High Energy Li-S Cells Using 3D Graphene™ for Aerospace Applications

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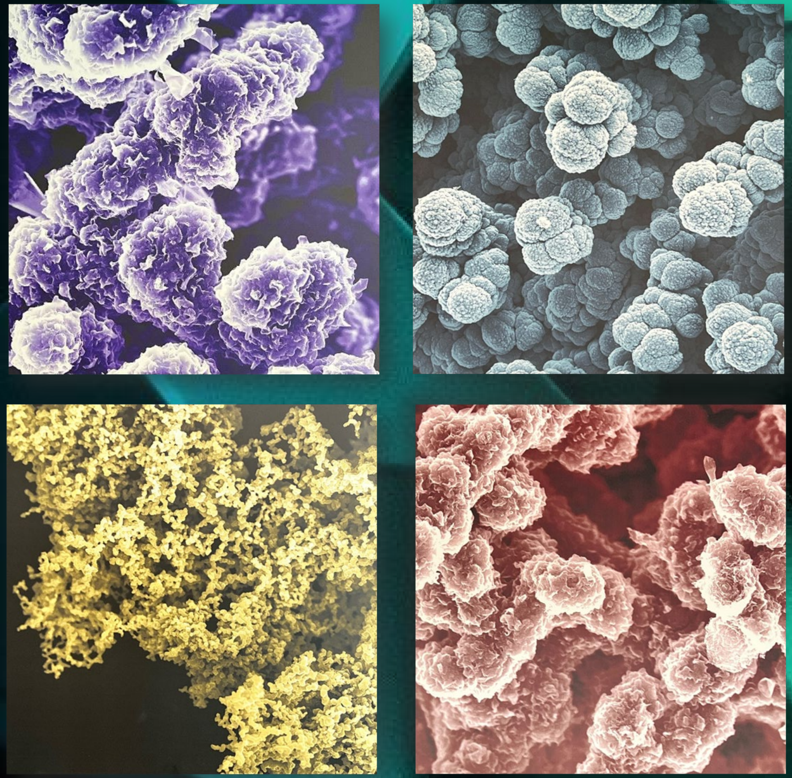


LYTEN

40th annual Space Power Workshop

April 25-27 2023, Redondo Beach, CA

LYTEN OVERVIEW

- Founded 2015 – inventor of Lyten 3D Graphene™
- Global leader in 3D Graphene IP (according to PatSnap)
  - >310 patents/pending
  - LytCell EV™ lithium-sulfur cells free of Ni or Co
  - 100% U.S. Sourced Battery Supply Chain
  - Sensors (including LIB safety sensors)
  - Composite material additives
- US Government / DoD Engagements
- HQ in San Jose, CA
  - > 260 employees with 70% hold engineering or advanced degrees in physics, chemistry
  - 6,600ft^2 lab space and 9,700ft^2 pilot cell production line
  - 9,000ft^2 graphene synthesis & post-processing line

Company Highlights

6 Years of R&D

Accelerated by multiple intelligence community and DoD contracts

4 Years of Product Manufacturing Development

10,000 Li-S cells produced since 2017. Customer graphene bulk shipments commence in 2023.

World Class Team

260 employees ~70% hold advanced engineering or science degrees

Battery Team : 65 (40 Scientists and Engineers);
Specific teams focused on: cathode, anode, electrolyte, separator, full cell integration, testing, manufacturing, and modeling

Extensive Patent Portfolio

310+ total issued/pending patent matters

>$210M capital through Series A

In process of closing Series B

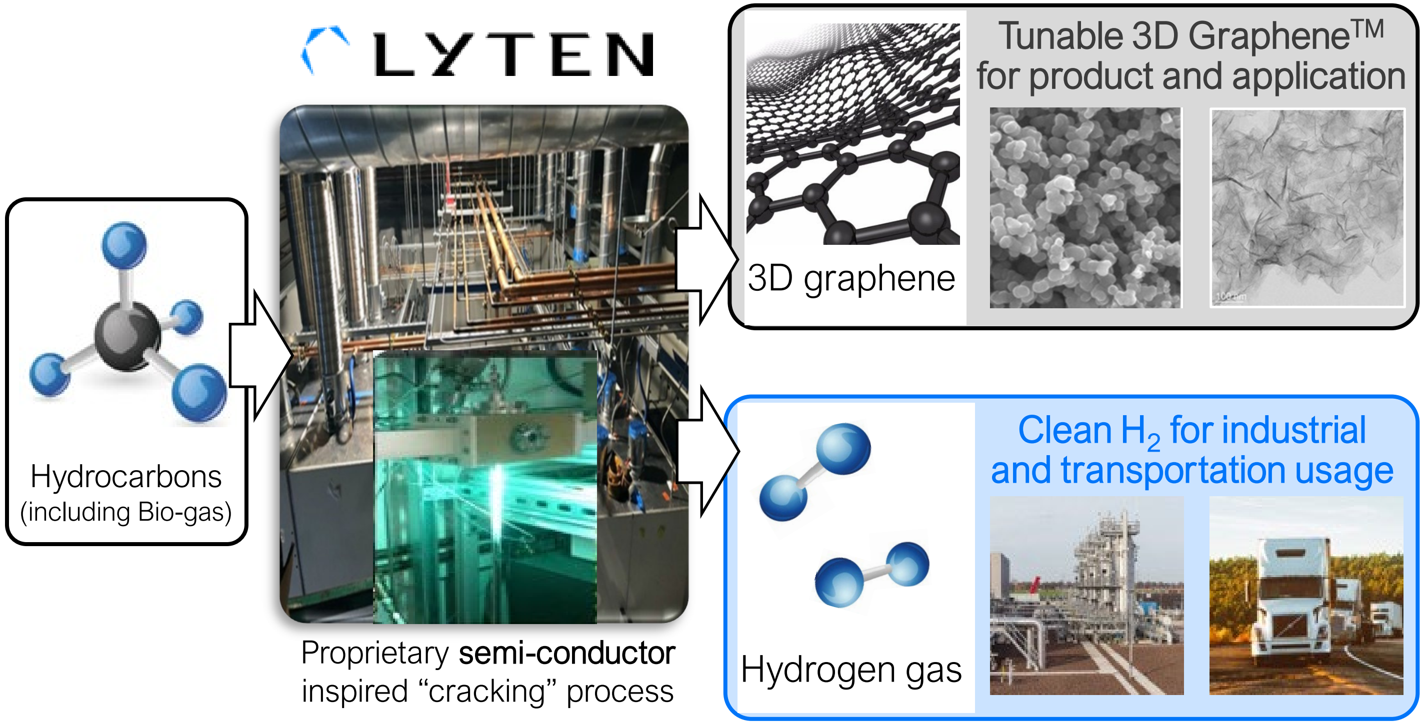
No Nickel, Manganese or Cobalt

100% U.S. Sourced Battery Supply Chain

Targeting gigaton scale decarbonization impact

LYTEN 3D GRAPHENE PROCES IS A DECARBONIZATION MATERIAL PLATFORM

Lyten has pioneered a revolutionary reactor technology designed to deliver clean carbon and clean hydrogen

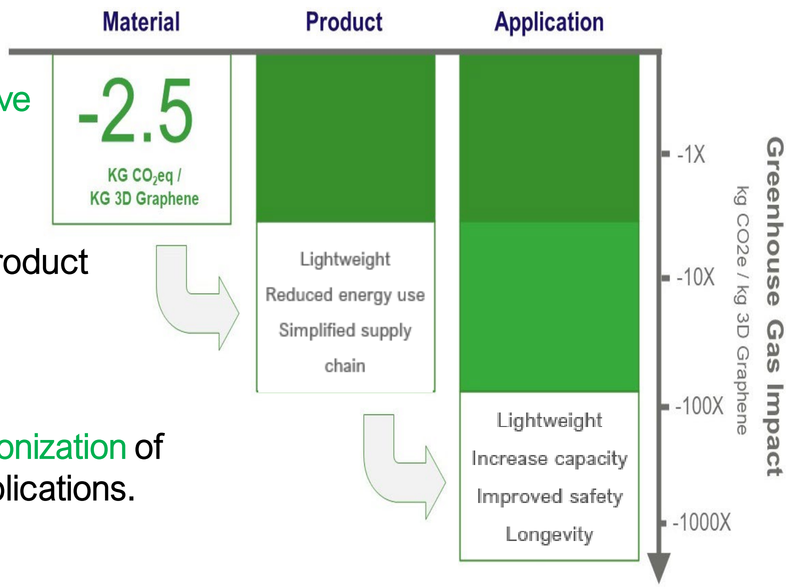


Every kg of Lyten 3D Graphene manufactured will have up to 4,000X decarbonization impact on the planet (kg CO_2e)[1]

A Carbon Negative Material…

Decarbonizing Product Manufacturing…

Enabling Decarbonization of Downstream Applications.



1 - Life Cycle Analysis of 3D Graphene and full life cycle of applications. Complete by Life Cycle Associates.

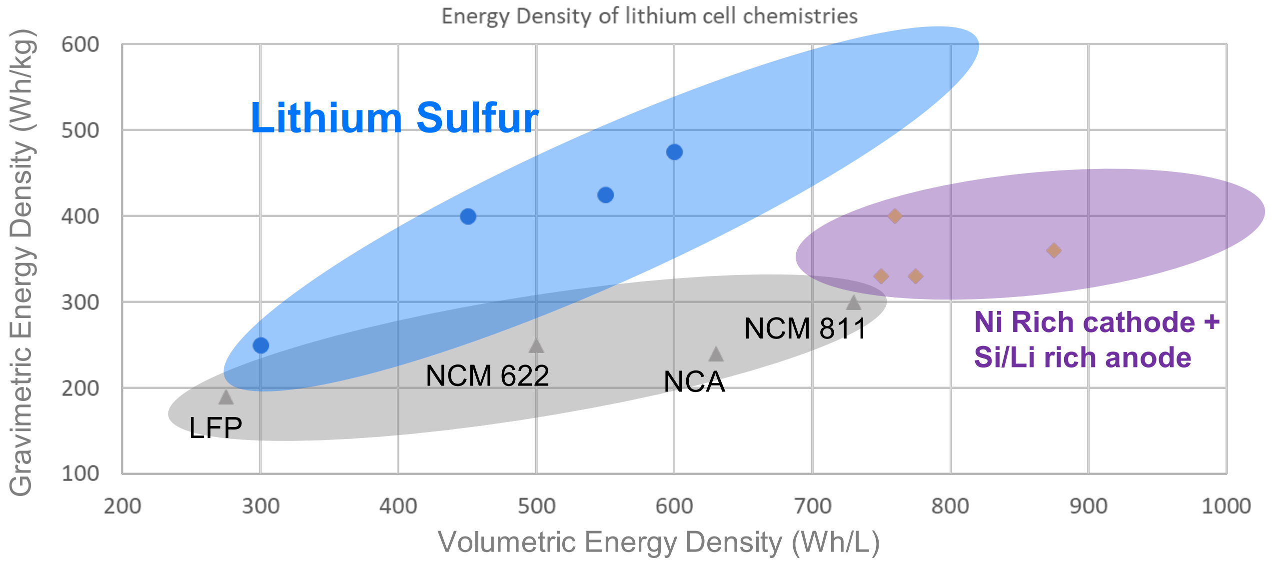
LITHIUM SULFUR- HIGH ENERGY AND SUSTAINABILITY

Key Challenges for Traditional LIBs

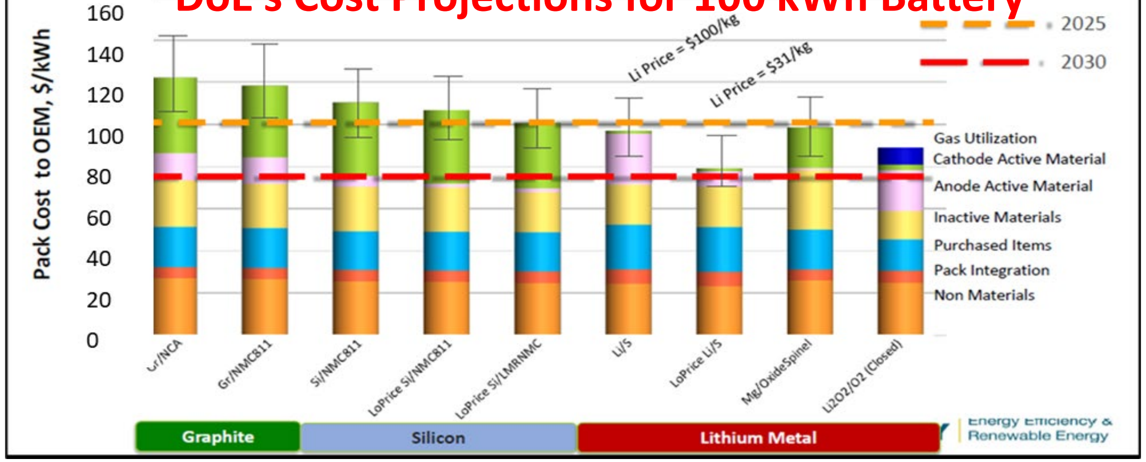
- Predominantly foreign-sourced active materials
- Cell performance reaching its fundamental limits
- Nickel shortfall in coming years

