Materials Challenges for Solid-State Batteries in Aerospace Applications

Yi Lin,[1] Vesselin Yamakov,[1] Ji Su,[2] Donald Dornbusch,[3] Rocco Viggiano[3]

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

2026 Space Power Workshop

Torrance, CA
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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-)

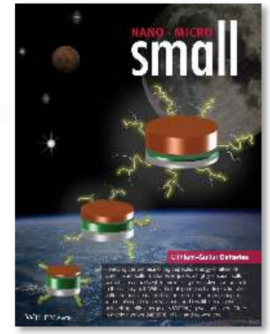
For electric aviation:

- **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

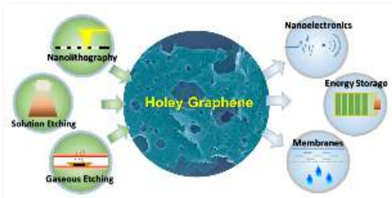
Battery Materials at NASA LaRC: A Personal Journey



Small **(2025)**

Holey Graphene Discovery

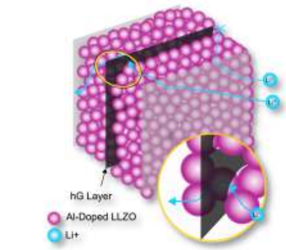
Supercapacitors



Mater. Res. Lett. **(2017)**

Li-Air Batteries

Li-S Batteries

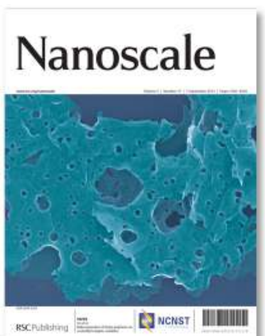


ACS Mater. & Interfaces **(2022)**

SABERS: Solid-State Li-S Batteries

SPEARS: SSBs for Space

2011 — **2015** — **2020** — **2025** — **2026**



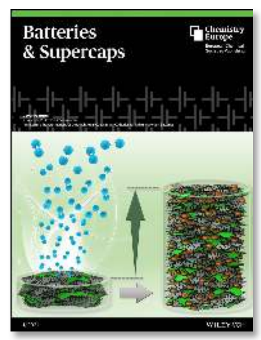
Nanoscale **(2013)**

Holey Graphene Supercapacitors

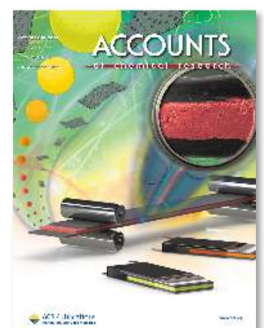
ACS Nano **(2014)**

Mars Air Batteries

CO_2-Power Conversion



Batteries & Supercaps **(2021)**



Acc. Chem. Res. **(2022)**

Battery Safety

Rechargeable Solid-State Batteries

Aviation SSBs

Fast-Charge

Polymer Electrolytes

Na-Based Solid-State Batteries

*Full video: https://www.youtube.com/watch?v=OGyn2PjBTN0
(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

