries
  - Composites
  - Sensors
  - US Government Applications
- 145k ft^2 Facilities in Silicon Valley
  - 3D Graphene Fab (2022)
  - Pilot Cell Production Line (2023)
- > 300 employees; >60% advanced degree holders

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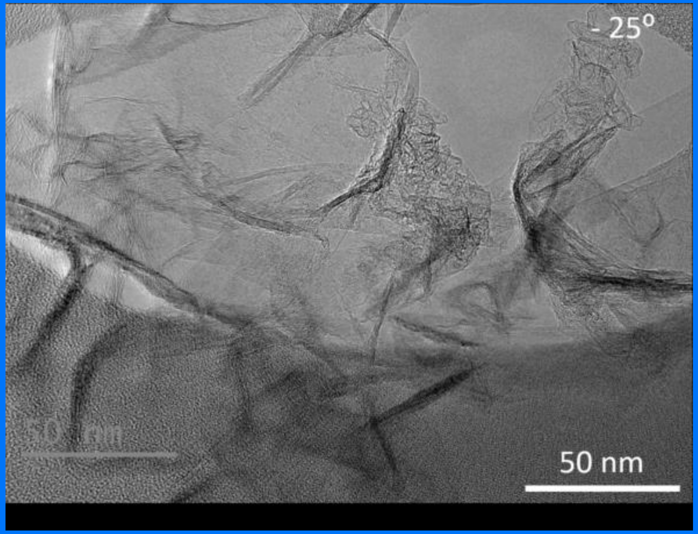
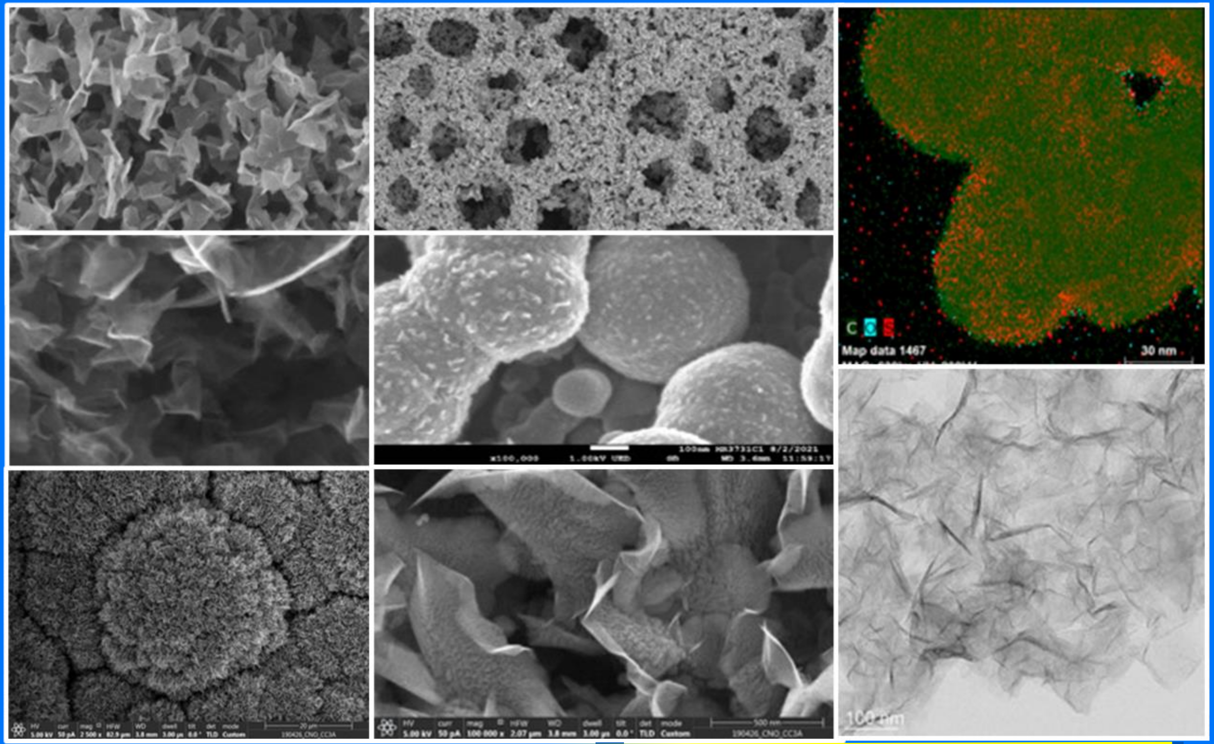
LYTEN 3D GRAPHENE TECHNOLOGIES

Lyten's 3D Graphene Tunability

Combines high conductivity with a highly tunable morphology, optimum surface area, pore size, pore distribution and tap density through process controls.





Including a Battery TR sensor

"Seeing" in entirely new ways

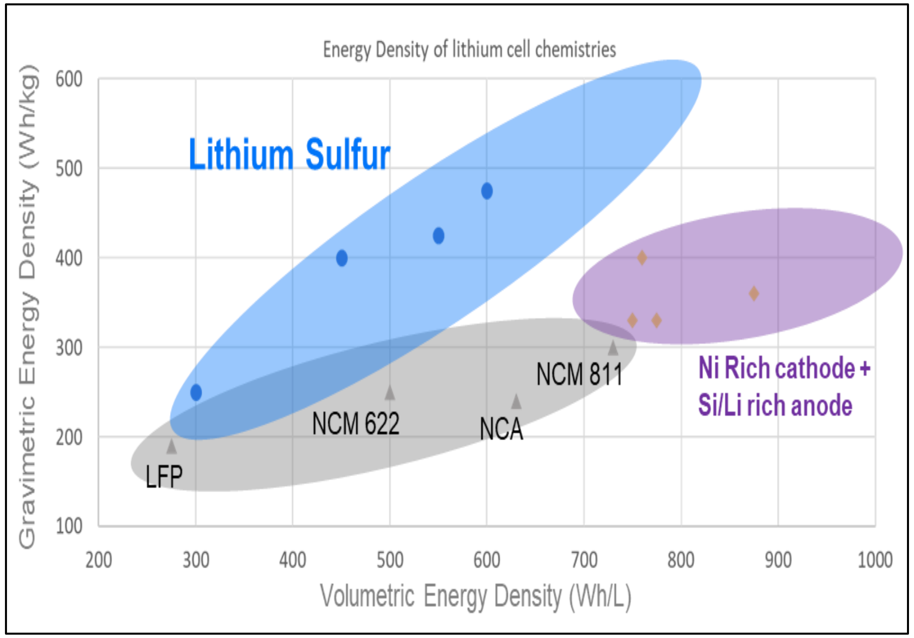
LITHIUM SULFUR- HIGH ENERGY AND SUSTAINABLE

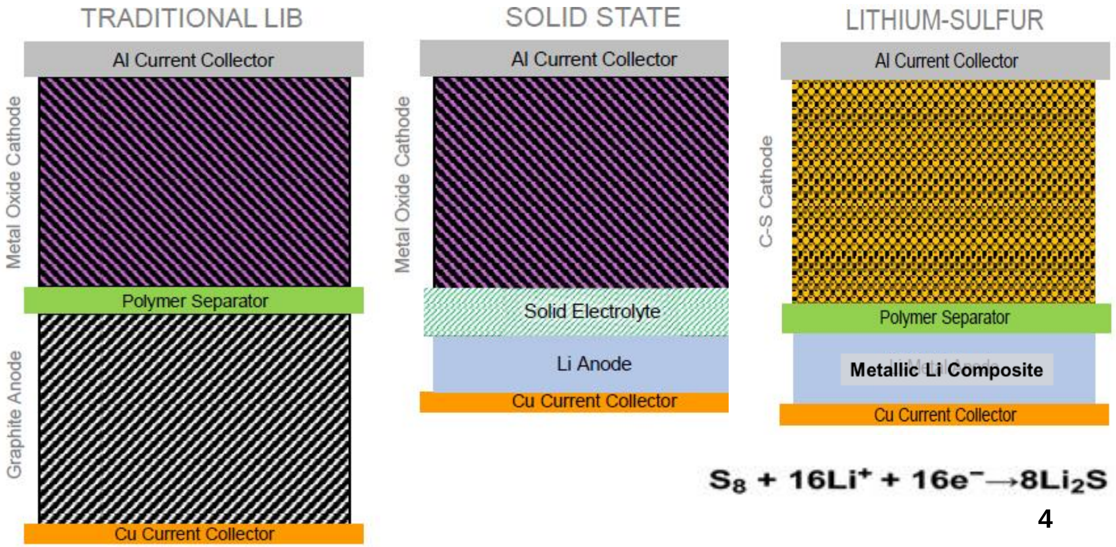
Key Challenges for Traditional LIBs

- Cell performance reaching its fundamental limits (300 Wh/kg)
- Predominantly foreign-sourced active materials
- Cobalt and nickel shortfall in coming years
- China has overwhelming dominance in the processed materials and also cell and battery manufacturing
- Safety concerns from thermal runaway are still prevalent

Key Advantages of Lithium-Sulfur Batteries

- Higher specific energy (Sulfur has 8x specific capacity vs. LIB cathode). At maturity, 600 Wh/kg and 800 Wh/L possible
- Domestic supply chain and free from nickel/cobalt/graphite
- Abundant, low-cost materials: sulfur, carbon and electrolytes
- Inherently safer due to unique chemistry
- Lyten architecture has a possible path towards low or neutral carbon footprint.