Key Advantages of Lithium Sulfur

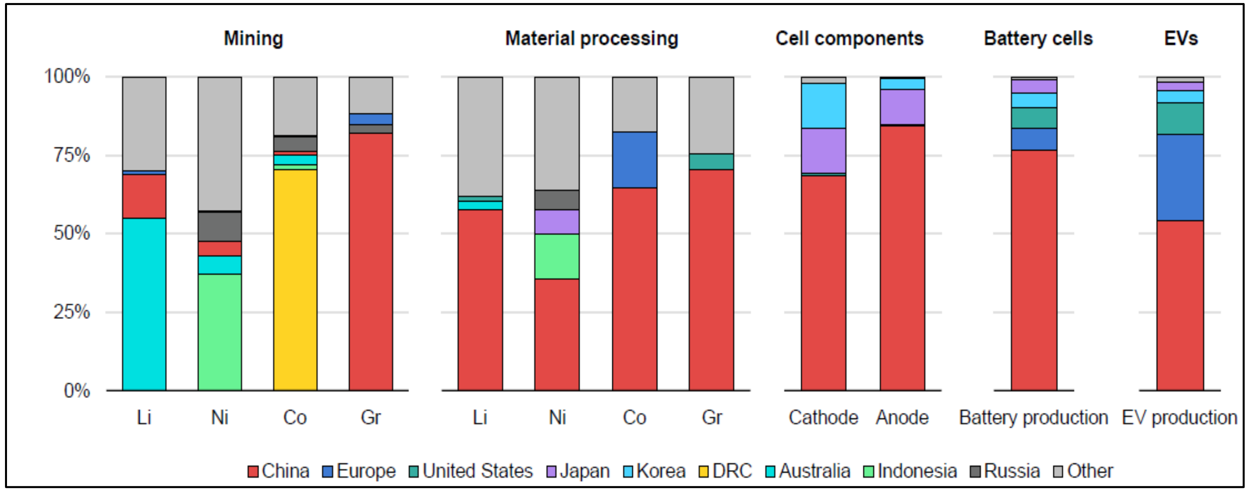
- Nickel/cobalt/graphite - free → fully domestic supply chain
- Abundant, low-cost materials: sulfur, carbon, solvents:
- Inherently safer due to unique chemistry
- At maturity, 600 Wh/kg and 800 Wh/L possible



DoE's Cost Projections for 100 kWh Battery



China dominates the entire downstream EV battery supply chain



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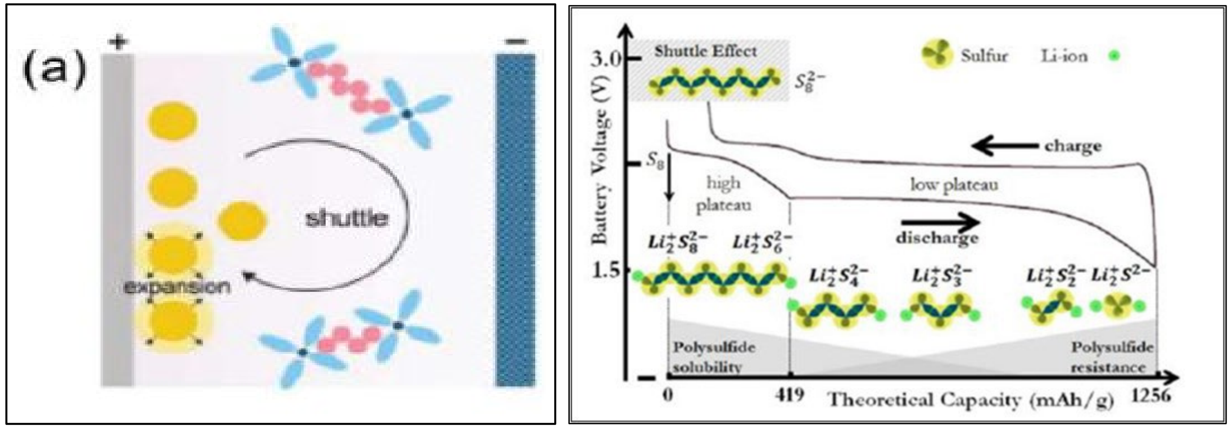
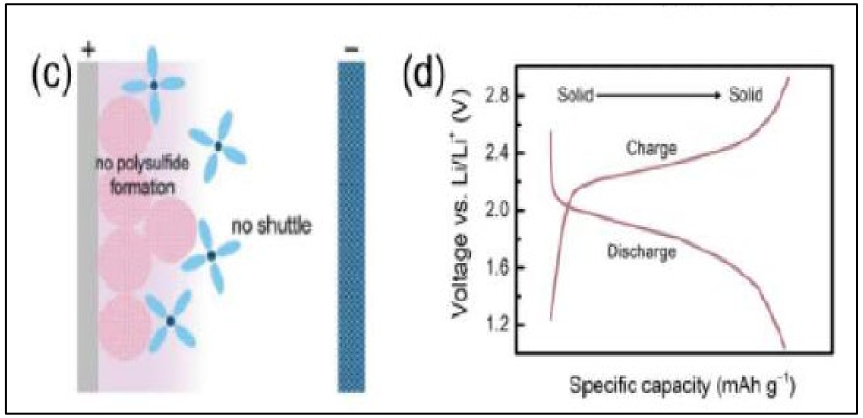
Meng Zhao, Bo-Quan Li, Hong-Jie Peng, Hong Yuan, Jun-Yu Wei, and Jia-Qi Huang, Angew. Chem. Int. Ed. 2020, 59, 12636–12652

Multiphase : Solid-Liquid-Cathode Reaction



- Conventional architecture
- Design of electrolyte is crucial to regulate polysulfide solubility
- Facile cathode kinetics
- High sulfur utilization
- Moderate cycle life limited by polysulfide shuttle effects

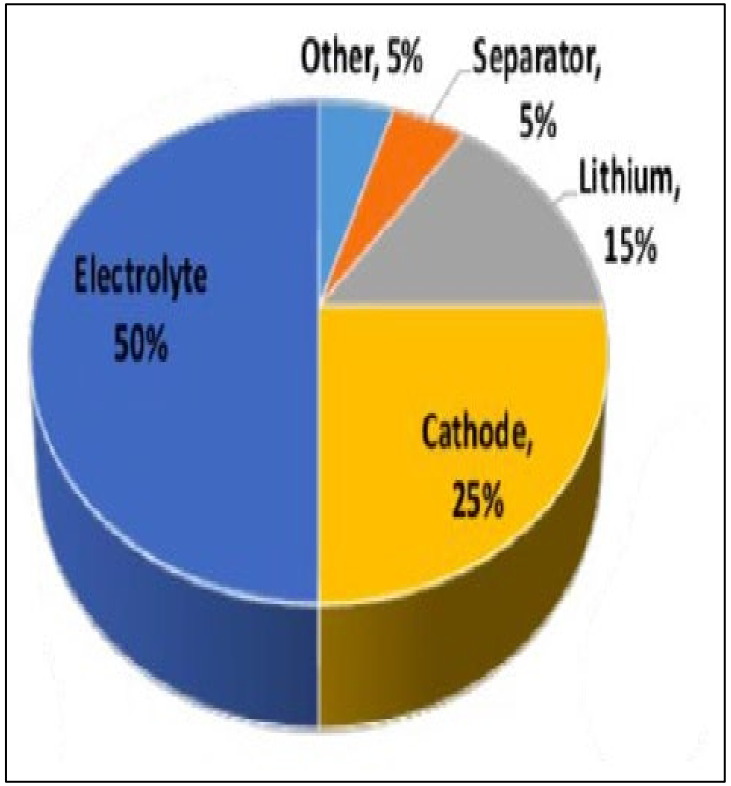
All Solid (Solid-Solid) Reaction

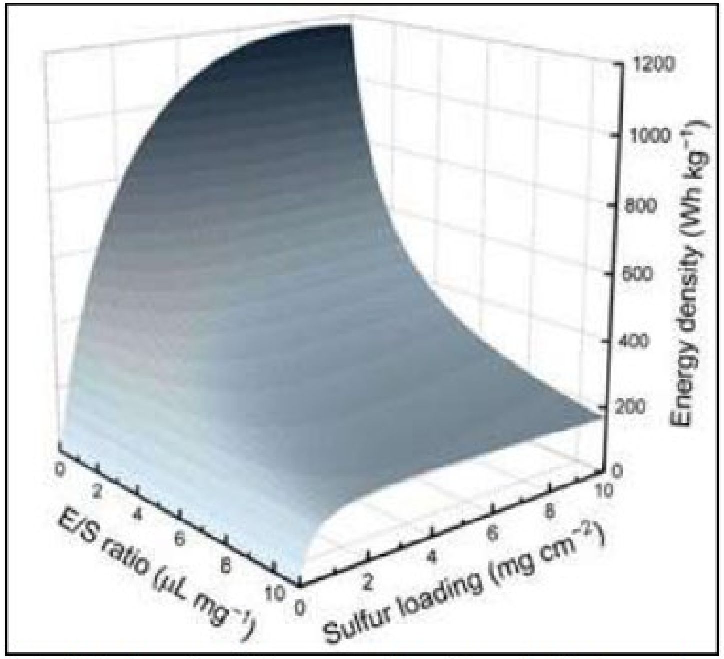


- Advanced architecture with
  - Sulfurized polymers
  - Gamma-phase sulfur
  - Solid electrolyte or ionic liquids
- Good cycle life due the absence of polysulfides but poor kinetics between insulating solid phases

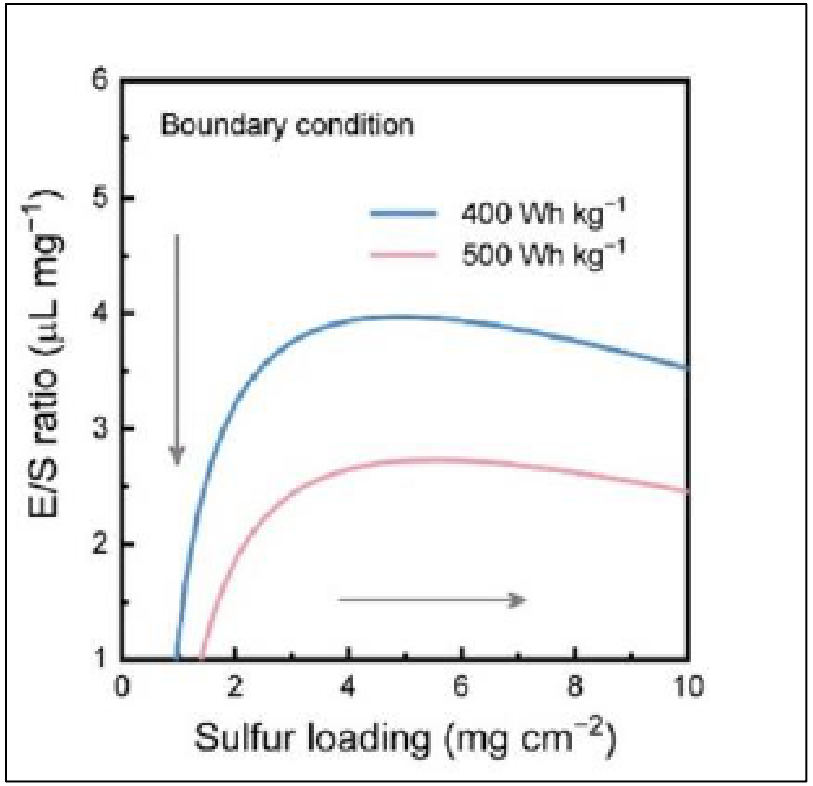
- Lyten is currently adopting the conventional design but is also exploring advanced architectures for longer cycle life

KEY DESIGN CONSIDERATIONS FOR HIGH ENERGY LI-S CELLS





Calculated gravimetric energy densities of a Li–S pouch cell depending on areal sulfur loading and E/S ratio



- Most of the studies reported in literature deal with low loadings and/or high E/S.
- High sulfur loadings (>5 mg of S/cm^2) and low electrolyte content are two most important parameters.
- Higher the sulfur loading, more will be the polysulfides in the electrolyte.

