

Lithium-Sulfur Cell Chemistry Unlocked by 3D Graphene for Next-Generation Energy Storage

NASA Battery Workshop

Zach Favors

VP of Battery R&D

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Key Team Members



- Dan Cook – CEO
- Celina Mikolajczak – Chief Battery Technology Officer
- Kumar Bugga – Fellow
- Karel Vanheusden – VP of Product Development
- Arjun Mendiratta – Director of Carbon Materials
- Anurag Kumar – Sr. Staff
- Jeff Bell – Cell Integration Manager
- Yongtao Meng – Sr. Manager
- Babu Ganguli – Sr. Manager
- Josh Baty – Director of Program Management

LYTEN OVERVIEW



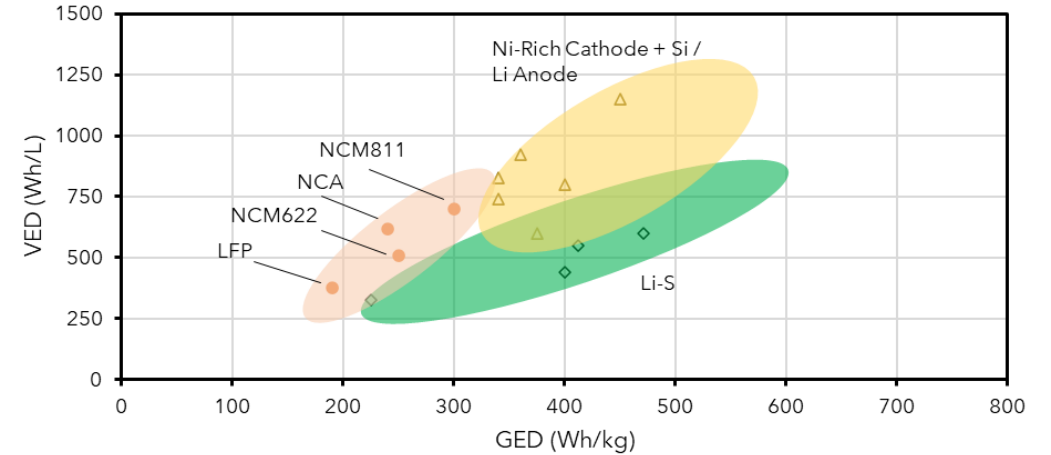
- Founded 2015 - inventor of Lyten 3D Graphene™
- Global leader in 3D Graphene IP (according to PatSnap)
 - >280 patents/pending (across Lyten technologies and applications)
 - >\$335M raised
 - LytCell EV™ lithium-sulfur cells / batteries
 - Sensors (including LIB safety sensors)
 - Composite material additives
- US Government / DoD Engagements
- HQ in San Jose, CA – Offices Opening in Detroit, MI and Reno, NV
 - > 200 employees and growing
 - Approx. 150,000 ft² total office, lab and mfg space
 - 6,600ft² lab space
 - 9,700ft² pilot cell production line (operational 1H23)
 - 9,000ft² graphene synthesis & post-processing line (opening Fall '22)

ATTRACTIVENESS OF LI-S

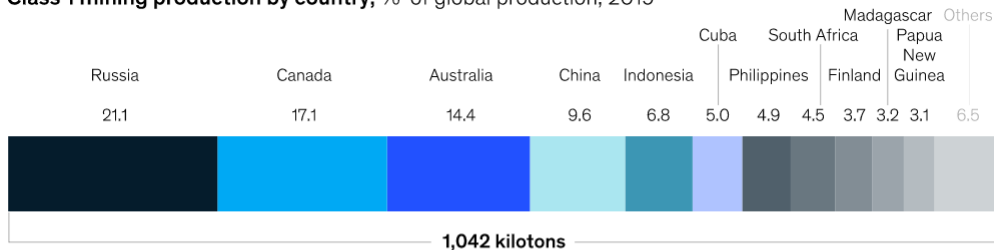
Key Advantages

- Nickel / Cobalt-Free Chemistry
 - Potential to leverage fully domestic supply chain
- At maturity, 600 Wh/kg and 800 Wh/L possible (rate-dependent)
- Higher inherent safety via lack of oxygen-evolving materials
- At scale, potential for production at <60 \$/kWh
 - Elemental sulfur widely available domestically.

Energy Density of Li Chemistries



Class 1 mining production by country, %¹ of global production, 2019



Class 1 refined production by country, %¹ of global production, 2019

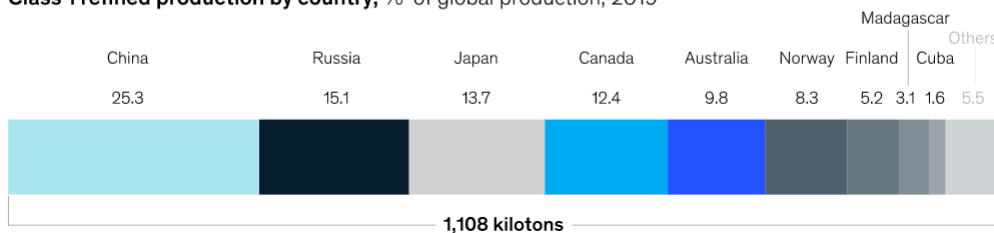
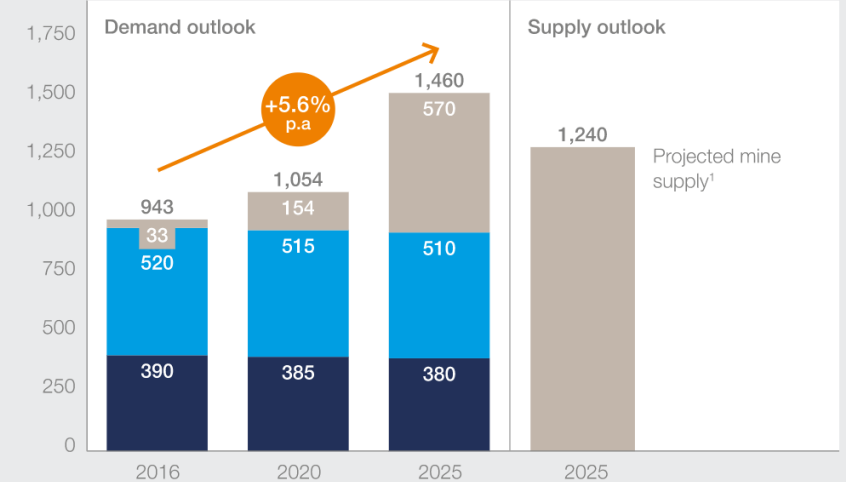


