JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Lithium Sulfur Batteries for Aerospace and Defense at JHU/APL

Space Power Workshop

Nicholas G. Pavlopoulos, PhD – Energy storage lead
Nicholas.Pavlopoulos@jhuapl.edu

1 May 2025

More Than 80 Years of Research and Development for the Nation

Transformative Innovation and Trusted Technical Leadership

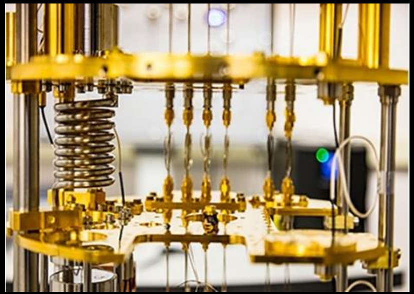

JOHNS HOPKINS
APPLIED PHYSICS LABORATORY
268,000 sq. ft. R&D facility
90,000 sq. ft. of lab spaces
REDD Research and Exploratory Development

Research Facilities

Operational Marine Bio

Additive Manufacturing Center

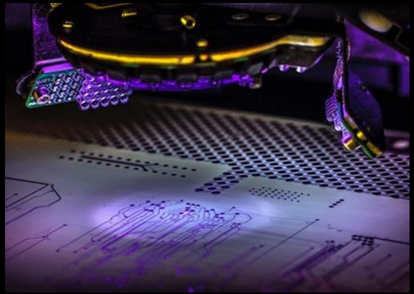
Advanced Optics and Photonics Laboratory



Low Temperature Quantum Device Laboratory

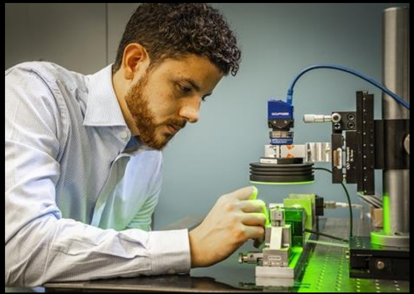
Vertically Accelerated Load Transfer System

