



Materials Challenges for Solid-State Batteries in Aerospace Applications

Yi Lin,¹ Vesselin Yamakov,¹ Ji Su,² Donald Dornbusch,³ Rocco Viggiano³

¹Analytical Mechanics Associates (AMA), Hampton, VA 23666; ²Advanced Materials & Processing Branch, NASA Langley Research Center (LaRC), Hampton, VA 23681; ³Materials Chemistry and Physics Branch, NASA Glenn Research Center (GRC), Cleveland, OH 44135.

2026 Space Power Workshop

**Torrance, CA
April 23, 2026**

All images & videos credit: NASA



NASA's Interest in Solid State Batteries (SSBs)

SABERS: Solid-state Architecture Batteries for Enhanced Rechargeability and Safety (2019-2024)



SPEARS: Solid Power for Extreme Environment Adaptability and Resilience in Space (2026-)

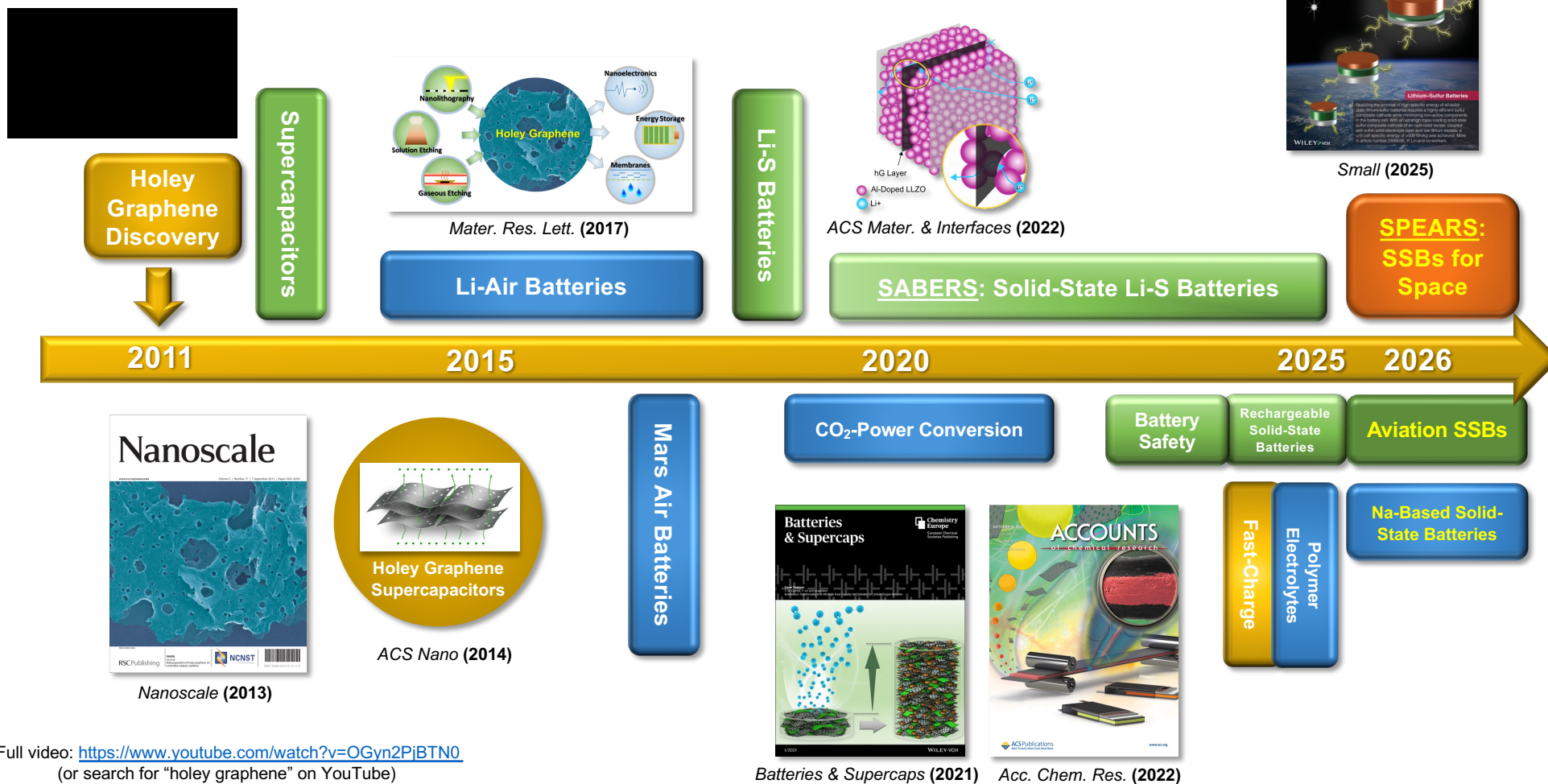
For electric aviation:

- ❑ The primary barrier to electric aviation is battery performance
 - ❑ Aerospace batteries require: safety, high energy density, fast discharge rate, longevity, lightweight packaging, and scalability
- ❑ Conventional lithium ion batteries (LIBs) are intrinsically unsafe:
 - ❑ With the use of organic electrolyte, conventional LIBs possess narrow operational temperature range and may undergo thermal runaway when heated or overcharged

For extreme space environment:

- ❑ No volatile or flammable liquids, allowing safe operation even in vacuum
- ❑ Solid-solid interfaces enable cell resiliency and longevity
- ❑ Cell performance tunable for energy, power, and durability
- ❑ Expanded temperature tolerance with extreme low temperature survivability *and* high temperature operation
- ❑ Reduced thermal management allows for lighter designs and longer missions

Battery Materials at NASA LaRC: A Personal Journey



*Full video: <https://www.youtube.com/watch?v=OGyn2PiBTN0>
(or search for "holey graphene" on YouTube)

Aviation Batteries from Materials Perspective

Energy

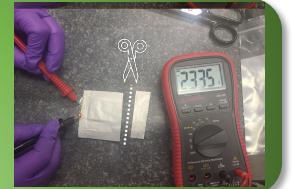
Battery chemistries with high theoretical specific energy (e.g.: Li-S: 2510 Wh/kg)



- High specific energy is one of the most critical metrics for aviation batteries
- Achieving 500 Wh/kg at the pack level may enable electric aircraft beyond 50 PAX

Safety

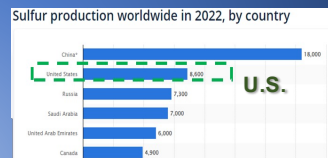
Made with non-flammable solid-state components and intrinsically much safer



- Aviation batteries require extremely low risk of battery failure such as thermal runaway
- Solid-state electrolytes are intrinsically non-flammable and may endure both hot and cold temperatures

Supply Chain

Primarily use abundant and inexpensive electrode materials



- Electrode materials of choice should be abundant and preferably sourced in the U.S.