Exhibit 4 Class 1 nickel supply-demand balance Kt

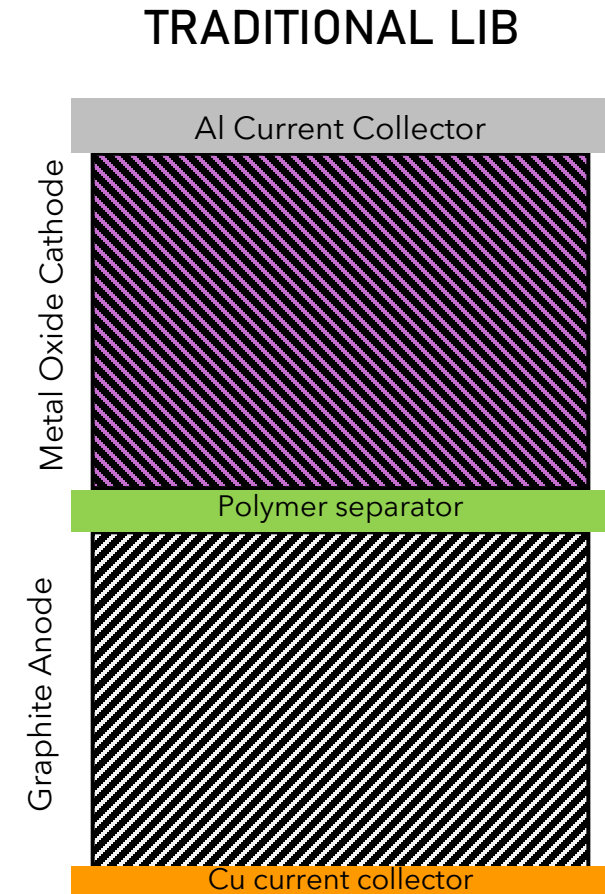
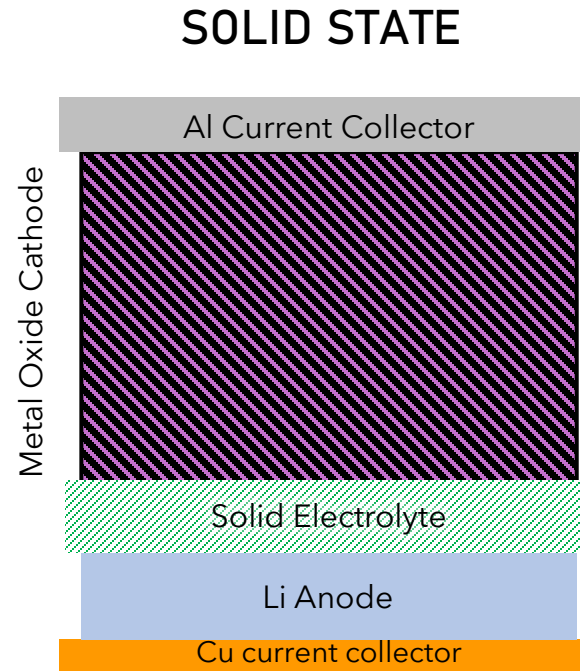
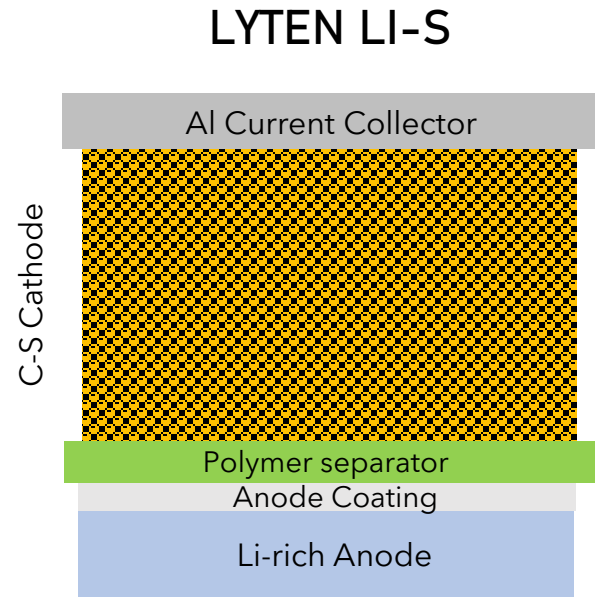
■ Battery demand
■ Class 1 non-stainless steel
■ Class 1 stainless steel

¹ Based on McKinsey nickel mine supply model, includes existing projects, brownfield and greenfield expansions in certain, probable, possible and unlikely projects.

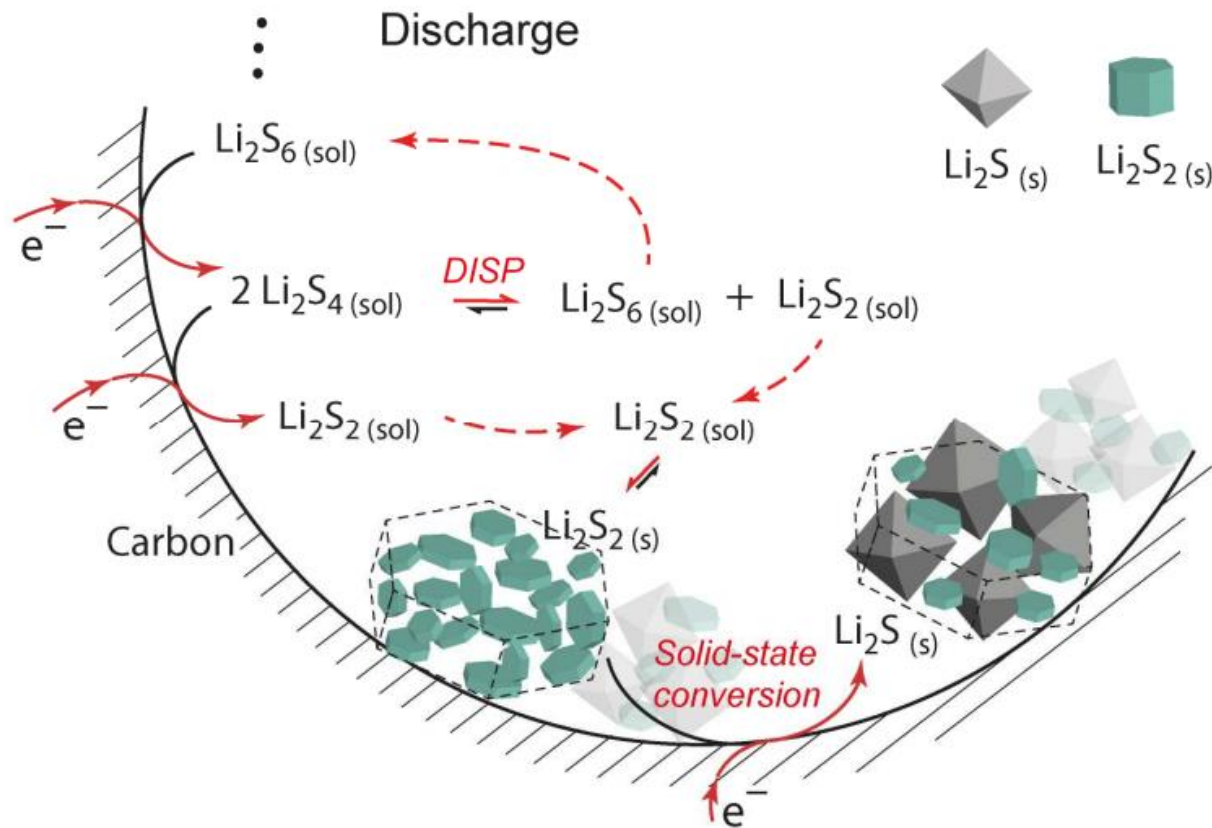
Source: McKinsey Basic Material Institute



LI-S CELL STRUCTURE



BASIC CHARGE-DISCHARGE REACTIONS



Key Attributes

- 2.1 V nominal discharge voltage vs. Li metal
- 1675 mAh/g theoretical sulfur capacity
- Conversion chemistry
 - Anode: $16\text{Li} \rightarrow 16\text{Li}^+ + 16\text{e}^-$
 - Cathode: $\text{S}_8 + 4\text{Li}^+ + 4\text{e}^- \rightarrow 2\text{Li}_2\text{S}_4$
 $2\text{Li}_2\text{S}_4 + 12\text{Li}^+ + 12\text{e}^- \rightarrow 8\text{Li}_2\text{S}$
- Liquid-state and solid-state reactions can occur simultaneously
 - Non-Faradaic reactions also prevalent (Li_2S_4 disproportionation)
 - Sulfide species can exist as solubilized or precipitated
- Li metal anode is stripped and plated normal to the anode surface.