Plant Growth Laboratory



Advanced Electrical Fabrication Laboratory

Genome Sequencing Laboratory



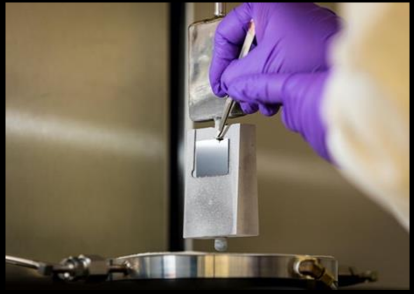
Materials Characterization Facility

Intelligent Systems Center

Materials for Extreme Environments Laboratory

Mechanical Fabrication Laboratory

Energy Storage Materials Laboratory



Semiconductor Thermoelectrics Applications and Research

Applied Battery R&D Facilities and Capabilities

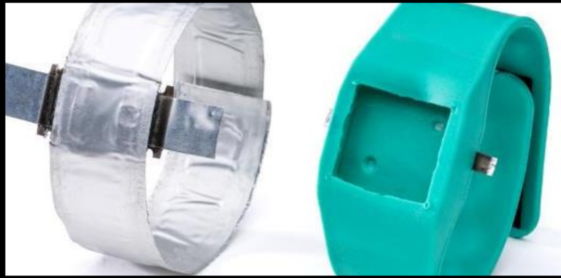
Chemistry and Manufacturing

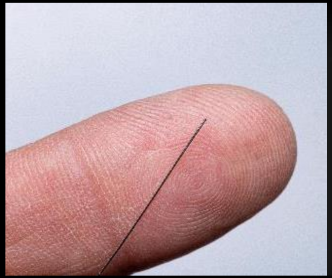




Custom Form Factors



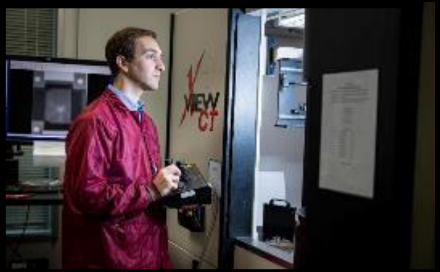




Advanced Testing Capabilities



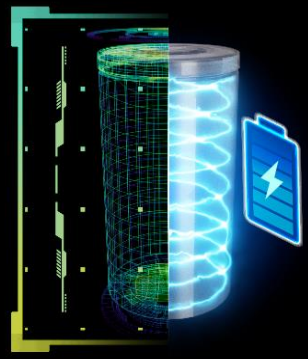




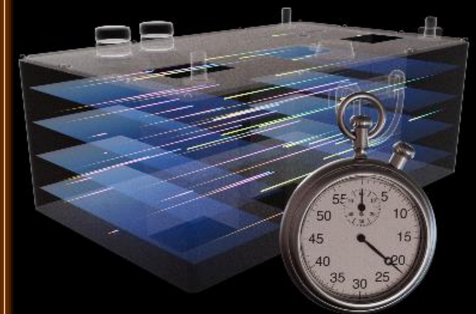
Battery Research Overview

INNOVATION THRUSTS

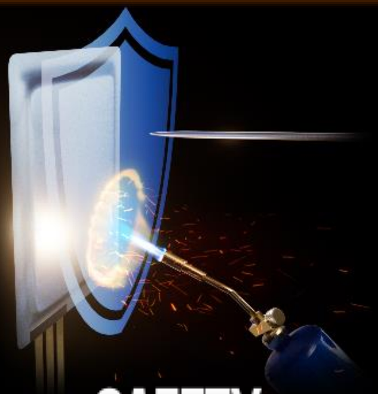
SUPPLY CHAIN



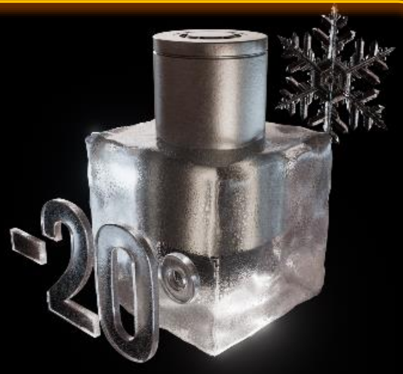
HIGH ENERGY DENSITY



FAST CHARGING



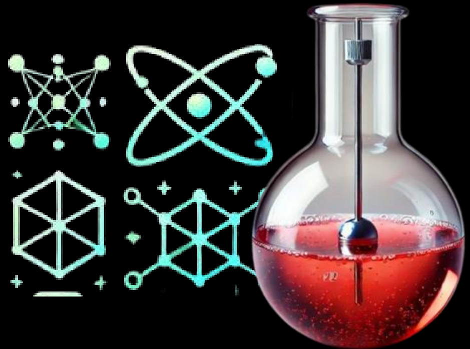
SAFETY



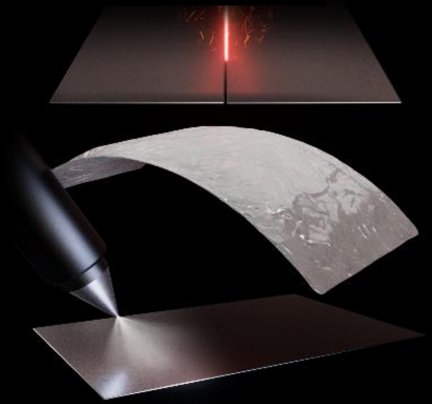
LOW TEMPERATURE

INNOVATION AREAS

INORGANIC CHEMISTRY



ORGANIC CHEMISTRY



PROCESSING & FORM FACTORS

VALIDATION & DERISKING

Powering the Future of DoD

Expeditionary Power

Extreme Environments

Increased Safety

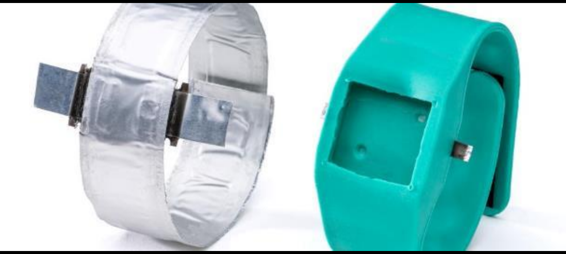
Multiple Battery Types

Energy Logistics

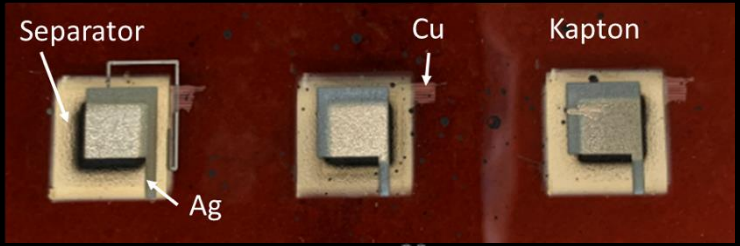
Dual Use

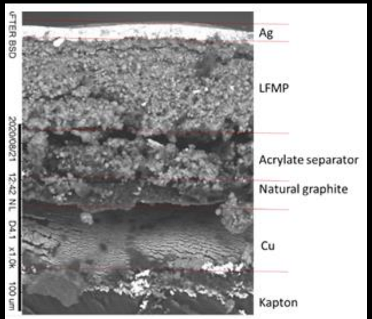
Battery Research at JHU/APL

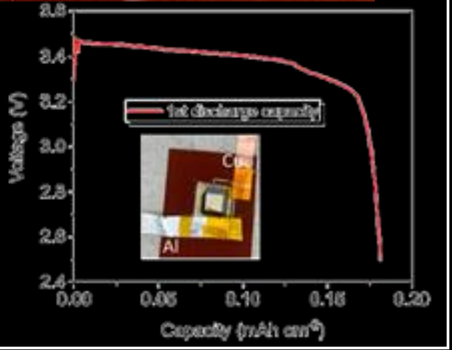
Wearable Batteries



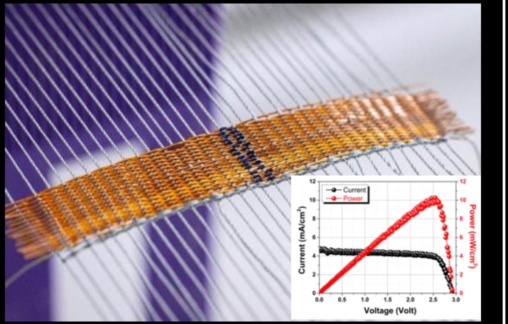
3D Printed Batteries

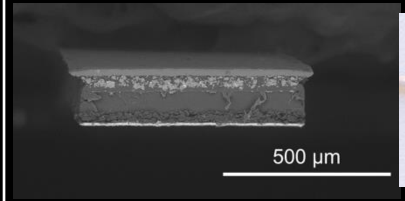


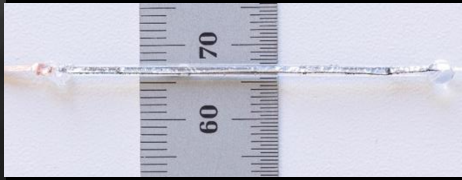




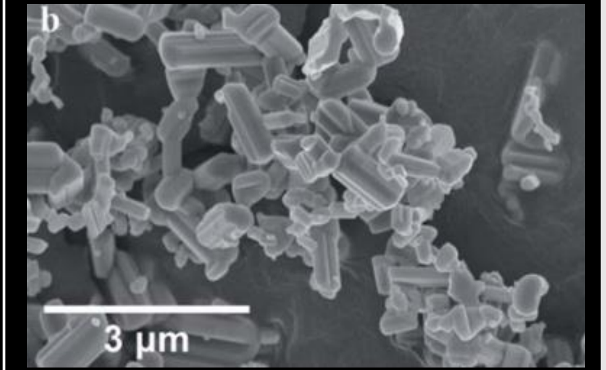