X. Yang, X. Li, K. Adair, H. Zhang and X. Sun, Electrochemical Energy Reviews (2018) 1:239–293

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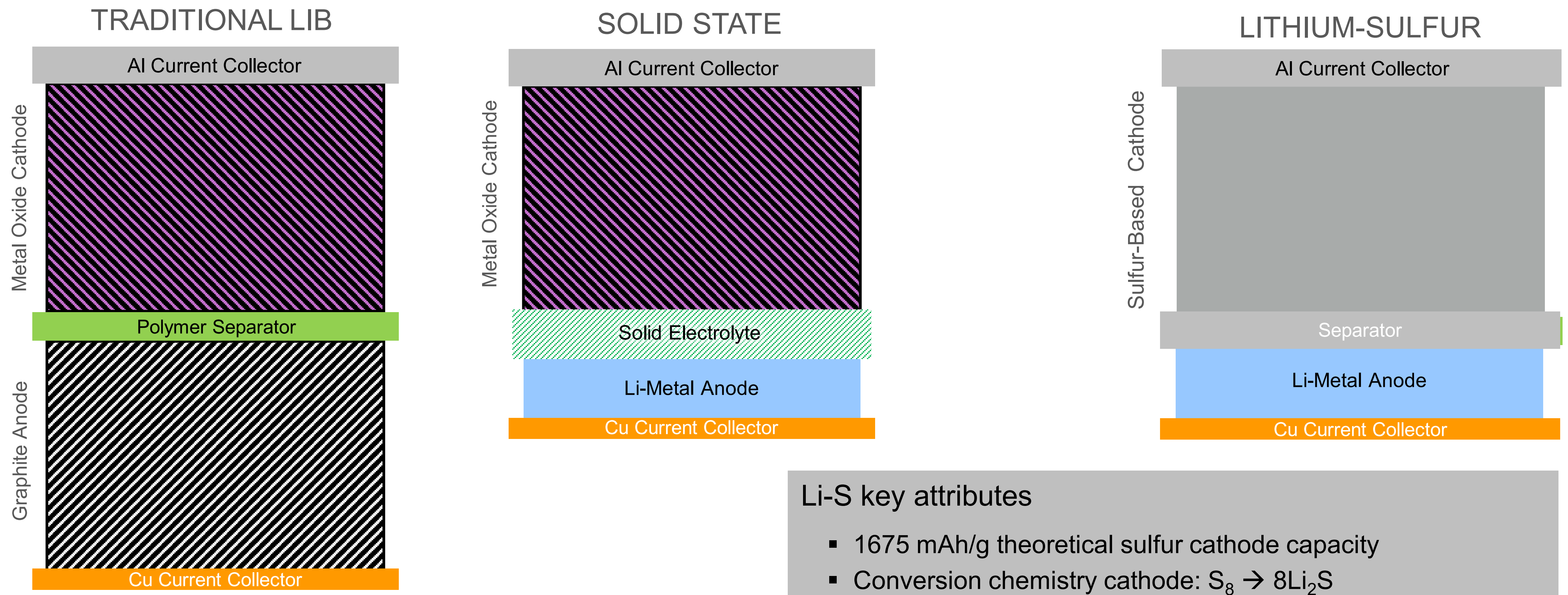
LI-S CELLS : DISTINCTIVE ATTRIBUTES AND HISTORIC CHALLENGES



Li-S key attributes

- 1675 mAh/g theoretical sulfur cathode capacity
- Conversion chemistry cathode: $S_8 \rightarrow 8Li_2S$
- Li metal anode is stripped and plated

Li-S historic challenges

- Polysulfide shuttle → Less than 100 cycles (typical)
- Sulfur is an insulator → Slow charge/discharge rates (C/10)
- Li metal degradation → Less than 100 cycles (typical)

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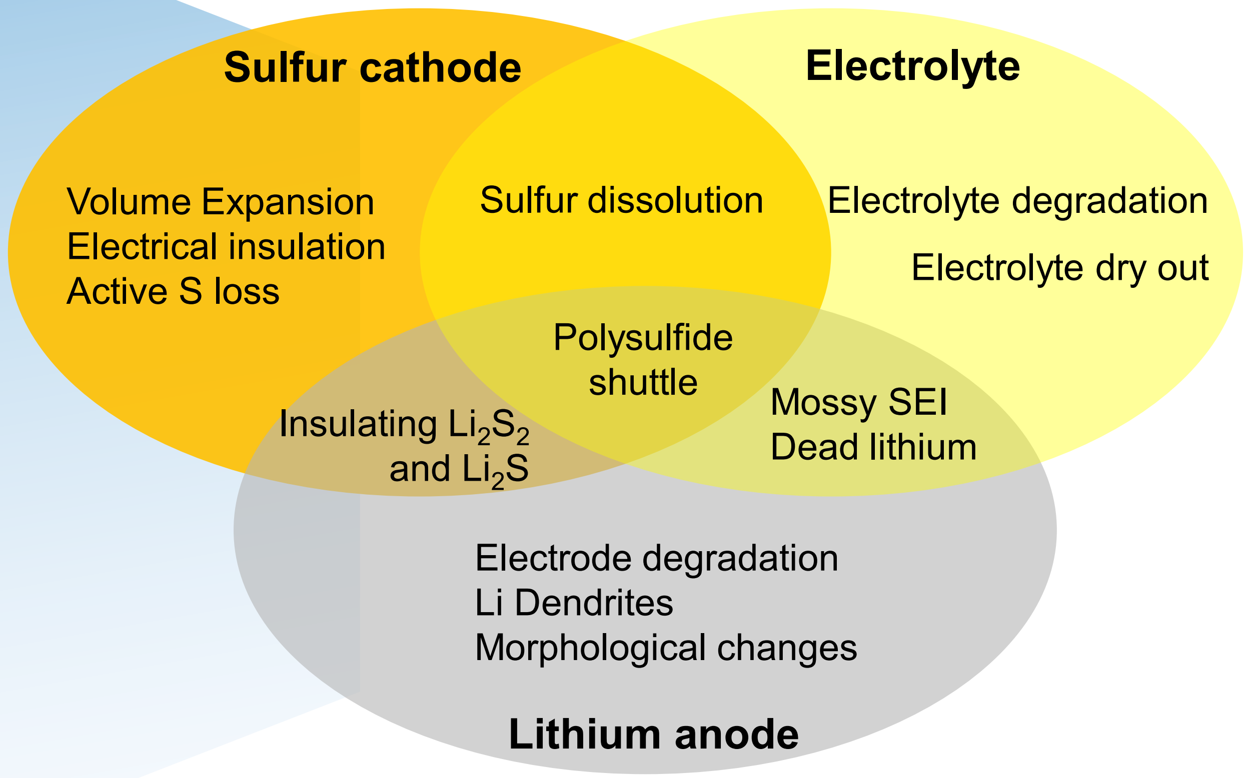
ADDRESSING ALL ASPECTS OF LITHIUM-SULFUR CELL DEGRADATION

Lyten Solutions

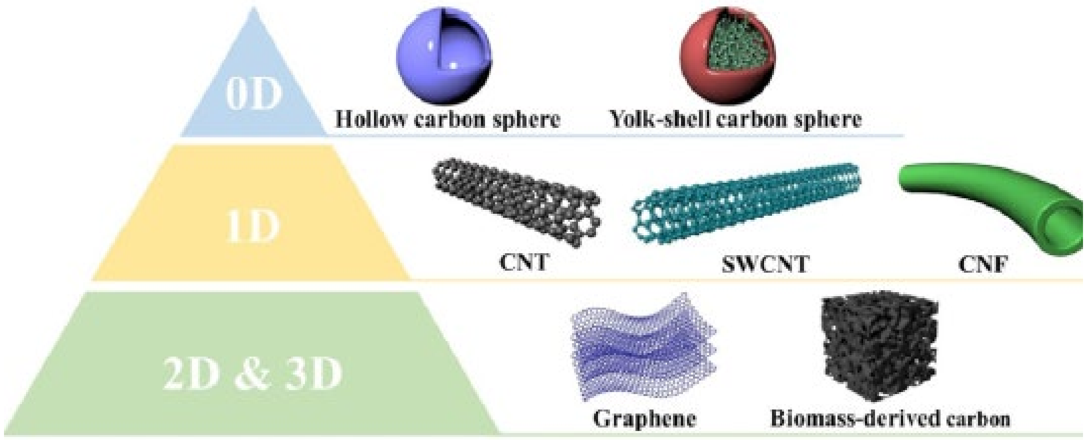
- 3D Graphene Cathode
- Stabilized Anode (composite)
- Proprietary Electrolyte
- Protective Coatings
- Charging Algorithms
- Catalysts
- Customized Separator

