Development of Lithium Sulfur Batteries for High Energy Applications

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Navitas Systems

A cell and battery design and manufacturing company

Research, design, development, and manufacture of advanced lithium cells and energy storage products and systems for both commercial customers and U.S. Government/military customers

Formed in 2011 with the merger of MicroSun Innovative Energy Storage Solutions and MicroSun Electronics, and the acquisition of A123 Systems' Government Solutions Group, located in Ann Arbor, Michigan.

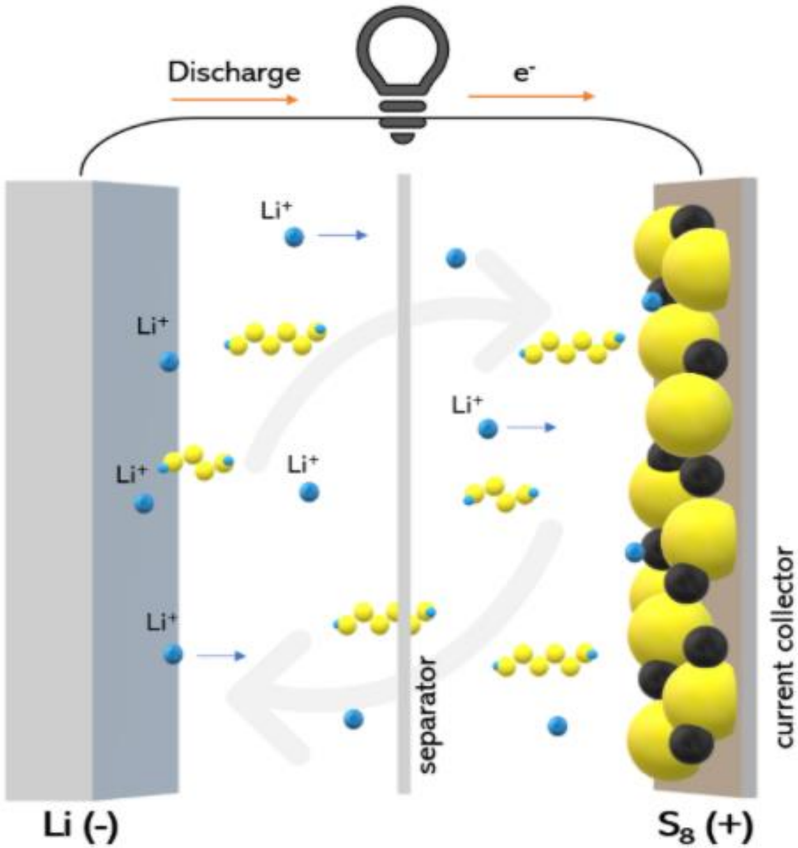
In 2019, East Penn Manufacturing– one of the world's leading battery manufacturers—acquired majority interest in Navitas Systems.

48,000 square foot R&D, Engineering, & Manufacturing Center. 100,000 square foot lithium battery pack Manufacturing Center.

Navitas' $15M state of the art automated production facility with the capability of producing up to 1M+ custom format pouch cells per year with 1 – 10 Ah capacity

Navitas Systems Advanced Solution Group

	Lithium Battery Solutions	System Design and Assembly	Electronics & Battery Management Systems (BMS)	Custom Cell Development	Analytical and Testing	Cell Chemistry R&D Advanced Chemistry and processing
Capability						
Scope	• Custom battery development, prototyping, and manufacturing • 12V NATO 6T Battery • 24V NATO 6T Battery • Multi-kWh motive application batteries • PowerForce™ Idle Reduction Battery • Frontierion™ Photovoltaic Interface + Energy Storage • Mission-critical UPS Systems	• Cell form factor and chemistry agnostic • >1kWh solutions • System mechanical and electrical design • Custom power electronics • Finite element analysis • Thermal modeling • Prototype and low-volume assembly in house	• Custom PCBA and wiring harness design and assembly • In-house SMT line • Customized configurable software • Box builds	• Custom prismatic cells • 2x2 to 12x22 cm form factors • In house slot-die coating • 650 sq. ft. dry room • Various Li-ion chemistries developed • Extreme high power and high energy density chemistries available; 100-600 Wh/L	• 500+ MACCOR test channels • Environmental control -70 to +200°C • Electrochemical Impedance Spectro-scopy • Scanning Electron Microscope with elemental mapping and inert gas sample transfer device • Analytical chemistry instrumentation • Cell tear down analysis	• Wet lab • Controlled atmosphere tube furnaces for synthesis • Custom anode, cathode, and electrolyte development • Battery materials and concepts evaluation •Advanced Chemical processing



Theoretical capacity of sulfur electrode:
1675 mAh/g

Key Limitations:
Low utilization of sulfur and fast capacity fading

4 Key components:
Cathode, anode, electrolyte, separator

Navitas is currently working on cathode and separator.

[Wikipedia]

Discharge:
Li^+ ions are stripped from the anode, *Lithium Polysulfides* (Li_2S_x) are formed in the cathode.

Recharge:
Li^+ ions are plated back onto the anode as the Li_2S_x moves towards S_8.

Outline

- Li S cathode work
- Bifunctional separator for LSB
- Li S stack development
- Navitas LSB road map and challenges
- Acknowledgements

Li-S Cathode Development Overview

Goal and Objectives

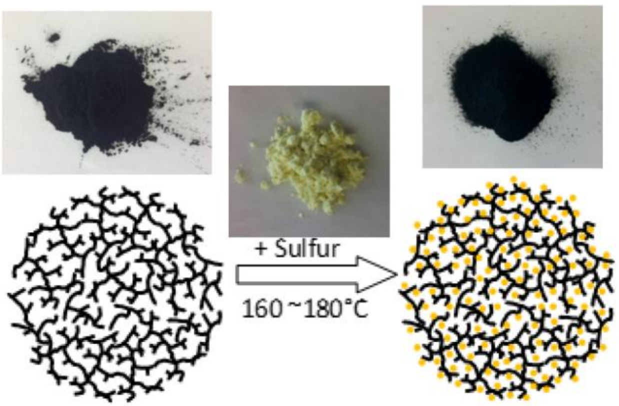
28V 30 Ah Li-S battery based on novel cathode chemistry and Navitas BMS

- Scale up cathode to 500 g per batch
- Build 3 Ah cells
- Demonstrate>300Wh/kg and >100 cycles
- Develop BMS for Li S battery
- Design 28 V, 30 Ah battery

Challenges for Li-S cathodes

- Low utilization of sulfur and fast capacity fading
    - Dissolution of polysulfides in electrolytes
    - Large volumetric changes of sulfur
    - Poor electronic conductivity of sulfur

Innovative Navitas cathode



Porous, **conductive** ceramic host with **high affinity** to sulfur and polysulfides

Key features and Benefits of Navitas cathode

- Intrinsically conductive cathode powder for high rate capability
- Porous for improved sulfur loading capacity
- High sulfur affinity for extended cycle life
- Compatible with established high volume electrode coating and cell assembly operations

The Navitas cathode is patent pending

Cathode: Porous Host

Key Properties of Ceramic Host

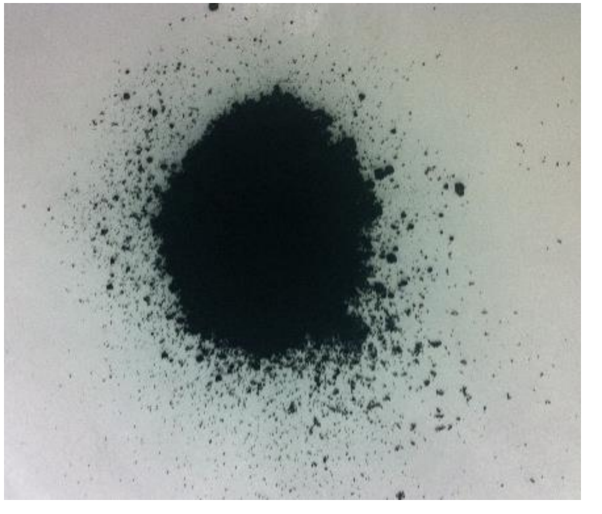
	Target	Results
Microstructure	Phase pure crystalline	Phase pure crystalline
Surface area	>100 m^2/g	**108** m^2/g
Porosity	> 50%	**50%**

- Challenge: Maintain porous structure/high surface area after thermal treatment
- Key accomplishment – Precursor modification mitigates pore collapse during thermal treatment