Textile/Fiber Power Sources

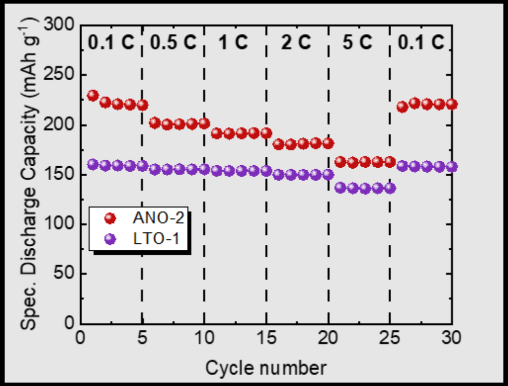


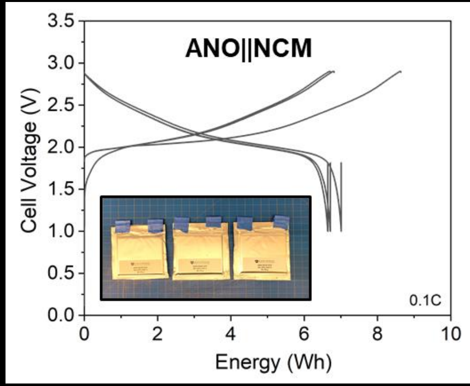




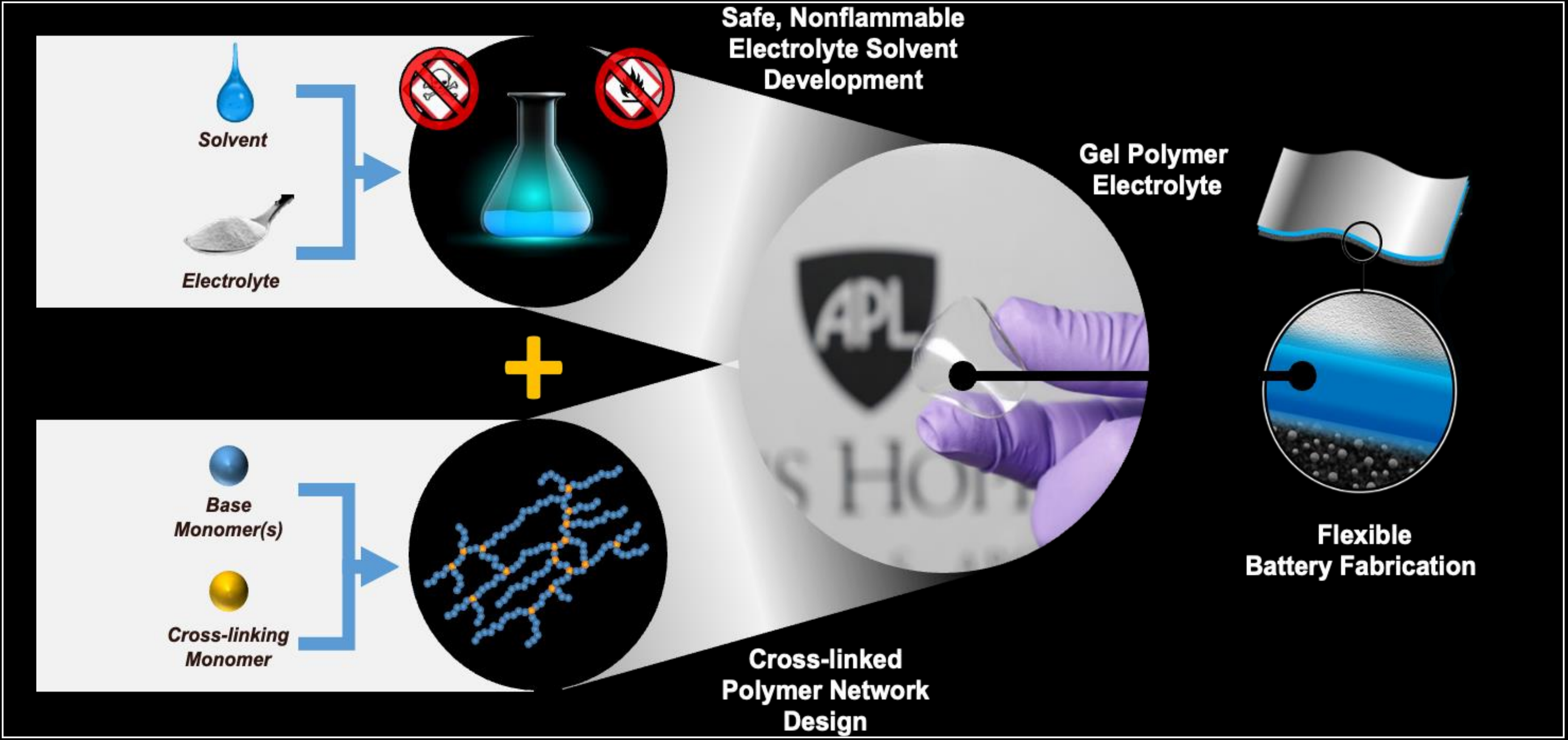
Novel Battery Electrodes





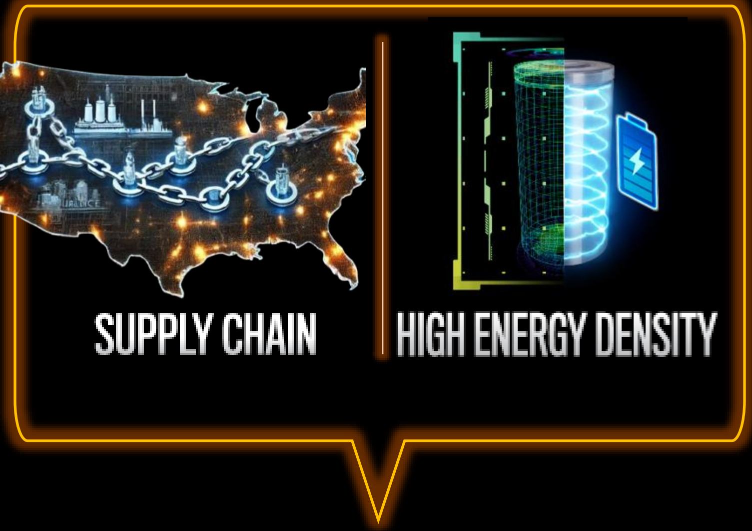


Transforming Battery Safety and Manufacturing

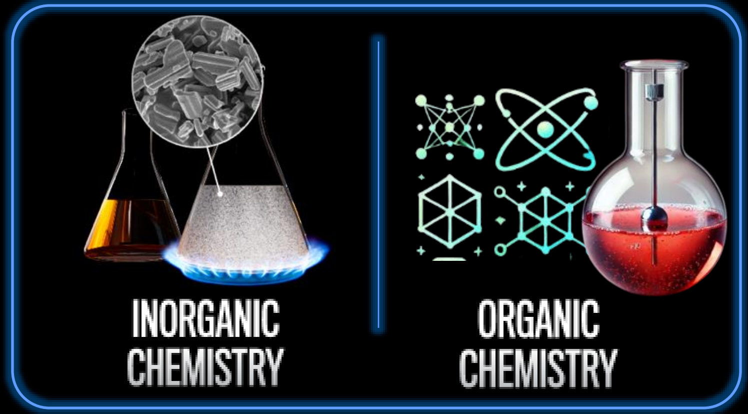


Lithium Sulfur in the Energy Storage Ecosystem

INNOVATION THRUSTS



INNOVATION AREAS



Extreme Environments

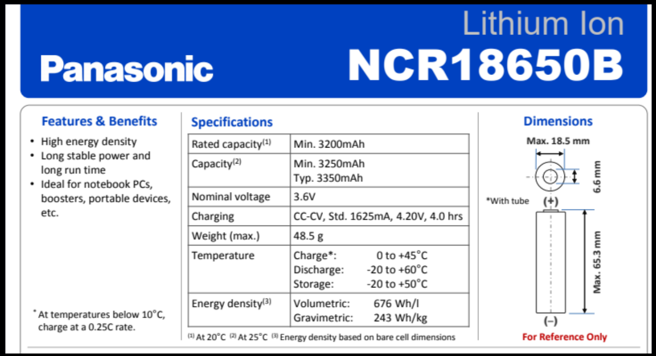
Increased Safety

Energy Logistics

Dual Use

Challenge, Vision, and Proposed Solution

SOA & Challenge



Lithium Ion

Panasonic NCR18650B

Features & Benefits

- High energy density
- Long stable power and long run time
- Ideal for notebook PCs, boosters, portable devices, etc.

* At temperatures below 10°C, charge at a 0.25C rate.

Specifications

Rated capacity(1)	Min. 3200mAh
Capacity(2)	Min. 3250mAh Typ. 3350mAh
Nominal voltage	3.6V
Charging	CC-CV, Std. 1625mA, 4.20V, 4.0 hrs
Weight (max.)	48.5 g
Temperature	Charge*: 0 to +45°C Discharge: -20 to +60°C Storage: -20 to +50°C
Energy density(3)	Volumetric: 676 Wh/l Gravimetric: 243 Wh/kg

(1) At 20°C (2) At 25°C (3) Energy density based on bare cell dimensions

Dimensions

For Reference Only

~240 Wh/kg at 100% DOD

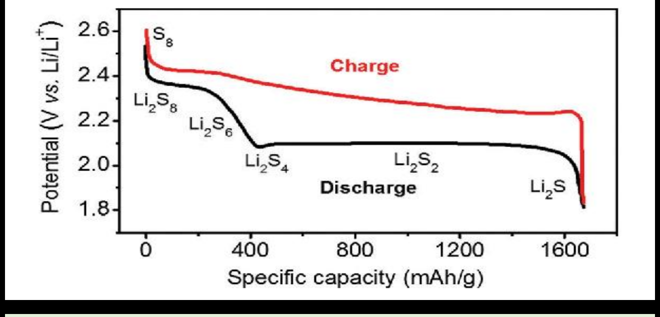
100 Wh/kg @ 40% DOD

48 Wh/kg @ 20% DOD

LIBs are stable for 1000s of cycles, but severely limited energy density at low DOD

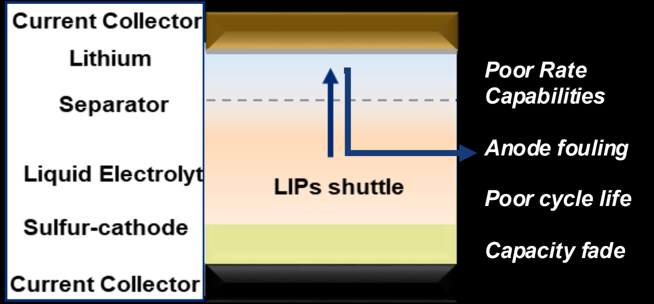
Vision

Benefits: Lithium sulfur affords high energy density at low DOD



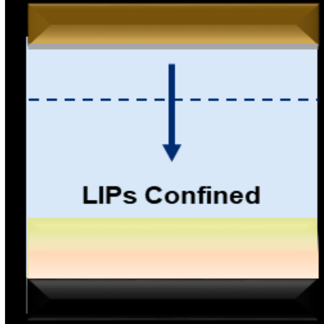
Target: Lithium Sulfur Batteries Optimized for Performance at Full and Low DOD