Lithium-Sulfur Cell Degradation Mechanisms

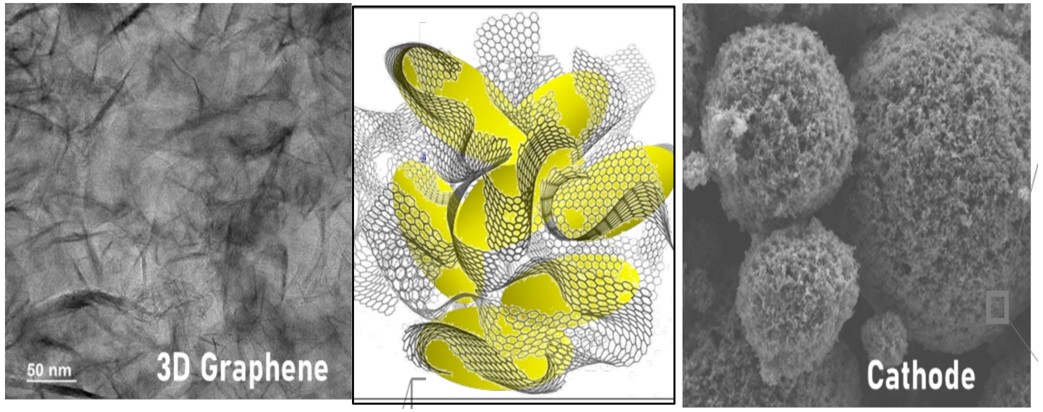


LYTEN'S UNIQUE 3D GRAPHENE

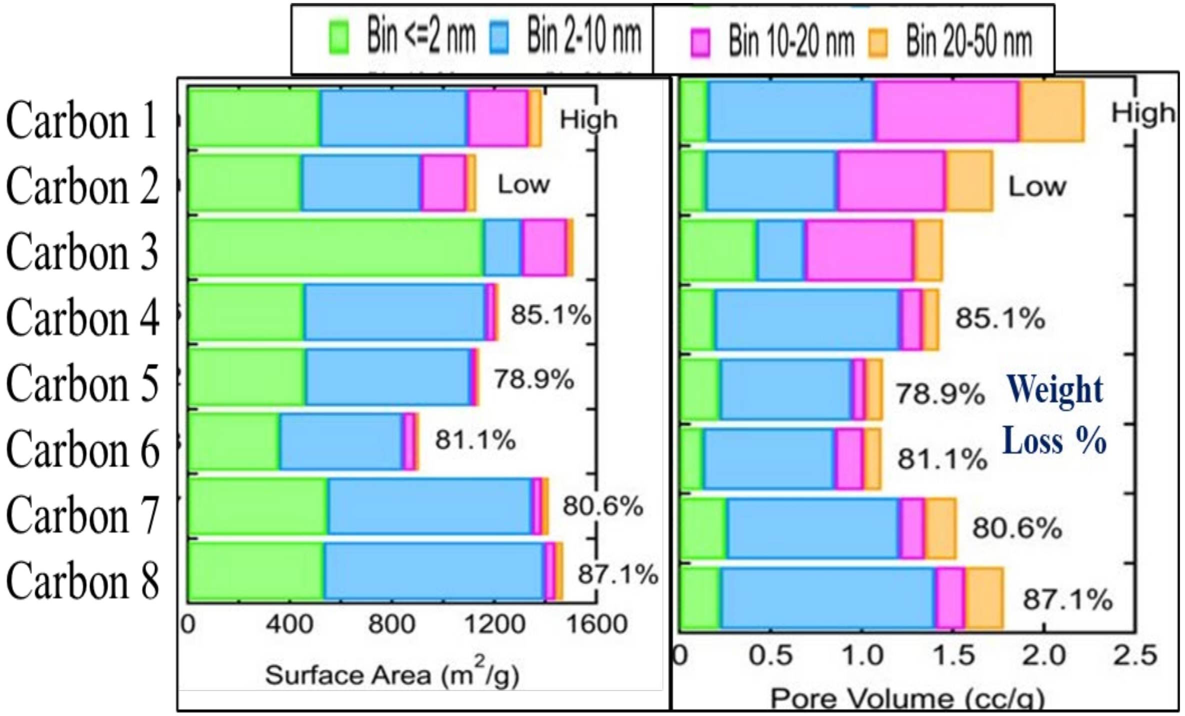
Porous Carbon Hosts



Lyten's 3D Graphene as Sulfur Host



Lyten's 3D Graphene Tunability



Morphological features of eight different carbons for example with the weight loss from TGA

Credit: Jyotsna Iyer et al

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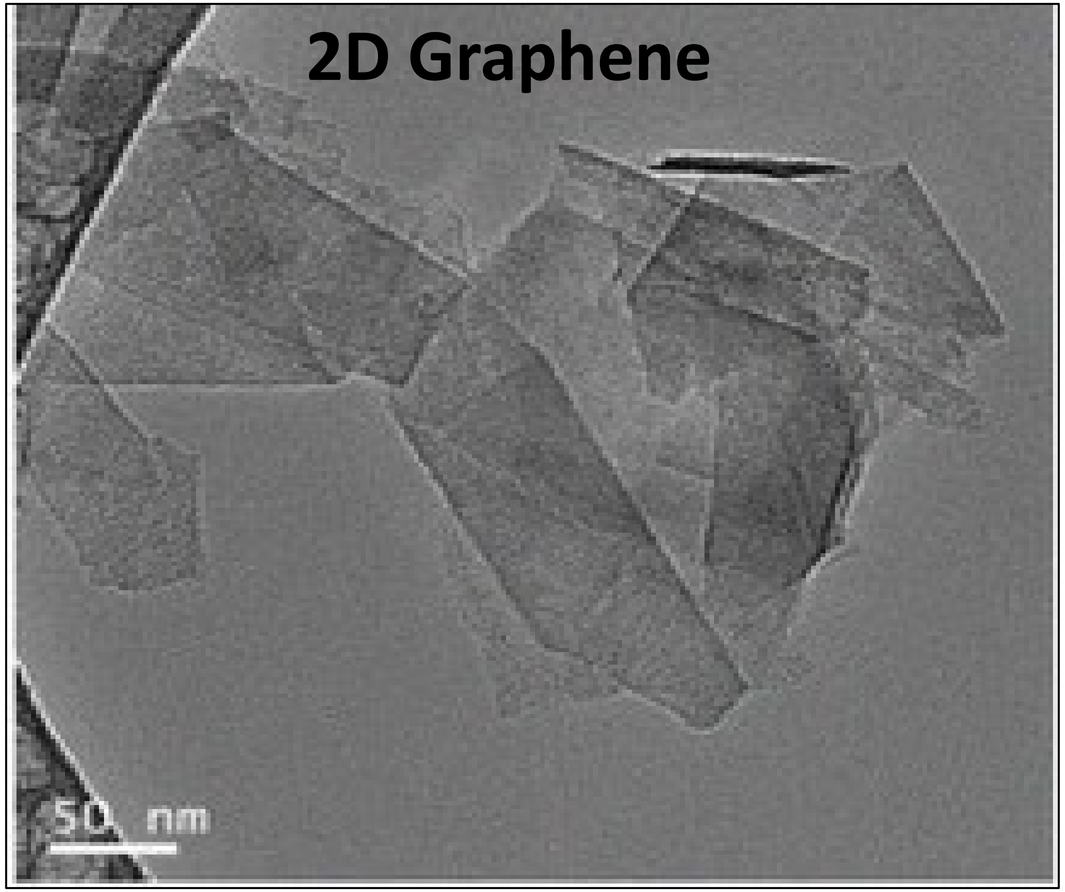
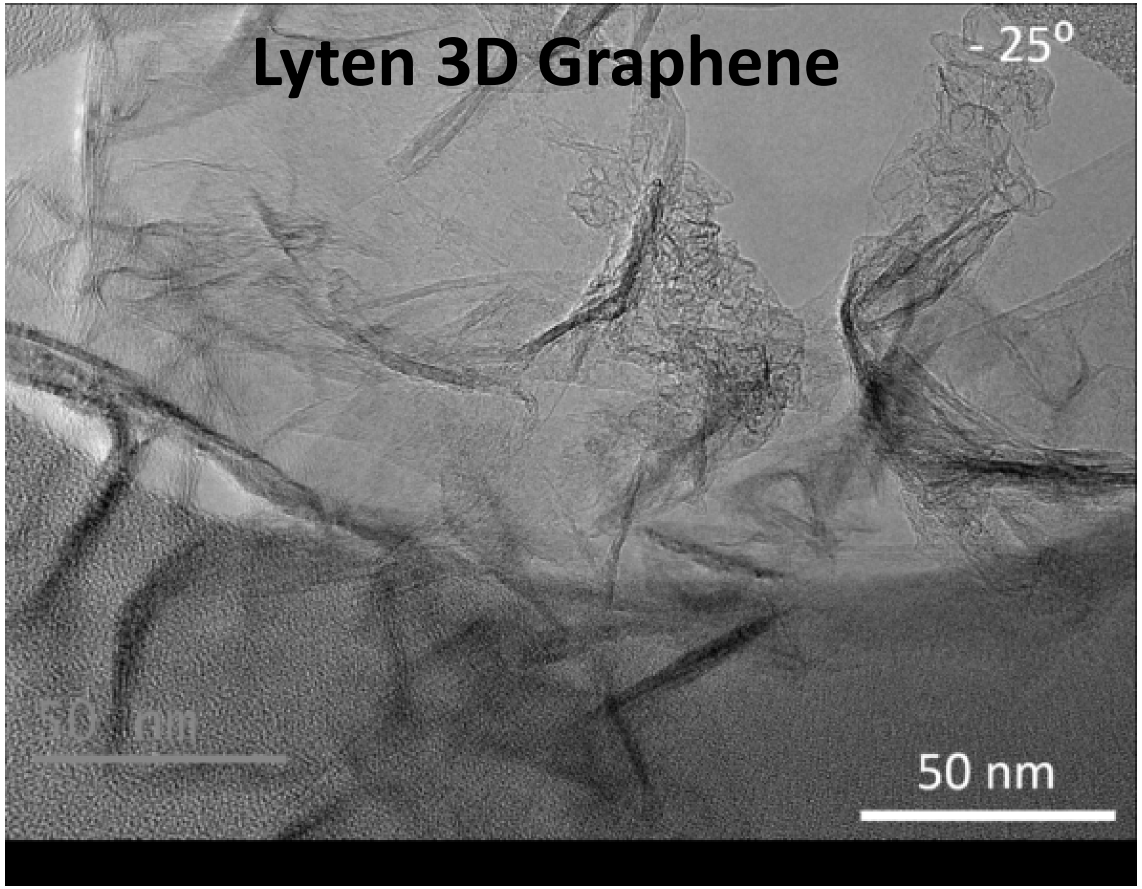
LYTEN TUNABLE 3D GRAPHENE™: THE INNOVATION ENGINE

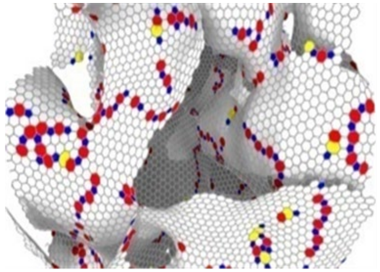
Tunable Pore Structure for Revolutionary Electrode Performance





3D Structure designed to be dramatically more reactive than historic (2D) graphene

Credit: Peggy Hines et al



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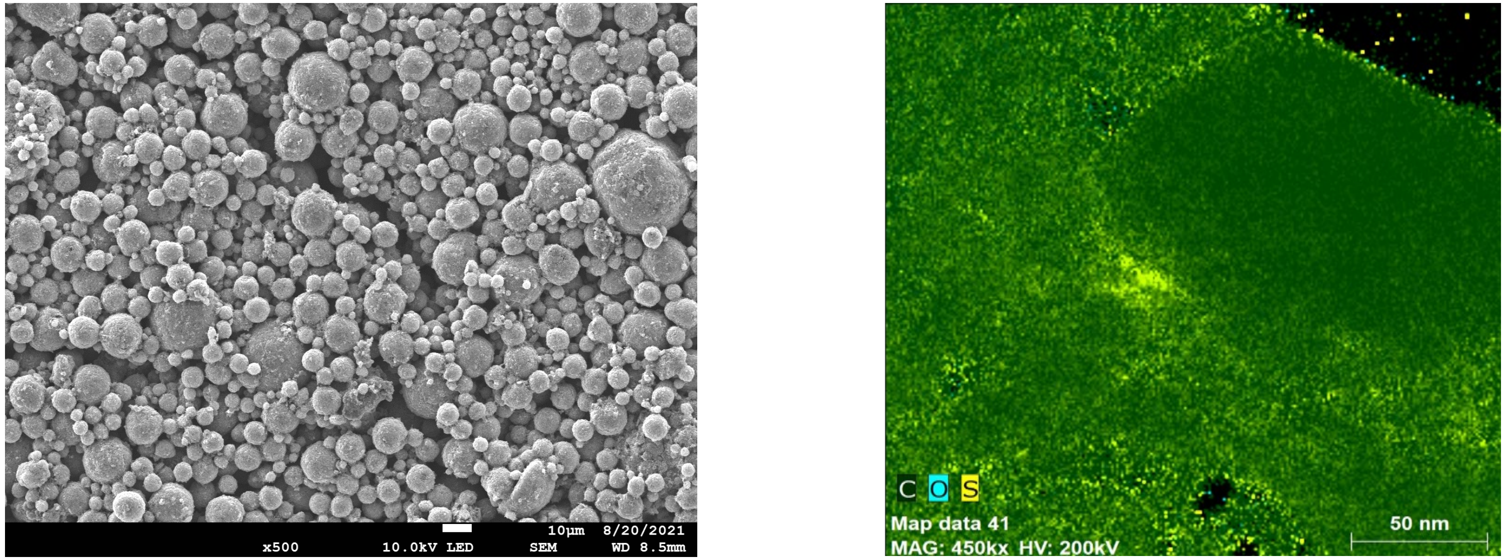
LYTEN 3D GRAPHENE-SULFUR CATHODE DEVELOPMENT