As-received precursor

Modified precursor

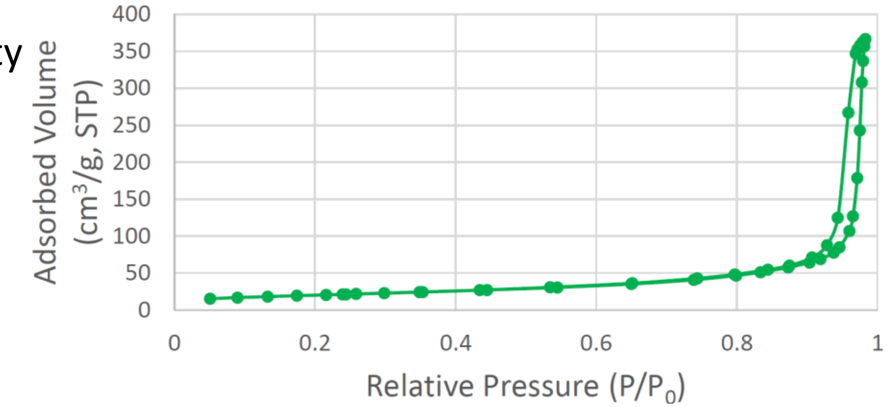
Navitas ceramic host



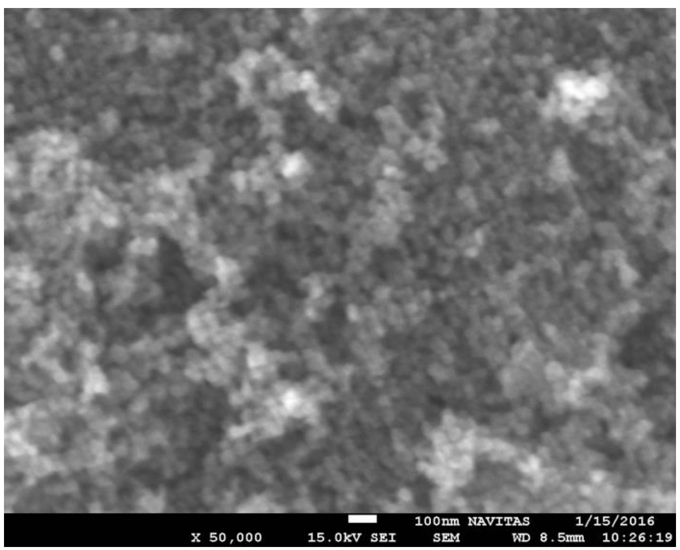
Cathode Development: Characterization

- Properties of ceramic host:
  - XRD: Targeted microstructure at high purity
  - SEM: nano particles & porous structure
  - N_2 adsorption: Mesoporous

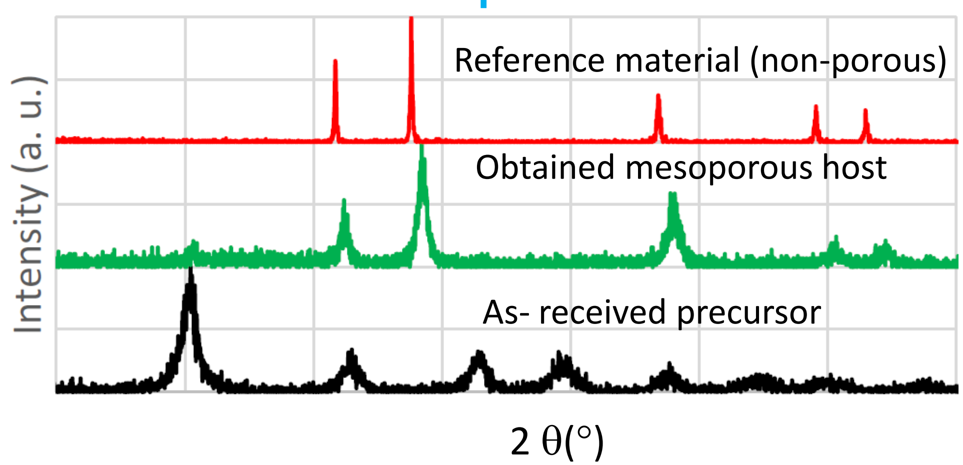
Isotherm of Ceramic Host



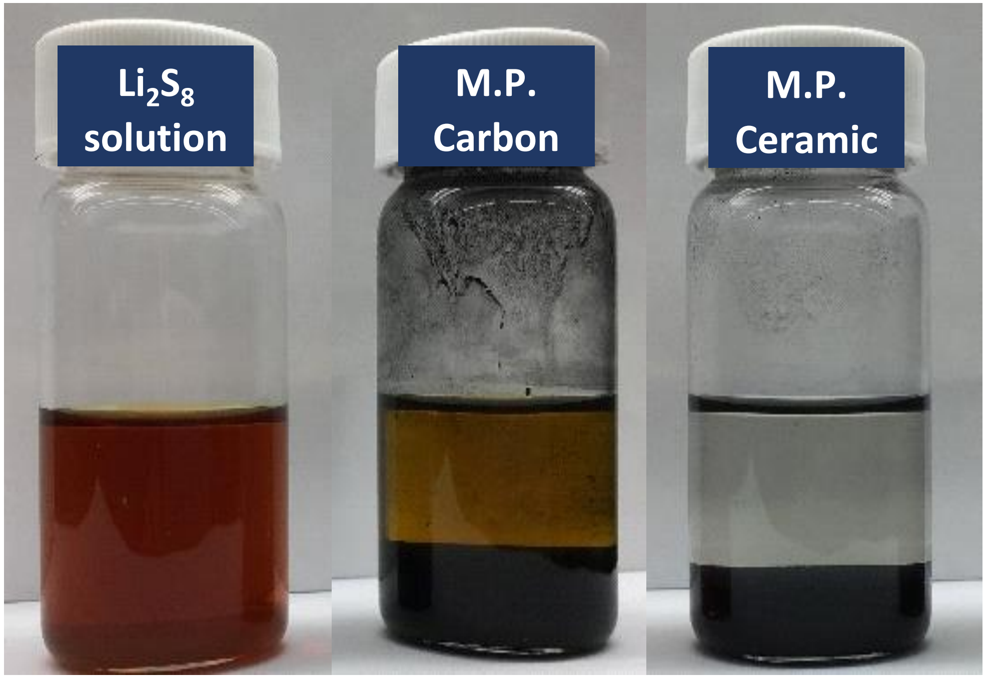
SEM image of Ceramic Host



XRD patterns



Cathode: High Affinity to Polysulfides

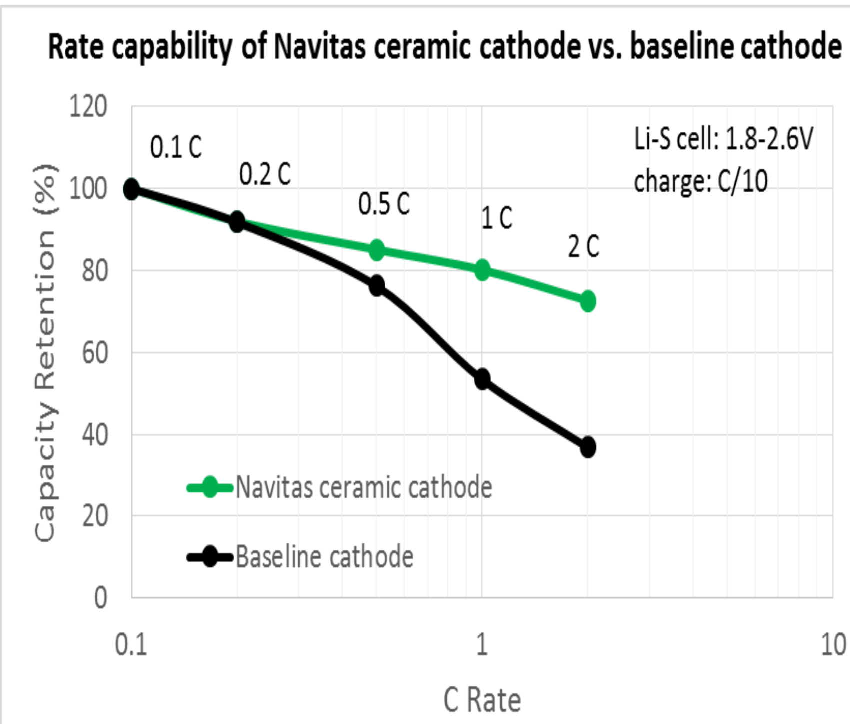


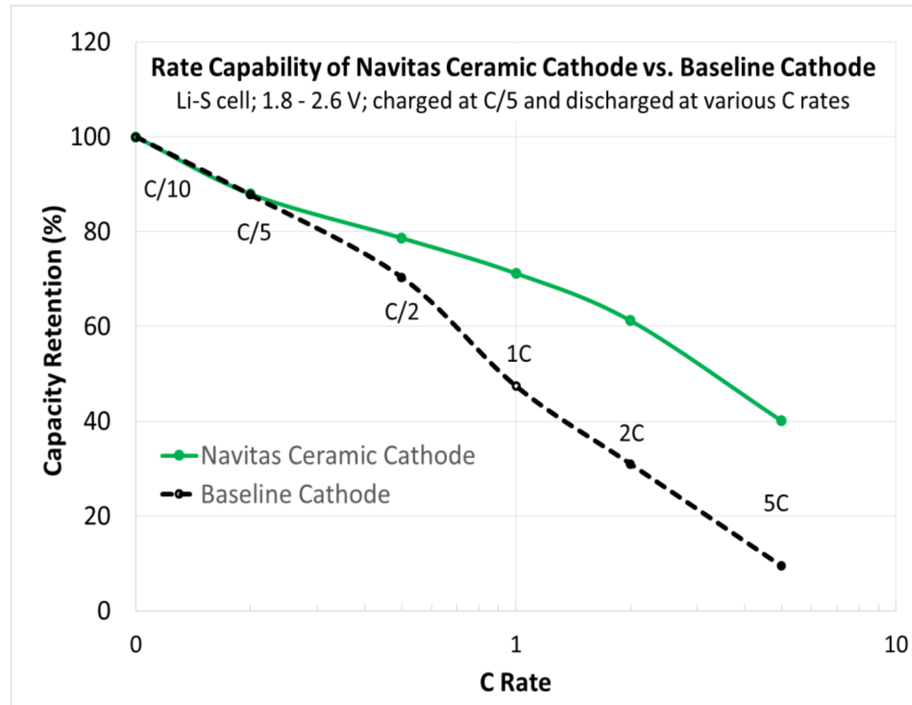
Sealed vials of Li_2S_8 solution, and after contact with ceramic and mesoporous carbon overnight