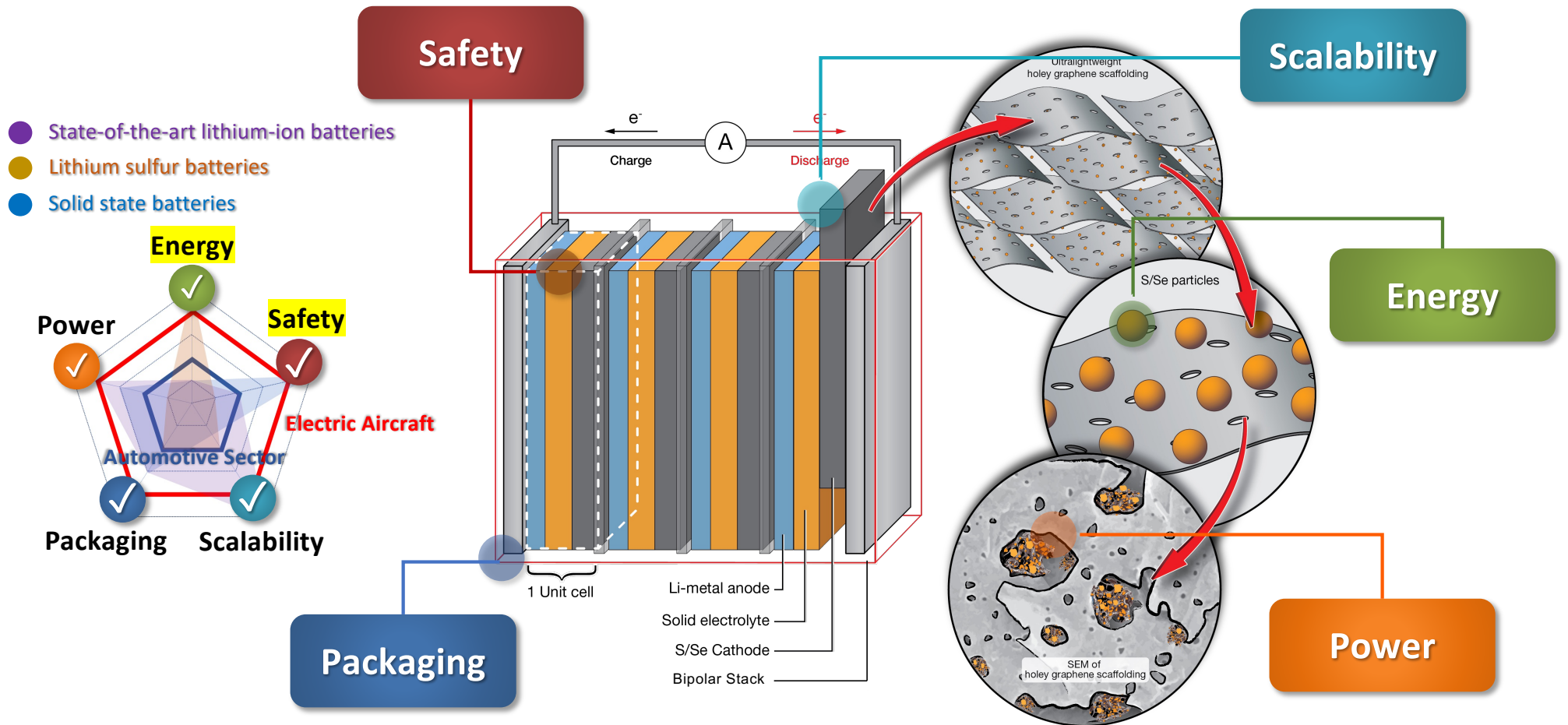
Sustainability

Choice of electrode materials, fabrication methods, recycling potentials



- Solid state batteries may fully utilize solvent-free manufacturing and enable convenient recycling

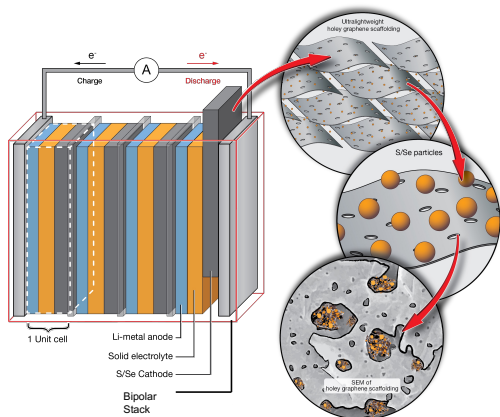
SABERS: Feasibility of SSBs for Electric Aircraft