$$S_8 + 16Li^+ + 16e^- \rightarrow 8Li_2S$$

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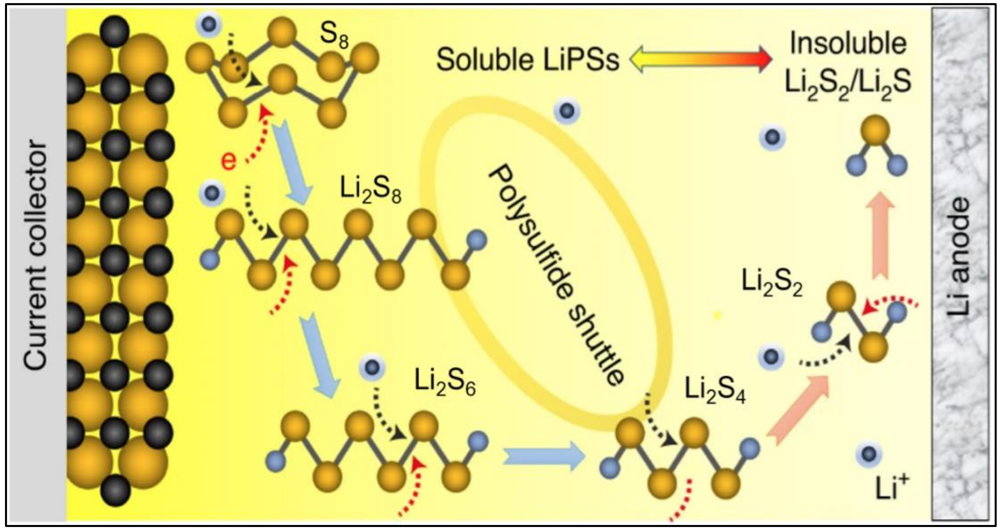
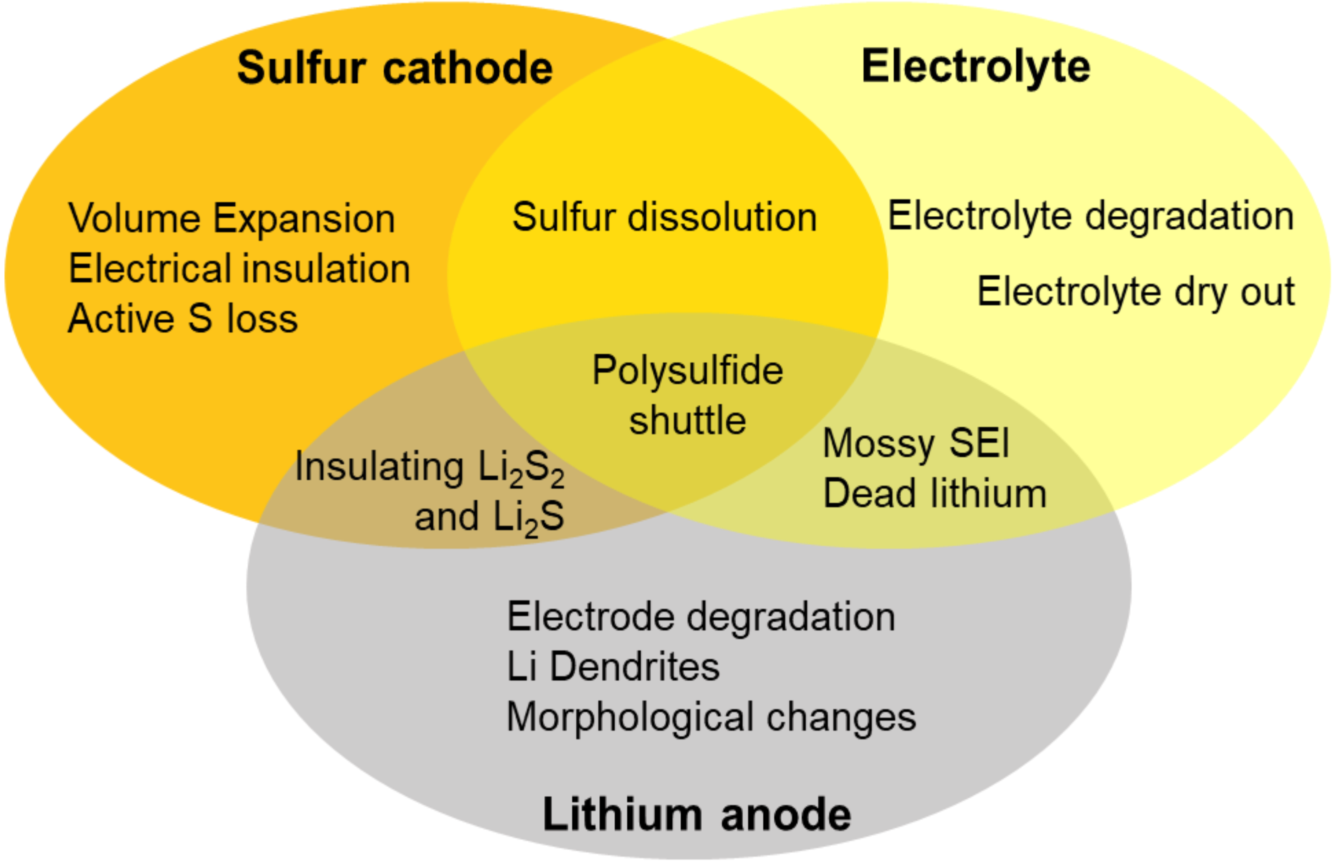
CHALLENGES OF LI-S CELLS

Polysulfide Shuttle



- Lowers cathode capacity and increases anode impedance
- The extent of shuttle depends on cathode architecture, nature of electrolyte and anode surface

Lithium-Sulfur Cell Degradation Mechanisms



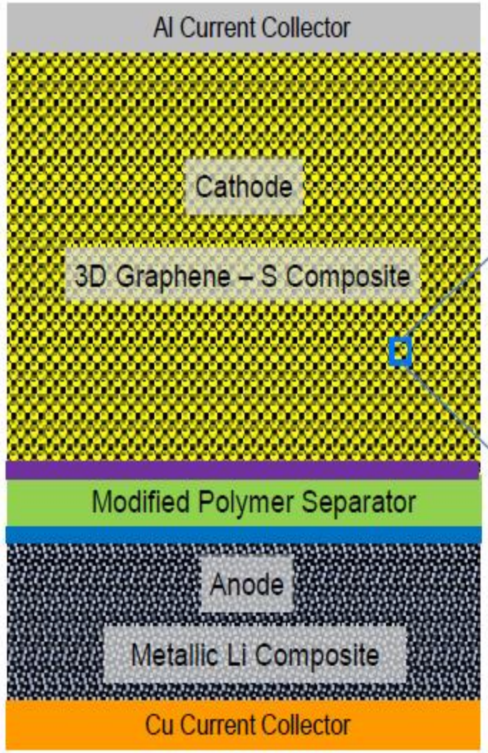
Meng Zhao, Bo-Quan Li, Hong-Jie Peng, Hong Yuan, Jun-Yu Wei, and Jia-Qi Huang, Angew. Chem. Int. Ed. 2020, 59, 12636–12652

LYTEN MITIGATES ALL DEGRADATION PROCESSES

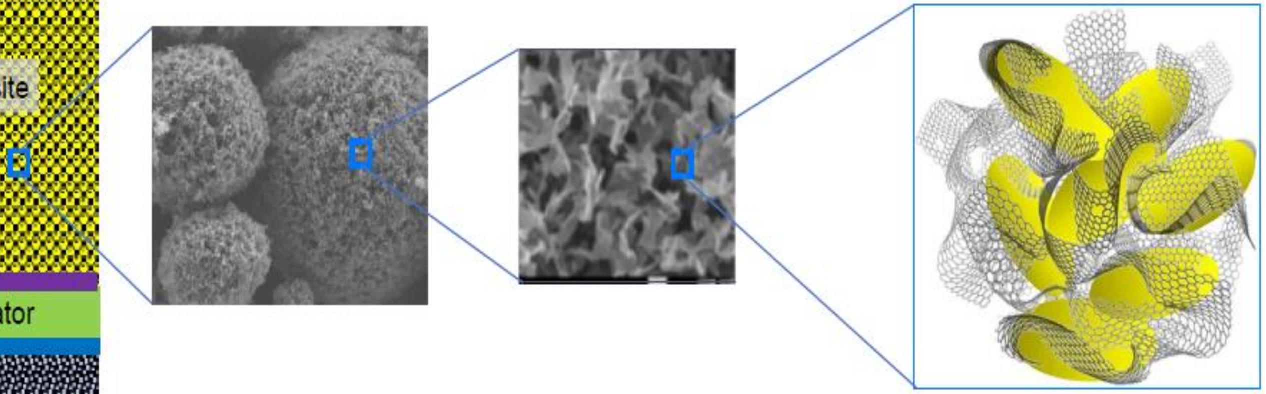
Lyten Solutions

- **3D Graphene Cathode**
- Stabilized Anode (composite)
- Proprietary Electrolyte
- Protective Coatings
- Charging Algorithms
- Catalysts
- Customized Separator

LYTEN LI-S Cell Architecture



- Nanostructured and functionalized 3D graphene mitigate polysulfide shuttle
- High conductivity of graphene enables higher charge/discharge rates

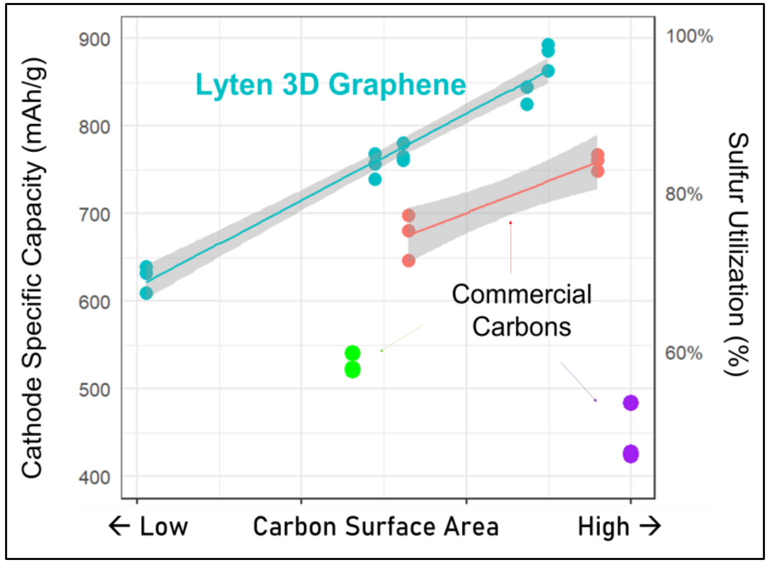


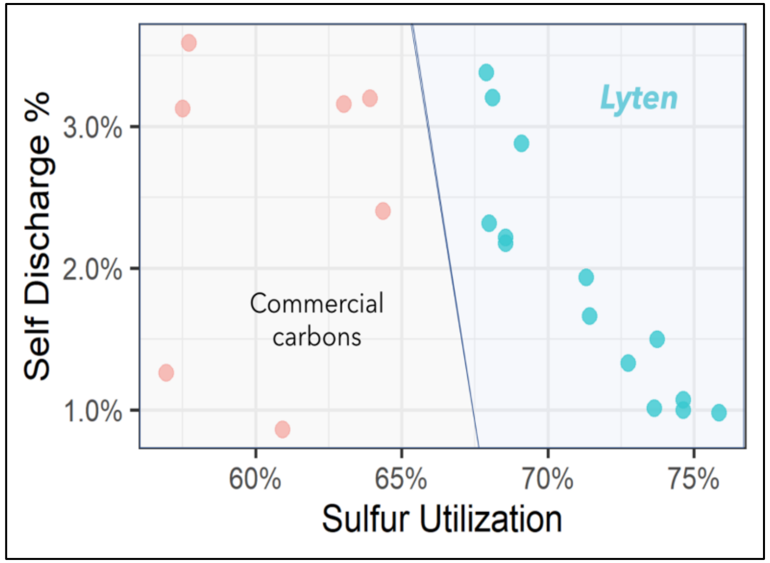
- Composite anode with protective coating (printed) mitigates anode degradation