Cathode: Conductive for Higher Rate

Rate capability advantage of Navitas cathode:

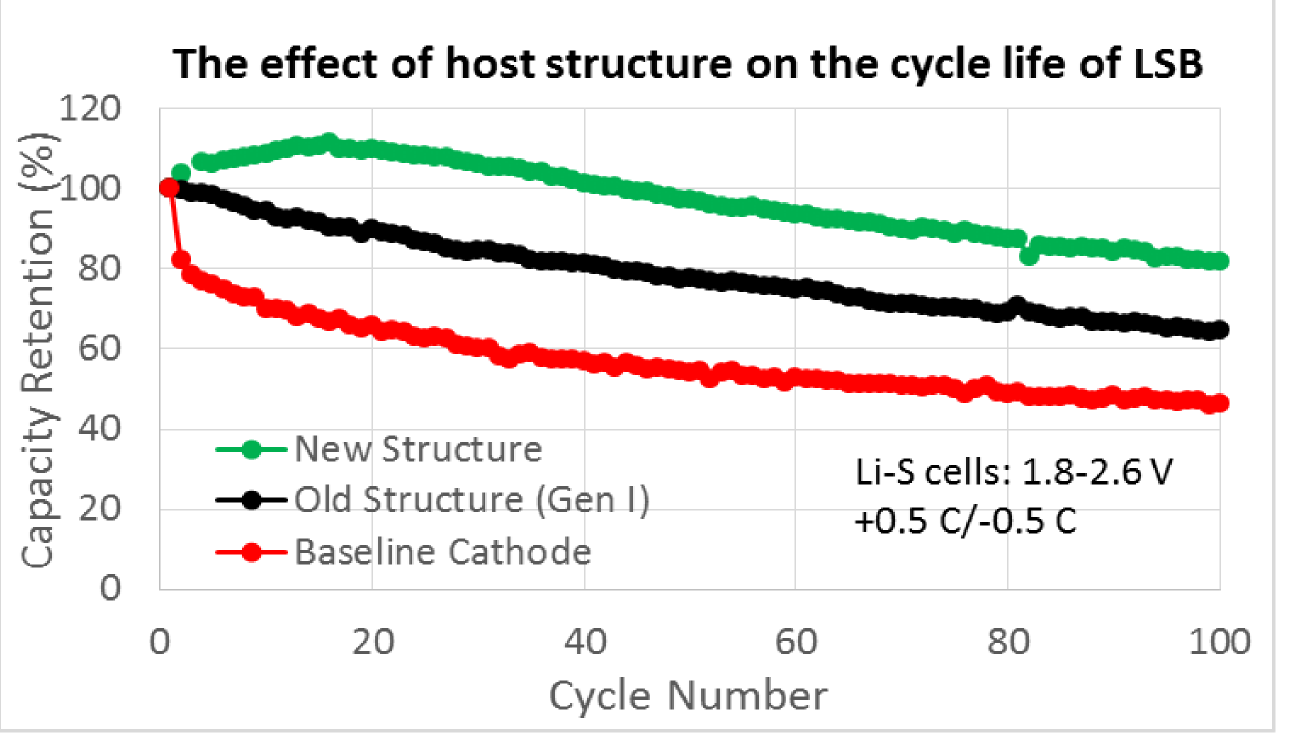
- Loading of electrodes: 0.6mAh/cm^2 (Left) and 1.5 mAh/cm^2 (Right)
- High rate (>2C): 2X better than porous carbon baseline
- Rate performance demonstrated at practical electrode loading and energy





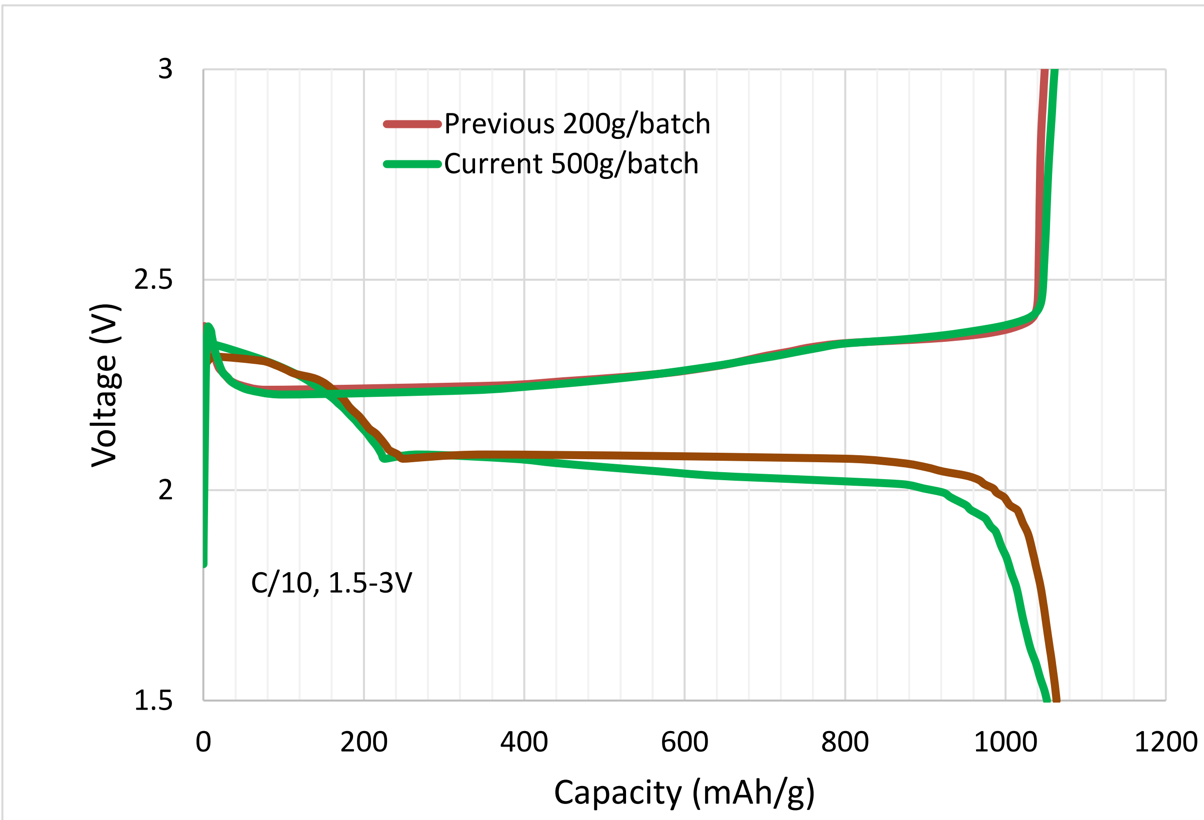
Cathode electrochemical evaluation: cycle life

- Design concept:
  - Control structure of host to further improve the affinity to sulfur
- Advantage of host with new-designed structure in terms of capacity retention:
  - 100 cycles: 82% new vs. 65% old