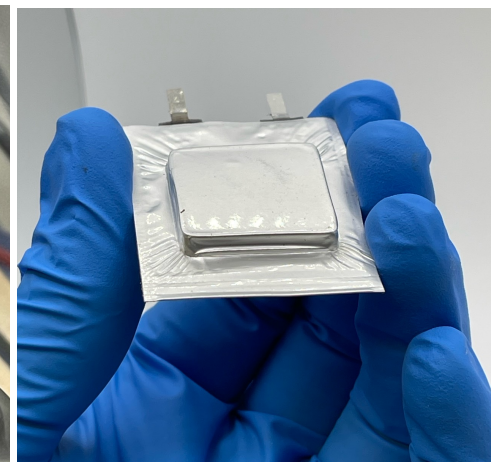
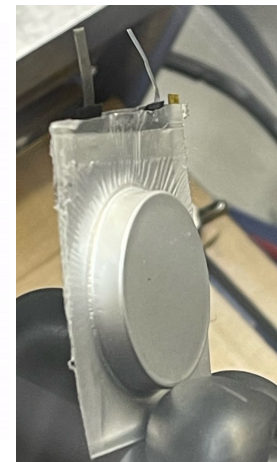
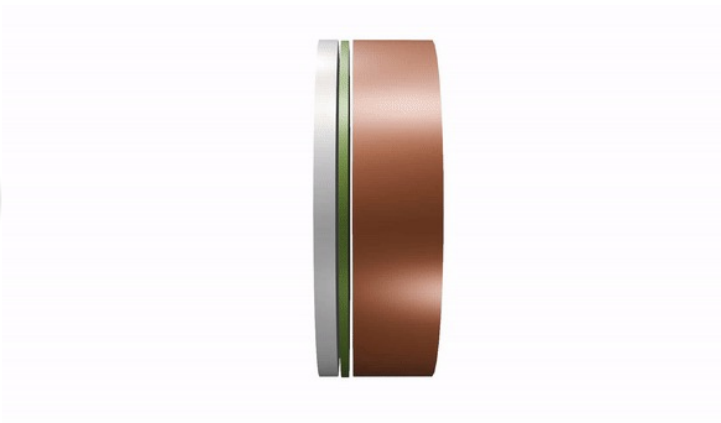
SABERS Concept and Prototype

From Energy Storage Materials Science to Aviation Battery Prototype Cells

Proposed Concept (2019)



Prototype 5-Layer Li-S Bipolar Stack Pouch Cell SSBs (2024)

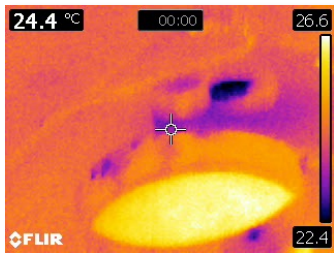


- ☐ Lithium-sulfur (Li-S) SSBs exhibit potential to achieve >500 Wh/kg in specific energy
- ☐ Demonstration of prototype multi-layer Li-S bipolar stack pouch cell SSBs with various form factors with consistent performance
- ☐ Power and cycling performance remain challenging

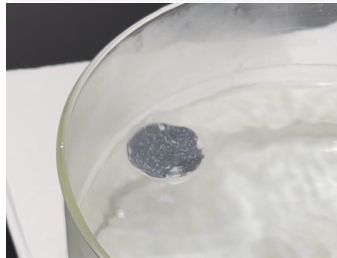
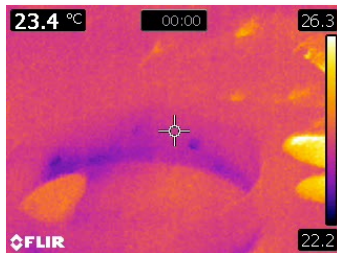
Safety and Operation under Hot and Cold

Solid-state batteries are intrinsically safer and exhibit wide temperature adaptability

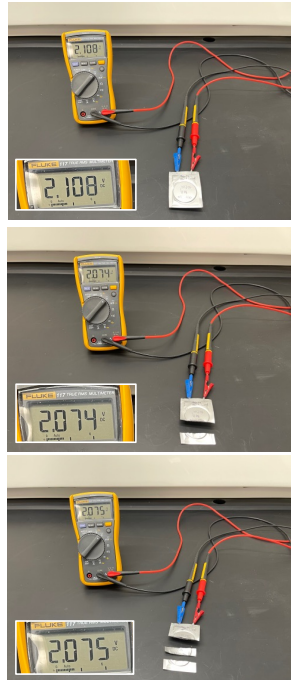
Li Metal with Liquid Electrolyte
Conventional Pouch Cell



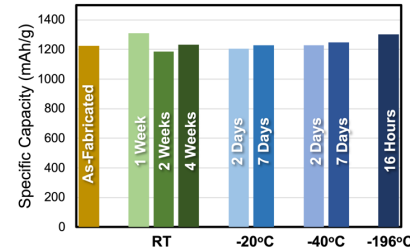
Li Metal with Solid Electrolyte
SABERS Pouch Cell



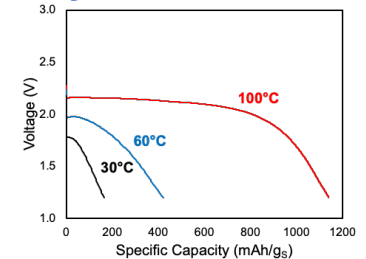
- Li metal anode with liquid electrolyte (flash point ~40°C) may spontaneously catch fire when contacting water, while SABERS solid-state electrolyte is not flammable when Li metal reacts with water.



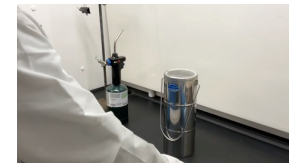
Safe Against Damage



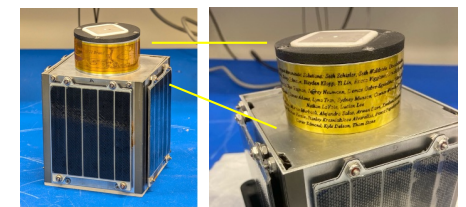
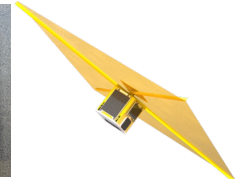
Storage in Cold and Extreme Cold



Perform in Warm and Hot



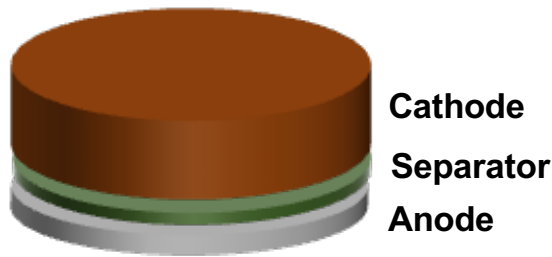
SABERS Cells Removed from Liquid Nitrogen Reservoir



SABERS Coin Cell in SmallSat (Launched in Jan. 2025)

- SABERS all-solid-state battery cells exhibit excellent shelf life and survive from low and extremely low temperatures. They exhibit normal functions after warming up to typical test temperatures.
- SABERS cells are safe in warm and hot temperatures (currently tested up to 150°C) and perform better under higher temperatures due to increased ionic conductivity of solid electrolytes.