Key Advantages

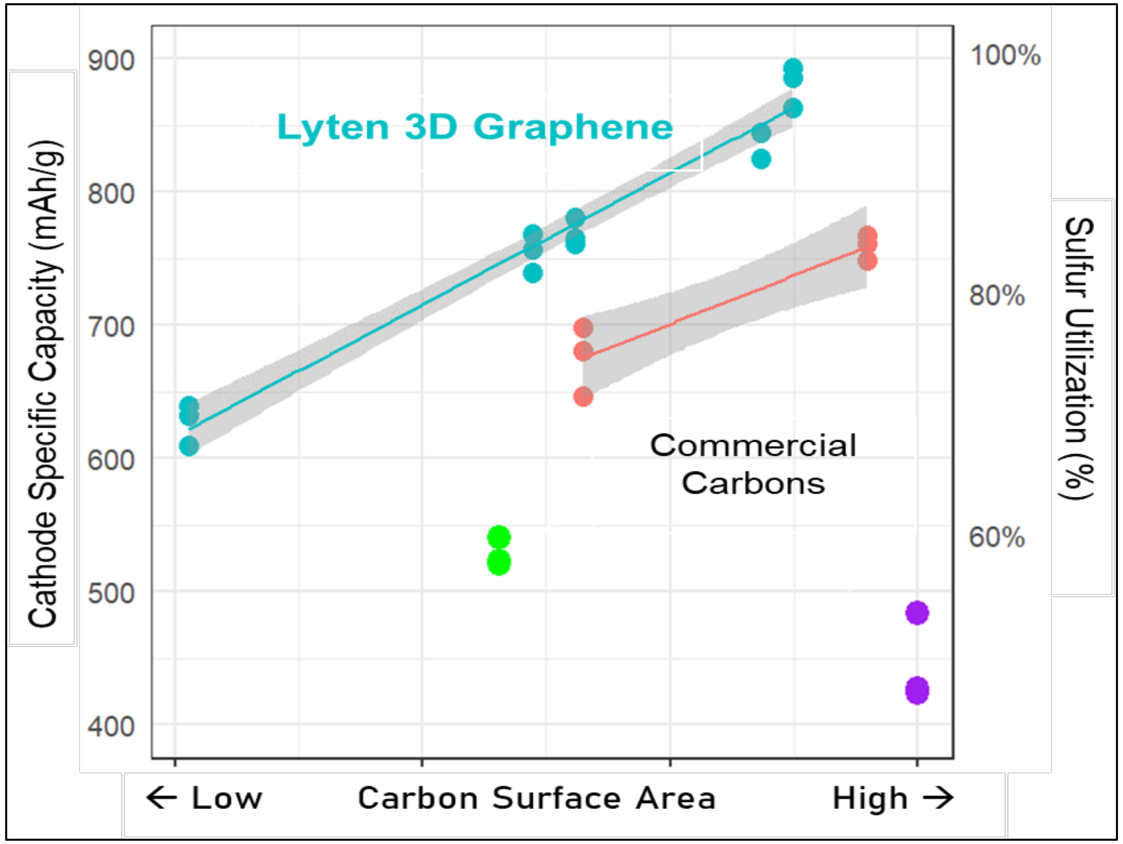
- Could be tuned to have optimum surface area, pore size, and pore distribution through process controls. Tap density of 3D graphene particles is also tunable.
  - Morphology and chemical environment of 3D graphene controls the sulfur cathode performance.
- Could be doped with aliovalent elements and be functionalized for enhanced sulfur affinity and kinetics
- Scalable process
- Outperforms high surface area commercial carbons



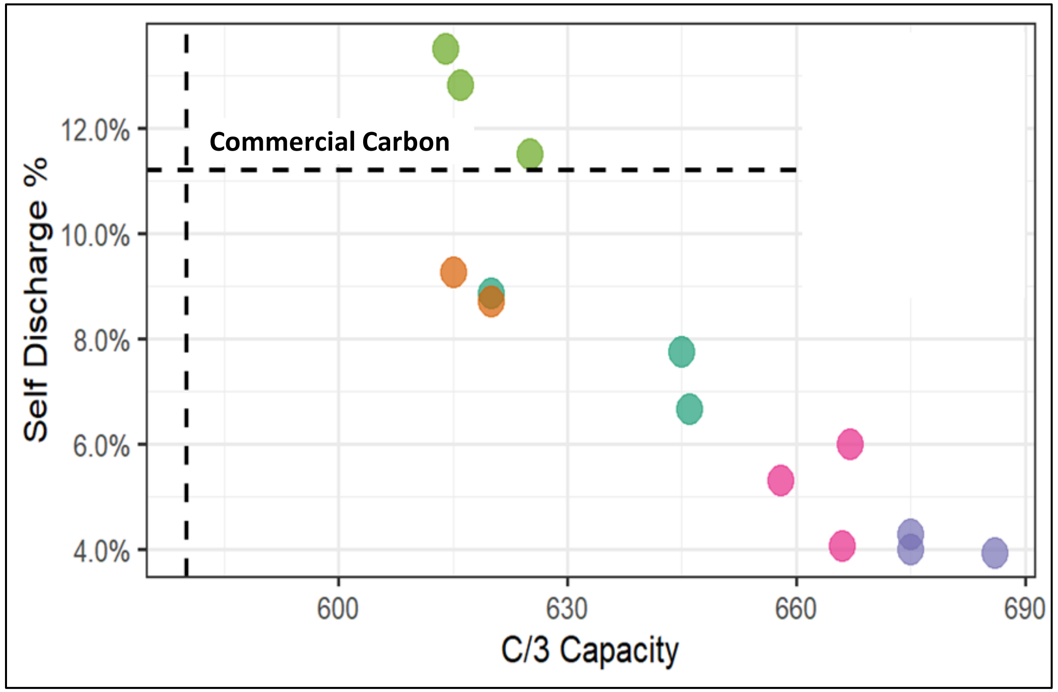
3DG-S composite powder and uniform distribution of sulfur from SEM_EDS (right)

LYTEN 3D GRAPHENE DEVELOPMENT

Capacity and S Utilization @C/20



Self-discharge @C/20

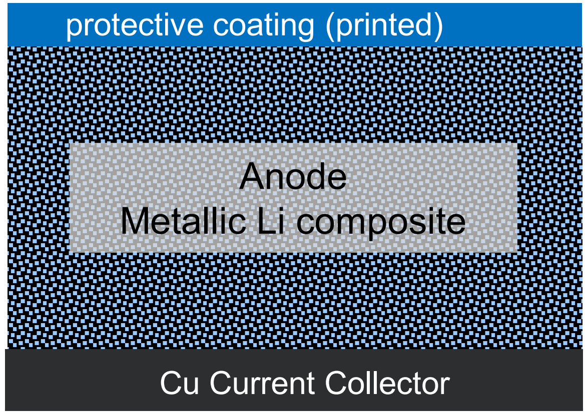


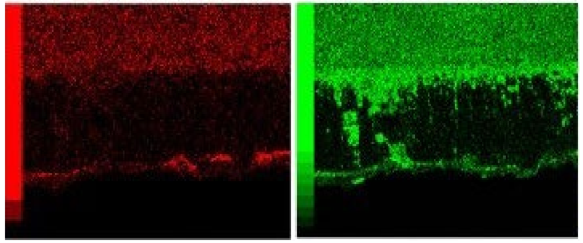
- Lyten 3DGraphene™ shows superior performance over best available commercial carbon
- Developed rapid screening protocols to facilitate the tunability of our material to quickly drive improved performance.