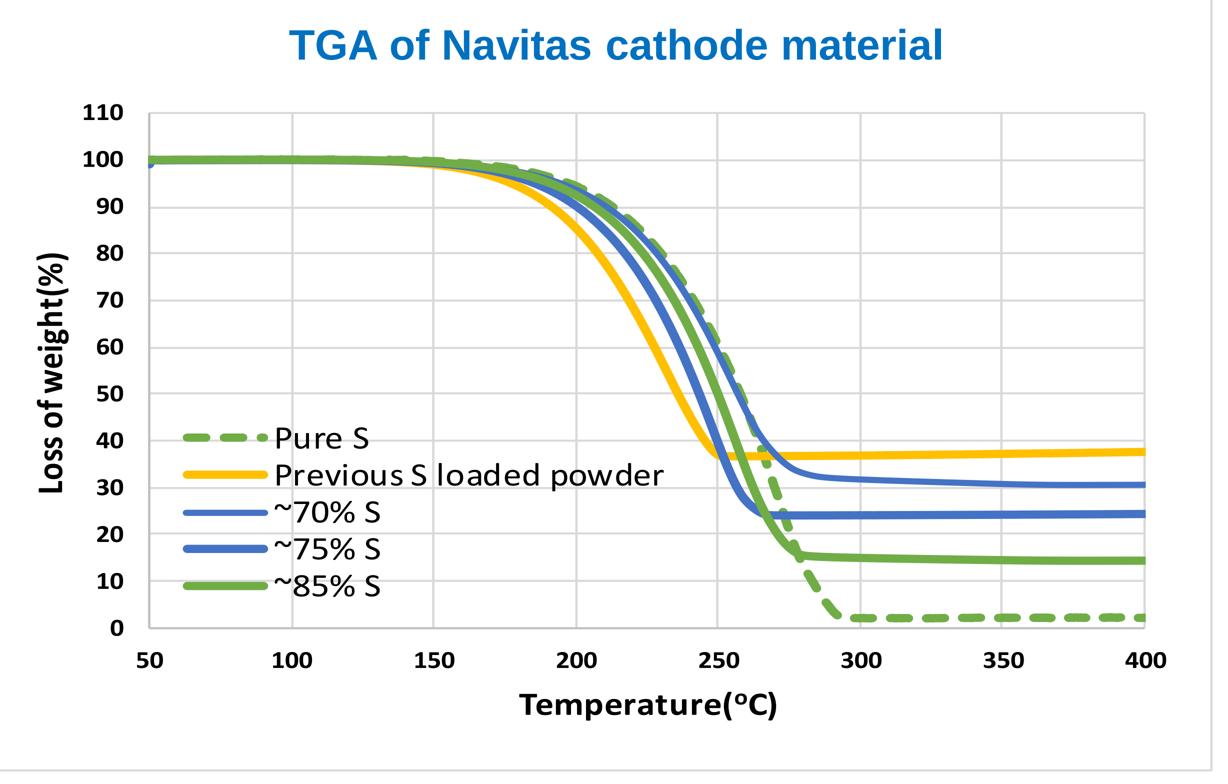
Cathode: Materials Scale Up

- Objective:
  - 200 g/batch→500 g/batch → 1,000g/batch cathode with specific capacity of 1,000 mAh/g
- Current Status:
  - 500 g/batch achieved



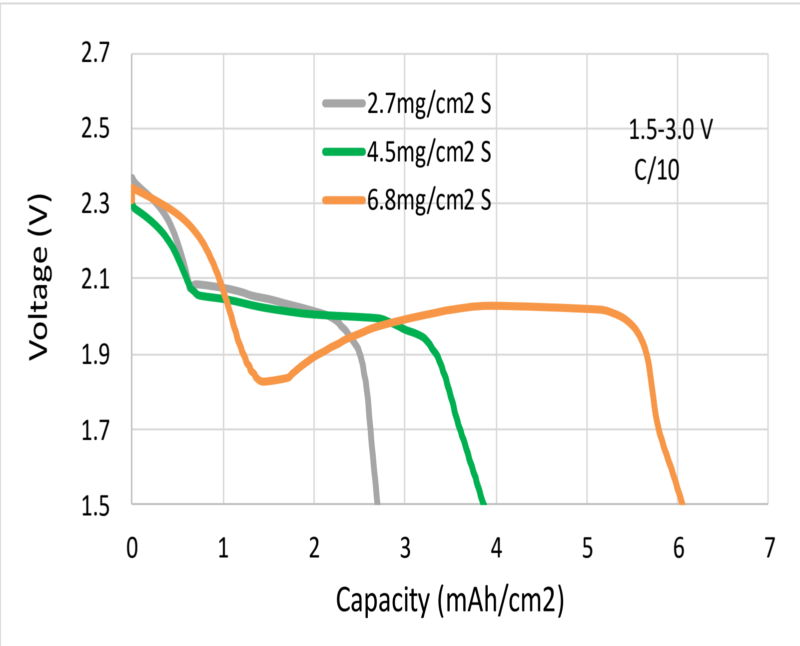
Cathode: high sulfur loading to host

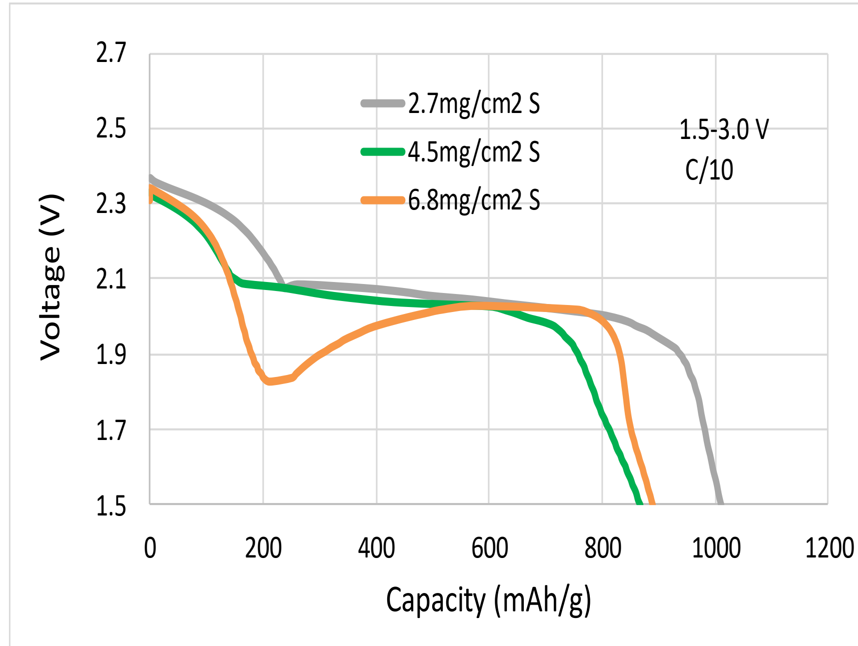
- Melt-diffusion approach for impregnation of sulfur:
  - Visual inspection: black-colored Navitas cathode material (→ encapsulation of S in pores)
  - TGA: ≥ 70 wt.% sulfur in Navitas porous cathode material



Cathode: high loading hand cast electrode

High loading cathodes (hand casting)





- 4mAh/cm^2 and 6mAh/cm^2 cathode were demonstrated with hand casting electrode
- >300Wh/kg goal possible with these high loading cathodes

Cathode: Pilot Scale Coating

- Pilot coating double side S cathodes (≥ 7mg/cm^2 S each side achieved)

Coater die head

Coater output

- Two challenges addressed:

(1) A stable cathode powder slurry was prepared at large scale with uniform dispersion of the constituents without loss of retention of sulfur

(2) The coating operation was performed without volatilizing the sulfur in the electrode drying.

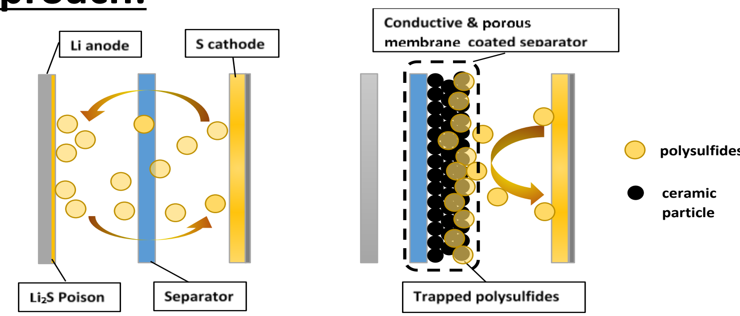
Extended Life High Energy Space Battery with Bifunctional Separator

Goal and Objectives

Demonstrate a bifunctional membrane separator for a cost effective, high charge efficiency and long cycle life LSB:

- Develop a conductive membrane precursor powder with engineered pore structure
- Produce >50m ceramic coated bifunctional membrane with roll to roll (R2R) coating
- Demonstrate 2Ah prototype Li-S bifunctional separator cells with 400 Wh/kg and 200% improvement in cycle life

Approach:



LSB with conventional separator

LSB with proposed bifunctional separator

- Conductive ceramic powder with engineered pores
- Scalable slurry casting method to coat the separator
  - ➢ Entrap dissolved polysulfides by its high affinity
  - ➢ Reuse the trapped sulfides through its conductive path (delithitation)

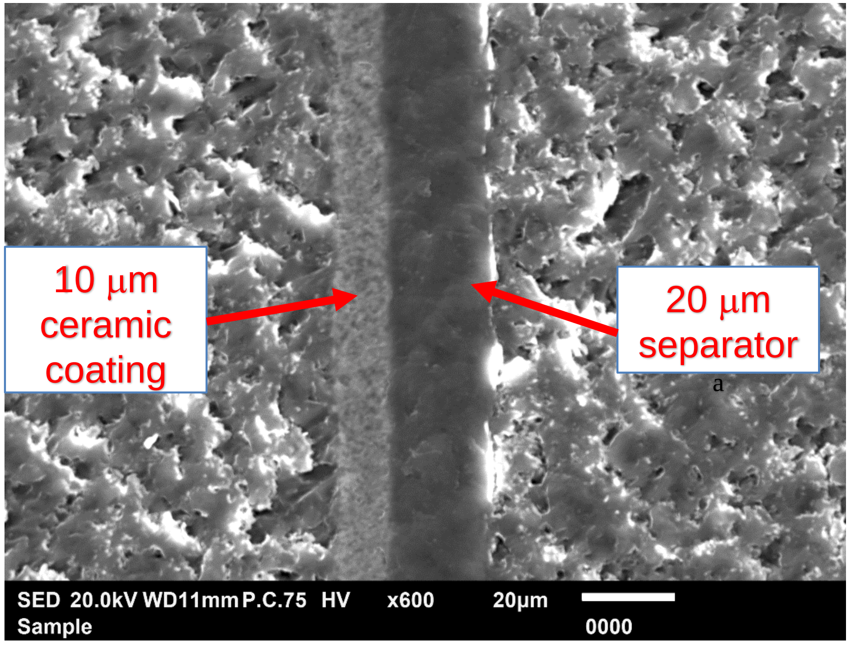
Key features and Benefits of Navitas separator