Challenge: Polysulfide diffusion and volume expansion



Proposed Solution

Chemistry and Processing Improvements to Enable LiS for Space



Additives
Separators
Hybrid Cathodes
Low density CCs

Practical Conditions

- *High cycle life (>100 cycles at full DOD and > 1000 at low DOD)*
- *Limited volume expansion*
- *Supply Chain Secure*
- *High energy density at low DOD*
- *Validate in 100 – 1000 mAh cells under reasonable conditions*

Lithium Sulfur Background: Literature & Leading Solutions

Battery Materials Research (BMR) program: Lithium Sulfur

Technology Status

	S_8		Sulfurized Polymer	Li_2S
	Liquid Electrolyte	Solid Electrolyte	Liquid Electrolyte	Liquid Electrolyte
Lithium Protection Required				
Stack Pressure Needed				
Volume Change				
Polysulfides Dissolution				
Elevated Operating Temperature				
Cycle Life Goal	1000	1000	1000	1000
Specific Energy Goal (Wh/kg)	500	300	300	300

Good Fair Unsatisfactory

Long-term Goal: 500 Wh/kg, 1,000 cycles
Near-term Goal: 275-300 Wh/kg, 1,000 cycles (Low-cost alternative to conventional lithium-ion batteries)

Five 5s: Key parameters required to achieve LiS cells in excess of 500 Wh/kg

Manthiram, EES, 2020.

Outlook

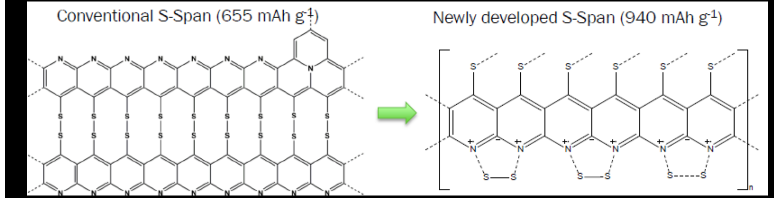
Sulfurized composites appear to be most promising near-term solution

Challenges

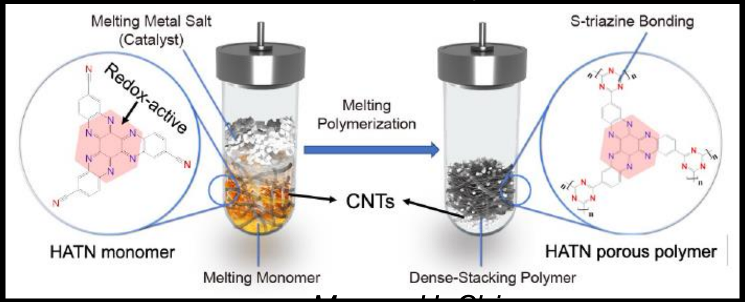
Poor cycle life <200 cycles
Poor specific energy < 200 Wh/kg in full cell

Emerging Areas of Research from Academia in the LiS Space

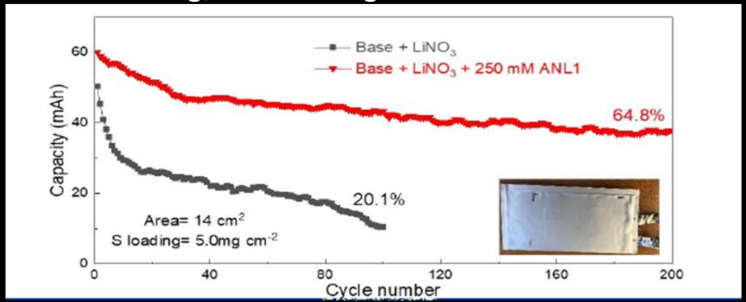
Sulfurized Composites & Electrolyte Additives



VTO BMR and Battery 500

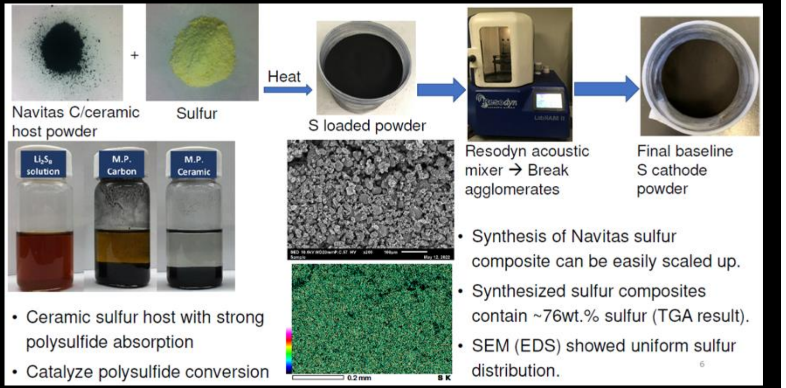


Meng, S. et al. Angew. Chem. Int. Ed.

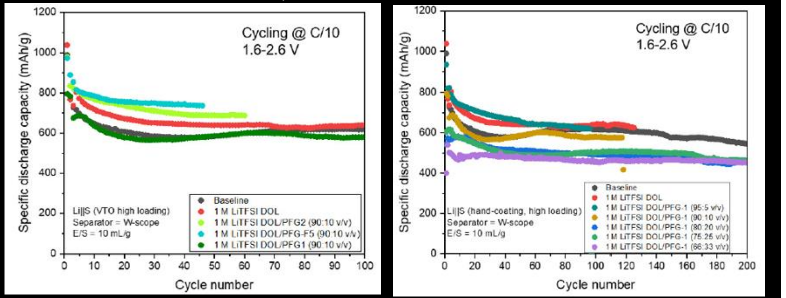


Wang, D. et al. 2024 VTO AMR.
Conductive sulfur polymers to limit volume expansion and resistance, fluorinated electrolyte additives to mitigate polysulfide shuttling

Scalable Solutions and Demonstrations



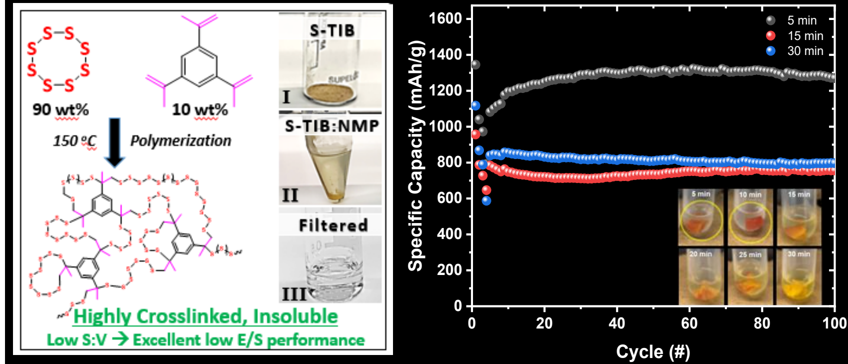
Xu, T. et al. 2024 SPW.