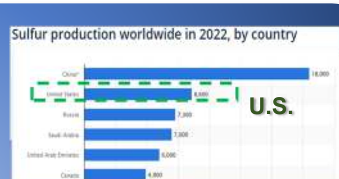
Safety

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



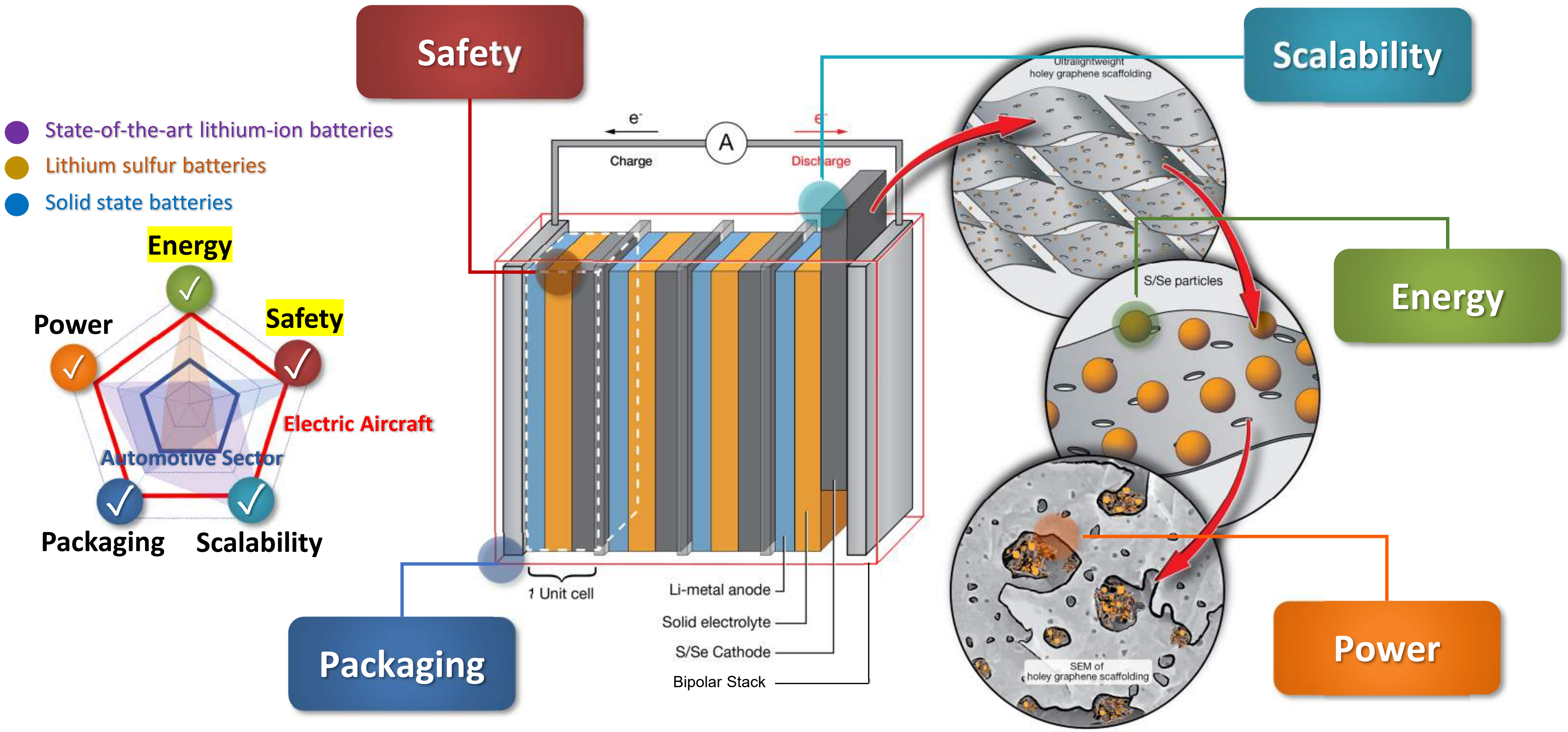
- Electrode materials of choice should be abundant and preferably sourced in the U.S.

Sustainability

Choice of electrode materials, fabrication methods, recycling potentials

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

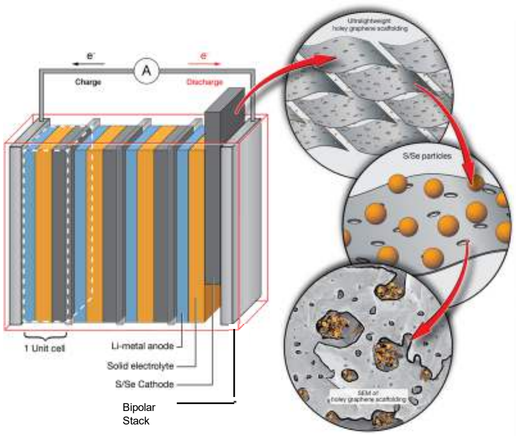
SABERS: Feasibility of SSBs for Electric Aircraft