LI-S ELECTROCHEMISTRY IS HIGHLY TUNABLE

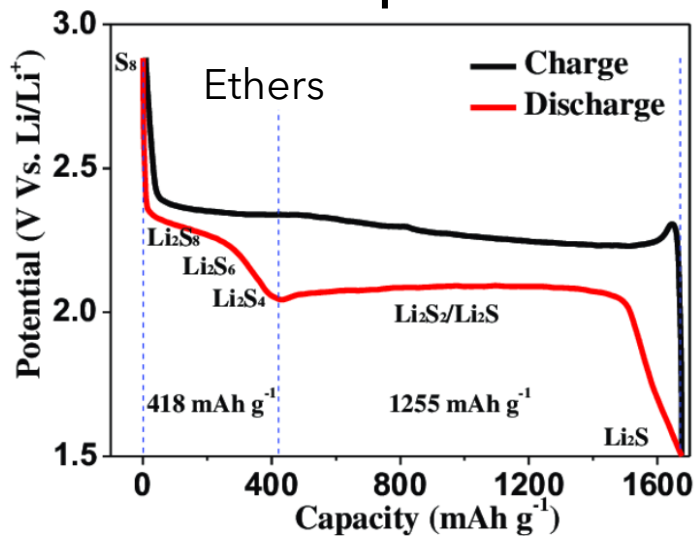
← Highly Solvating Electrolytes

Sparingly Solvating Electrolytes

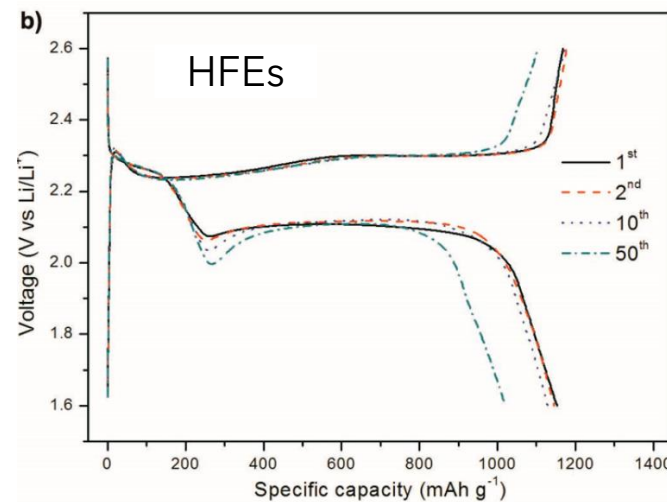
Non-Solvating Electrolytes →

← Liquid/Solid-State Conversion

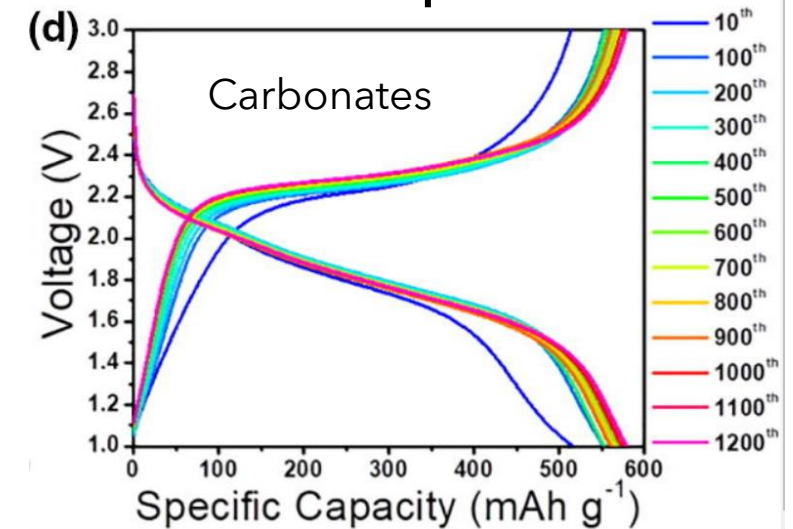
All Solid-State Conversion →



- High specific energy
- Fast kinetics
- High power
- High shuttle effect



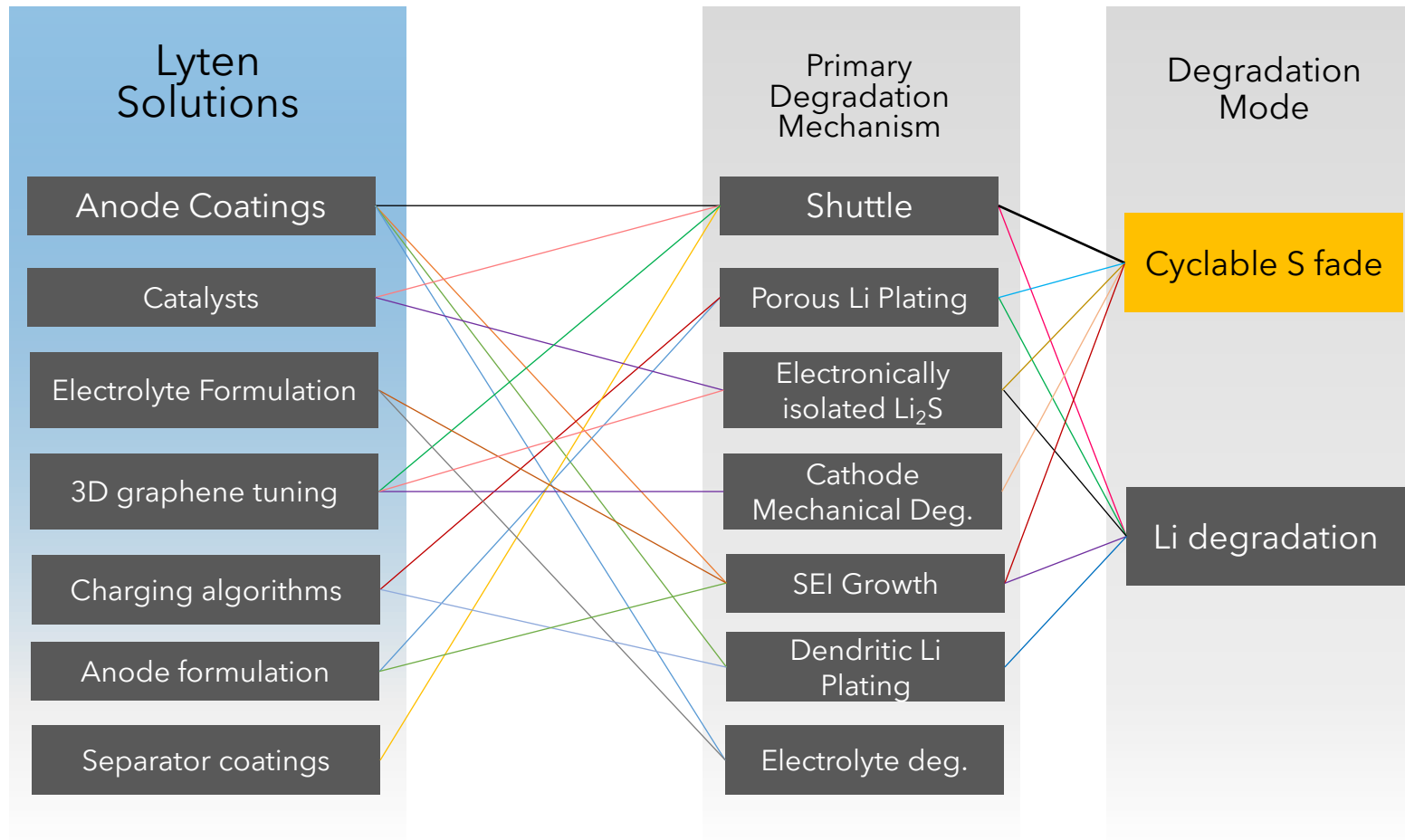
- Low shuttle effect
- Poorer cold temp performance
- Quasi-solid state reactions



- High cycle life
- No shuttle effect
- Lower voltage
- Lower Wh/kg

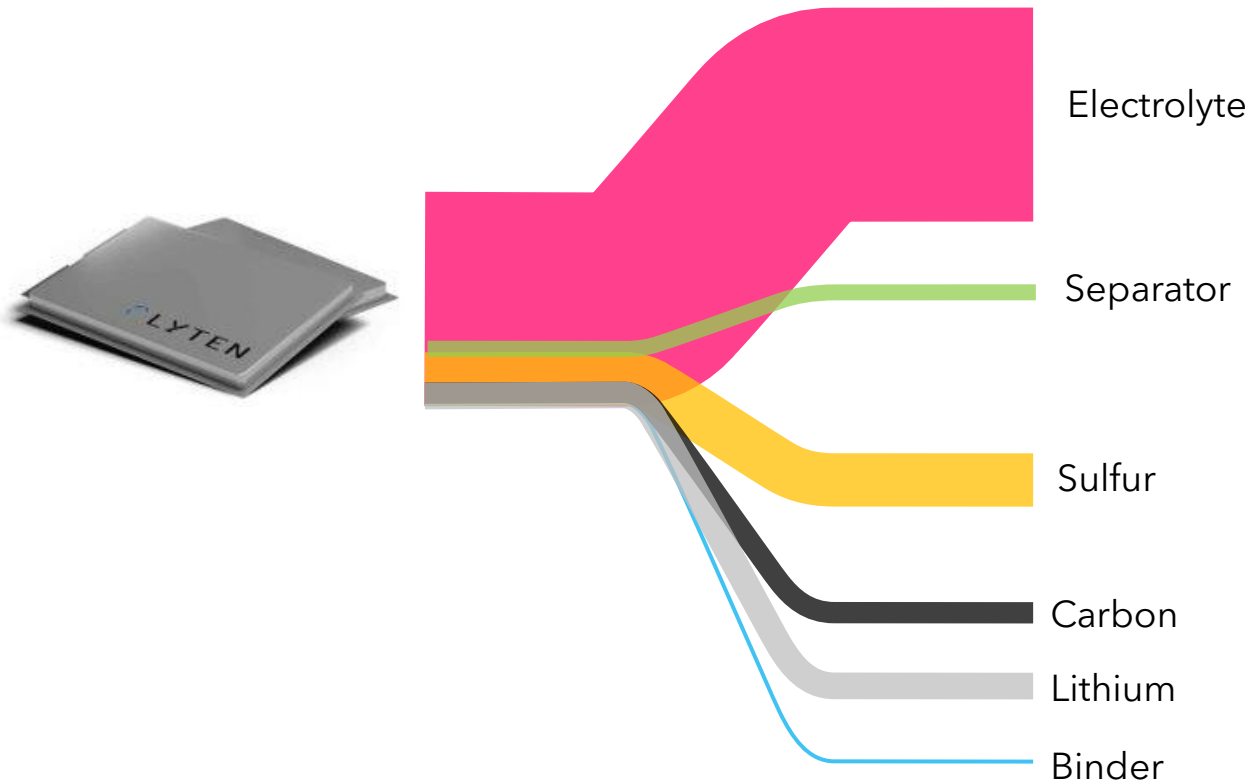
ADDRESSABLE LIFE CYCLE CHALLENGES IN LI-S