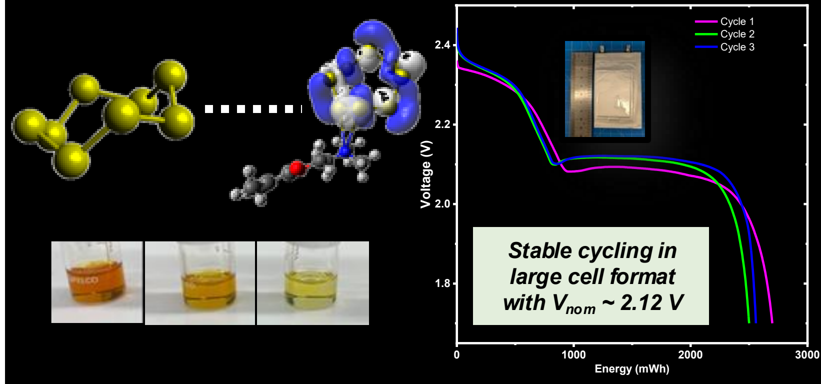
Xu, T. et al. 2024 DOE VTO AMR.
Pilot scale coatings and demonstrations, E/S loadings ~ 5-10 uL/mg S, S loadings ~ 3-5 mAh/cm²

JHU/APL's Innovations for the Li-S Ecosystem

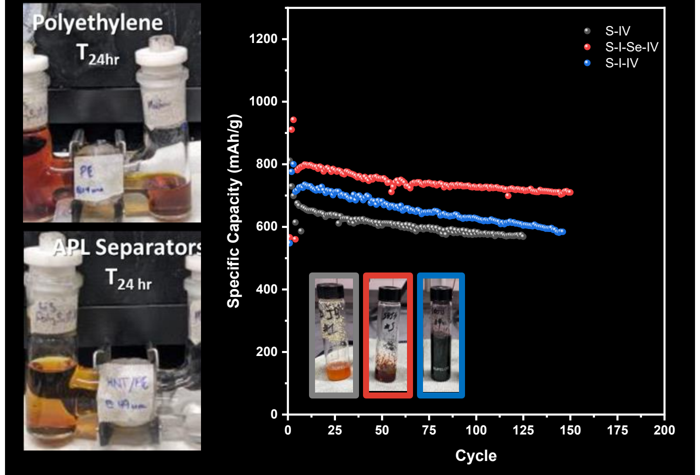
INNOVATIONS



OPTIMIZING PERFORMANCE OF HIGH SULFUR CONTENT CATHODES

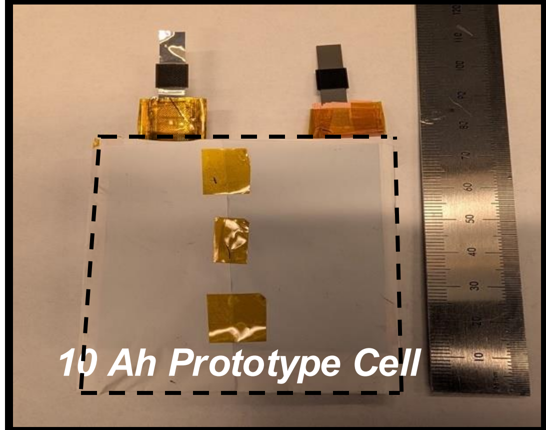


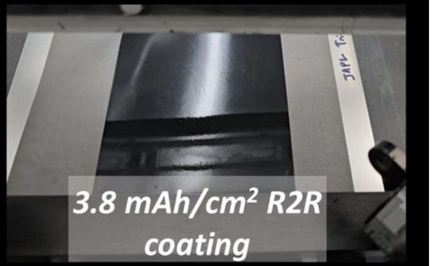
SYNTHESIZING AND FORMULATING PERFORMANCE ENHANCING ADDITIVES



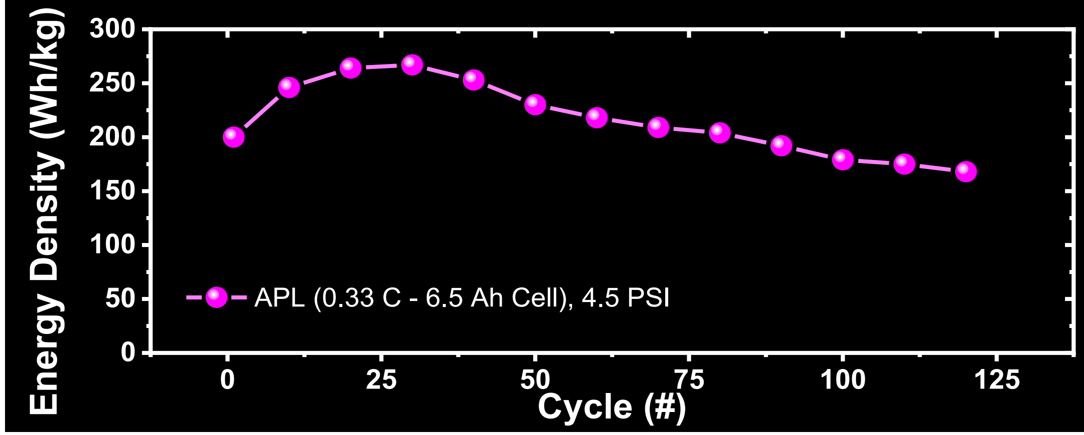
NEW CAM MATERIALS and SEPARATORS

IMPACT



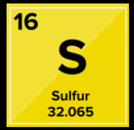


Scalable Innovations Roll to roll coating

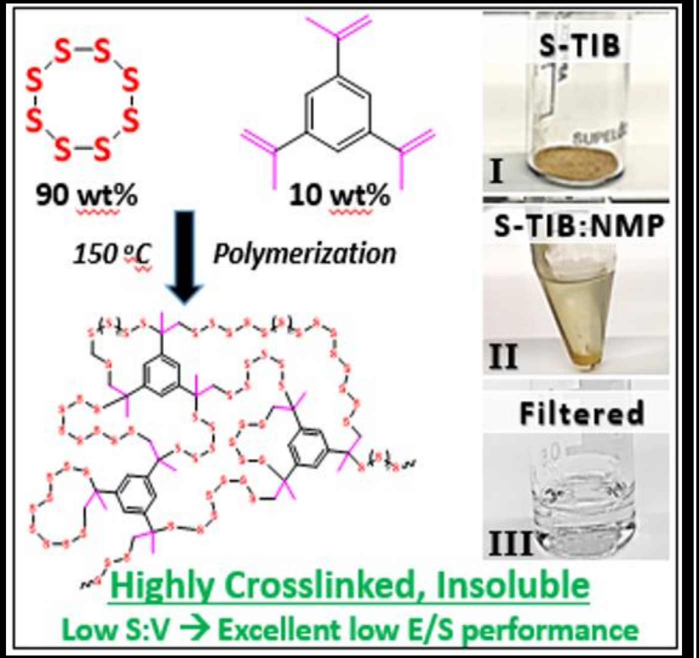


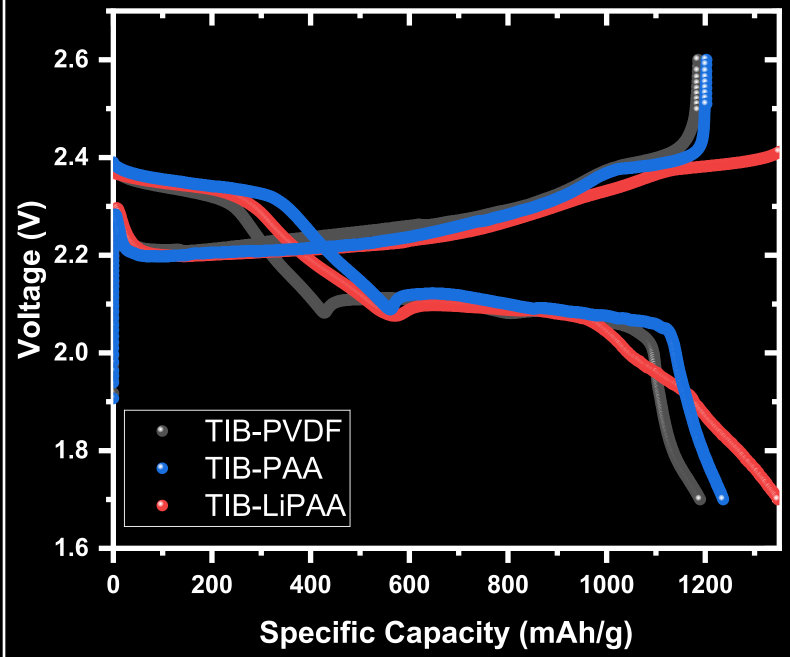
**Experimental data projected from 1 Ah pouch to 6.5 Ah pouch*