Materials Challenges in SSBs



Separator: A solid electrolyte layer:

- Ionic conductivity
- Processibility
- Mechanical properties
- Chemical/electrochemical stability against anode

Anode (foil, substrate, or composite):

- Uneven Li stripping and plating
- Dendrite formation
- Volume change

Solid-State Cathode composite:

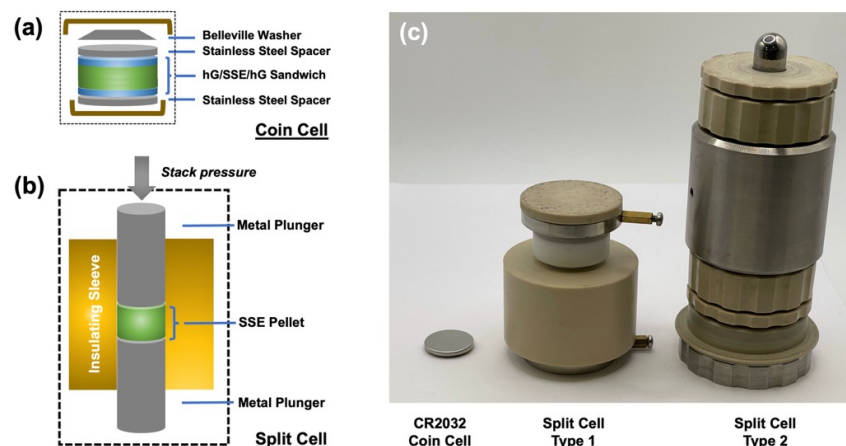
- Cathode is a multi-component composite
 - Cathode active material (CAM), solid electrolyte “catholyte”, carbon, and binder
- Processing: How to mix them?
 - Mixing sequence
 - Mixing intensity
 - Wet vs. dry
- Electrochemistry: How to maximize performance?
 - Ion conducting pathway
 - Electron conducting pathway
 - Side reactions (e.g. catholyte decomposition)

And ALL the interfaces!!

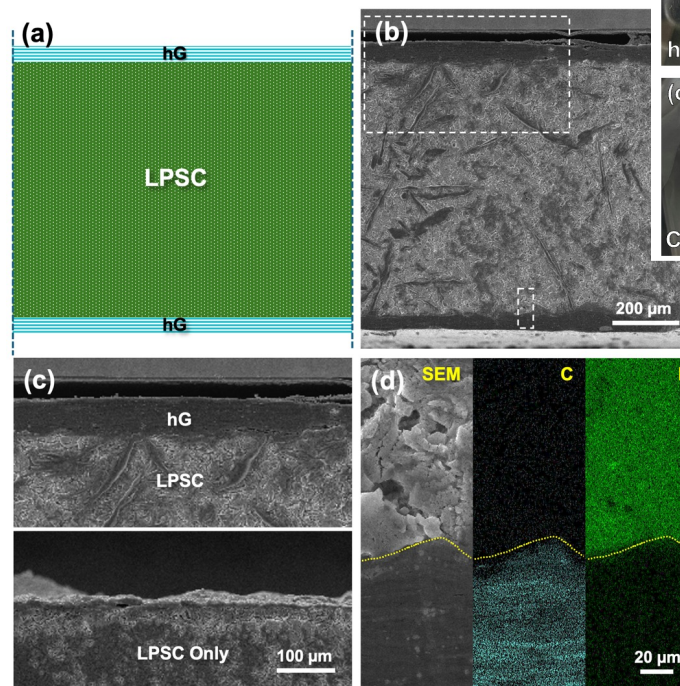
...and packaging.

Challenge 1: Solid Electrolyte Ionic Conductivity

- ❑ Solid electrolyte ionic conductivity is pressure dependent. But to what extent?
- ❑ Can coin cells be used for reliable ionic conductivity measurements?



	Split Cells	Coin Cells
Stack Pressure	Varies	Low
Industry Standard Casing	No	Yes
Disc Fabrication	In Situ	Freestanding
Airtight Testing	Moderate	Excellent



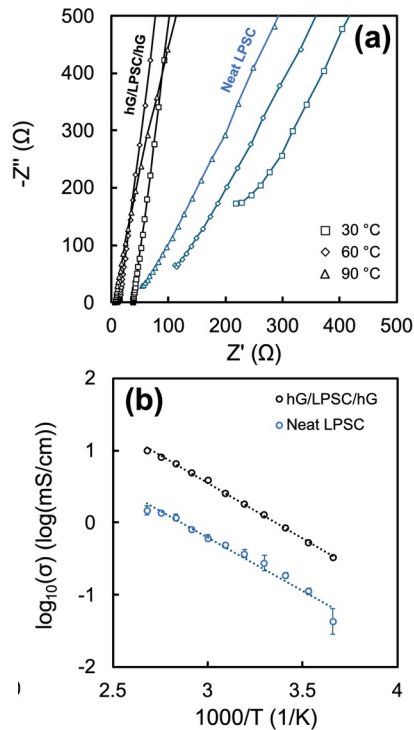
- ❖ hG: Holey graphene
- ❖ VGCF: Vapor grown carbon fiber
- ❖ C45: Super-P C45 (carbon black)
- ❖ KB: Ketjen black

- ❑ Using dry-pressable hG as current collector electrodes allows consistent fabrication of robust, freestanding hG/solid electrolyte/hG sandwich discs, enabling reliable ionic conductivity measurements with coin cells