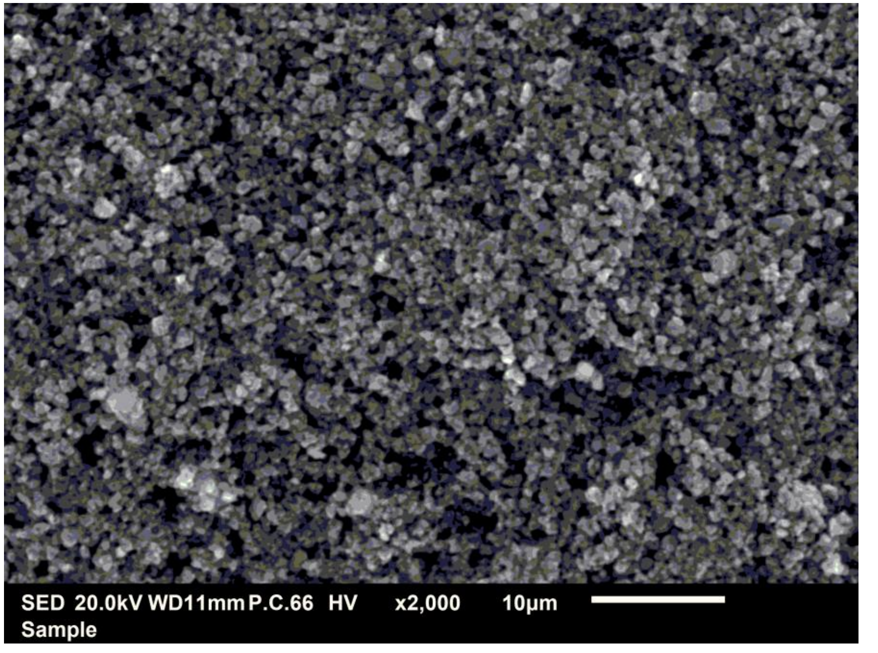
- Porous ceramic host with high affinity to sulfur and polysulfides
- Intrinsically conductive ceramic powder enables reusing of trapped sulfides
- Machine coating scalable

Application/Market

- Energy storage solutions for surface missions on moon and Mars - Energy storage systems for
  - ➢ landers
  - ➢ construction equipment
  - ➢ crew rovers
  - ➢ science platforms.