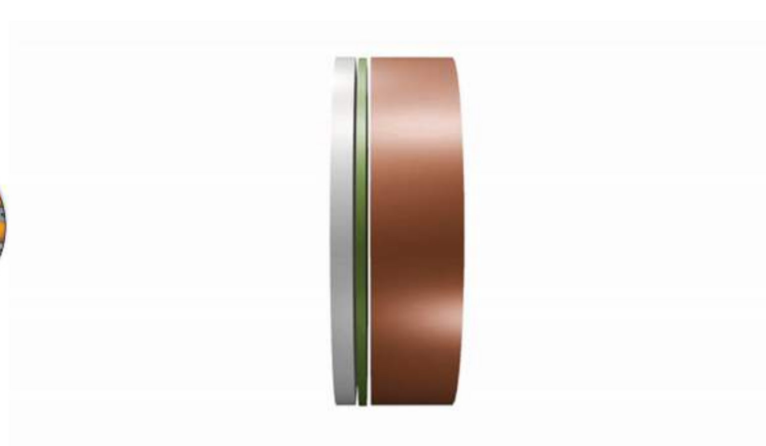
SABERS Concept and Prototype

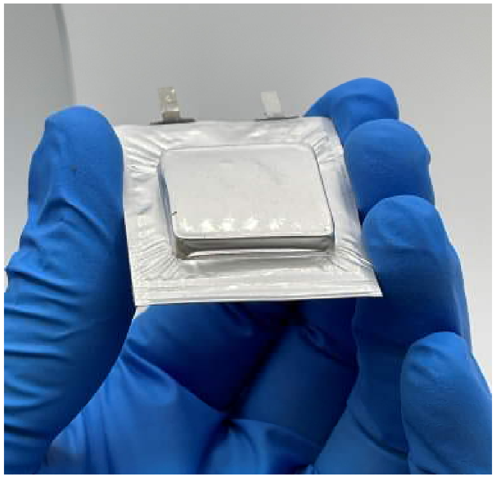
From Energy Storage Materials Science to Aviation Battery Prototype Cells

Proposed Concept (2019)



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



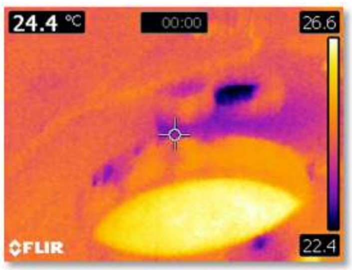


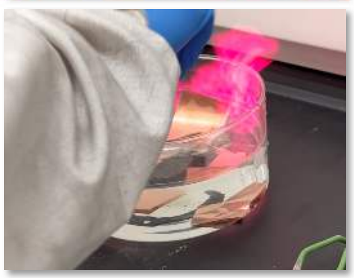
- ❑ Lithium-sulfur (Li-S) SSBs exhibit potential to achieve >500 Wh/kg in specific energy
- ❑ Demonstration of prototype multi-layer Li-S bipolar stack pouch cell SSBs with various form factors with consistent performance
- ❑ Power and cycling performance remain challenging

Safety and Operation under Hot and Cold

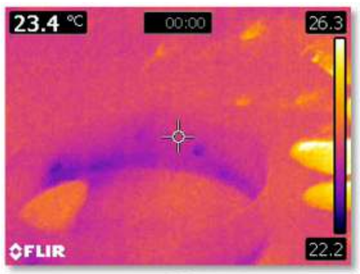
Solid-state batteries are intrinsically safer and exhibit wide temperature adaptability

Li Metal with Liquid Electrolyte
Conventional Pouch Cell

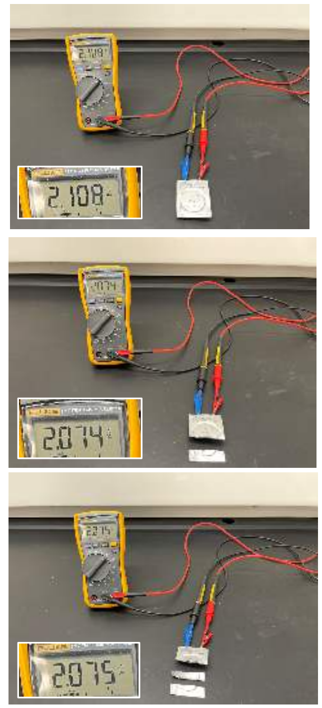




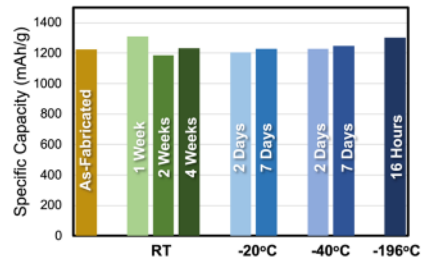
Li Metal with Solid Electrolyte
SABERS Pouch Cell