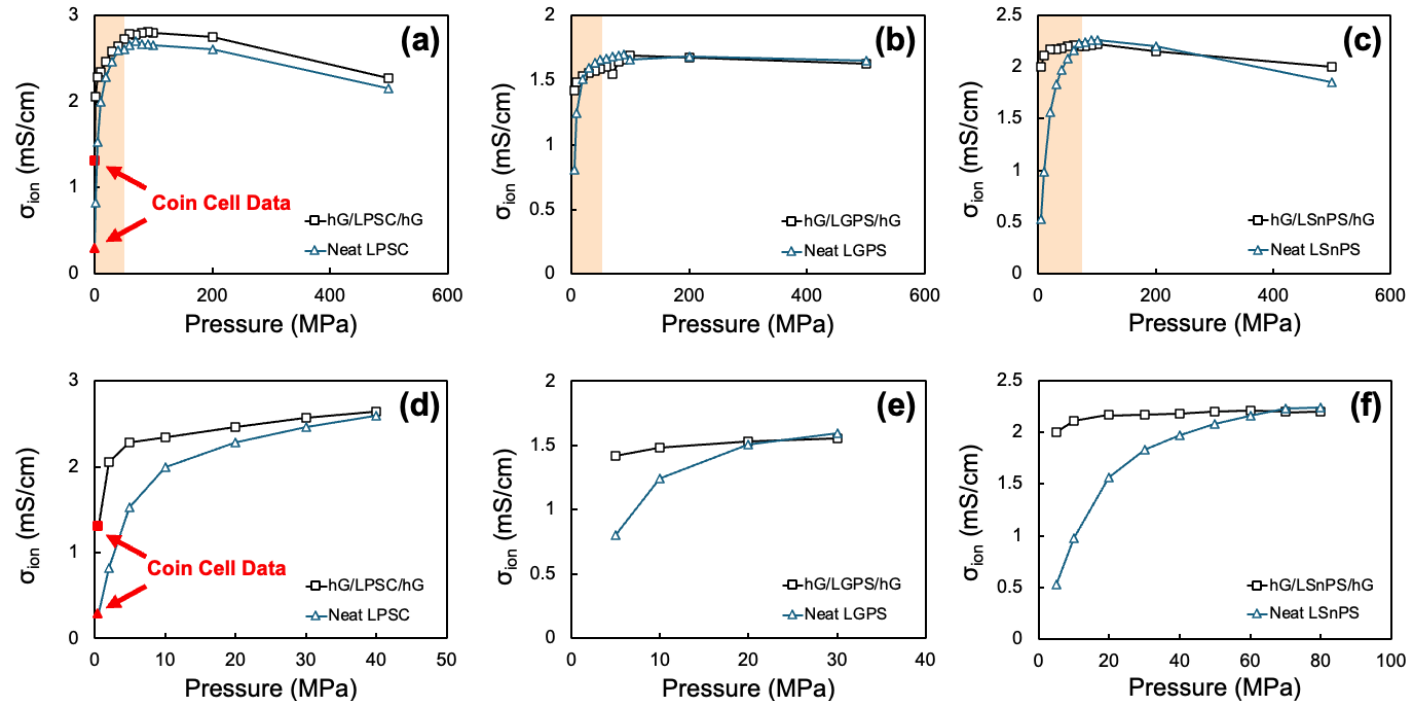
Front. Energy Res. **2025**, 13, 1684653.

Challenge 1: Solid Electrolyte Ionic Conductivity

Coin Cells



Split Cells with Precise Stack Pressure Control



- ❑ Conformal hG-SSE contact is critical to enable accurate account for the true ionic conductivity of SSEs under low stack pressure conditions
- ❑ Ionic conductivity of sulfide electrolytes decreases with stack pressure, but the reduction might not be as steep as some experiments suggest

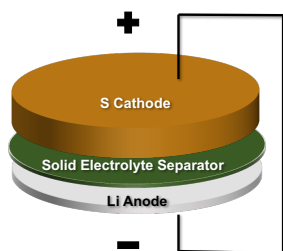
Front. Energy Res. **2025**, 13, 1684653.

❖ LPSC: lithium phosphorus sulfur chloride
❖ LGPS: lithium germanium phosphorus sulfide
❖ LSnPS: lithium tin phosphorus sulfide

Challenge 2: Sulfur Composite Cathode

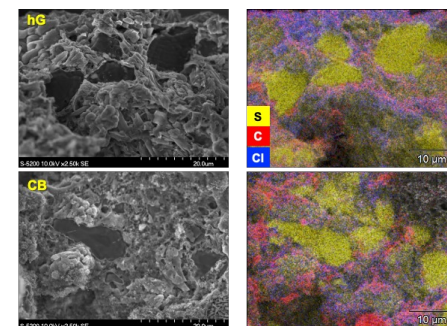
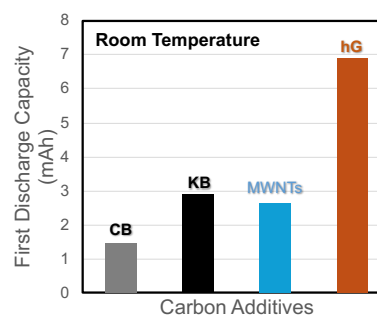
□ How to overcome the intrinsic insulating properties of S?

A Solid-State Li-S Cell

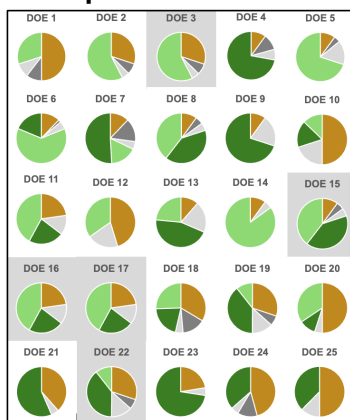
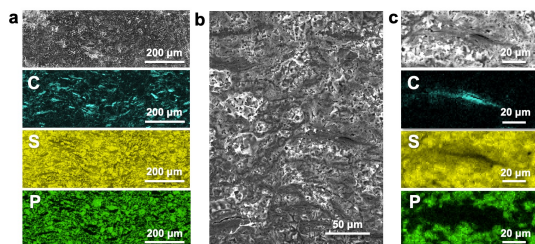


- **Cathode:** S and necessary additives to make it electrically (thus carbon) and ionically (thus solid electrolyte) conductive
- **Solid electrolyte (SSE) separator:** A solid layer that conducts Li ion but insulates electrons
- **Anode:** Li metal

Holey graphene enabled solvent-free processing of S composite cathode with superior performance vs. other carbon additives.