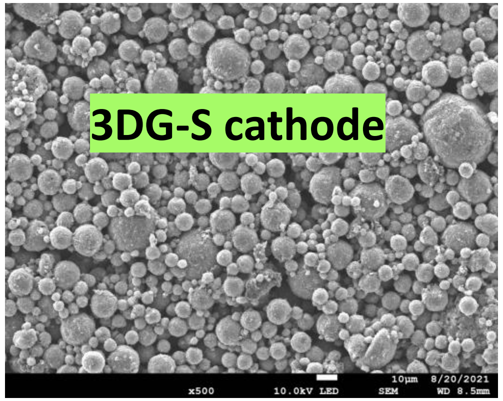
LYTEN 3D GRAPHENE™ VS. COMMERCIAL NANOCARBONS

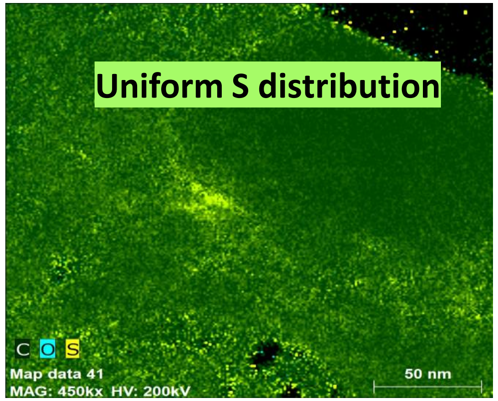
Lyten 3D Graphene forms the primary structure of the cathode

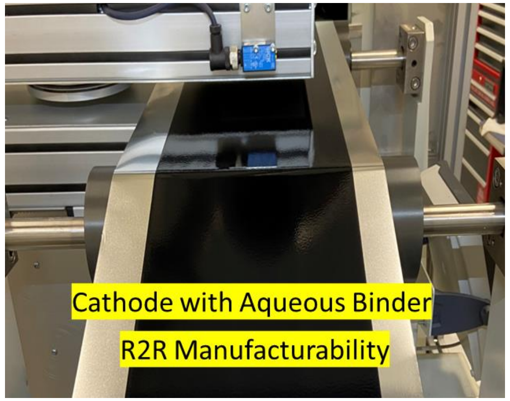
- Chemical environment of 3D graphene may be tuned with aliovalent doping and functionalization to enhance sulfur affinity and kinetics
- Outperforms high surface area commercial carbons. Unique core-shell structure, coupled with high surface-area, results in excellent utilization and low self-discharge.
- Cathodes fabricated with spray-dried active materials with aqueous binder using standard coaters



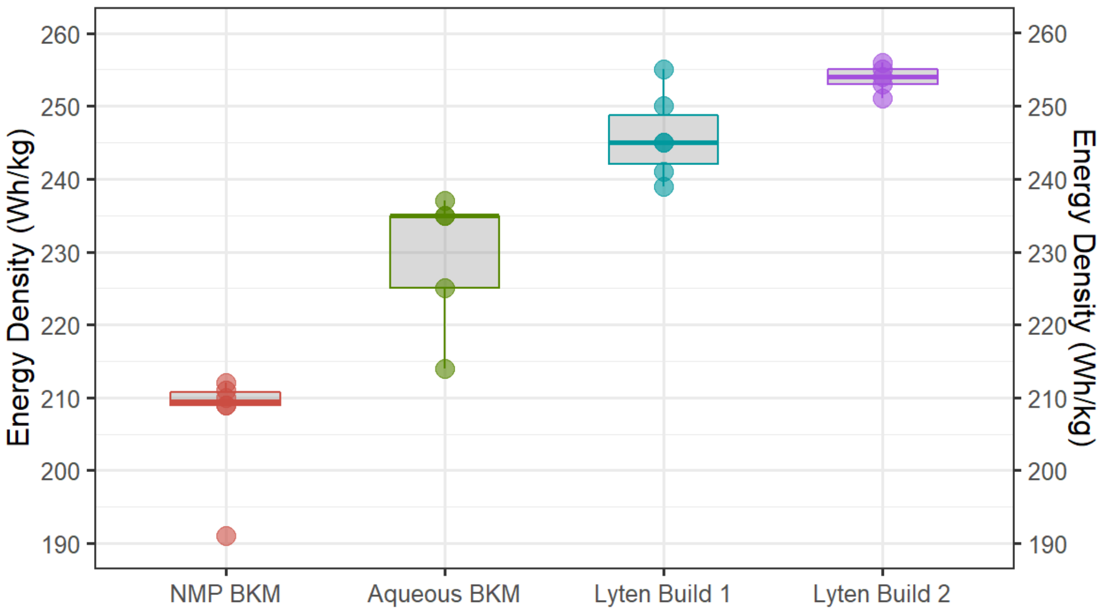


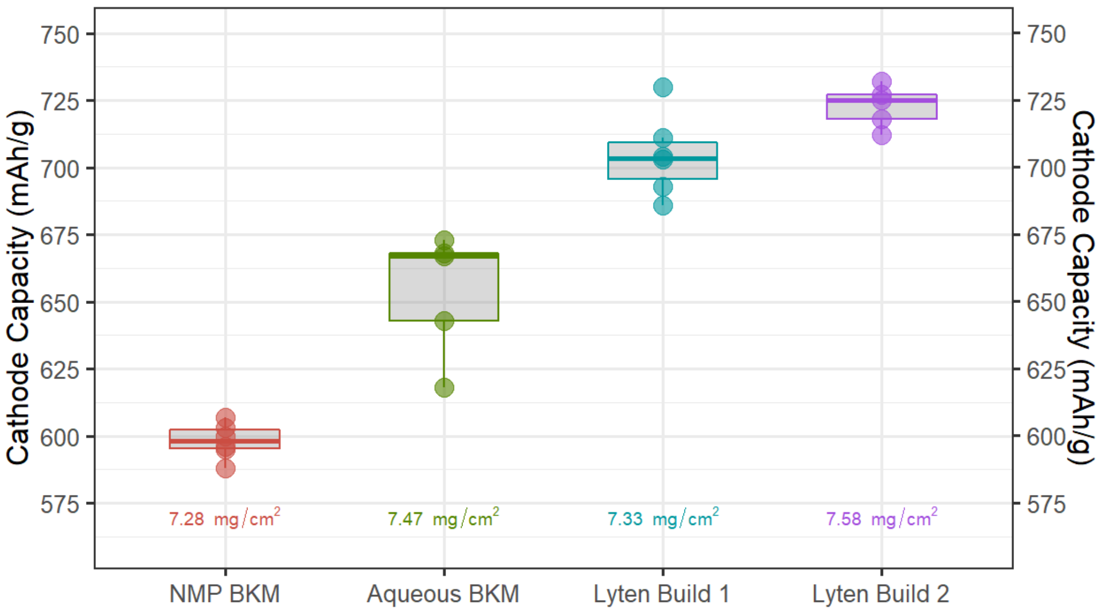






ENHANCED WH/KG WITH CATHODE IMPROVEMENTS





- Synergistic improvements to Lyten 3D Graphene, post-processing, and slurry formulation has yielded a >20% increase in gravimetric energy density (Wh/kg)
- Implementation of aqueous cathode provides substantial cost, manufacturing, and environmental benefits

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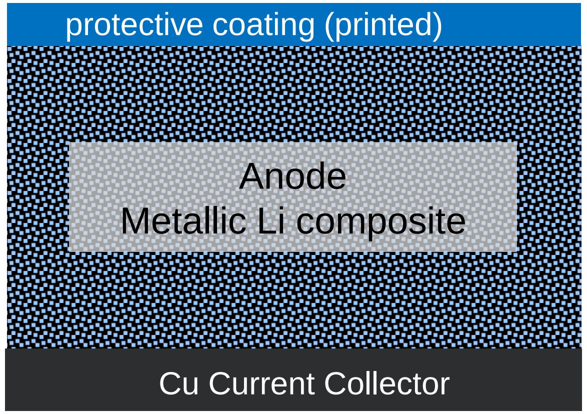
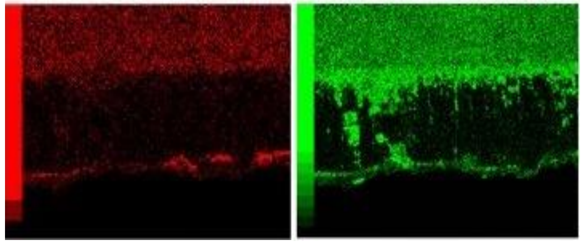
OPTIMIZATION OF ANODE DESIGN FOR IMPROVED CYCLE LIFE