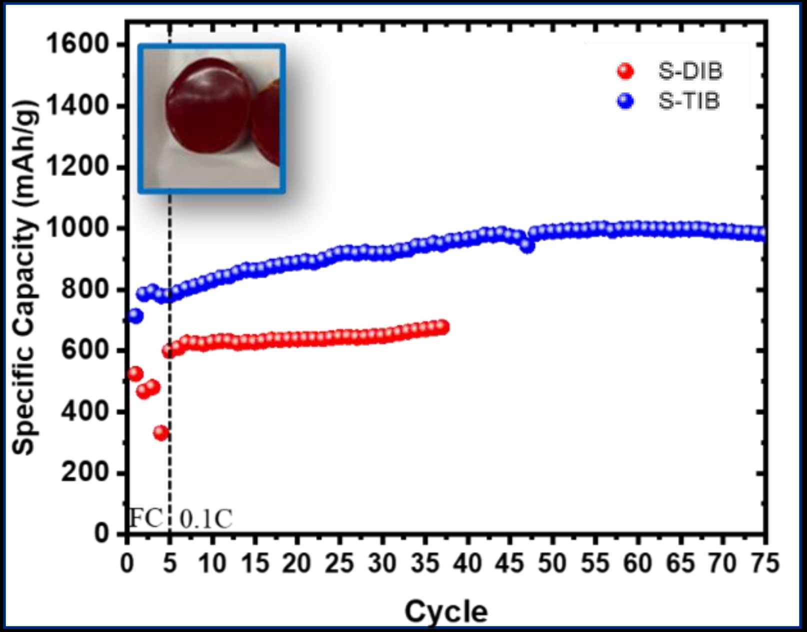
Expanding the range of IV materials



IV Polymers can exhibit up to 1500 mAh/g theoretical capacity compared to 650-940 mAh/g for S-PAN



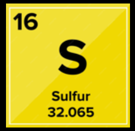




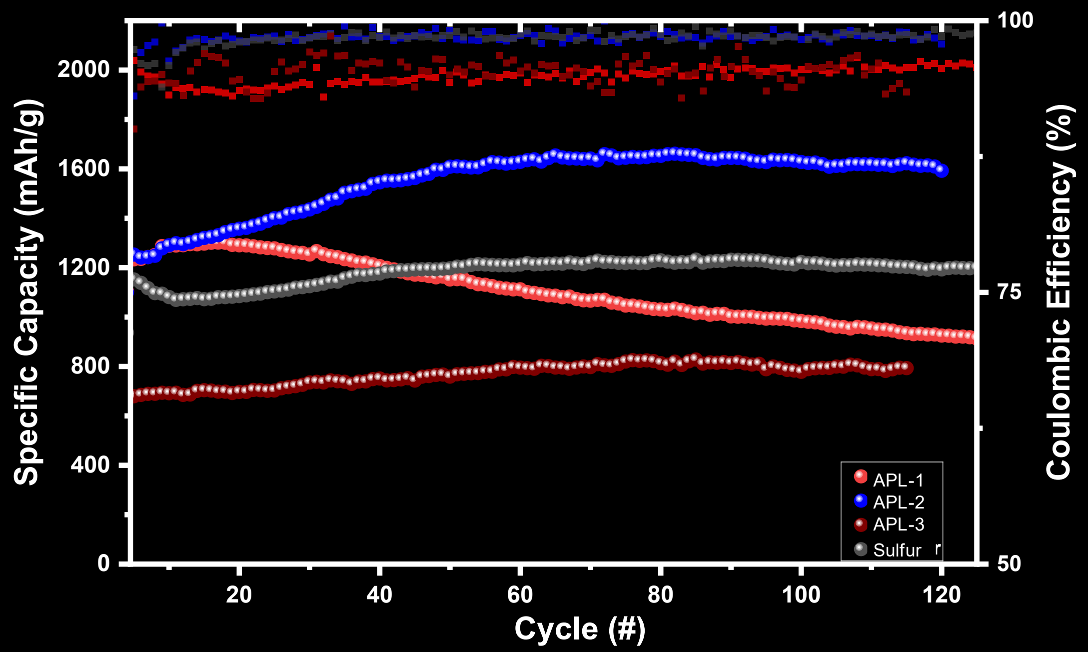
Initial work centered on multi-functional crosslinkers based on previous studies on IV monomers

Several early conditions exceeded 1000 mAh/g capacity on cycling at low loading, and approached ~ 1000 mAh/g over extended cycling at C/10

Amine Additives for Improved Sulfur Utilization



Novel Amine based Polymer Additives Enabled Tunable Sulfur Binding and Activation

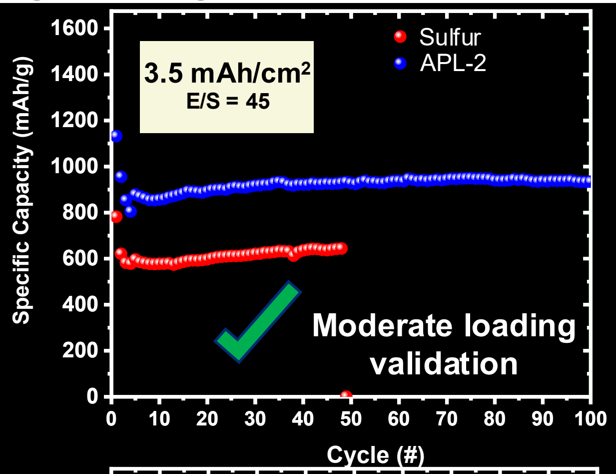


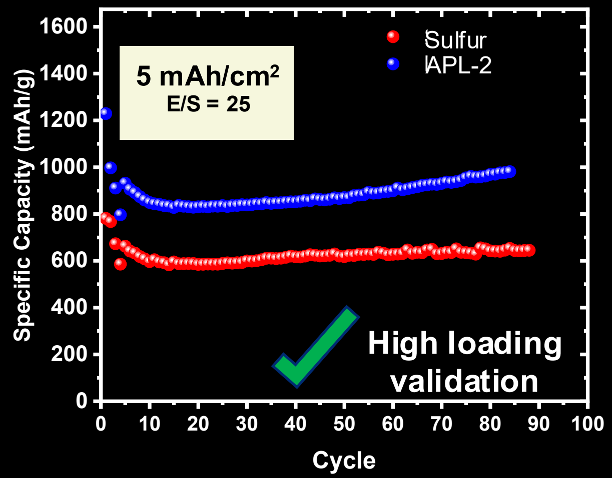
Under initial screening, amine additives are observed to enable near theoretical capacity with > 1600 mAh/g. Activation is due to tunable sulfur-nitrogen binding interaction.