Credit: Anurag Kumar et al

OPTIMIZATION OF THE ANODE DESIGN FOR IMPROVING CYCLE LIFE

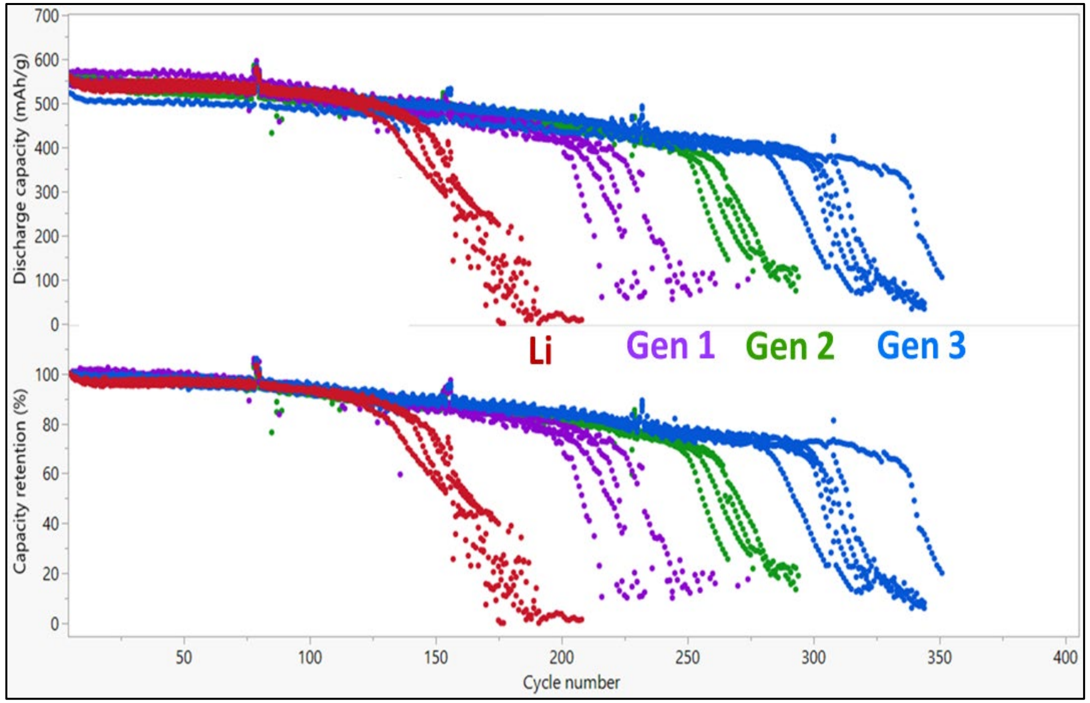
Schematic of Lyten Anode



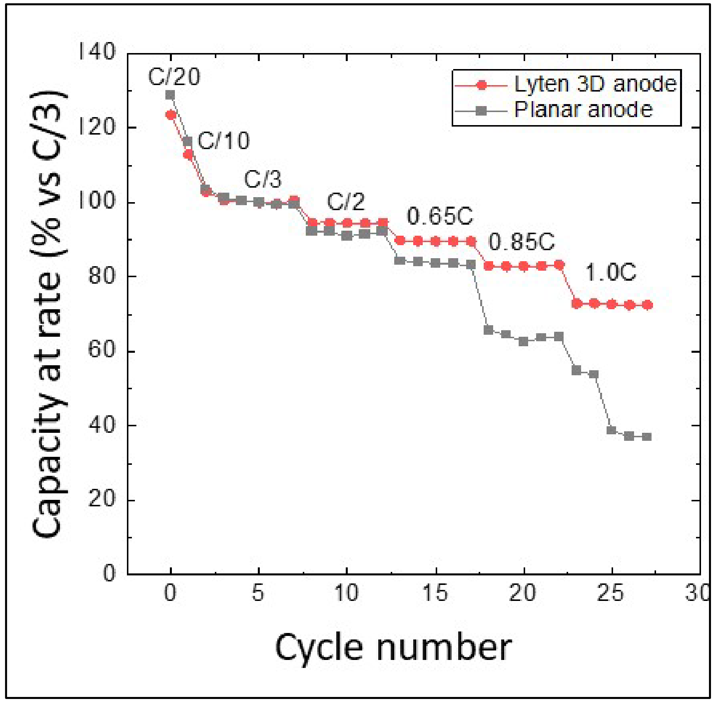


SEM / EDS of Anode + Coatings

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



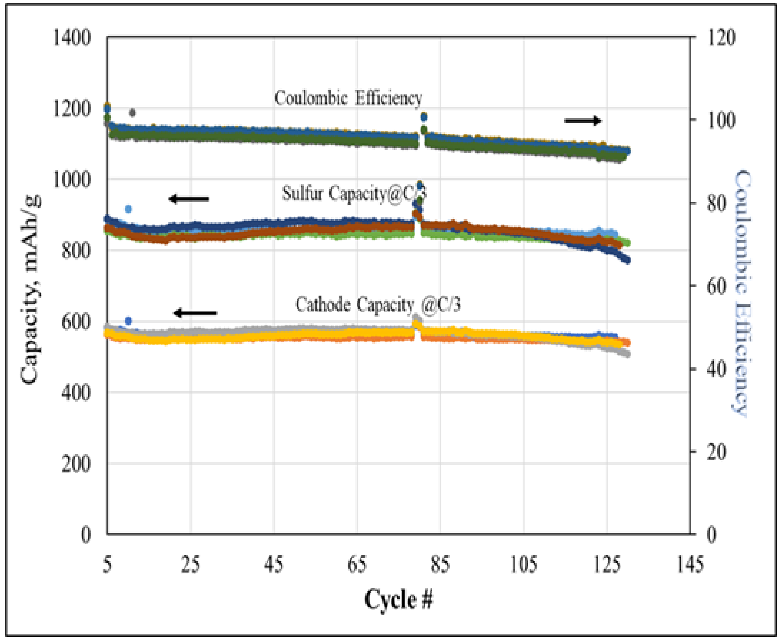
High-rate Capability with 3D Anodes



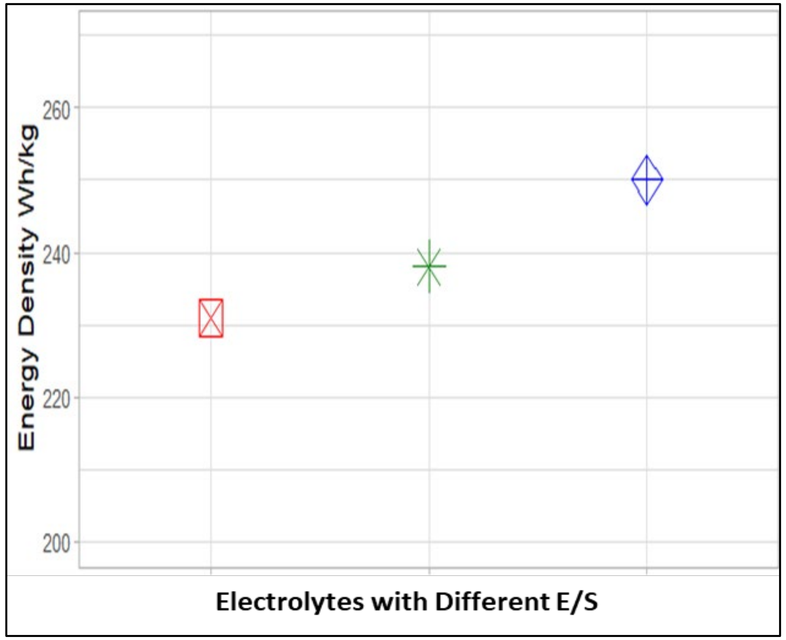
- Composite anode with protective coating (printed) improves cycle life and the 3D designs improve rate

Credit: Yongtao Meng et al

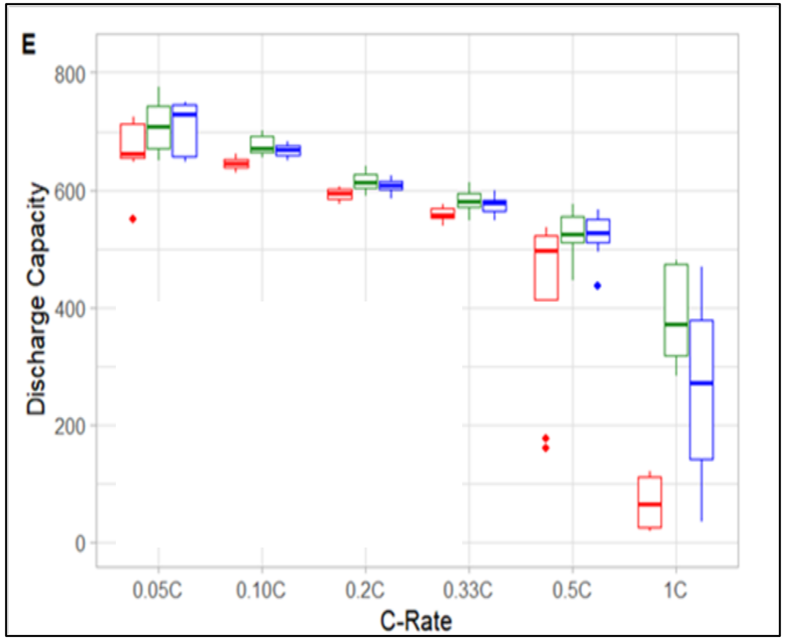
Gen1 Electrolyte with Gen 1 Anode



Electrolytes for Improving Wh/kg



Electrolytes for High-rate Capability



- Electrolyte has dual and conflicting role: i) Stable towards the anode and ii) Support sulfur kinetics (solid-liquid-solid reaction)
- Evaluated several formulations and optimized the electrolyte composition in terms of solvents, salts, redox catalysts and also flame-retardant additives (not shown here).
- Semi-solid/solid electrolytes are being explored.

Credit: Babu Ganguli et al

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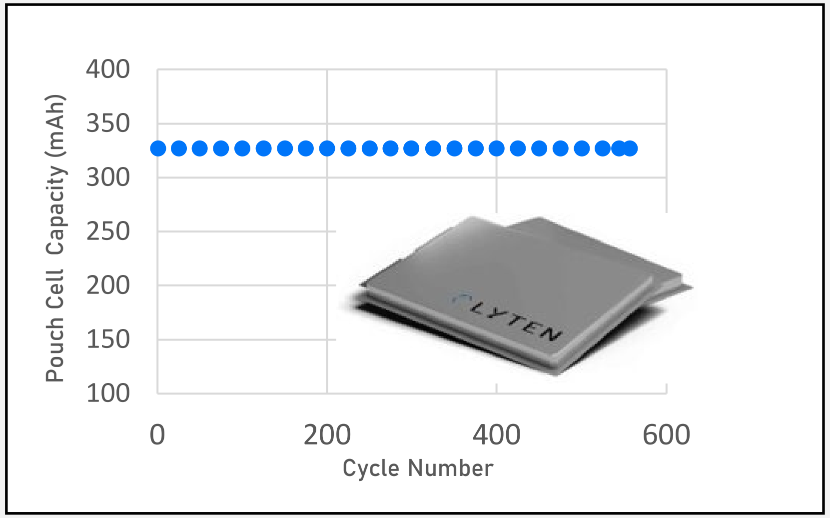
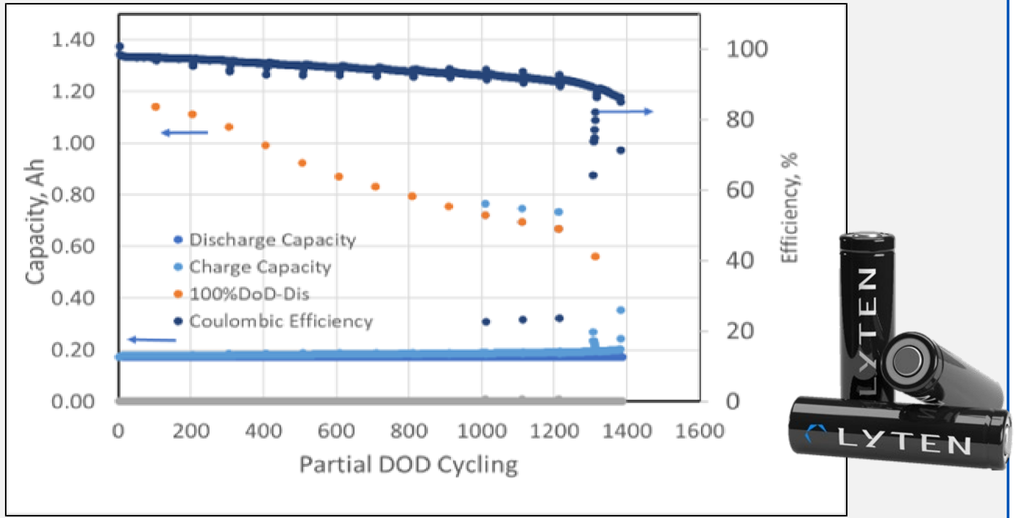
ELECTROCHEMICAL PERFORMANCE: PARTIAL DOD CYCLING (LEO)

Historical
~ 75 Wh/kg cells

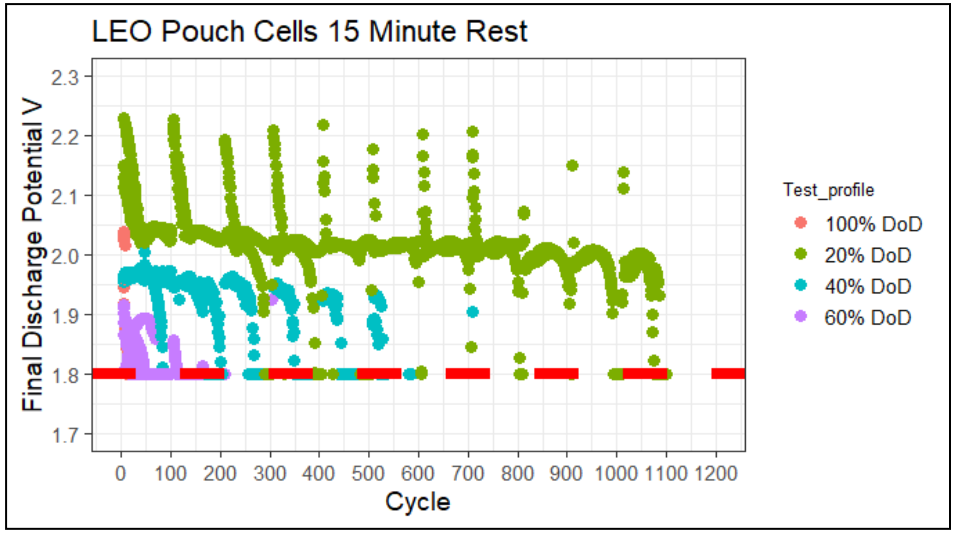
Lyten's 1st Gen pouch cell at 40% DOD LEO Protocol
(moderate sulfur loading, high E/S, low anode current density)

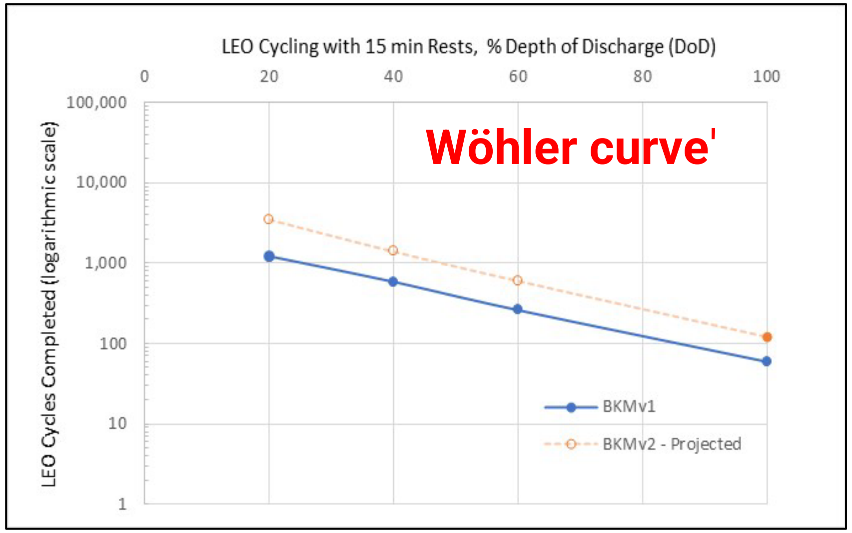


Lyten's 1st Gen 18650 cells at 20-40% DOD
(moderate sulfur loading, moderate E/S, low anode current density)