Network Diagram of Cycle Life Degradation Modes

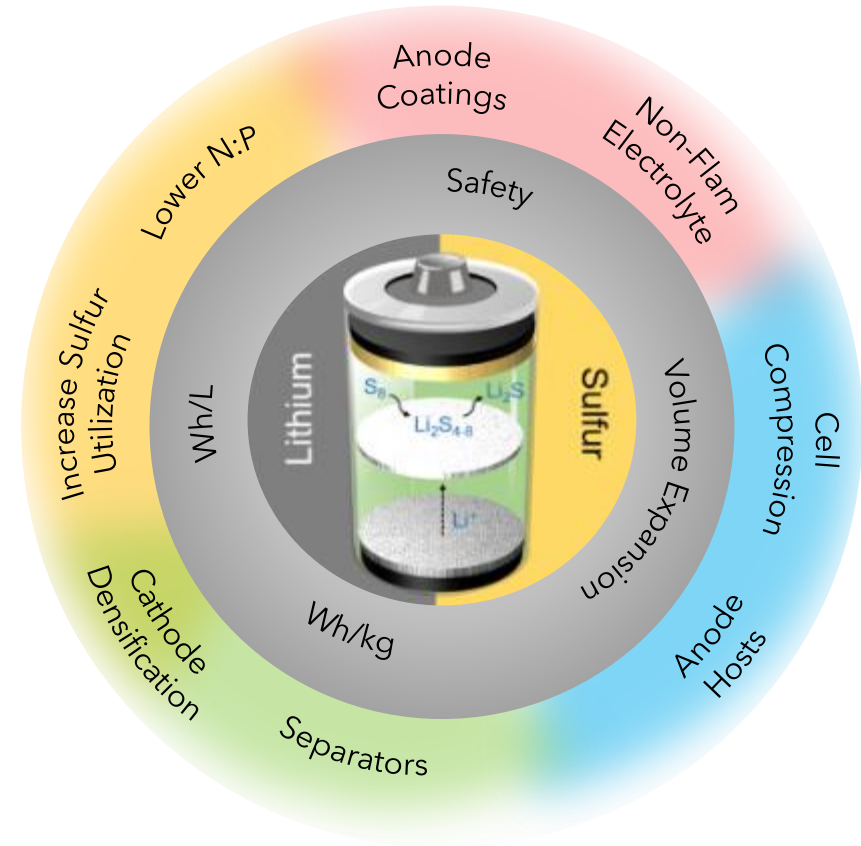


ADDRESSABLE CELL CHALLENGES IN LI-S

Li-S Cell Mass Breakdown

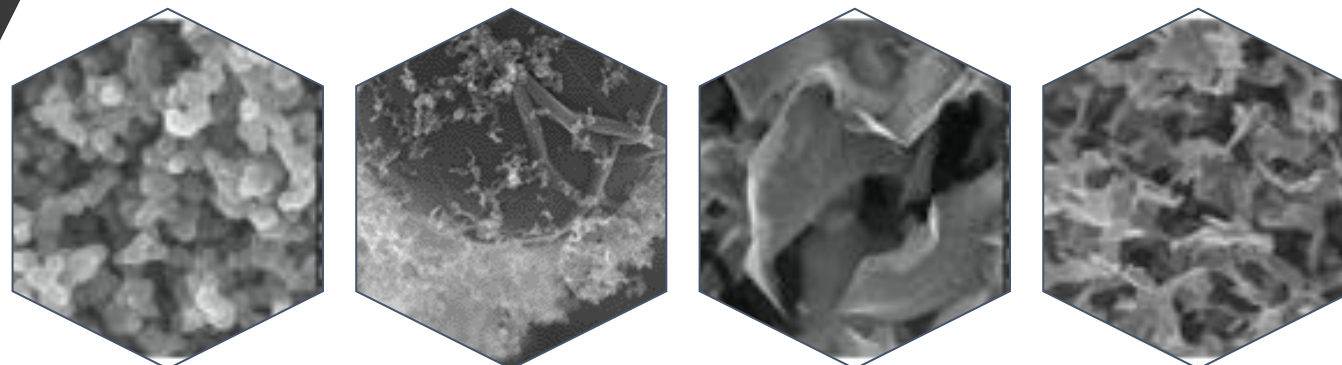
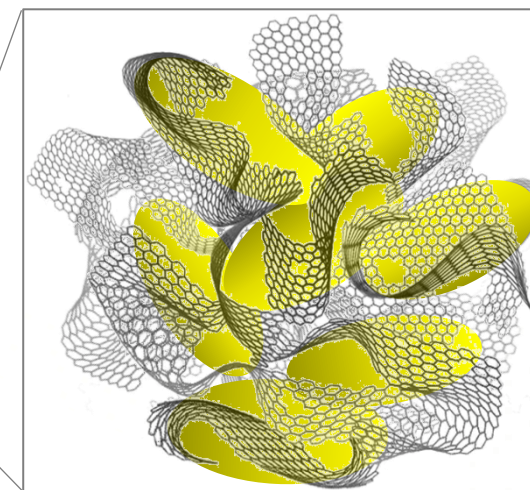
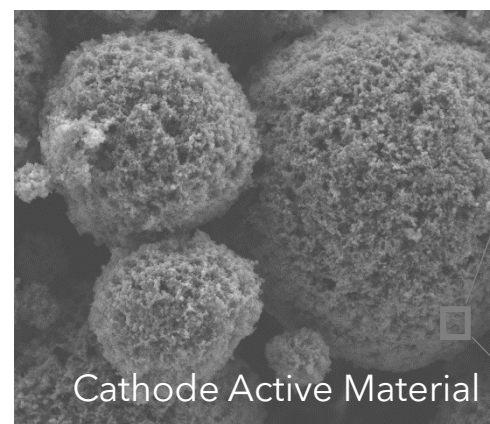
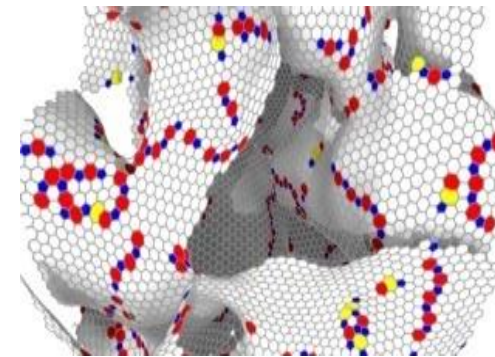
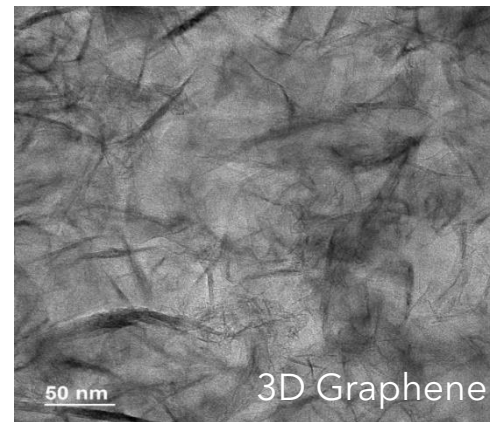
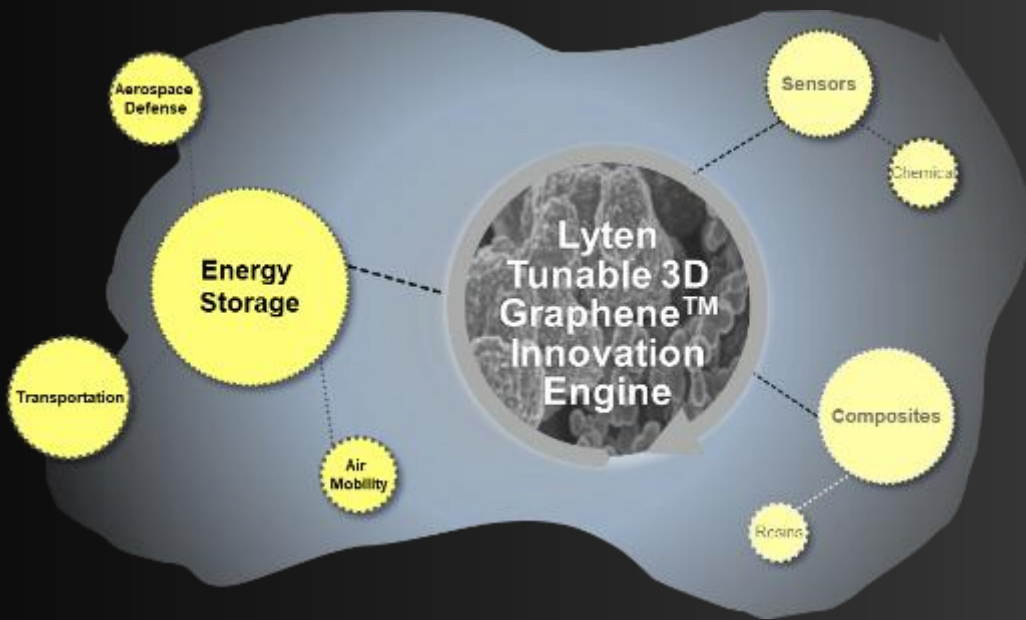