SEM images of coating





Cross Section

- 10 µm thickness

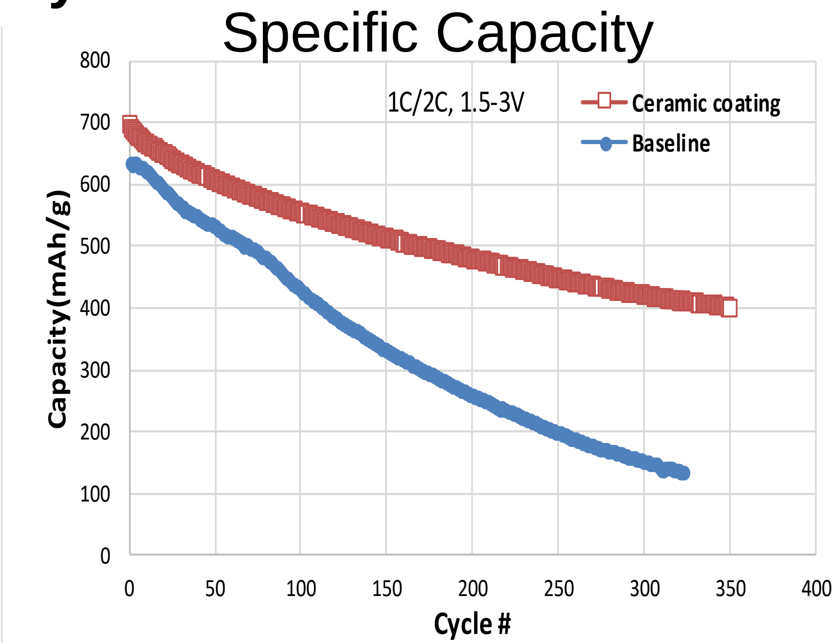
Dispersion

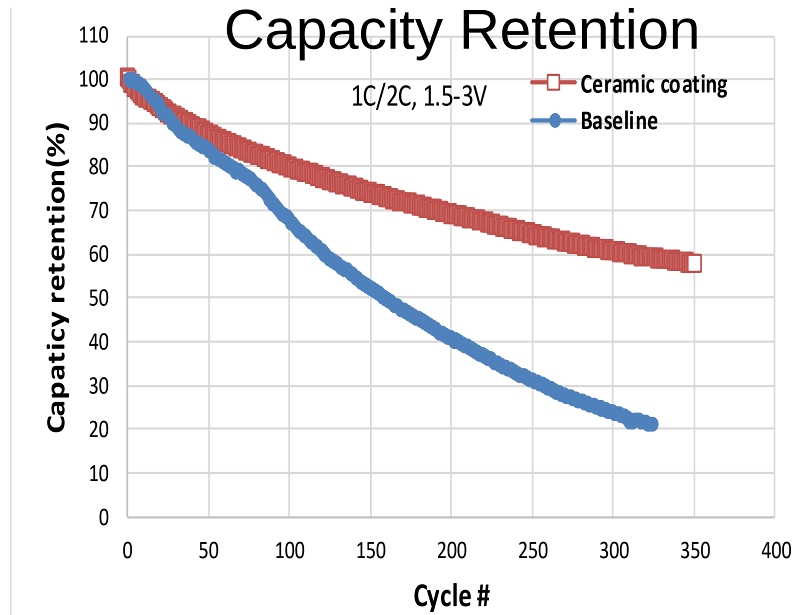
- Homogeneous

10µm thick uniform ceramic coating was achieved

Li-S SLP Cell Demonstration - Cycle Life

Cycle life with and without bifunctional separator in pouch cell



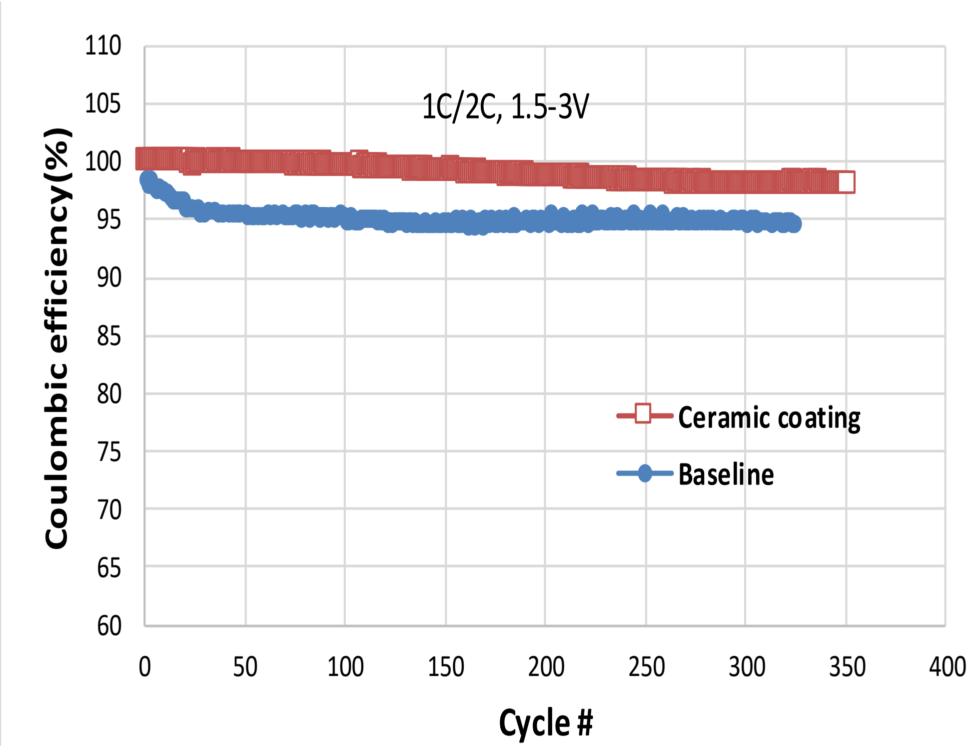


Cycle life improvement from the new separator

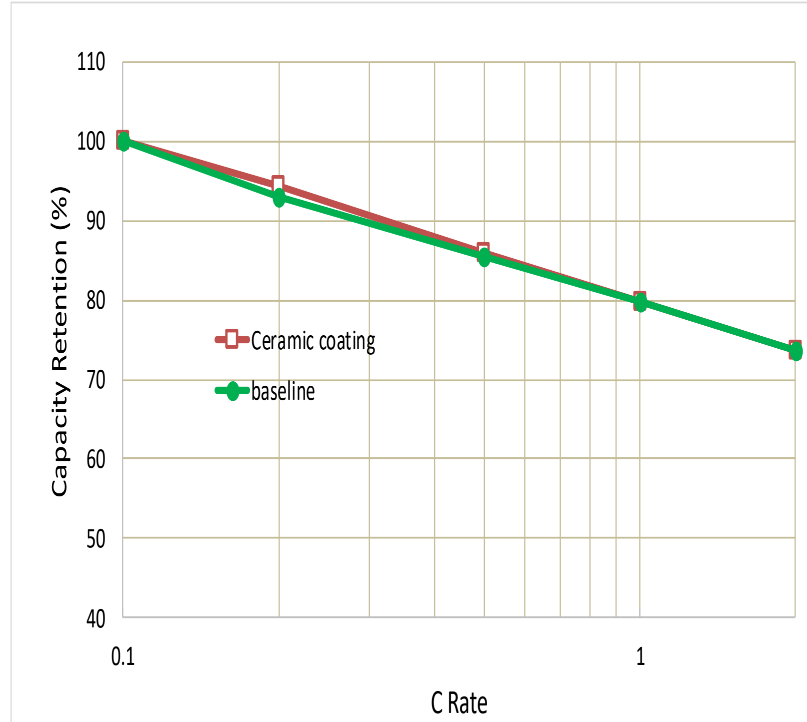
End Point of Cycling	Cell w/ Baseline Separator	Cell w/ Bifunctional Separator	Cycle Life Improvement	Target
600mAh/g	17	53	3.1 X	2 X
500mAh/g	67	165	2.5 X	
400mAh/g	112	345	3.1 X	

SLP Cell Demonstration

Coulombic efficiency



Rate capability



- Cycling efficiency improvement from coated separator observed
- 80% capacity retention at 1C demonstrated

Separator: Material Scale Up

In-house hand casting

NASA SBIR Phase II

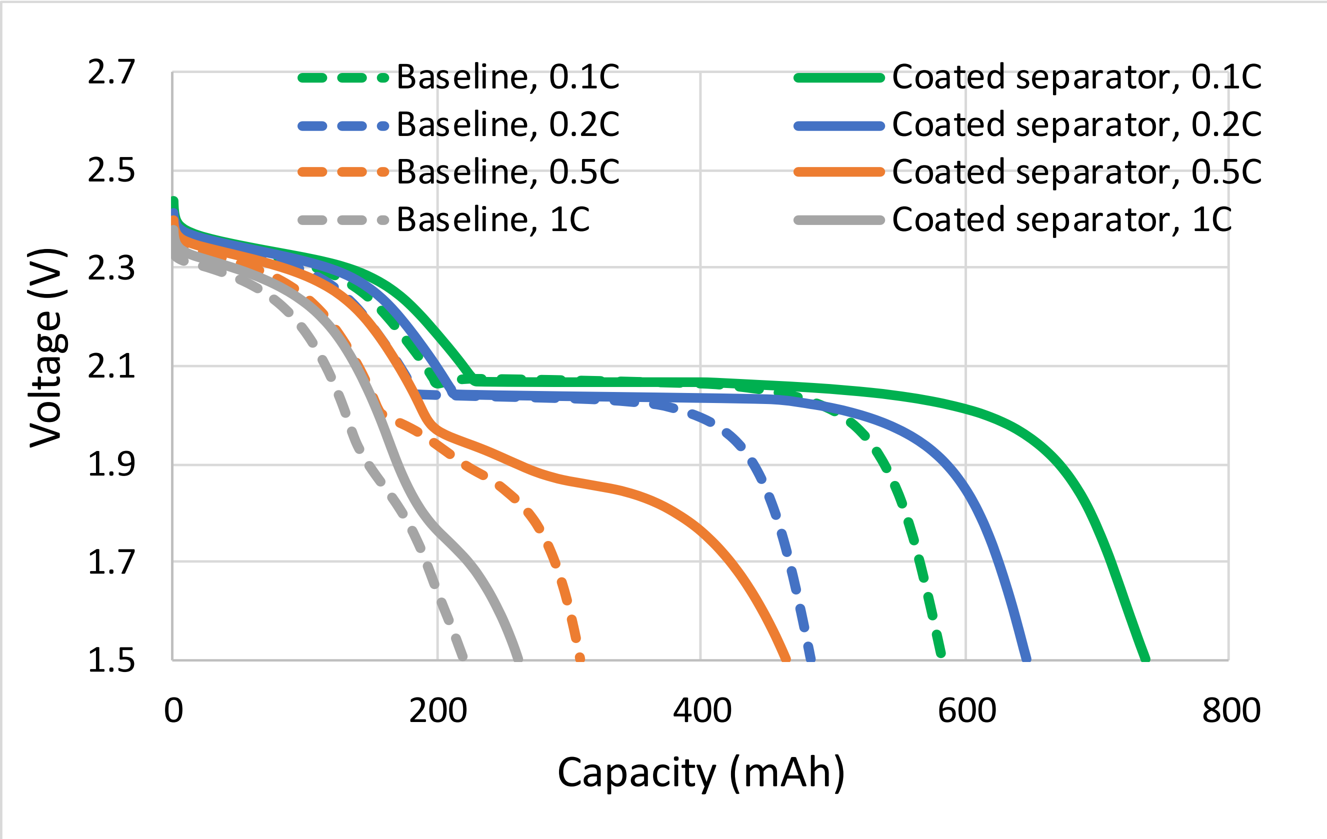
Contract #: 80NSSC18C0099

50m R2R machine coated bifunctional separator

R2R processed separator allows Navitas to perform extensive cell performance test with variable cell format.

Separator: 700mAh MLP Stack Demonstration

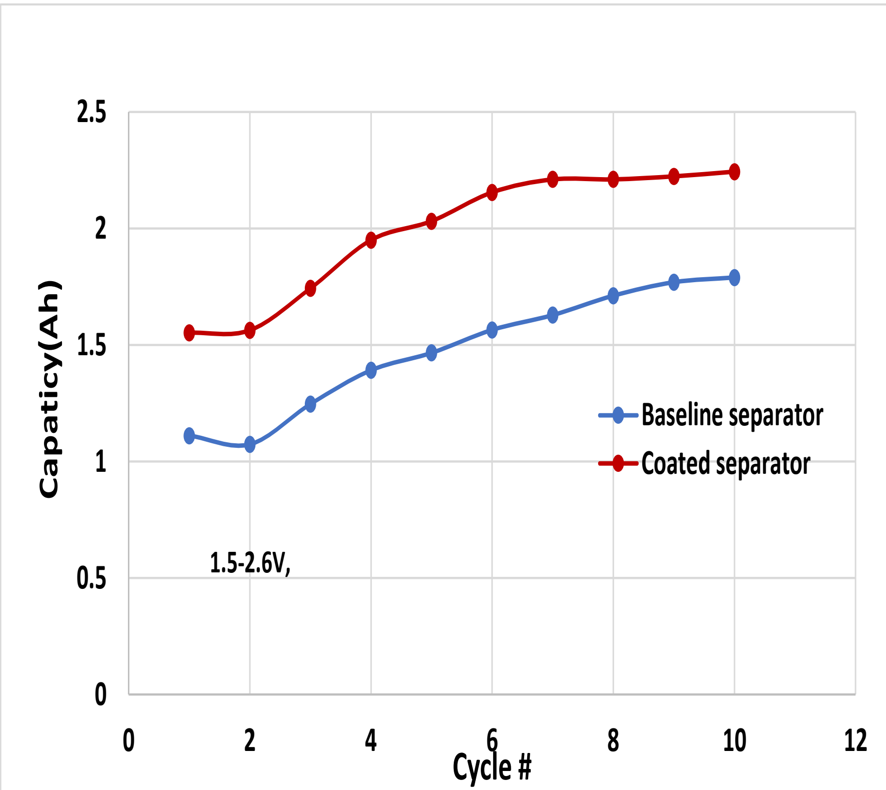
Multilayer (700mAh) stack with baseline and coated separator

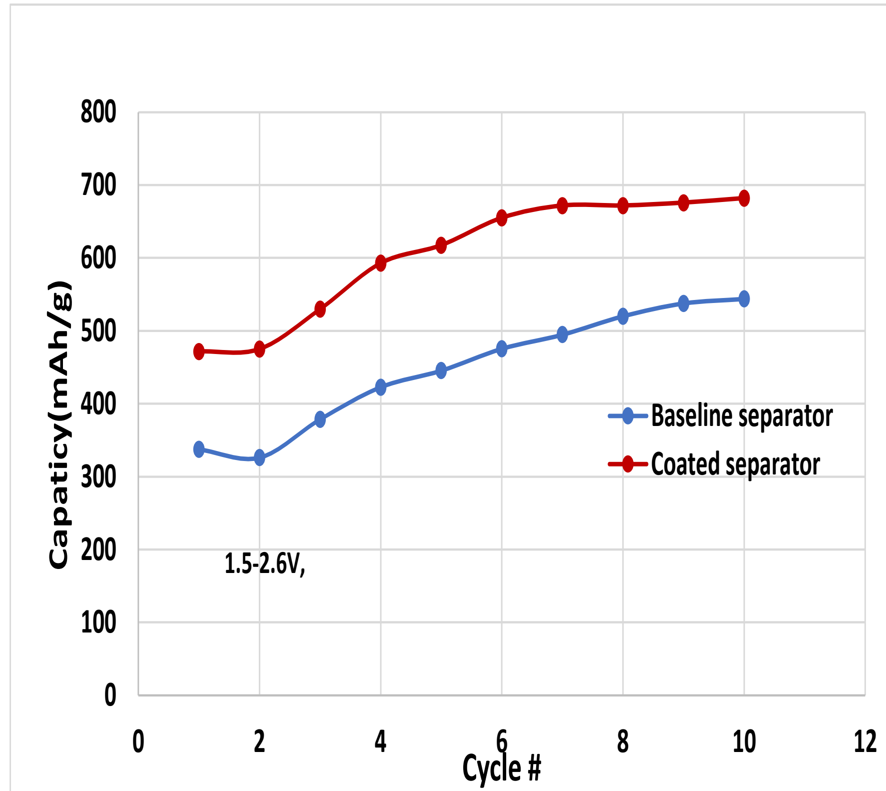


- Cathode: 2.5mg/cm^2 S. E/S ~5, 1.5-2.8V, ambient temperature
- Coated separator demonstrated higher capacity at various rates