2022 Cells
~200 Wh/kg cells





Credit: Brandan Taing et al

SUMMARY OF PERFORMANCE IN PROTOTYPE CELLS

18650cells

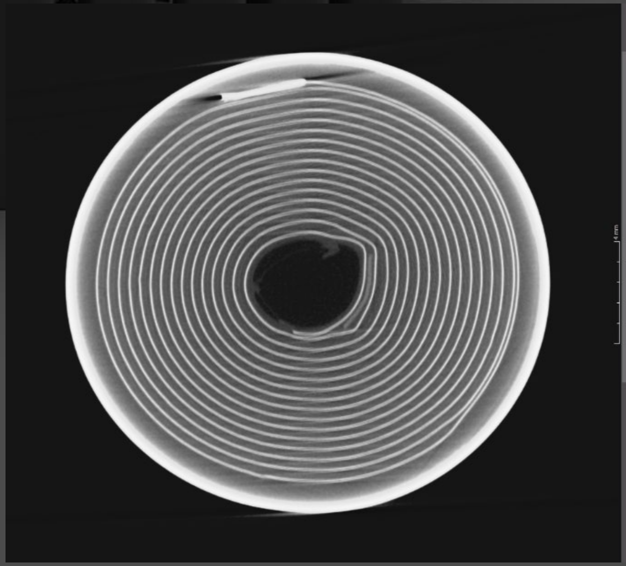
Multi-layer Pouch (MLP) cells

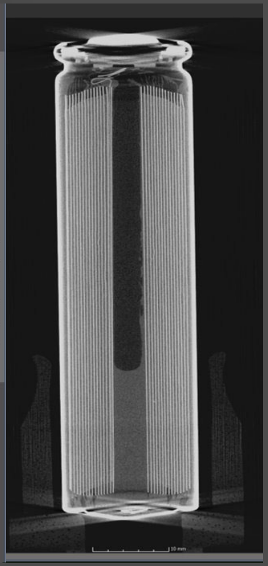
Performance metric	Performance of small engineering cell formats	
	Q4 2022	Q1 2023
Capacity, C/3 rate, 25 °C **(Ah)**	1.2	1.4
Specific Energy, C/3 rate, 25 °C **(Wh/kg)**	225	270
Volumetric Energy Density, C/3 rate, 25 °C **(Wh/L)**	375	400
Cell Voltage, nominal, 25 °C **(V)**	2.1	2.1
Specific Power, 10 sec., 2C, 25 °C **(W/kg)**	700 W/kg	800 W/kg
# Cycles	~150 Full DOD C/3 symmetric ~600 50% DOD (LEO protocol) 1200 cycles at 20% DOD	In progress

Manufacturing | Pilot

Capabilities:

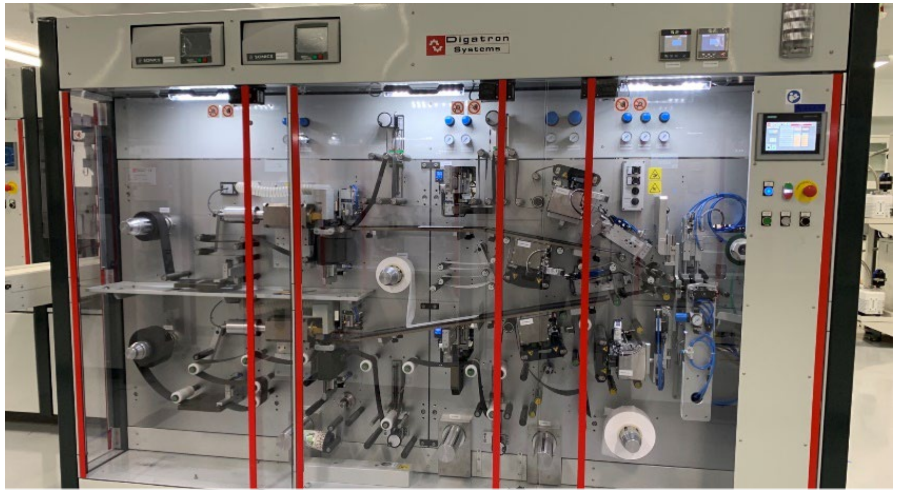
- Name Plate capacity of 200,000 total cells a year or 2 MWh
- Capable of both Cylindrical and Pouch Cell Formats
- Serve as test bed for Li-S Manufacturing
- Servicing medium to small sized customers such as boutique applications (aerospace, automotive, etc.)





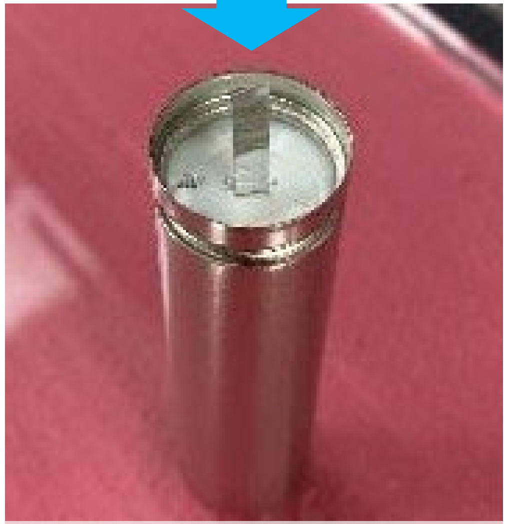
PILOT LINE SUPPORTS POUCH AND CYLINDRICAL CELL ENGINEERING

Lyten pouch cell line

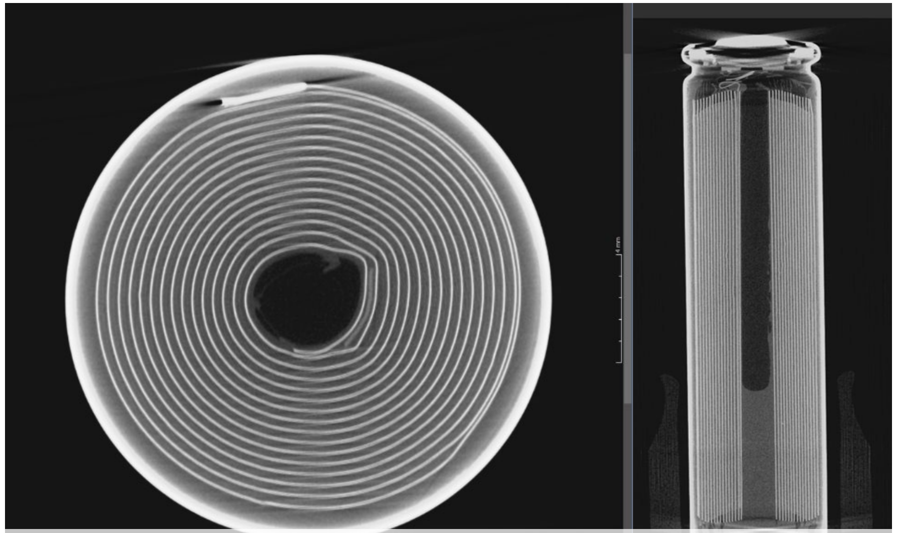


Lyten cylindrical cell line (18650, 2170, 2650, 4680)

Lyten Li-S jelly roll



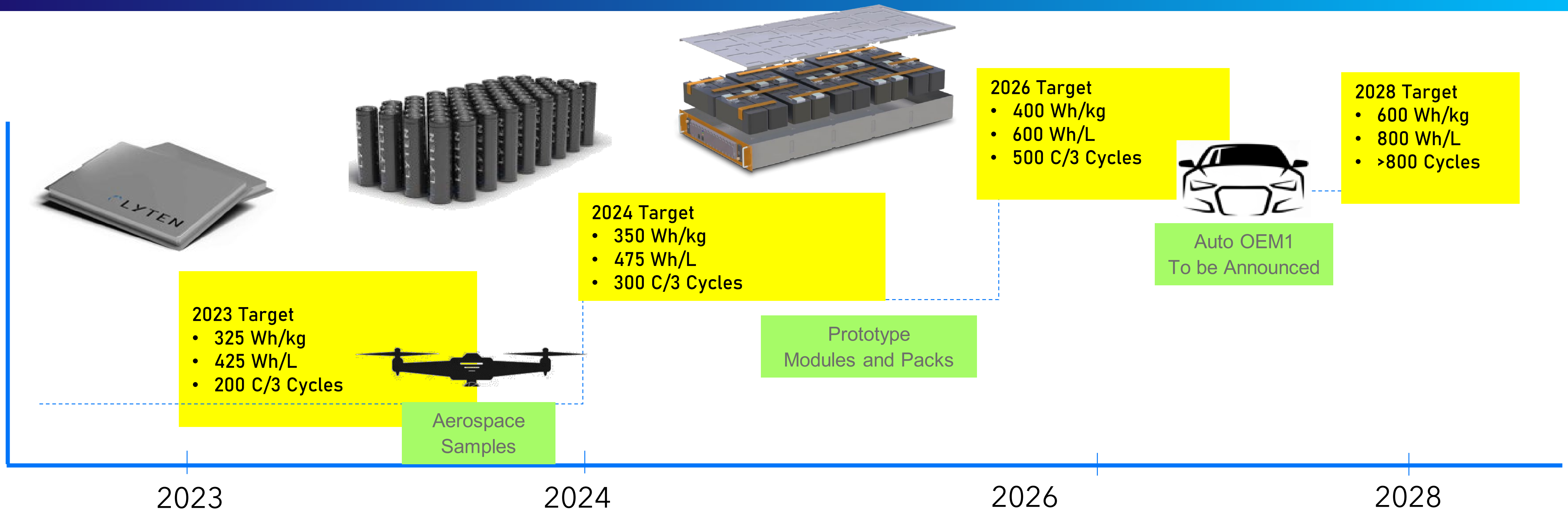
Lyten Li-S 18650 assembly



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)**

LYTEN LI-S CELL PERFORMANCE AND PRODUCTION ROADMAP



Scale	**Low volume**	**Low volume** San Jose semi-auto pilot line (2MWh)	**Medium volume production** Small Gigafactory (1-2 GWh)	**High volume production** First Large Gigafactory
TRL	**3 - 4**	**5 – 6**	**7 – 8**	**8 - 9**
Customers	Commercial samples Auto OEM A-sample	Select commercial Samples Auto OEM A, B-sample Commercial aerospace samples	Targeted commercial customers Auto OEM A, B, & C-samples EVTOL customers	Targeted customers Auto OEM customers EVTOL customers

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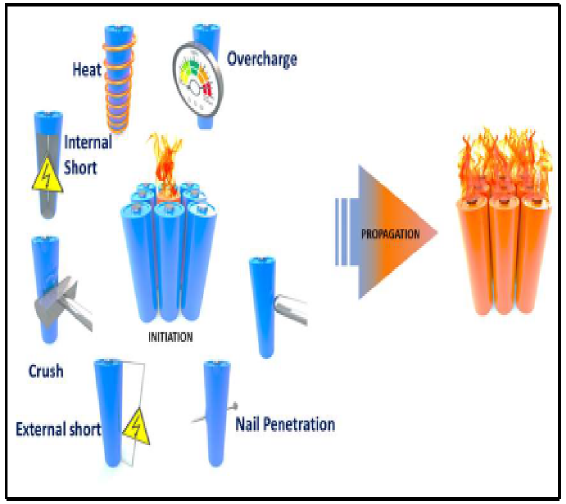
Li-Ion Cells – Thermal Runaway and Thermal Propagation

Li-ion cells can experience thermal runaway during
- Overheat
- Overcharge
- Nail penetration
- Crush test
- External short
- Internal short

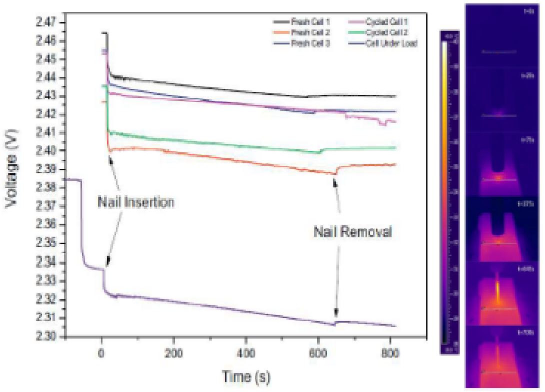
Cells may experience sidewall rupture during failure