Cell Level Addressable Challenges



LYTEN 3D GRAPHENE®

DESIGNED TO BE DRAMATICALLY MORE REACTIVE THAN HISTORIC 2D GRAPHENE

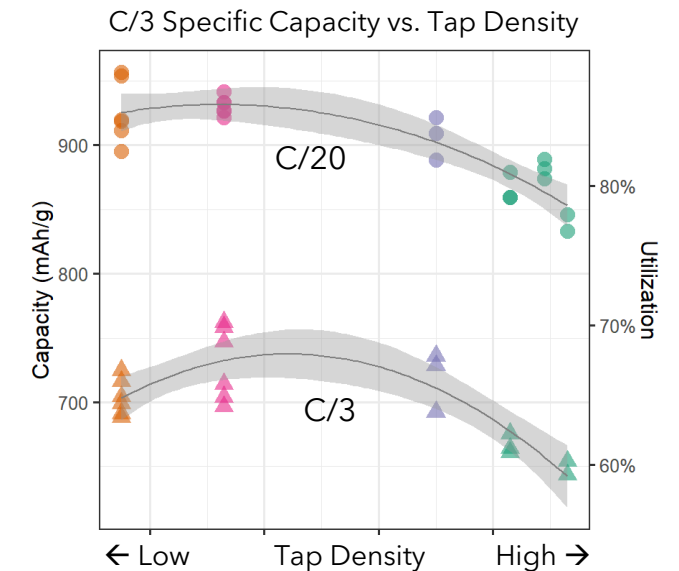
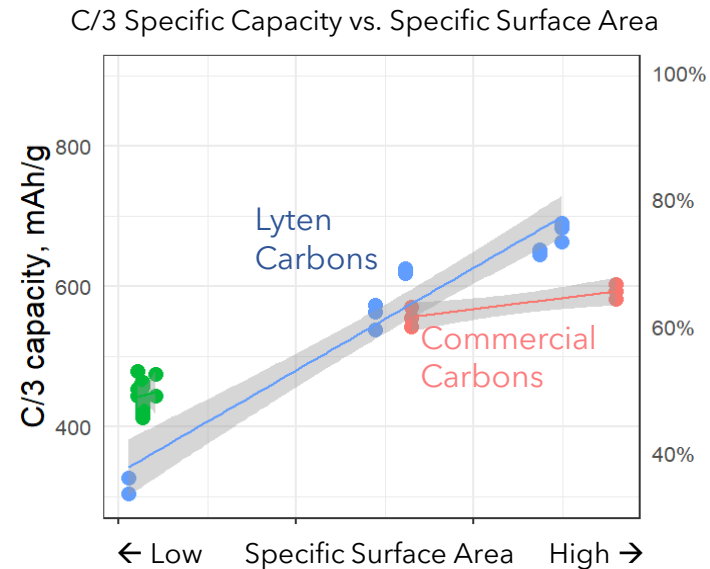
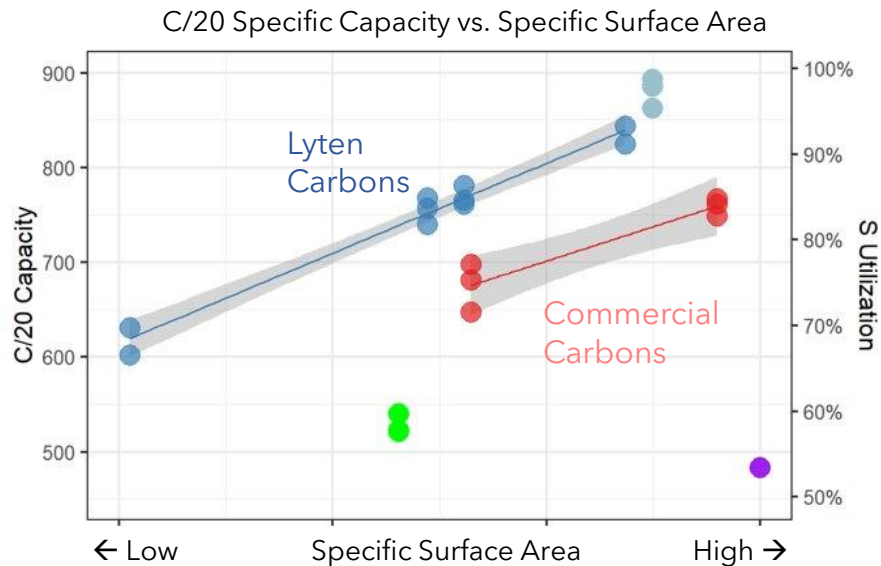
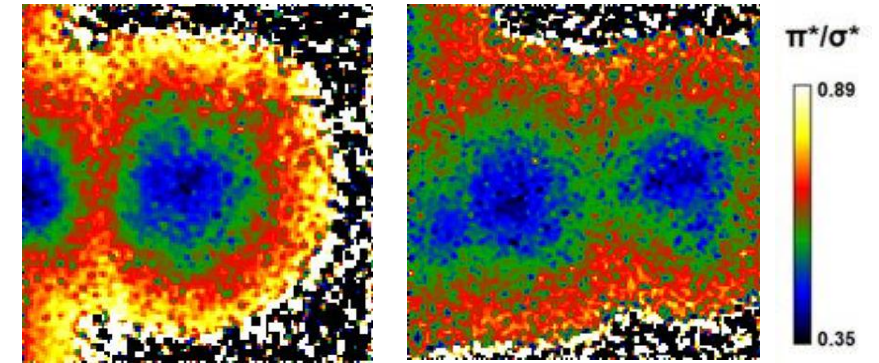