Separator: 2Ah MLP Stack Demonstration

Multilayer (2Ah) stack with baseline and coated separator

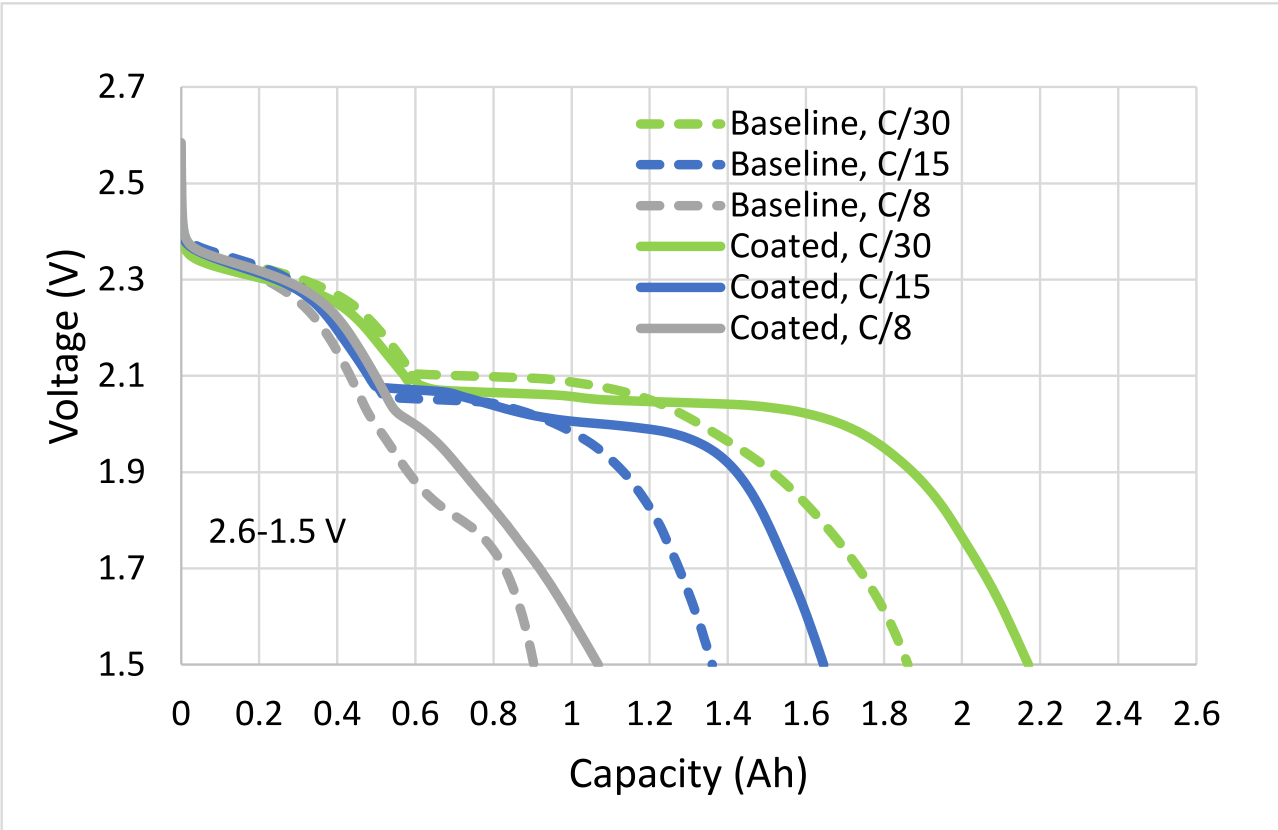




- Cathode: 6 mg/cm^2 S. E/S ~5, 1.5-2.6V, ambient temperature, Initial 10 cycles at low C/30 rate
- Coated separator demonstrated higher initial capacity

Separator: 2Ah MLP Stack Demonstration

Multilayer (2Ah) stack with baseline and coated separator

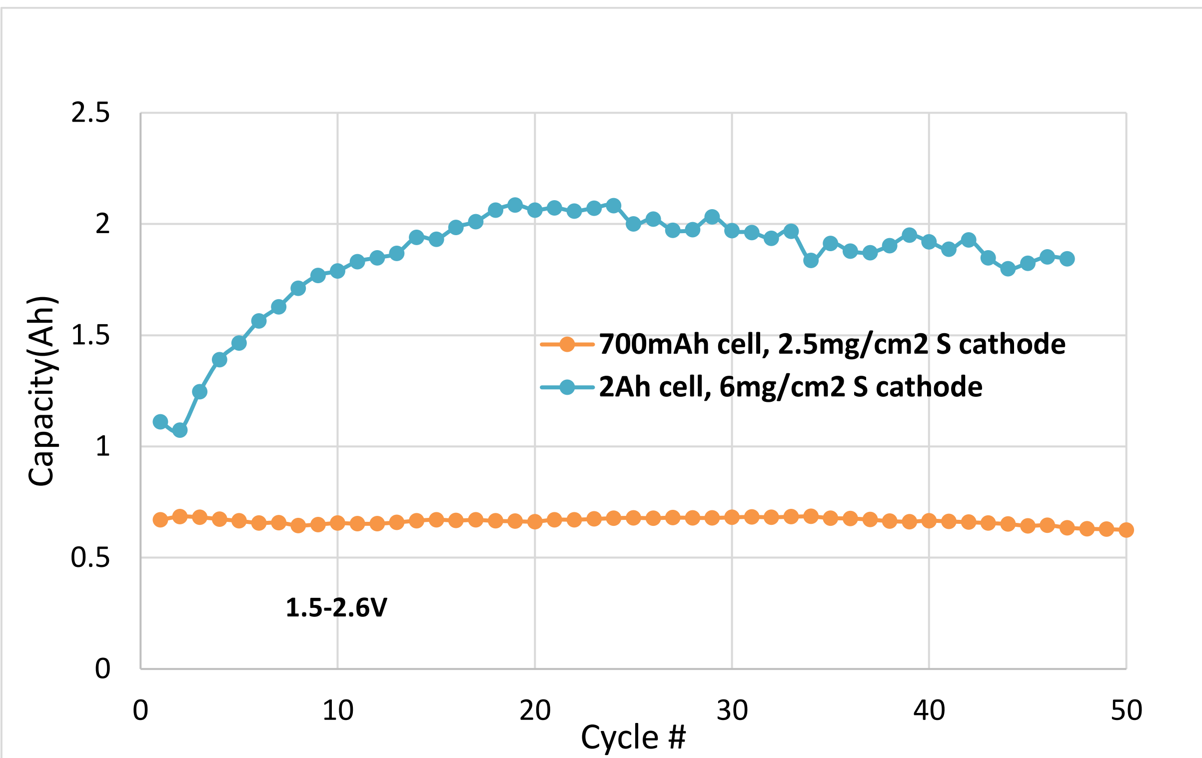


- Cathode: 6 mg/cm^2 S. E/S ~5, 1.5-2.6V, ambient temperature, Coated separator demonstrated higher capacity at various rates

LSB stack development: 700mAh to 2Ah

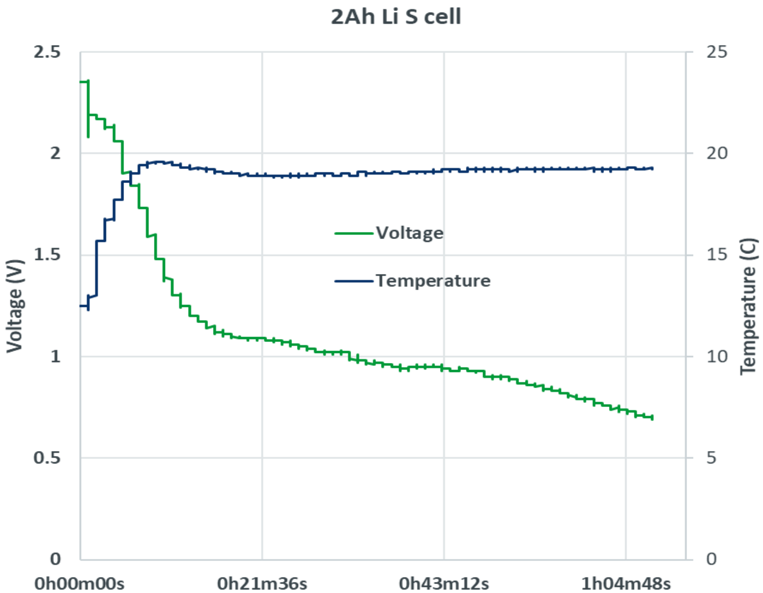
Multilayer stack with different capacities