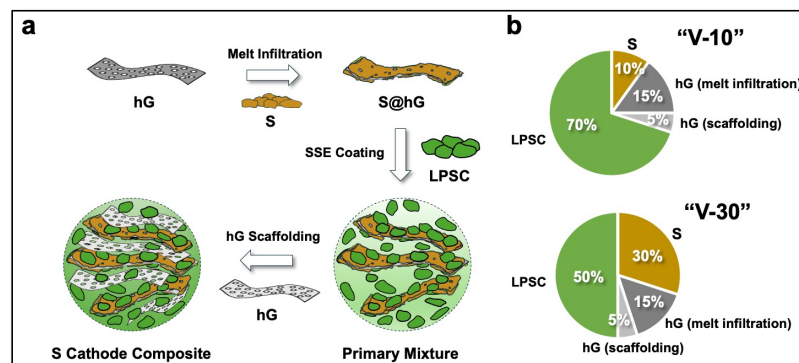


A Design-of-Experiment (DOE) Guided Optimization



Optimized cathode microstructures enabled maximal S utilization for battery reactions.

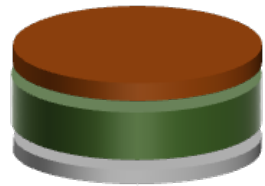
S Composite Cathode Fabrication and Compositions



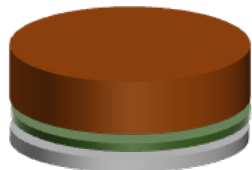
- Small 2025, DOI:10.1002/smll.202409536.

Challenge 2: Sulfur Composite Cathode

□ How to realize the specific energy promise of solid-state Li-S batteries?



- **Thin** cathode (less S)
- **Thick** SSE
- Energy **inefficient**

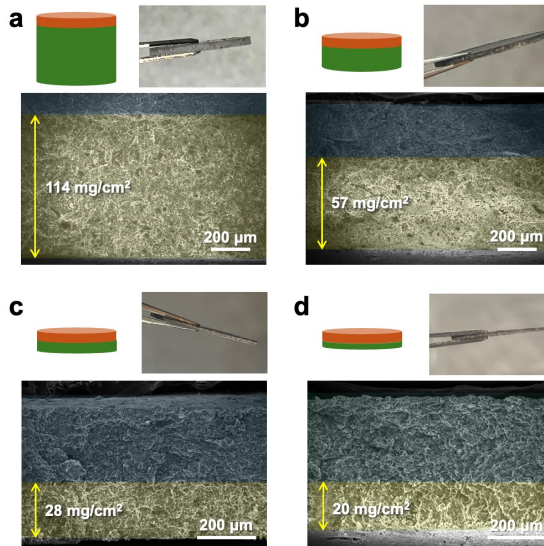


- **Thick** cathode (more S)
- **Thin** SSE
- Energy **efficient**

Solvent-free fabrication of thick S cathode exhibits excellent performance with optimized composition and processing

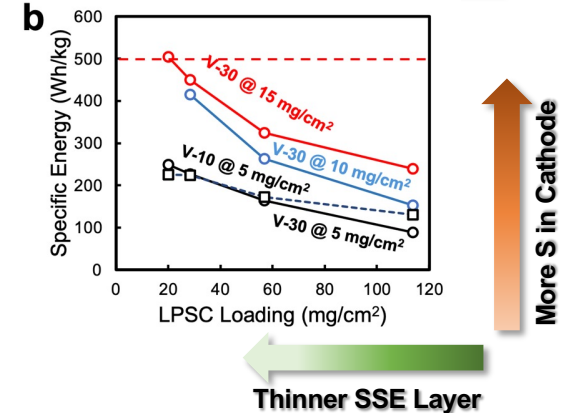
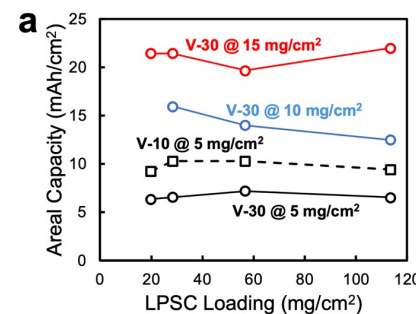
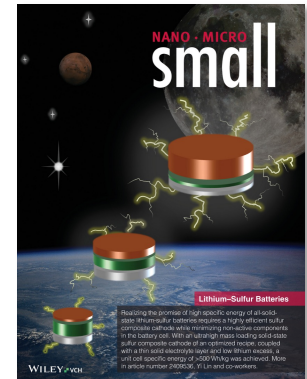
- Thick cathodes are difficult to prepare using conventional solvent-based approaches.
- Nonoptimized thick cathodes typically exhibit significantly reduced performance due to poor electrical and ion transport

Thick S Cathode with Thin SSE Layer



Thick SABERS S Cathode + Thin SSE enabled:

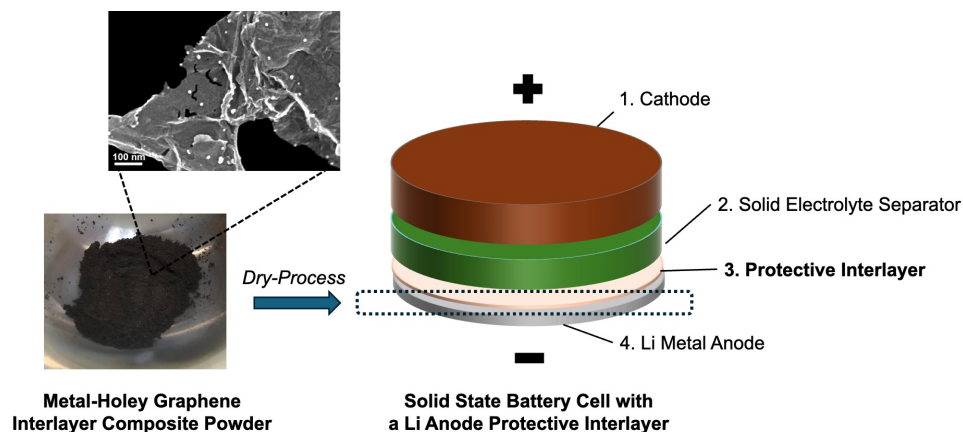
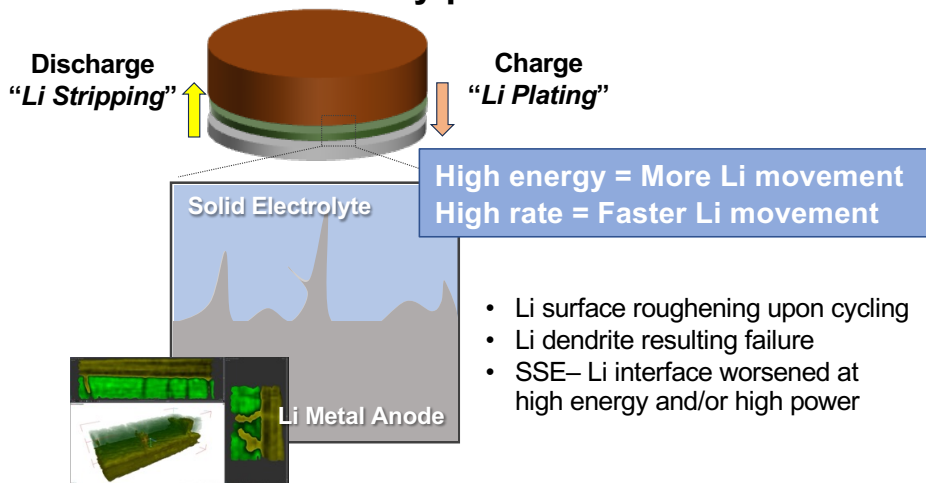
- >20 mAh/cm² cathode areal capacity (highest reported)
- >500 Wh/kg unit cell (cathode + solid electrolyte + Li anode) specific energy (highest reported)
- All achieved with minimal stack pressure (< 2 MPa vs. 10 – 200 MPa)



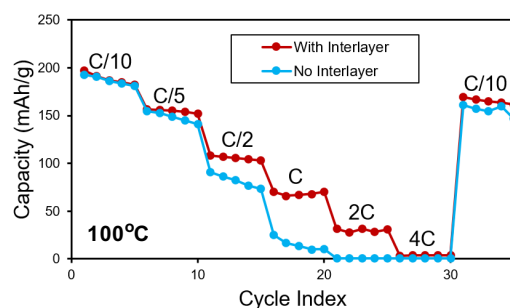
Unit cell specific energy can be further improved to >600-800 Wh/kg with sufficiently thin (<100 μm) SSE layer.

Challenge 3: Anode - Solid Electrolyte Interface

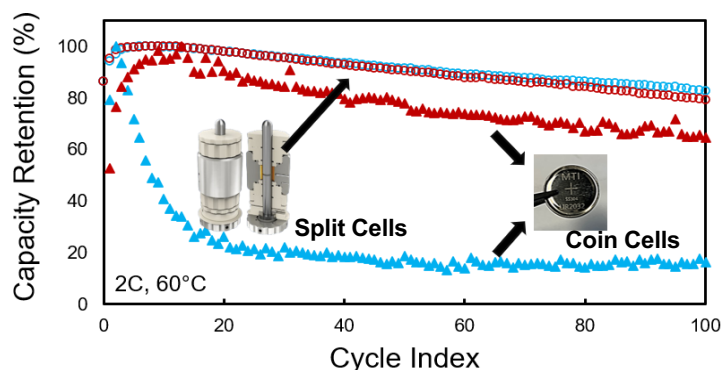
□ How to effectively protect the most vulnerable interface in a rechargeable solid-state battery?



Improved Power/Rate Performance

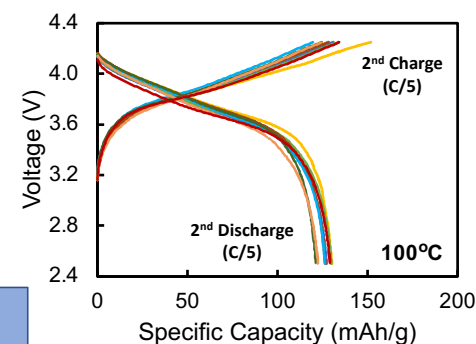


ACS Appl. Energy Mater. 2026, in press.



Protective interlayer enabled excellent cycling performance at low stack pressure (coin cells)