LYTEN 3D GRAPHENE DEVELOPMENT

Key Advantages

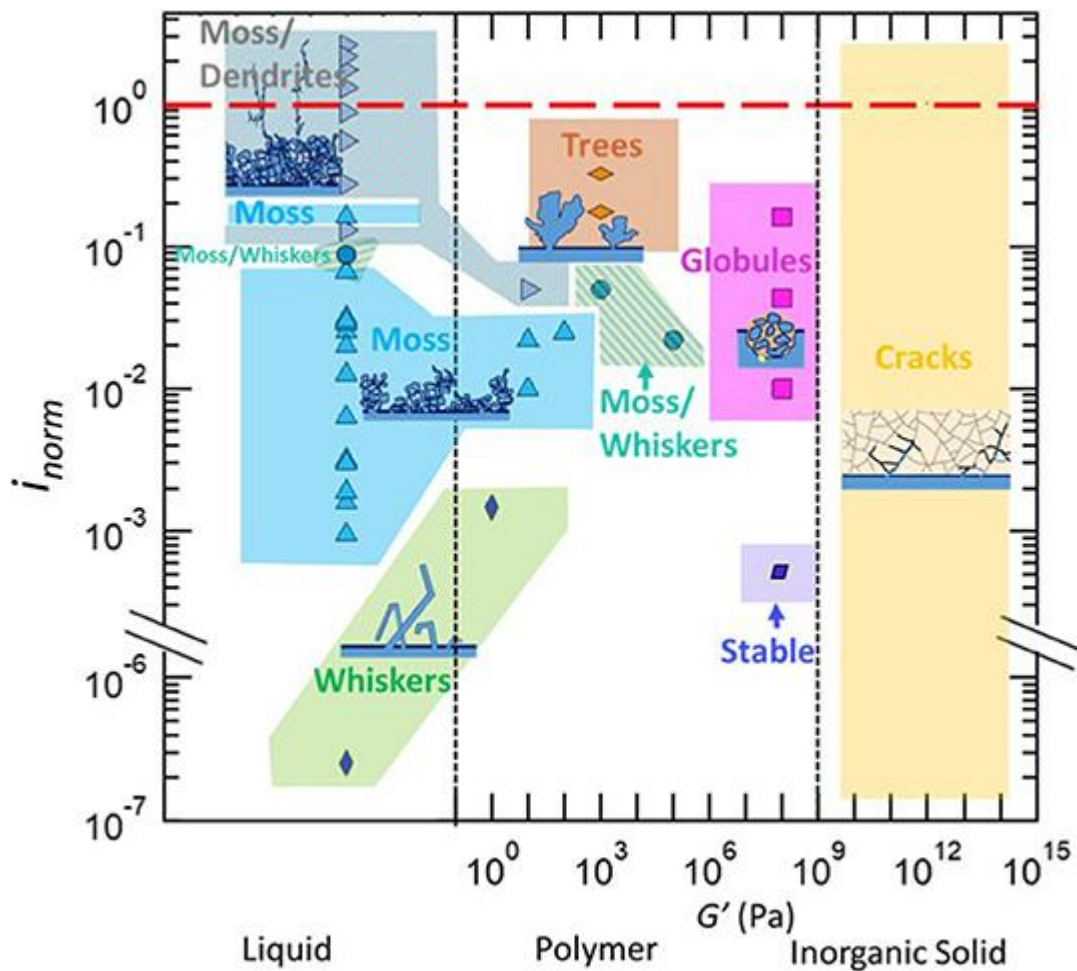
- Able to tune surface area, pore size, and pore distribution through process controls. Tap density of carbon particles also tunable.
 - Li-S performance is related to both surface area, pore size, and pore distribution.
- Dopable
 - Able to dope carbons with higher valence atoms to increase catalytic activity of the graphene
- Outperforms high surface area commercial carbons at all C-rates

In-house TEM / EELS - Lyten Carbon

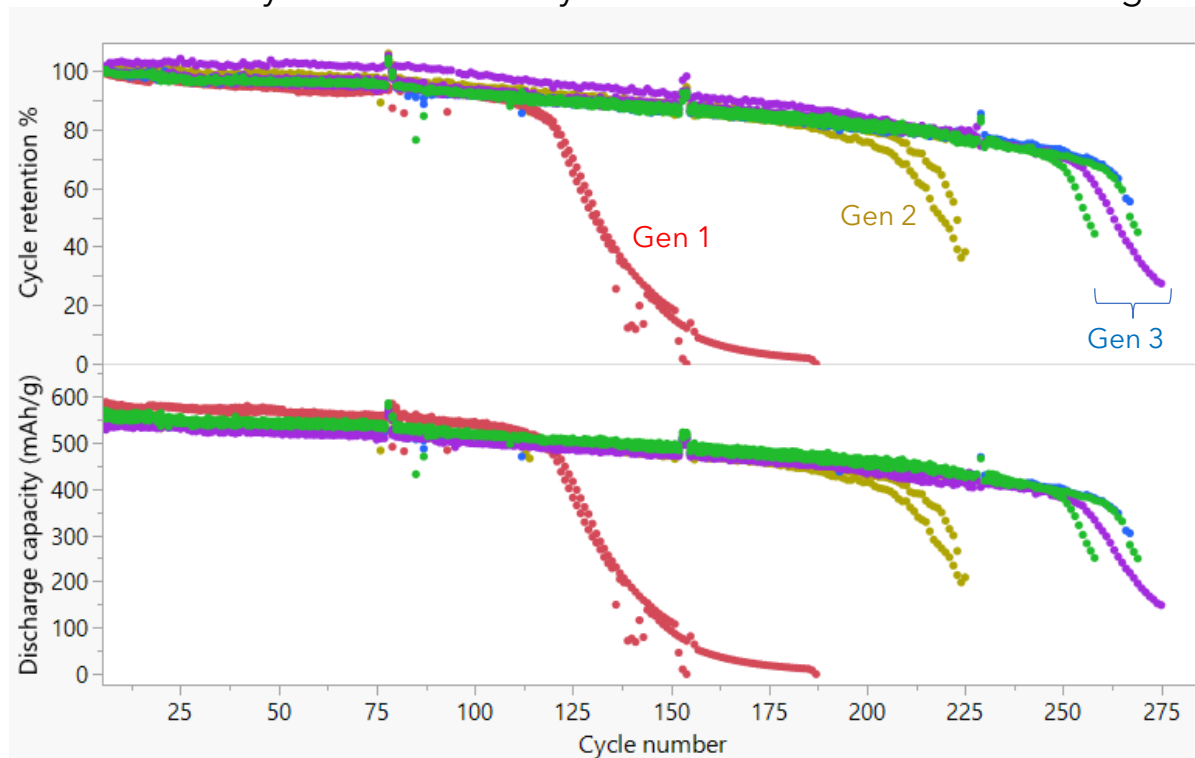


ANODE MATERIAL DEVELOPMENTS

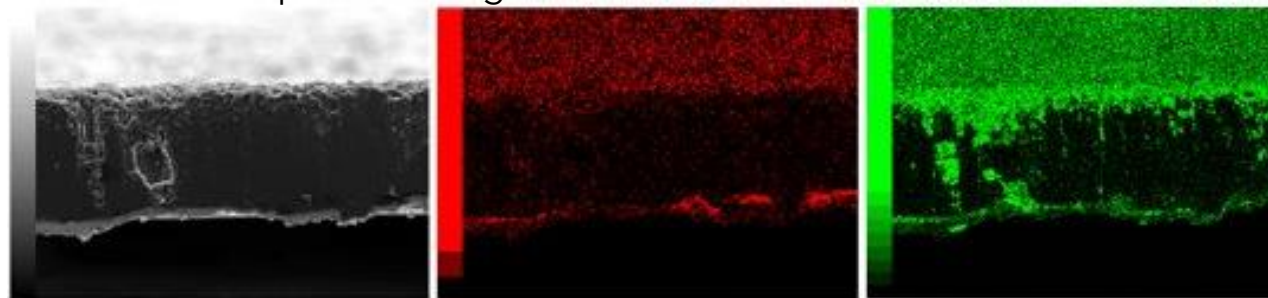
Increasing difficulty in processing →



Cycle Life of New Lyten Anode Formulae and Coatings



SEM / EDS Maps of Coatings

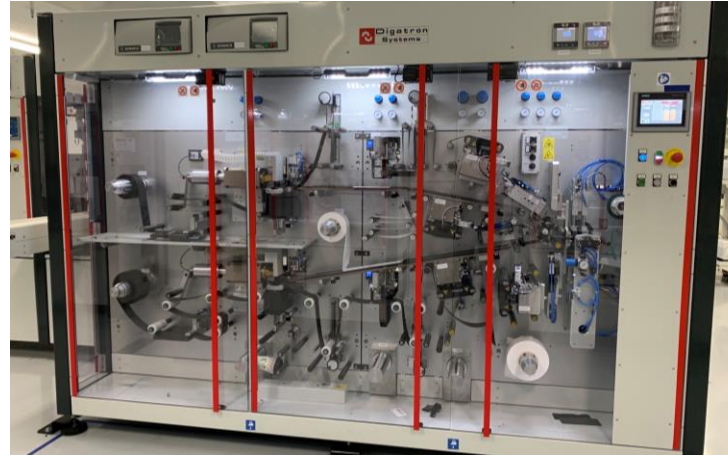


ACTIVE LYTEN CELL DEVELOPMENT

Lyten Pouch Line



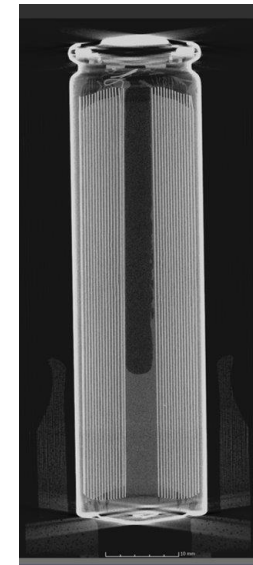
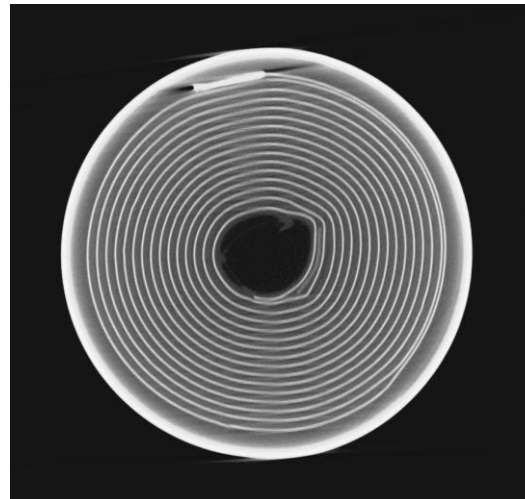
18650 / 21700 / 26650 Lyten Line