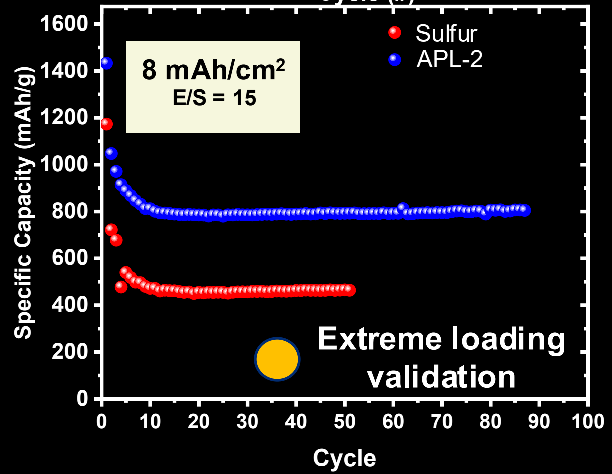
Increasing Active Loading of Amine Additive Formulations

Pre-Pouch Cell Active Loading Scaling and Evaluation

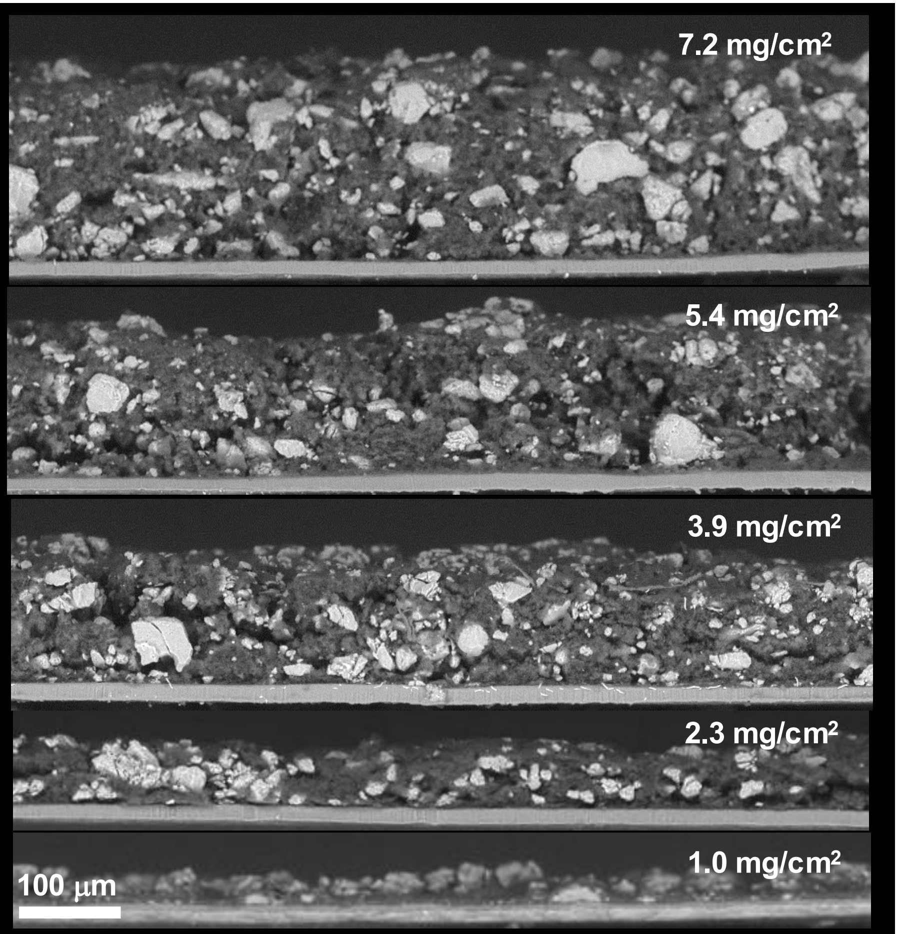
Increase areal capacity (loading) while progressively decreasing electrolyte to determine optimal performance