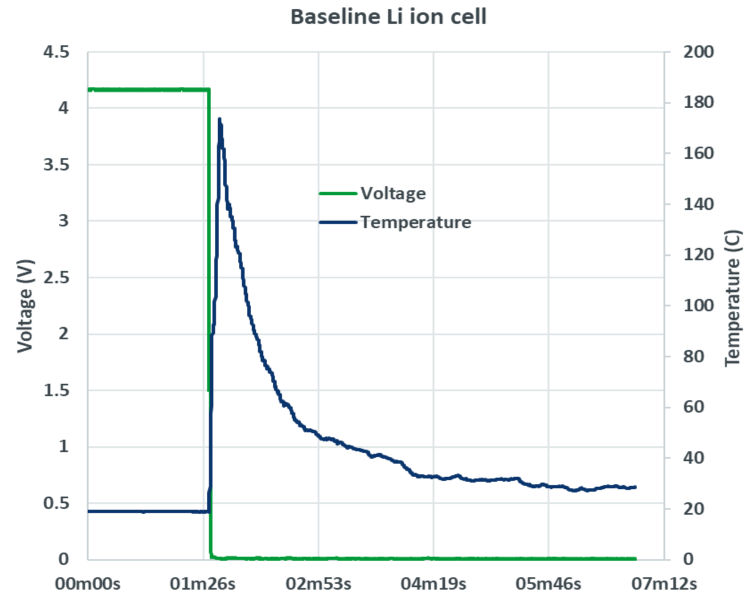
- Pilot coated S cathodes of various loadings (2.5 → 6 to 9 mg/cm² S)
- Li/Cu → pure Li foil

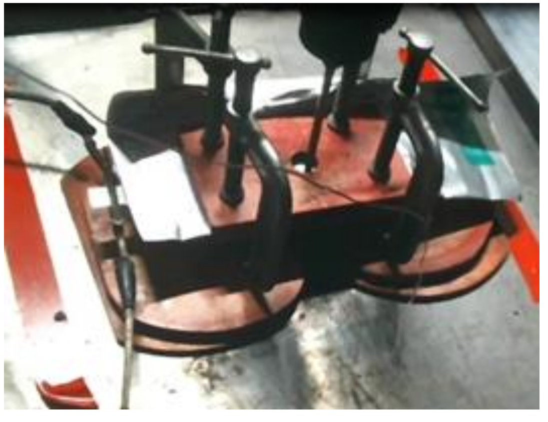


- 700mAh cell: 2.5mg/cm² S, Li/Cu anode, C/10
- 2Ah cell: 6mg/cm² cathode, pure Li anode, C/30
- E/S ratio ~5, ambient temperature

LSB 2Ah cell Safety demonstration

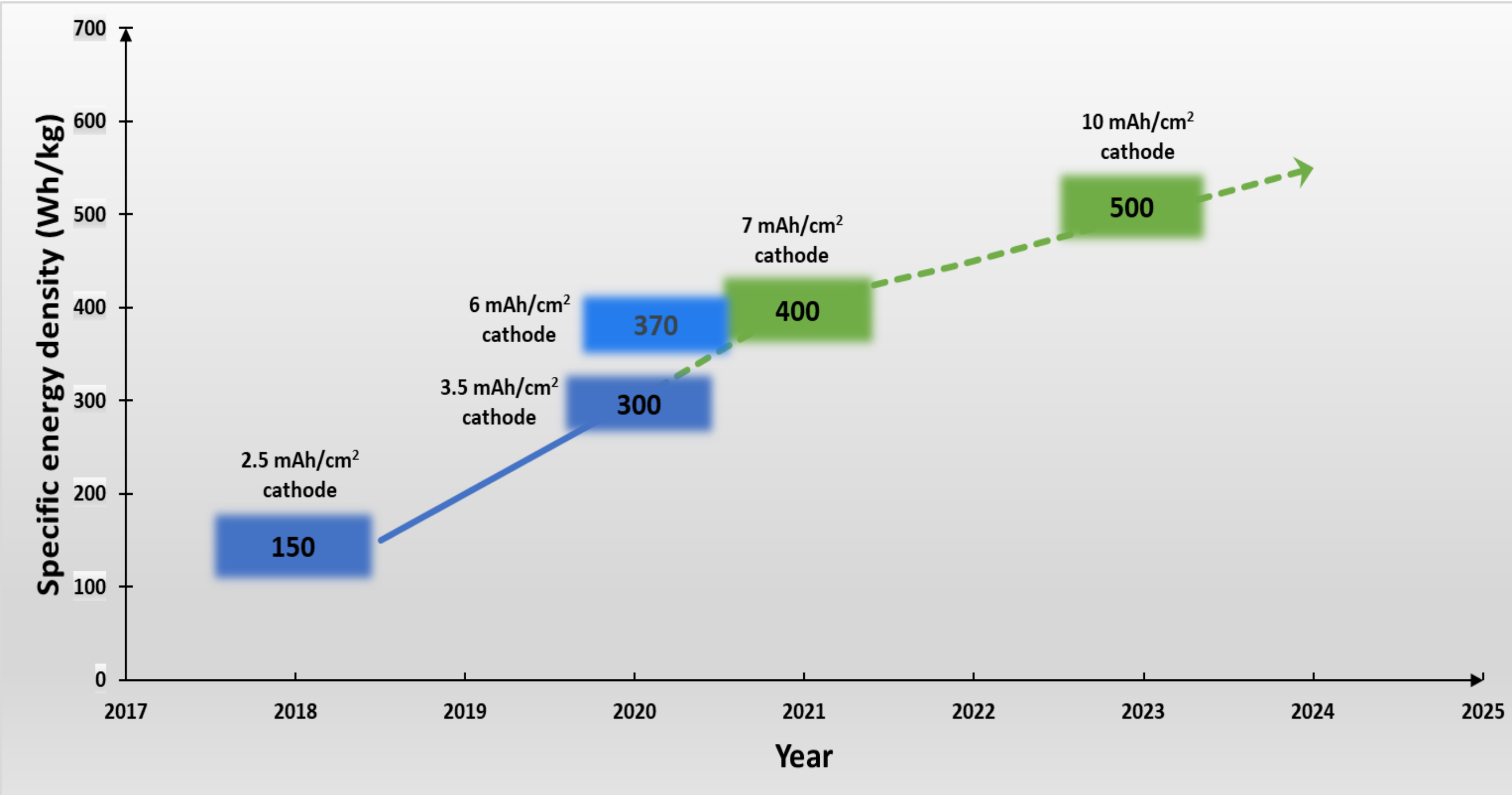






2Ah Li S cell (left)and 2Ah Li ion cell (right) nail penetration tests

Navitas Lithium Sulfur Battery Roadmap



Along with the development of ceramic based cathode and bifunctional separator, Navitas is working towards the commercialization of high energy LSB.

Current Challenges for Navitas in LSB

Challenges

Cycle life at high energy design (up to 10 mAh/cm^2 electrode to reach 500 Wh/kg)	Li anode surface protection and electrode re-design
Sulfur utilization at high energy design (high S loading)	Cathode host and composition
Li metal anode protection	Protection layer/electrolyte additives
Electrolyte/S ratio ≤3 mL / g for high energy design	Reduce reaction between Li and electrolyte
Cell Swelling	Reduce reaction between Li and electrolyte
Self-discharge rate <2% per month	Separator/ Anode and electrolyte development

Navitas welcomes further collaborations from university, national lab, and industry partners to advance LSB technology.

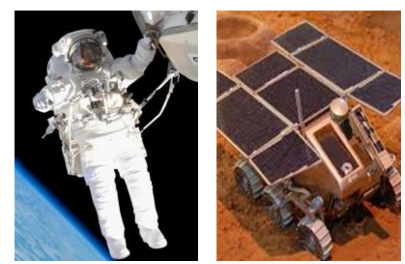
Summary: Navitas Current and Future Focus in LSB

- Scaling up the cathode material and fabricate Li-S 28V, 30Ah battery in aviation platform with BMS (Navy SBIR Phase II)
- Optimizing and scaling up bifunctional separator for LSB (NASA SBIR Phase II)
- Extended Cycle Life High Energy Lithium Sulfur Batteries (NASA SBIR Phase I, completed)
- Further developing R2R bifunctional separator and test LSB with AIAA protocols required for space qualification (USAF & NASA, application pending)
- Adopting solid state electrolyte (Army SBIR Phase II, with a university partner)
- Conducting Li metal anode protection (DOE Battery 500 Phase II, with DOE lab)

Navitas LSB targeting 10X VRLA and 1.5X conventional LIB specific energy

NAVAIR 28V, 30Ah Battery in F/A-35 platform

Batteries for soldier / airman portable powder and UAV applications



NASA space suits, landers, rovers, science platforms, solar arrays

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