Lyten Li-S Jelly Roll



In-house X-Ray CT Scans - 18650

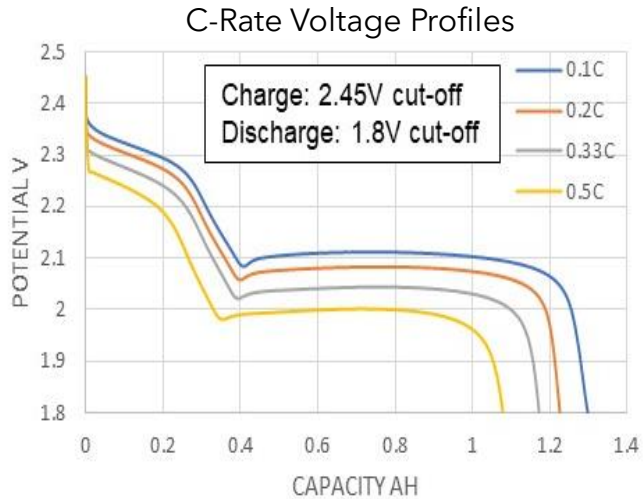
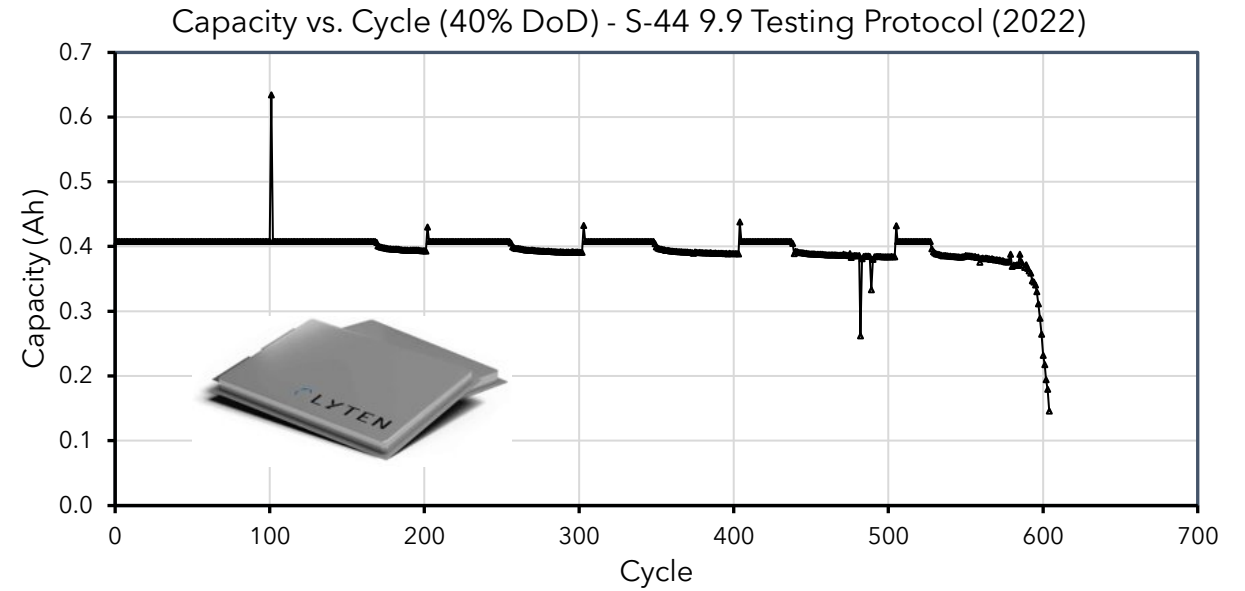
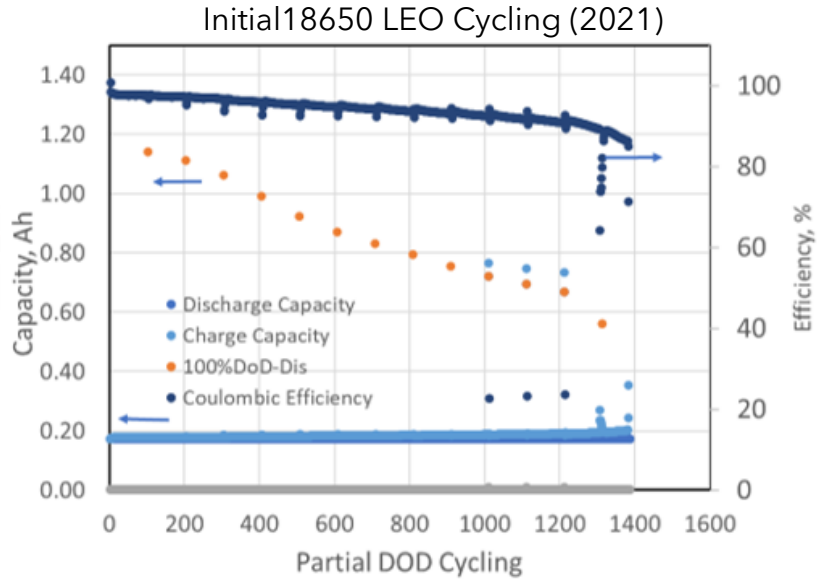