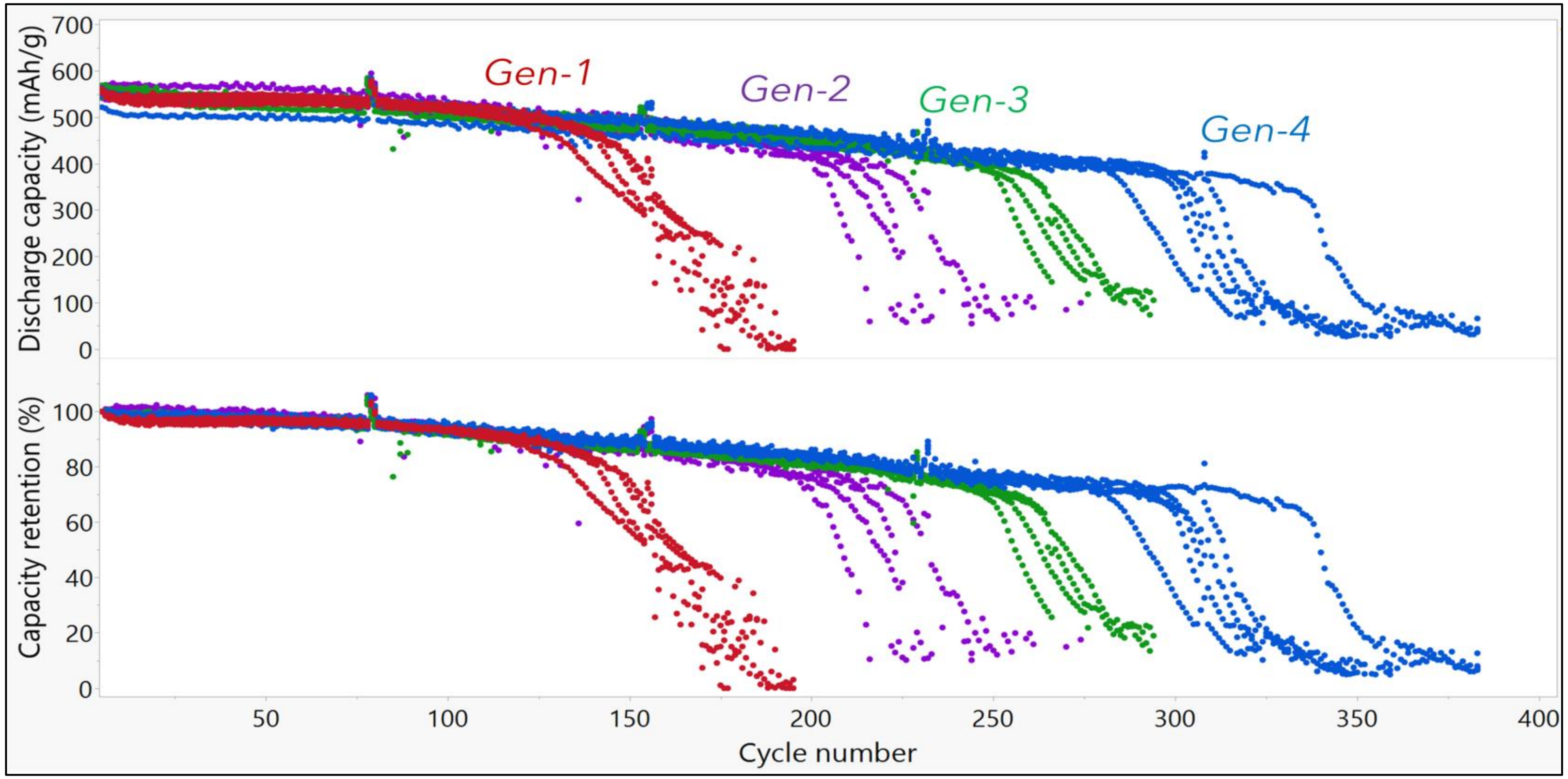
Schematic of Lyten Anode





SEM / EDS of Anode + Coatings

Cycle Life @ C/3,100% DoD with Different Anode Designs

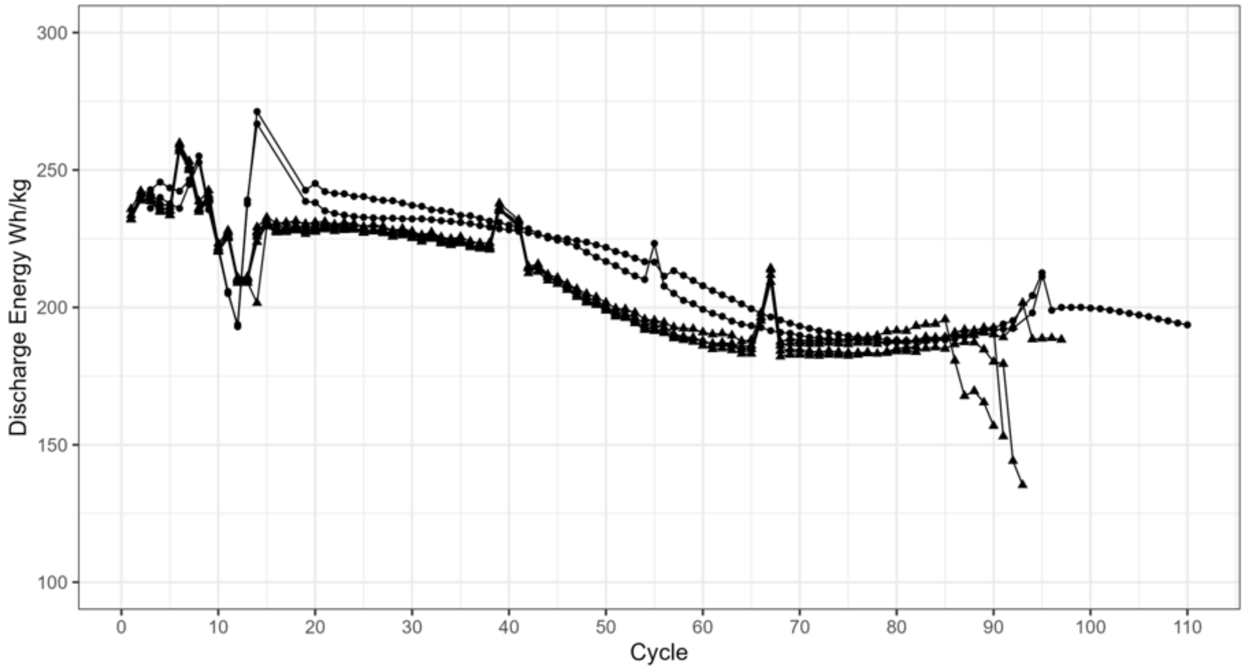


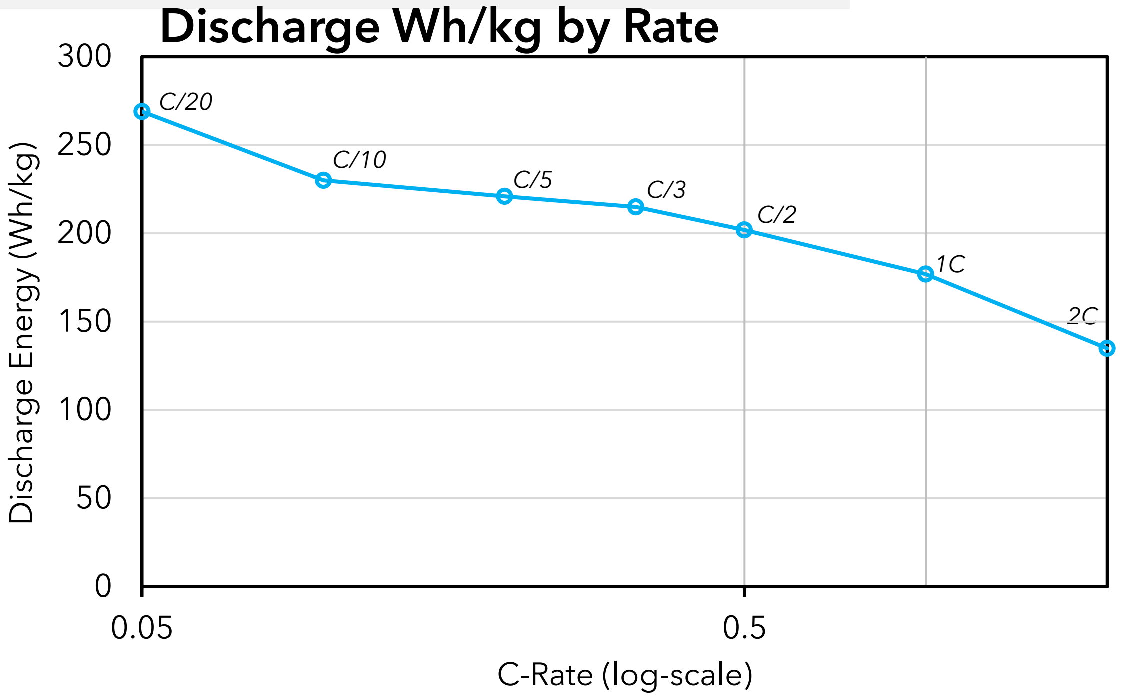
Composite anode with protective coating improves cycle life by 2-3 times vs. Li

POUCH CELLS 3RD PARTY TESTING (~1Ah)

Produced cells in June for 3rd party cycle testing :6 cells sent to third party

- 255 Wh/kg demonstrated at C/10 ; 210 Wh/kg demonstrated at 1C
- Cells reached a maximum of 110 cycles, and all stopped due to soft shorting issue
- Remaking sample to send this quarter with new binder that is resistant to soft shorts





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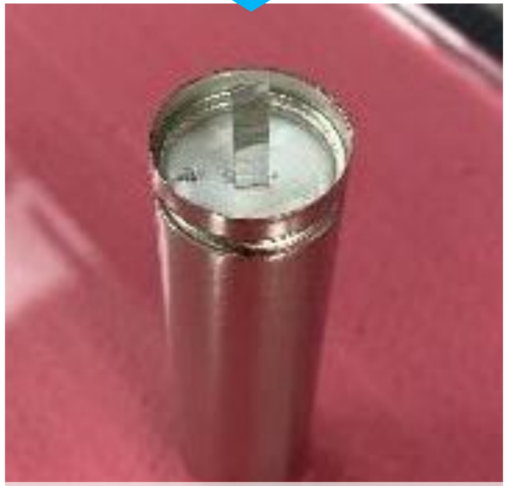
PILOT LINE: POUCH & CYLINDRICAL CELL FABRICATION