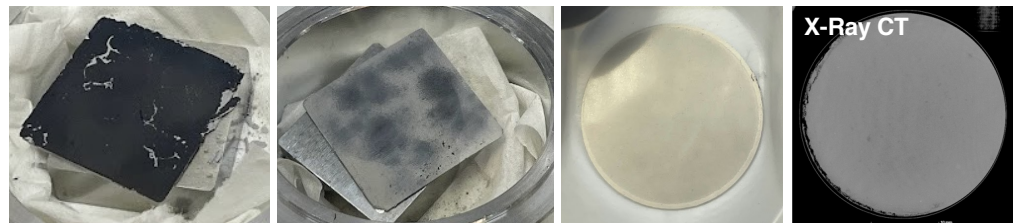
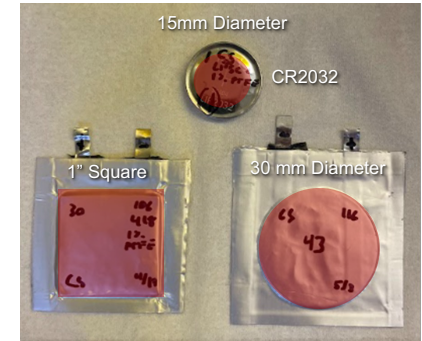
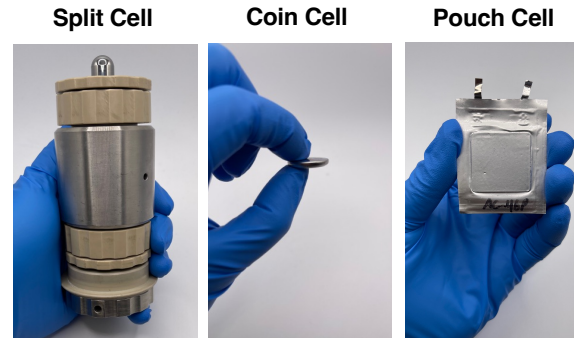
Dry-Pressed Interlayer Allowed for Consistent Cell Fabrication



Challenge 4: Scale Up Engineering

□ How to scale up the cell fabrication with retained robustness and performance?

	Split Cells	Coin Cells	Pouch Cells
Stack Pressure Control	Excellent	Low	Excellent
Industry Standard Casing	No	Yes	Customized
Part Availability	Moderate	Yes	Yes
Cost	High	Low	Moderate
Field Testing Capable	No	Yes	Yes
Practical Applications	No	Moderate	Yes



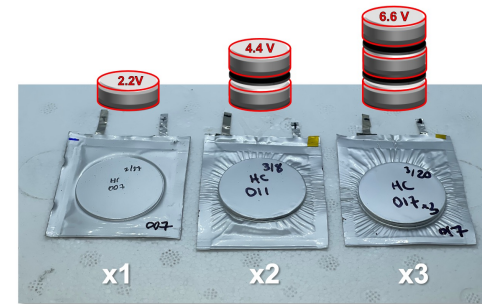
Generation 1
All Powder Processing

Generation 2
Binder in SSE Layer

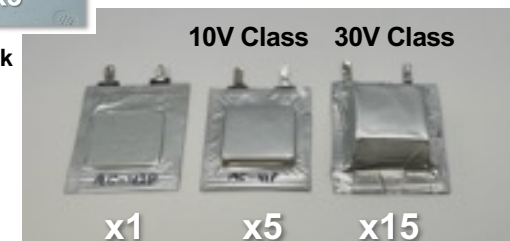
Generation 3
Binder in Both SSE Layer and Cathode

- Dry powder processing for cathode and SSE layer were successful in coin cell fabrication but challenging for pouch cells due to much increased aspect ratio (area : thickness)
- The use of microfibrinous PTFE binder significantly improves mechanical performance of solid layers with retained cell performances

Circular format pouch cells were first attempted to establish workflow and cell performance baselines



Single- and Multilayer Bipolar Stack
"Cookie" Pouch Cells



Single- and Multilayer Bipolar Stack
"Cracker" Pouch Cells

NASA Battery Materials Team Capabilities



Thrust I

A Fundamental Knowledge Package
Experiments + Computation

Battery Material
Chemistry and
Processing

Battery Cell
Performance

Mechanistic
Investigation

Computational
Models

Non-Destructive
Evaluation

Machine Learning

Thrust II

Small-scale Prototyping
A Bridge to Demo and Commercialization

Scale-up
Engineering & Testing

Customized
Cells & Packs

Lab-Scale Automation

Acknowledgements



- ❑ NASA Convergent Aeronautics Solutions (CAS) Project
- ❑ NASA Transformational Tools and Technologies (TTT) Project
- ❑ NASA Game Changing Development (GCD) Program



Current Team Members:

- | | |
|--------------------|--------------------------|
| ❑ Ji Su | ❑ Rocco Viggiano (GRC) |
| ❑ Vesselin Yamakov | ❑ Donald Dornbusch (GRC) |
| ❑ Dan Perey | ❑ Seth Schisler (ARC) |
| ❑ Sang-Hyon Chu | |
| ❑ Hailey Moore | Retirees: |
| ❑ Joe Smith | ❑ John Connell (retired) |
| ❑ Jin Ho Kang | ❑ John Hopkins (retired) |
| ❑ Godfrey Sauti | ❑ Glen King (retired) |

❑ Student Interns and Trainees:

- ❑ **2019 – 2022:** Elizabeth Barrios, Bryson Clifford, Christian Plaza-Rivera, April Rains, Brandon Walker
- ❑ **2022:** Daniel Caicedo, Abigail Durgin, Prabhat Jandhyala, Bona Kim, Sophie Kiley, Ashley Lam, Thomas Neufus, Rehan Rashid, Lucy Somerville, Luis Valdez
- ❑ **2023:** Melissa Chang, William Dai, Sayyam Deshpande, Amol Gupta, Ethan Higginbotham, Shane Lindsey, Claudia Lopez, Alanis Matias-Perez, Abraham Nicolson, Coby Scrudder, Aoife Zuercher
- ❑ **2024:** Demetrius Burns, Autumn Avery, Alan Cancel, Hanjing Chen, Kelsey Crawford, David Forslof, Ashley Gomez, Alison Kavanagh, Kelton McGrath, Jason Packard, Vergil Schreiber, Daniel Thornton
- ❑ **2025:** Demetrius Burns, Karen Cabrera, Alan Cancel, Marion Fowler, Mason Graves, Cameron Jensen, Kyle Johns, Idil Kilic, Heesoo Kim, Josh Klatzkow, Rose Yesl Lee, Jason Packard, Adi Rangyyan, Eric Schwaller, Jacob Sheldon, J. Chelsea Stephens, Justin Wang, Cole Wanner, Sean Wilkerson, Jerry Zhang
- ❑ **2026:** Paola Marcela Algeria Orellana, Yolmarie Del Valle Gonzalez, Kira Hollowed, Cameron Jensen, Heesoo Kim, Idil Kilic, Rose Yesl Lee