UNITED STATES
SPACE FORCE



DEFENSE
INNOVATION UNIT

LEO LI-S CYCLING



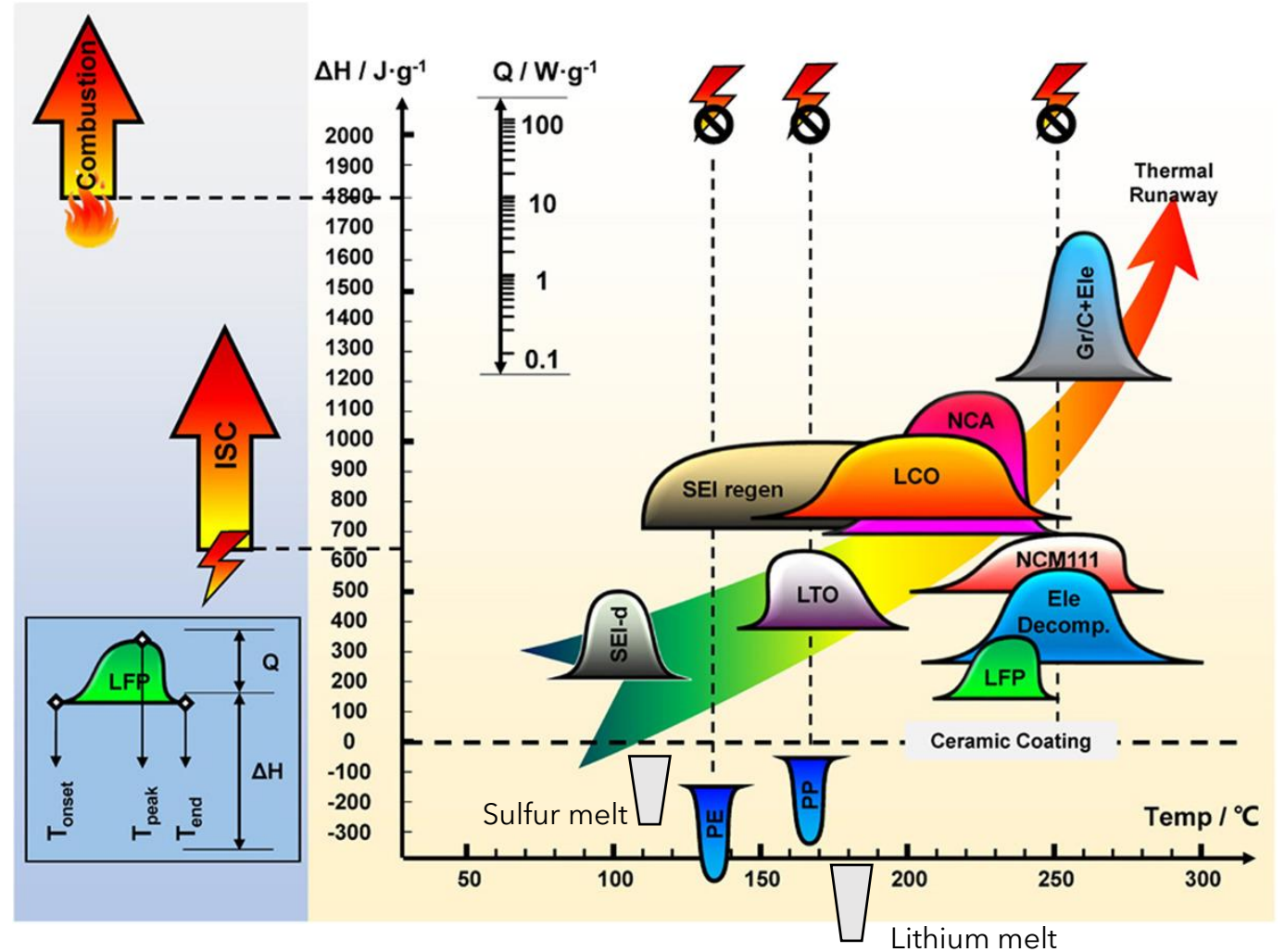
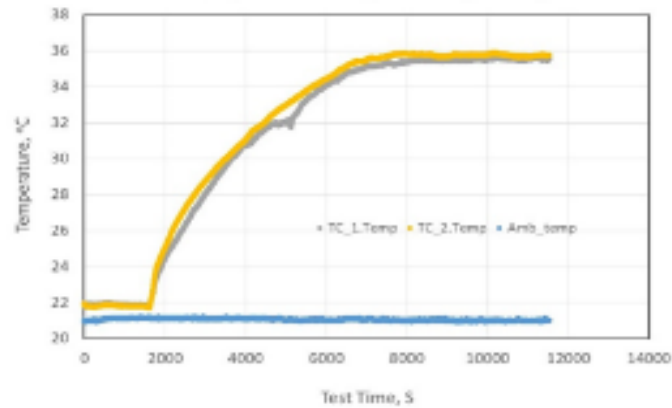
LEO Life Cycle Protocol			
DoD	Discharge Rate	Charge Rate	Time per Cycle
20%	C/2.92	C/5.08	96 min (61-min charge, 35-min discharge)
40%	C/1.46	C/2.54	96 min (61-min charge, 35-min discharge)
60%	C/0.97	C/1.69	96 min (61-min charge, 35-min discharge)
100%	C/3	C/3	6 hours (3-hour charge, 3-hour discharge)

LI-S SAFETY

Key Attributes

- Li-S is inherently safer than traditional Li-ion technology.
- Lack of an oxygen-evolving cathode material reduces the probability of a sustained thermal "runaway" event
- Passivation / coating layer(s) on the anode can decrease anode reactivity.

5V Overcharge Test → 14°C Rise

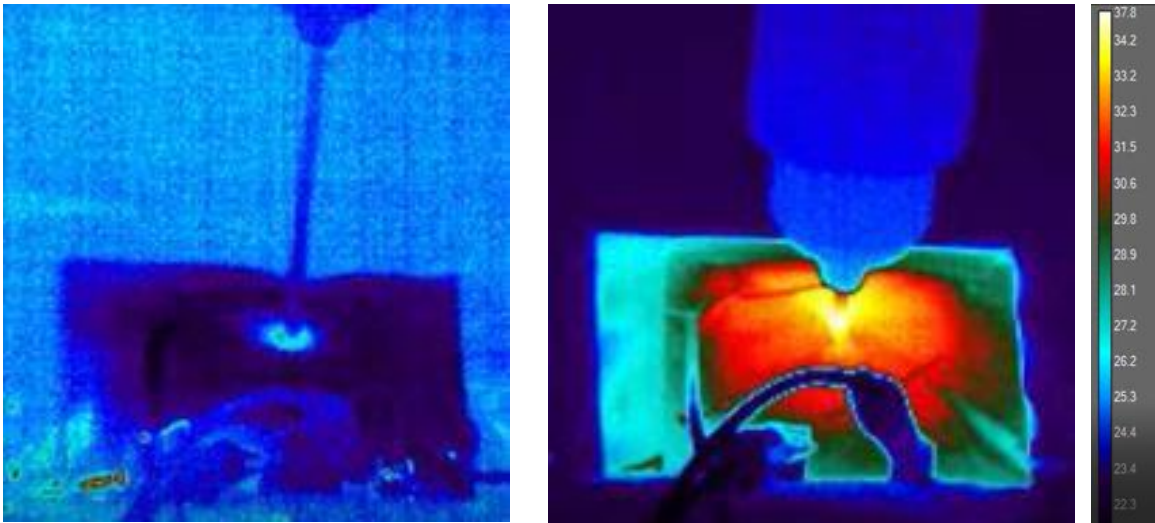


CELL ABUSE TESTING

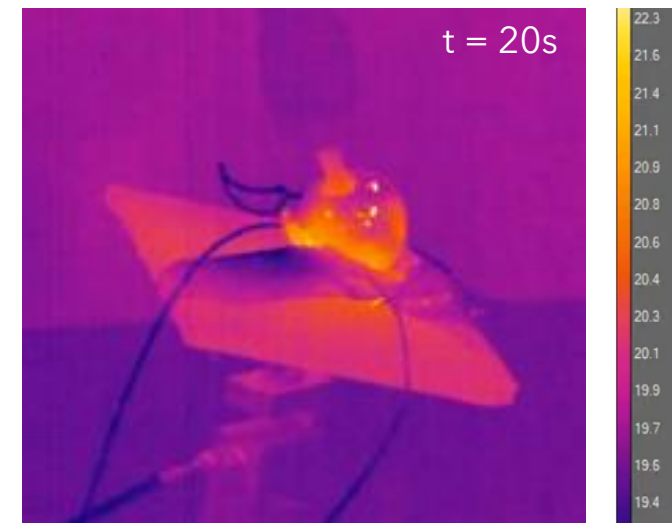
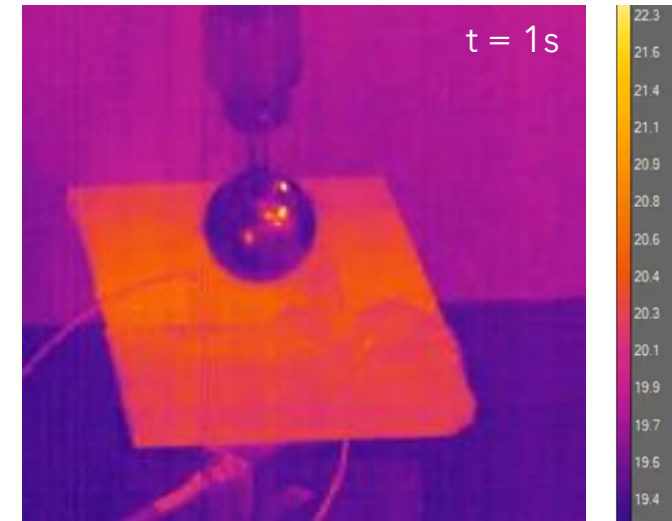
Key Results

- Temperature increased $\sim 10^{\circ}\text{C}$ in nail pen test.
- Similar behavior was reported in 16 Ah cells from Oxis by the Imperial College group [I. Hunt et al, J. Energy Storage 2 (2015) 25-29].
- This is possibly due to the non-conductive reaction products such as Li_2S formed locally at the penetration site due to high currents, which insulate the short circuit and allow the cell to behave normally.
- Lyten will continue to evaluate larger cell formats with newer formulations.

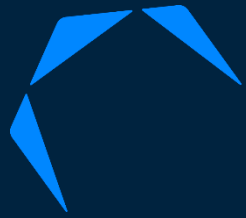
Nail Penetration Test



Crush Test



Thank You!



LYTEN

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