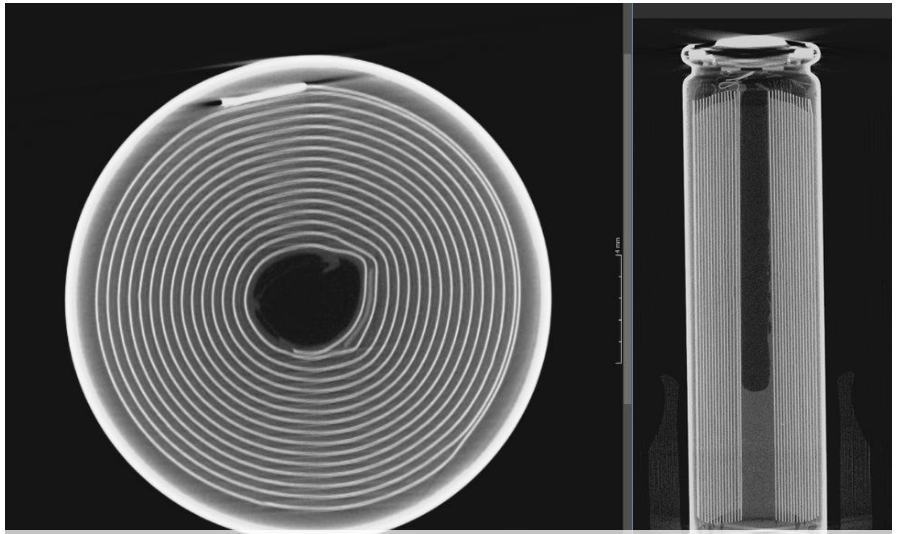
Lyten pouch cell line

Lyten cylindrical cell line (18650, 2170, 2650, 4680)

Lyten Li-S jelly roll



Lyten Li-S 18650 assembly



In-house X-ray CT scans - 18650

- Semi-automated line in dry-room (2 MW capable)
- No custom cell assembly equipment
- Water based cathode slurry (no NMP)

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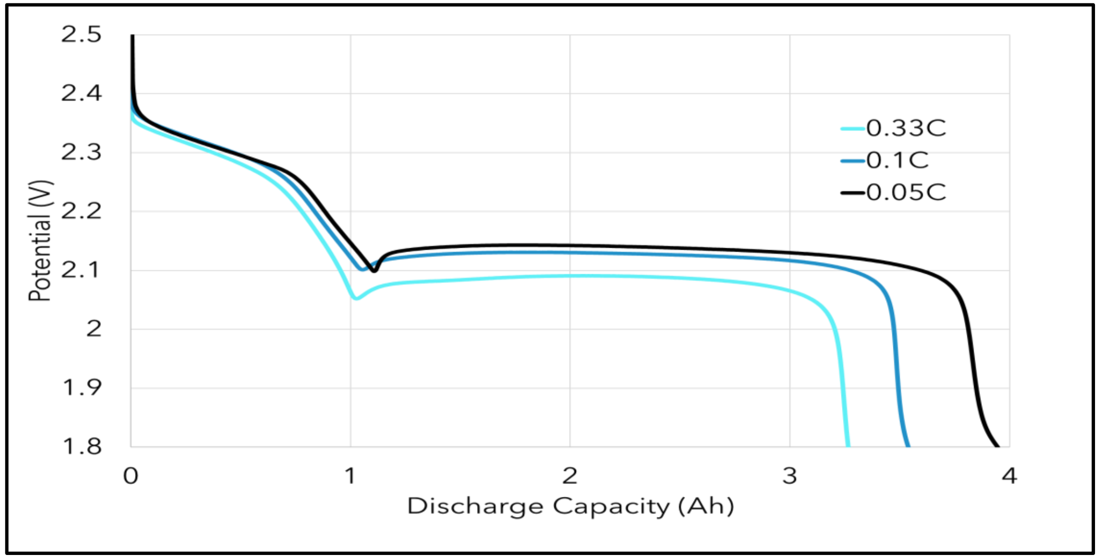
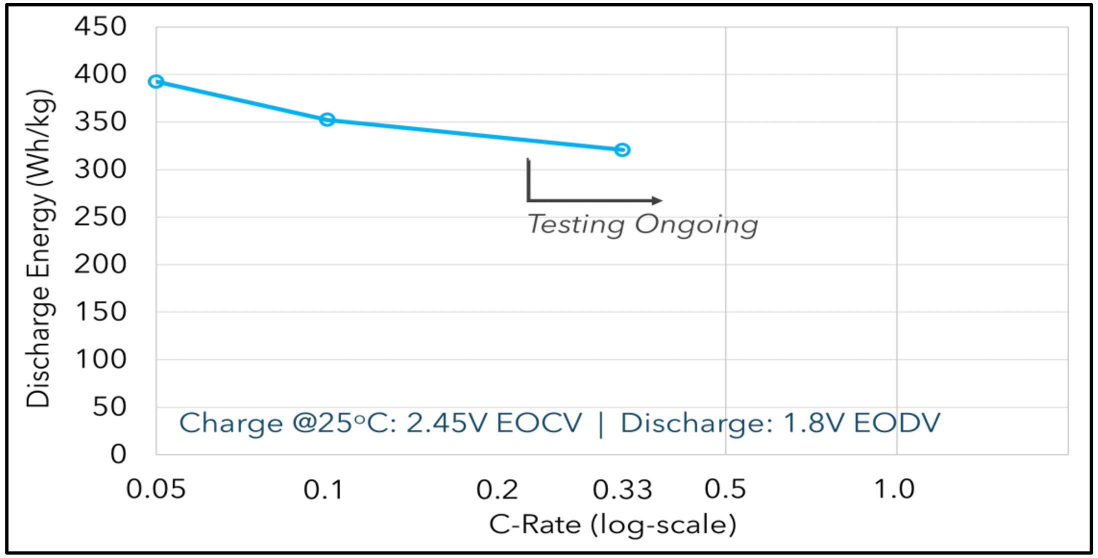
A RECENT LI-S POUCH CELL (~3.25AH)

Specifications

Rated Capacity	3.25 Ah @ 0.33C
Capacity	Min: 3.2 Ah Max: 3.3 Ah
Nominal Voltage	2.1 V
Charging	CC (C/3), 2.45V EOCV
Mass (typical)	21.7 g (+/- 0.1g)
Operating & Storage Temperature	Charge: 0 - 30^{0}C (ongoing) Dischg.: 0 - 30^{0}C (ongoing) Storage: 0 - 30^{0}C (ongoing)
Energy Density	Volumetric: 450 Wh/L Gravimetric: 320 Wh/kg
Cycle Life	Testing Ongoing

Discharge @ Different Rates





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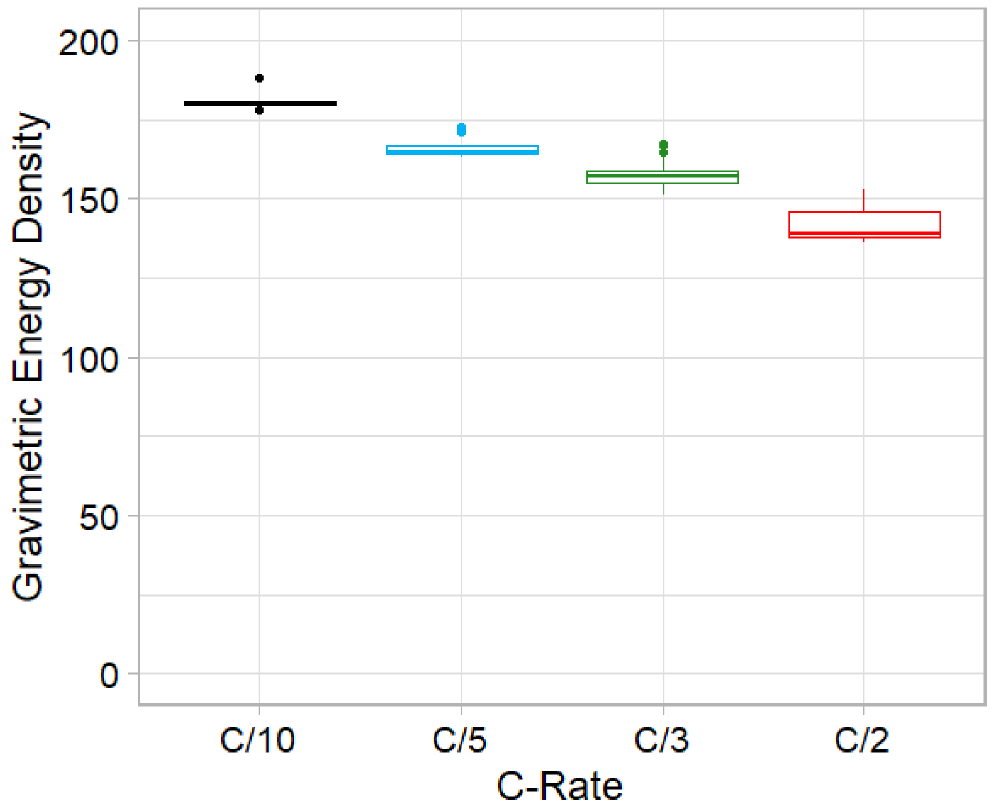
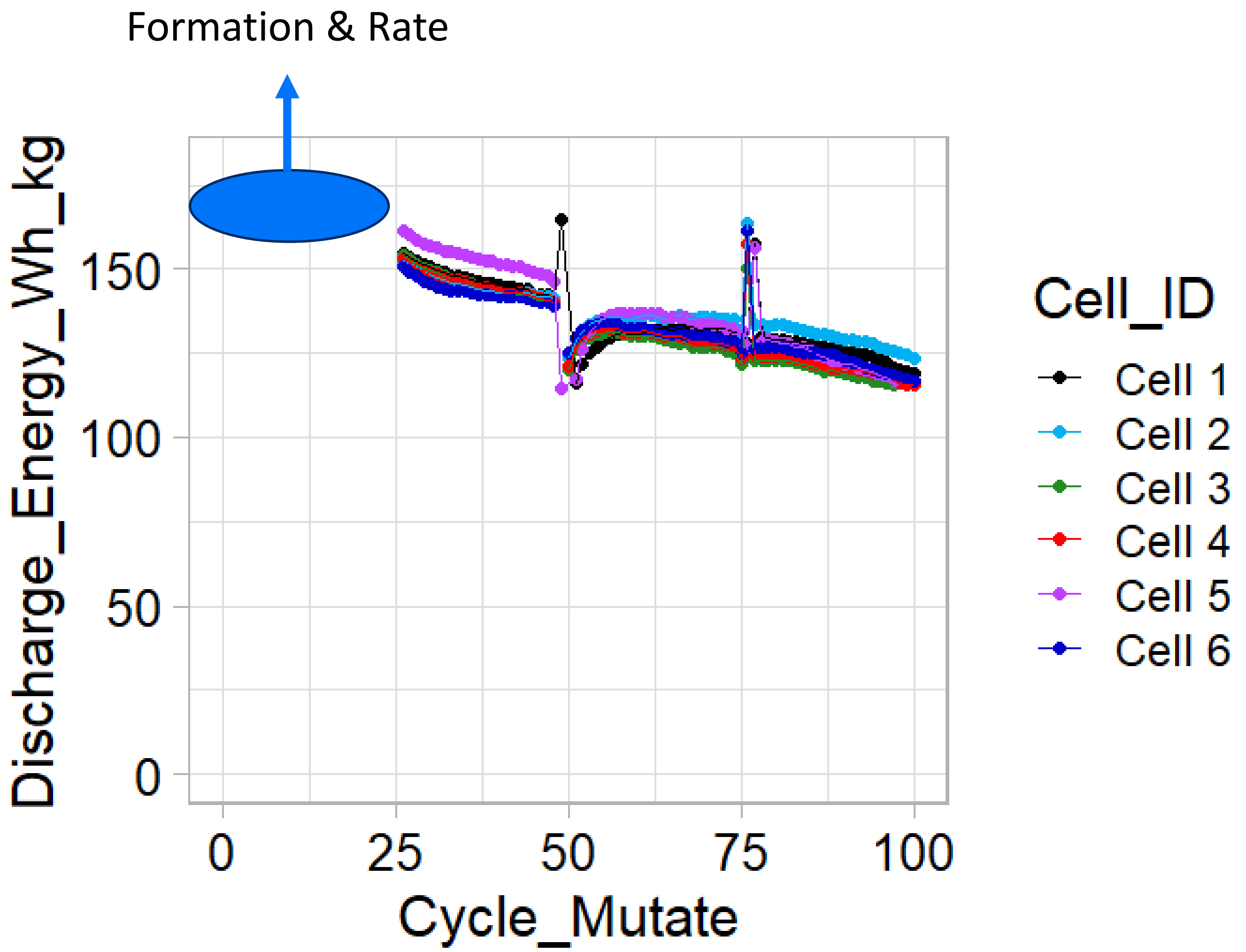
A RECENT LI-S CYLINDRICAL 18650