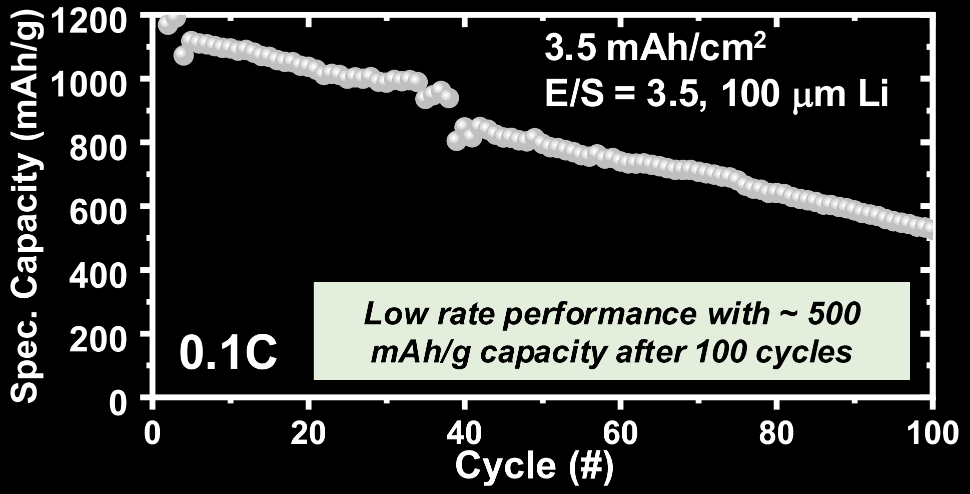


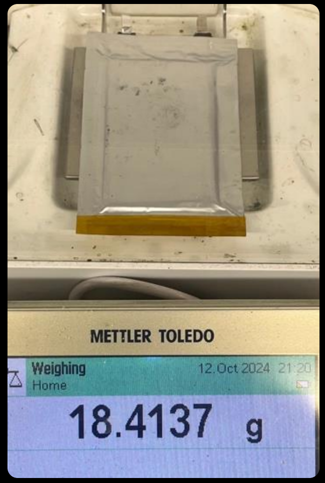
Thickness increases with Loading

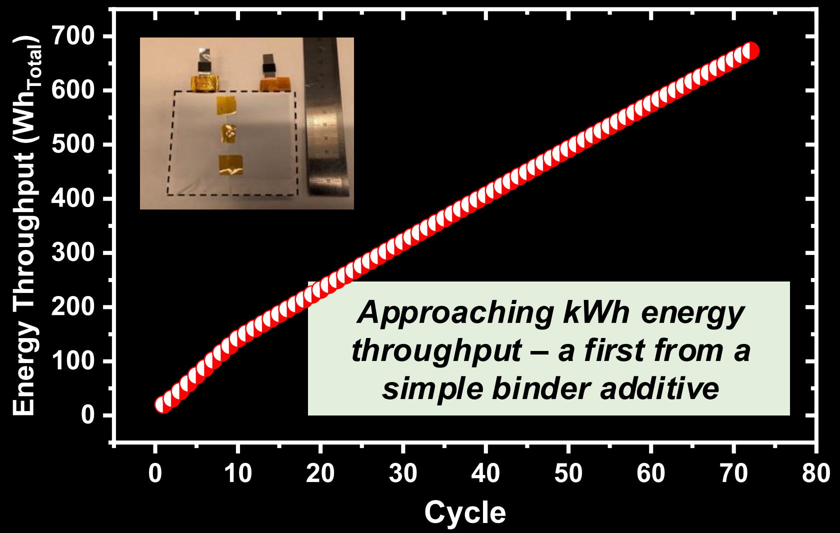


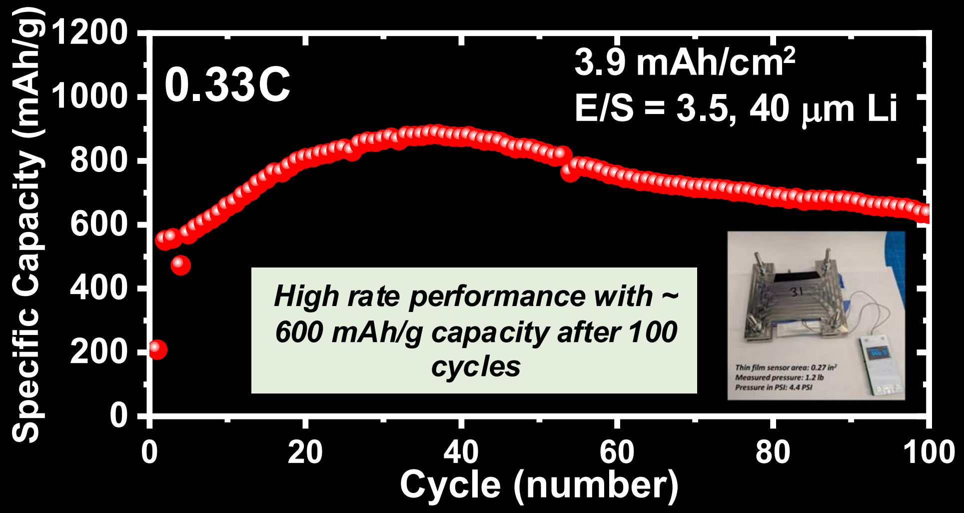
Leading formulation was evaluated for performance at increasing loadings, revealing excellent performance at moderate and high loadings at low rate (0.1C)

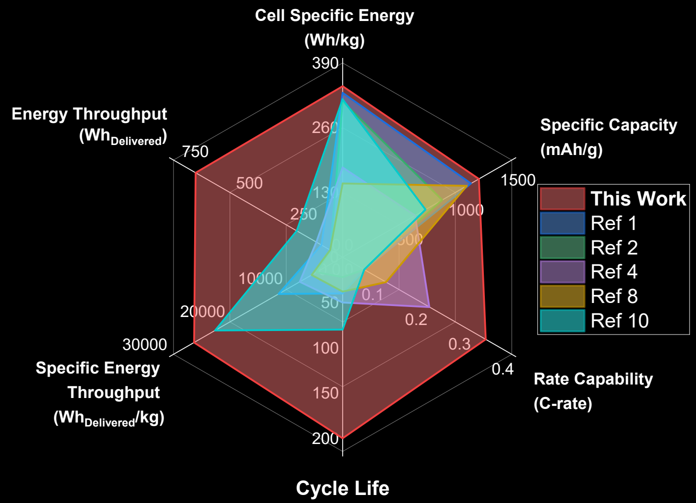
Optimized Full Cells with Realized Energy Density > 250 Wh/kg









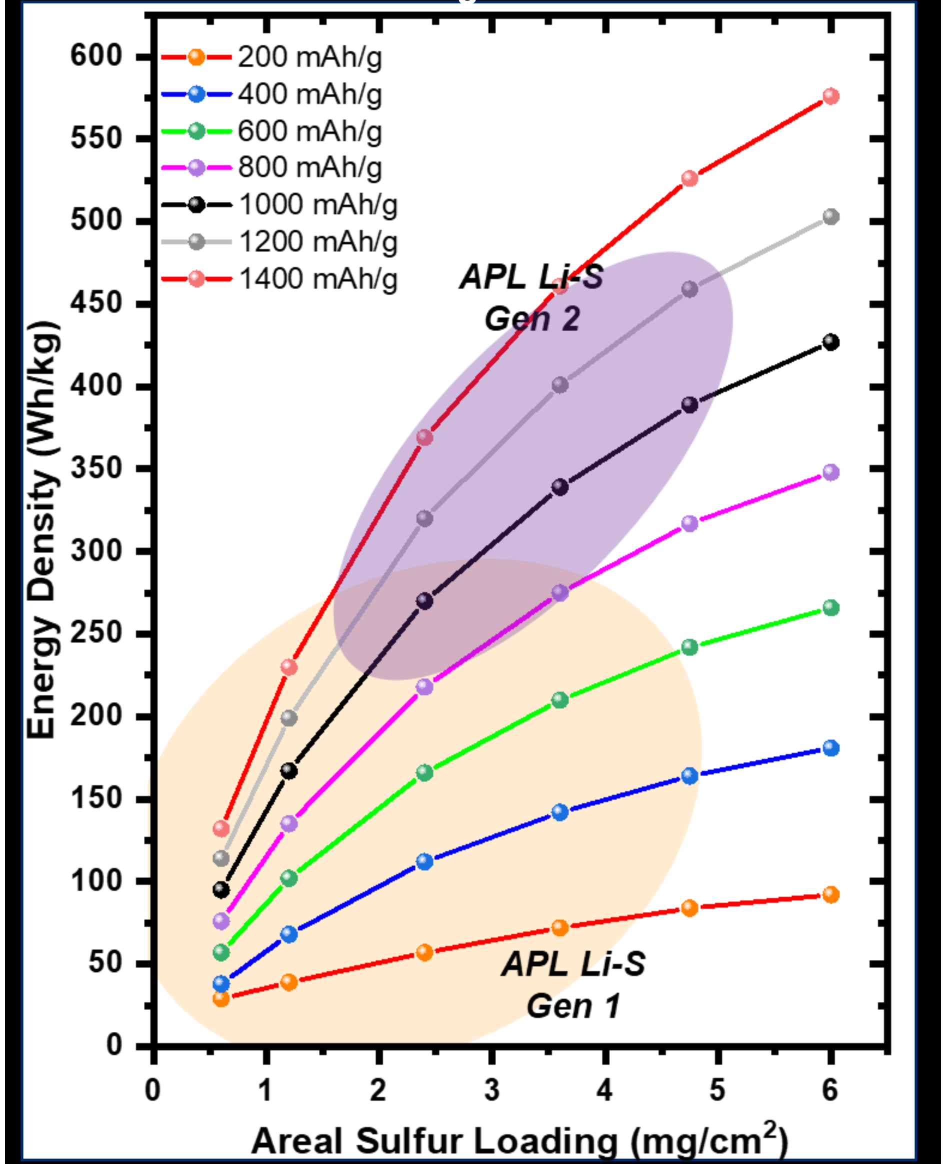


Developed chemistries enable 250-300 Wh/kg <u>currently</u>, with <u>projections based on current data</u> suggesting optimized cells will enable 300-400 Wh/kg performance in moderate size cells (6.5 Ah), and 400-540 Wh/kg in pack-ready large cell formats (61 Ah)

Conclusion and Future Work

- Lithium sulfur is the only fully domestic secondary cell chemistry that can exceed 350 Wh/kg
- The lithium sulfur ecosystem is growing, but to date no commercially available lithium sulfur cells
- JHU/APL's innovations provide a low cost, scalable and domestic supply chain secure alternative/risk mitigation for leading startup-phase commercial entities
- Low pressure tolerant chemistries will be tested in cylindrical cell formats going forward
- Partnership opportunities to combine additives with commercial sulfurized cathode formulations with improved sulfur distribution, and inverse vulcanized cathodes for novel carbon/binder systems

Projected Peak Energy Density as a Function of Sulfur Loading and Utilization



Nicholas.Pavlopoulos@jhuapl.edu

JOHNS HOPKINS

APPLIED PHYSICS LABORATORY