Thermal runaway failure can propagate from cell to cell and to the entire battery



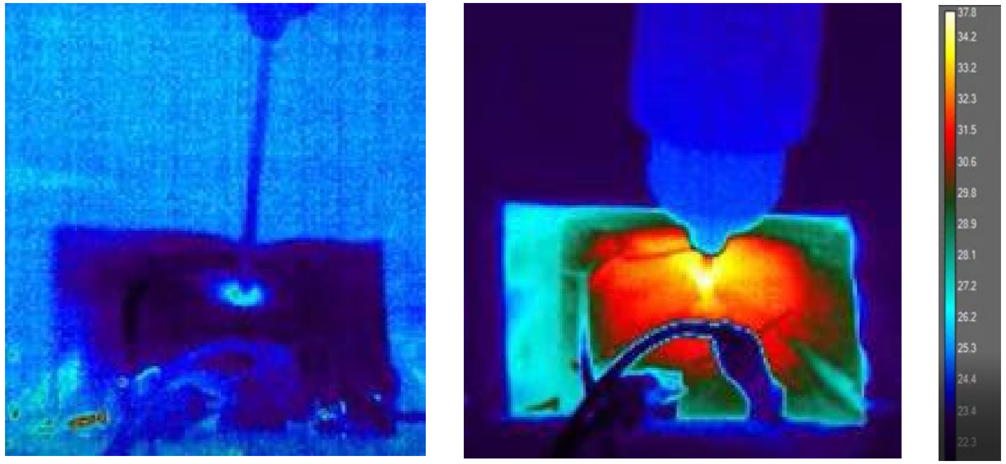
Nail Penetration on 16 Ah Li-S cells

Li-S cells tolerant to nail penetration
- Cells continued to provide current during and for a short period after penetration.
- Mild temperature rise approximately 5–10°C,
- No flames, smoke or charring were evident, unlike in Li-ion cells.



I. Hunt, Y. Patel, M. Szczygielski, L. Kabacik, G. J. Offer, J. Energy Storage 2 (2015) 25–29

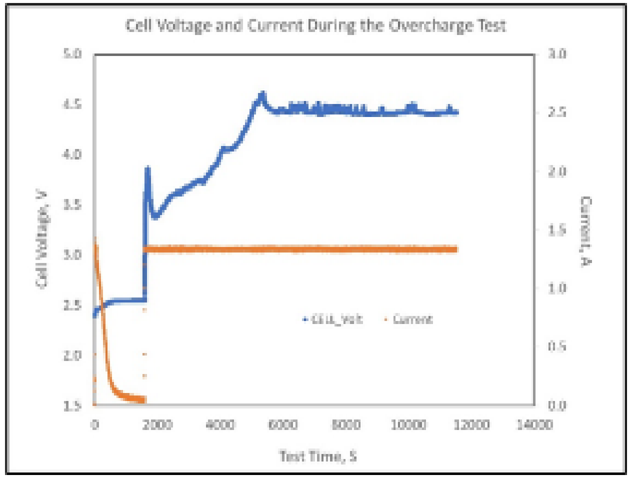
Lyten Li-S Pouch Cells

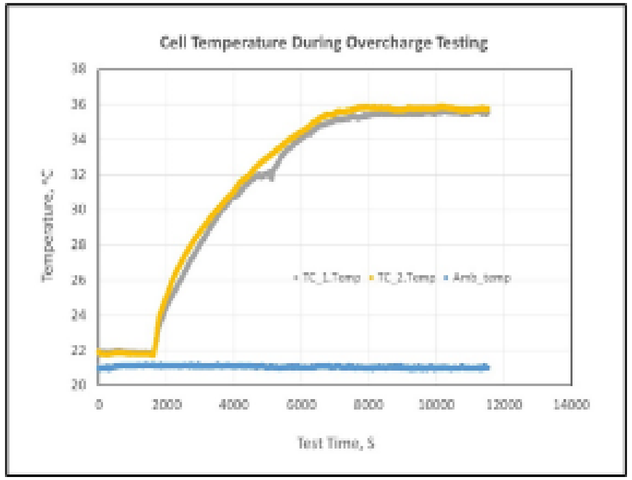


Nail penetration test shows no thermal runaway[1]

- Temperature rose by about 10°C. More interestingly, the cell was able to continue to provide current during and for a short period after penetration.
- 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.

Overcharge of Lyten Li-S Pouch Cells

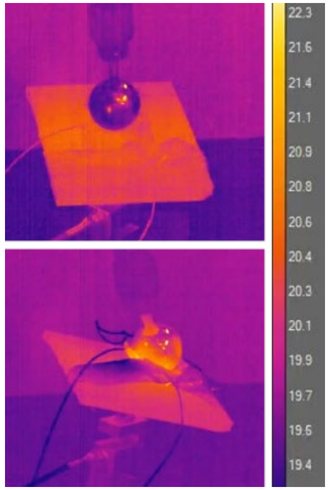


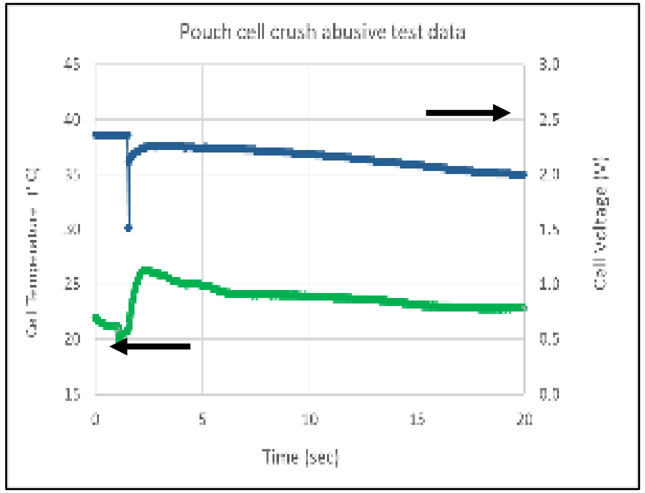


Overcharge test (5V, 4 h) shows no thermal event[1], only 10 °C increase

- During overcharge, the cell voltage rose to and plateaued at 4.5 V and the temperature increased by ~12°C without any flame, charring rupture.
- Once again, this behavior is consistent with the observations of Huang et al. , J. Energy Storage Materials, 30, September 2020, 87-97).
- Attributed to the disproportionation reaction of long chain lithium polysulfides, the inexistence of oxygen evolution in cathode and the low boiling point of electrolyte, which make the Li-S pouch cells safer during overcharge tests.

Crush Test of Lyten Li-S Pouch Cells





Conditions:

- crushing head: 2” sphere
- Speed: 2mm/s
- Peak crushing force: 2000 lb.

Results:

- No significant temperature rise, or voltage drop
- No gassing or swelling

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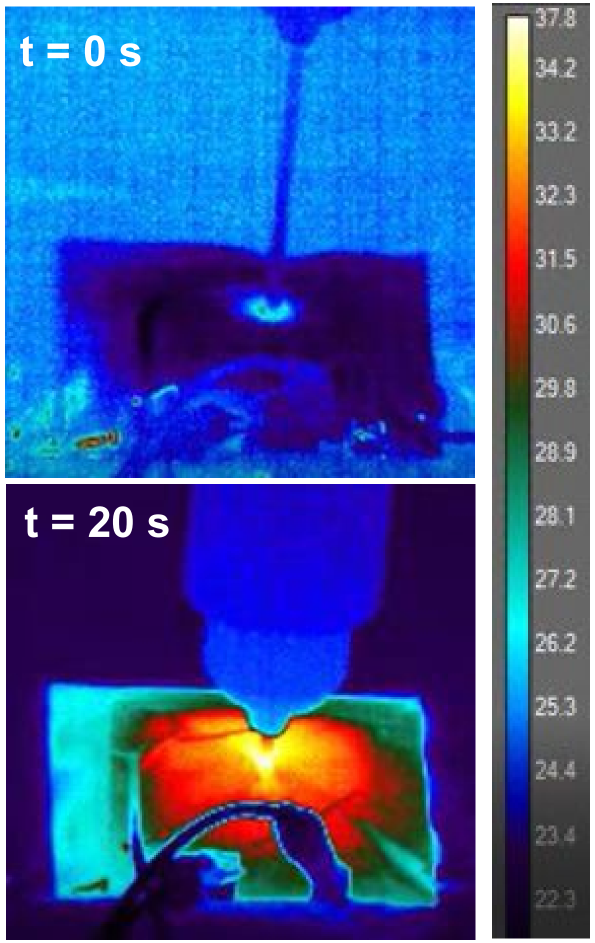
SAFETY: TESTS AT INDEPENDENT LAB SHOW CELL ABUSE TOLERANCE

2nd Round

Nail Penetration Test

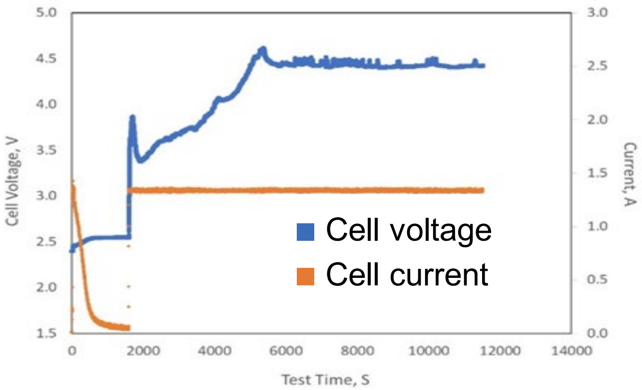
IR camera images

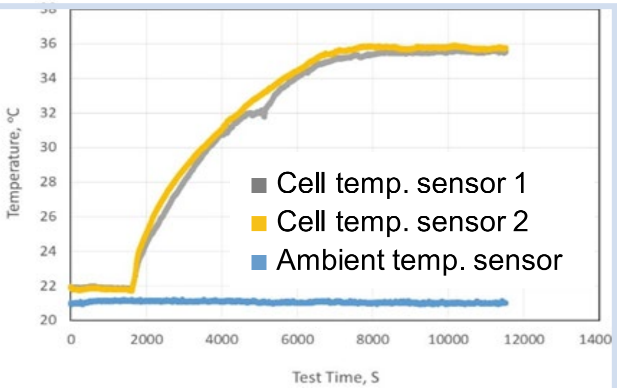


Electrical	External Short	Rapid drop to 0V	pouch	1.90 Ah	No damage/fire, T_{max} = 26 °C
			18650	1.03 Ah	No damage/fire, T_{max} = 37 °C
	Over charge	1C Charge until > 200% SoC	pouch	1.87 Ah	No damage/fire, T_{max} = 32 °C
			18650	1.36 Ah	No damage/fire, T_{max} = 93 °C
	Over discharge	1C Discharge	pouch	1.85 Ah	No damage/fire, T_{max} = 26 °C
			18650	1.24 Ah	No damage/fire, T_{max} = 37 °C
Mechanical	Nail Penetration	3 mm Nail puncture at 10 mm s^{-1}	pouch	1.86 Ah	No damage/fire, T_{max} = 35 °C
			18650	1.43 Ah	No damage/fire, T_{max} = 62 °C
	Ball Crush	51 mm Sphere at 2 mm s^{-1}	pouch	1.75 Ah	No damage/fire, T_{max} = 27 °C

Overcharge Test

Cell voltage, current and temp. vs. time





Lyten is performing additional safety tests on various cell formats with latest formulations

LYTEN

I-S VALUE PROPOSITIONS

LYTEN'S UNIQUE LI-S WILL CREATE A DISTINCTIVE VALUE FOR AN ARRAY OF APPLICATIONS INCLUDING AUTOMOTIVE

LYTEN

Lowest $/Wh	**Replacing Ni-based cathodes with Sulfur lowers 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
Sustainable Supply Chain	**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