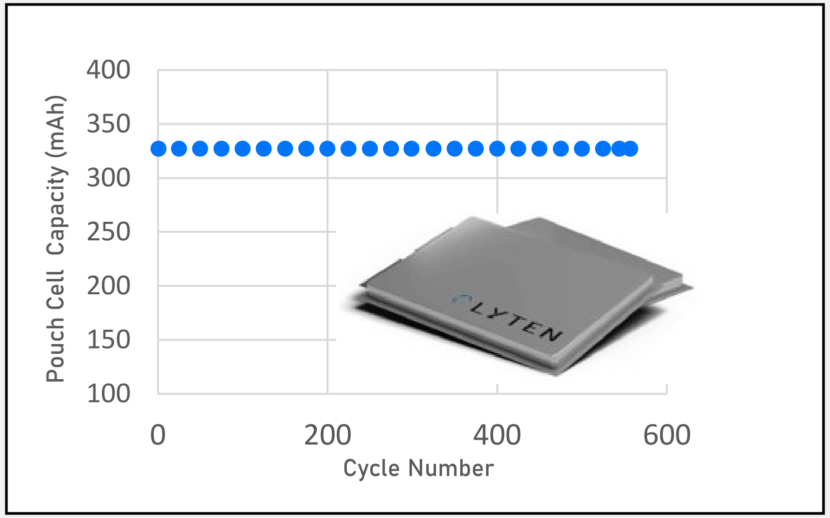




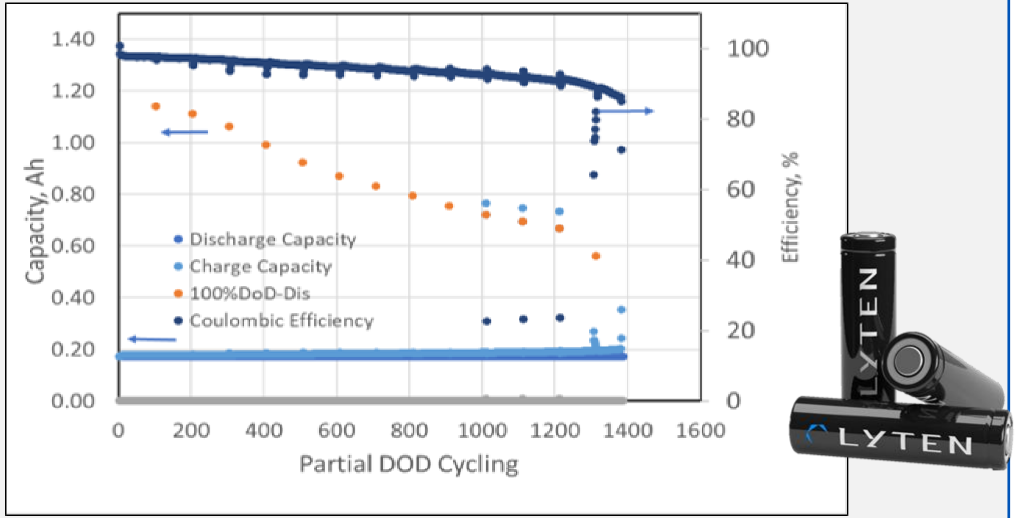
PARTIAL DOD CYCLING (LEO)

Historical
~ 75 Wh/kg cells

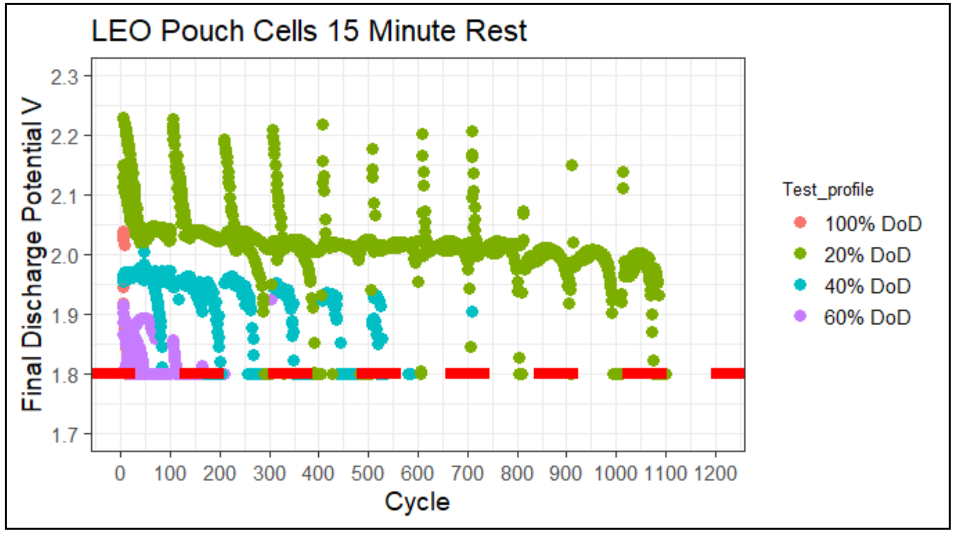
Lyten's 1st Gen pouch cell at 40% DOD

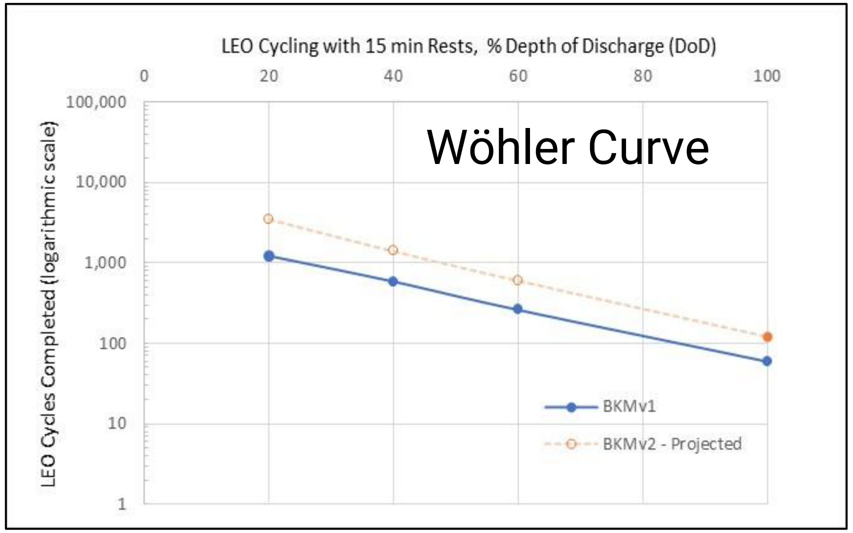


Lyten's 1st Gen 18650 cells at 20-40% DOD



2022 Cells
~200 Wh/kg cells





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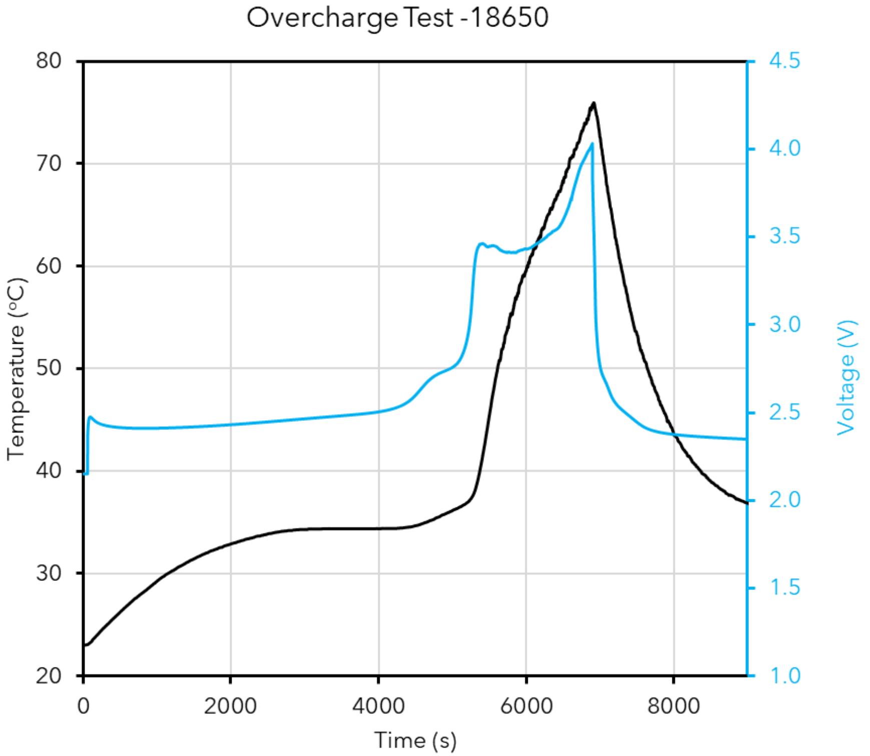
OVERCHARGE TEST – 18650

- 18650s are overcharge tolerant to 180% SOC at 1C charge rate
- Oxidation of solvents at ~3.5V is exothermic and provides bulk of the heating beyond 100% SOC.
- 1C charging heats cells to 37°C by 100% SOC.
- No cell mass change is observed.

Cell mass before test	20.4g
Cell mass after test	20.4g
OCV before test	2.14 V
OCV 10 mins after test	2.30 V
ACR before test	134 mOhm
ACR after test	n/a



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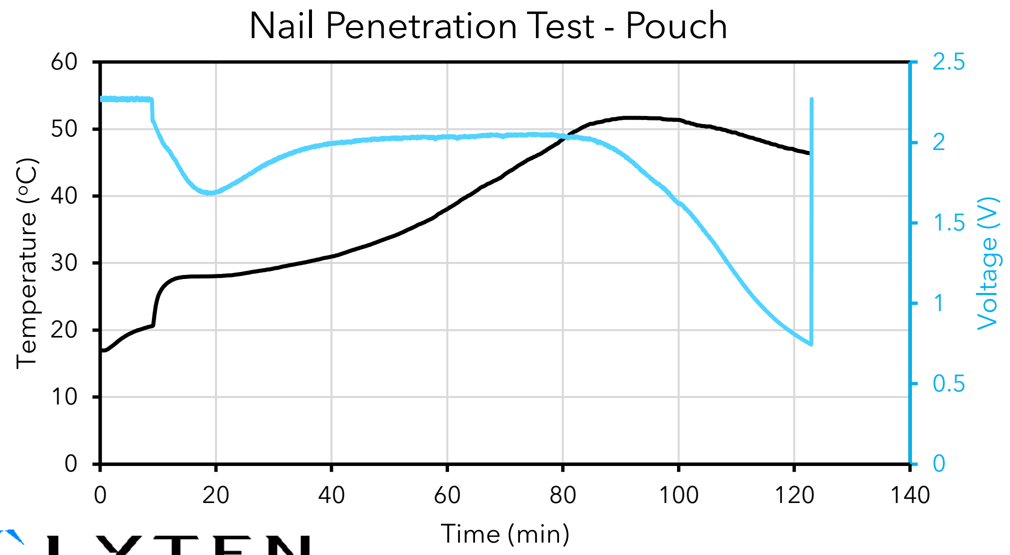
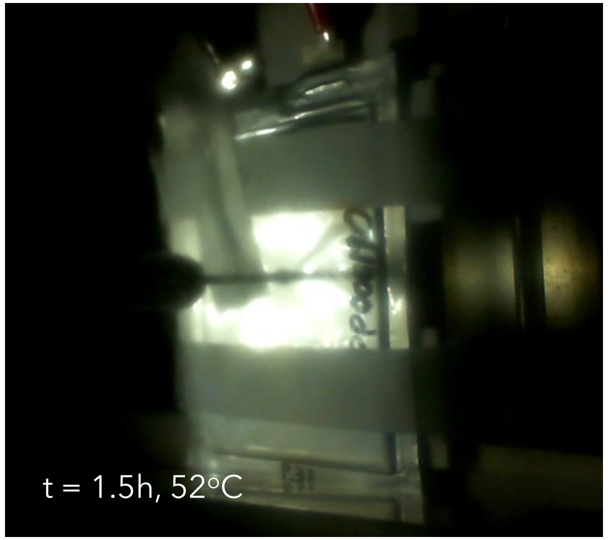
NAIL PENETRATION TEST – POUCH CELLS

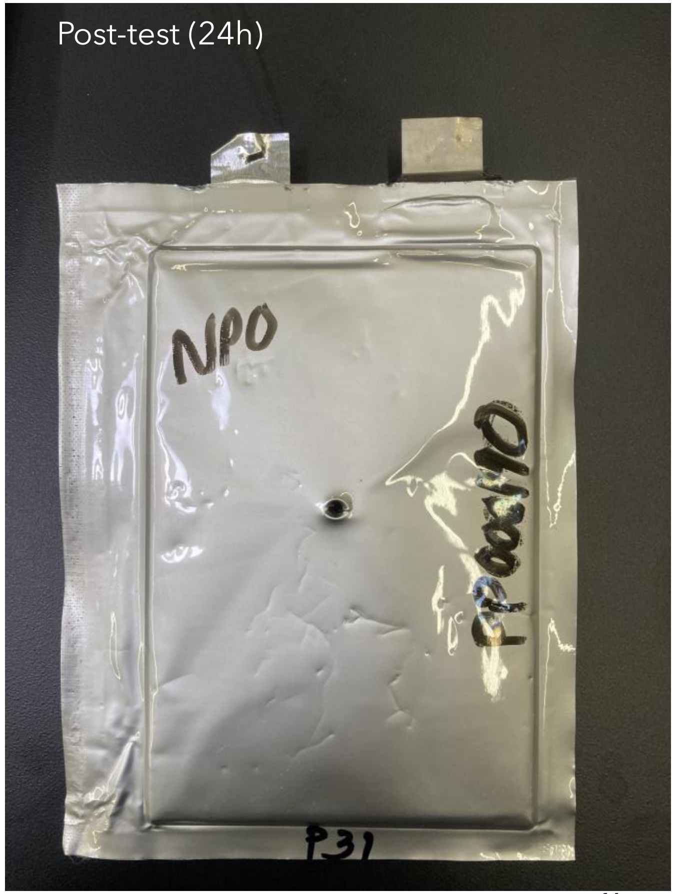
Cell mass before test	23.2g
Cell mass after test	23.2g
OCV before test	2.29 V
OCV 10 mins after test	0.66 V
ACR before test	23 mOhm
ACR after test	70 mOhm

- Pouch cells at 100% SOC have demonstrated no thermal runaway even after 24h of continuous nail penetration.
- Modest cell heating is observed (50 – 55°C)
- Voltage recovers to 2.15V in some cases when the nail is removed, indicating removal of the short (below).



Test Screenshots





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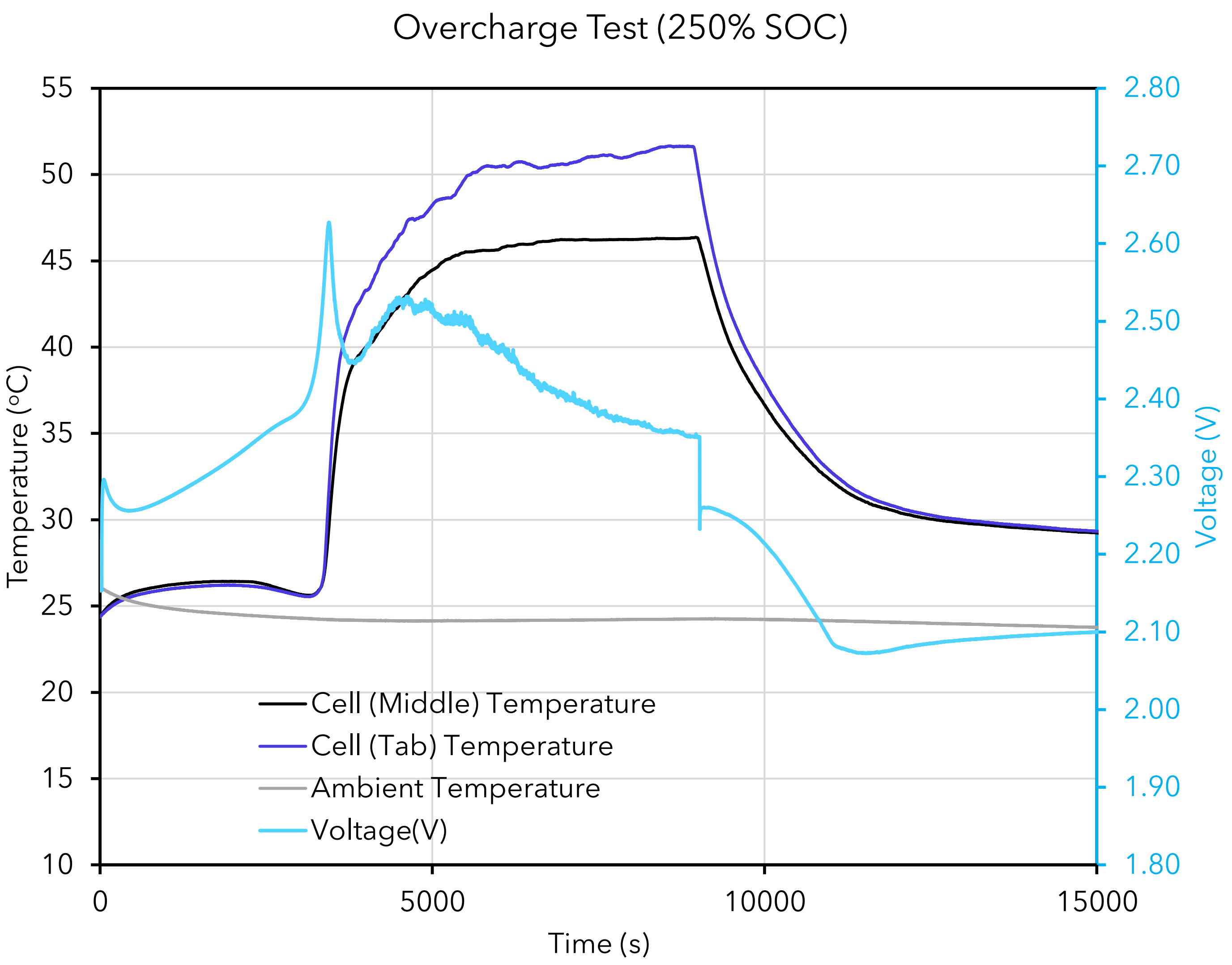
OVERCHARGE – POUCH CELLS

- Pouch cells demonstrate no thermal runaway under 1C overcharge to 250% SOC.
  - No gassing
  - No change in cell mass
- Cells only show modest heating to 50 – 55°C
- Dendritic shorting is evident under 1C overcharge, but still no thermal runaway.

Cell mass before test	23.3g
Cell mass after test	23.3g
OCV before test	2.15 V
OCV 10 mins after test	2.09 V
ACR before test	8.3 mOhm
ACR after test	33.65 mOhm



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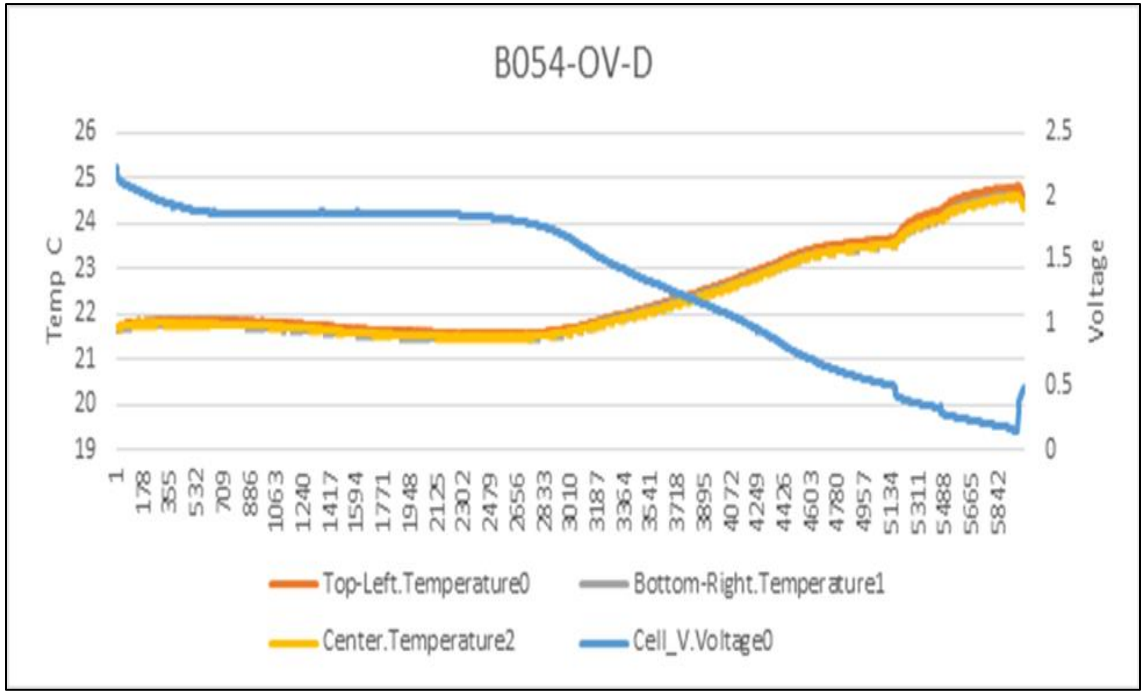
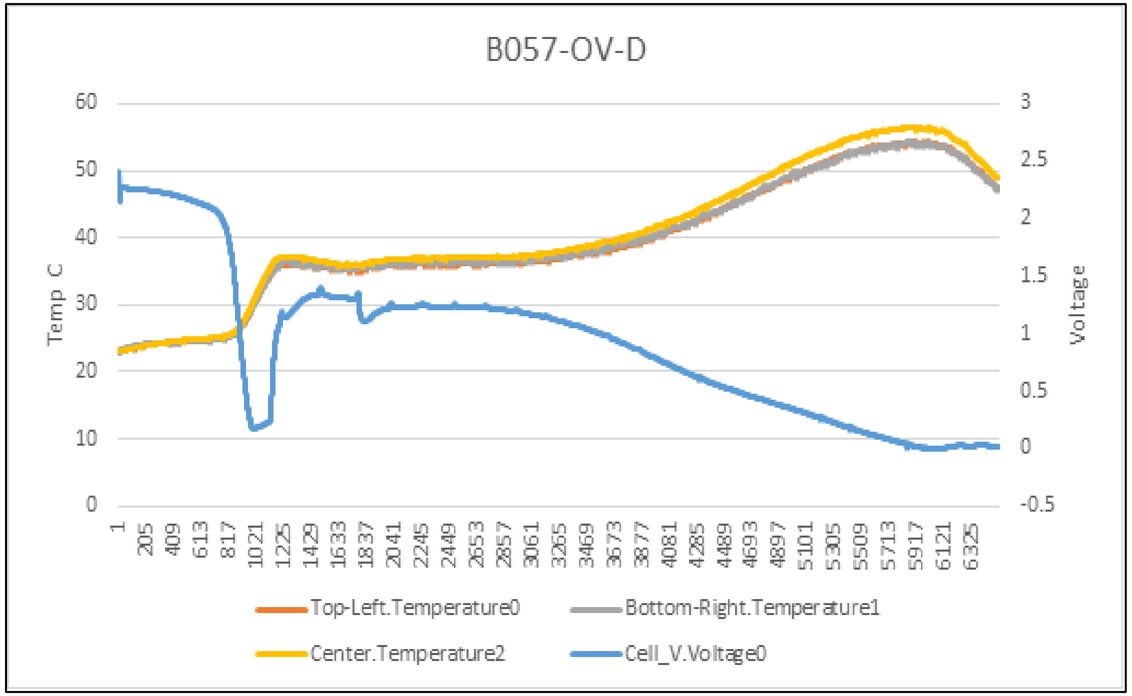
OVER DISCHARGE

Pouch Cell

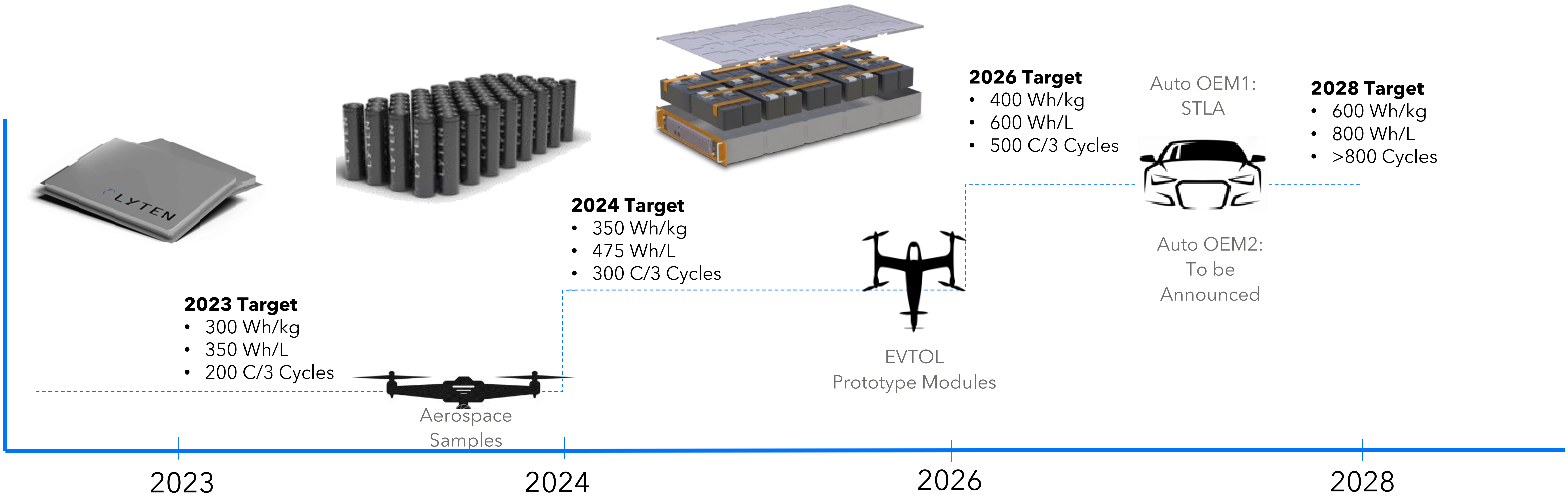


18650 Cell



- No Damage, fire, venting was observed
- All cells were discharged at a 1C rate

LYTEN CELL PERFORMANCE AND PRODUCTION ROADMAP



Scale	**Low volume** San Jose semi-auto pilot line (2MWh)	**Low volume Plus** San Jose semi-auto pilot line (2MWh) New 300MWh Facility	**Medium volume production** Small Gigafactory (1-5 GWh)	**High volume production** First Large Gigafactory
TRL (Automotive)	**3 - 4** Auto OEM A1	**5 - 6** Auto OEM A, B-sample	**7 - 8** Auto OEM A, B, & C-samples	**8 - 9** Auto OEM customers
TRL (Low Volume)	**5 - 7** Low volume special purpose cells	**8 - 9** Low volume applications		

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LI-S VALUE PROPOSITIONS

Lowest $/Wh	Replacing Ni-based cathodes with Sulfur is projected to lower raw material BOM cost by >50%
High Specific Energy (Wh/kg)	>2x practical specific energy compared to existing technologies
Abundant and Accessible Raw Materials	Sulfur is abundant in high quantities as a byproduct of minerals and petrochemical production – eliminates world reliance on scarce Ni resources
Reliable North America Raw Material Supply	Target 100% sourced and manufactured in NA: Lyten could help OEMs meet 2025 USMCA mandates
Decarbonization Material Platform	Target: 60%+ lower cell material emissions – eliminate conventional cathode active material production, eliminate conventional graphite processing, generate graphene and H_2 from light hydrocarbons
Safety	Strong resistance to overcharge, metal contamination, and puncture failure modes
Minimal Technology Switching Costs	Lower greenfield capex and minimal incremental brownfield conversion capex due to a simpler manufacturing process and Li-ion B facility compatibility

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