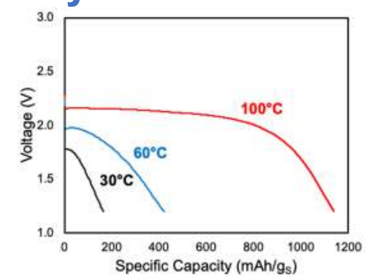
- Li metal anode with liquid electrolyte (flash point ~40°C) may spontaneously catch fire when contacting water, while SABERS solid-state electrolyte is not flammable when Li metal reacts with water.



Safe Against Damage

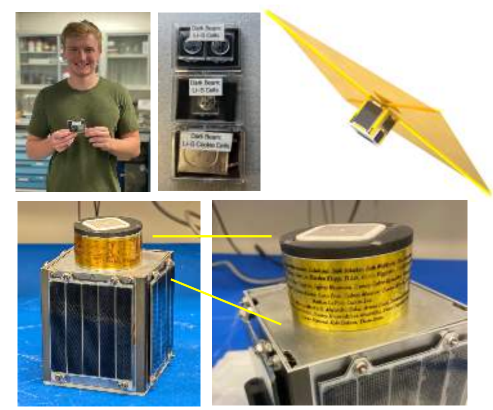


Storage in Cold and Extreme Cold



Perform in Warm and Hot

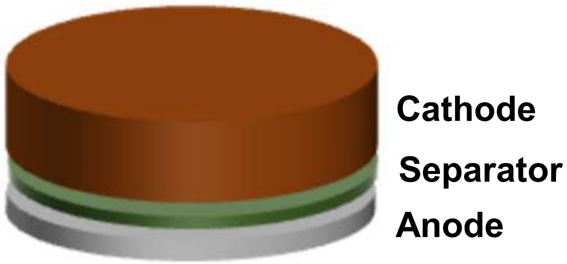
SABERS Cells Removed from Liquid Nitrogen Reservoir



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

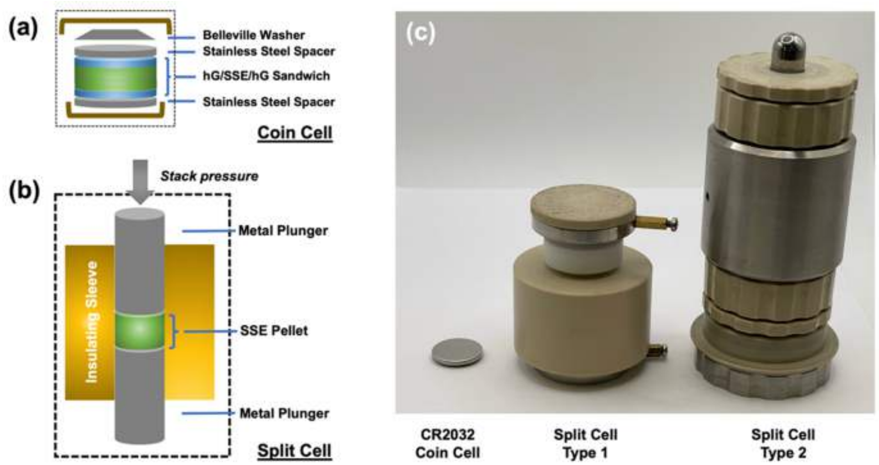
Solid-State Cathode composite:
- Cathode is a multi-component composite
  - Cathode active material (CAM), solid electrolyte “catholyte”, carbon, and binder
- Processing: How to mix them?
  - Mixing sequence
  - Mixing intensity
- Electrochemistry: How to maximize performance?
  - Ion conducting pathway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

And ALL the interfaces!!

…and packaging.

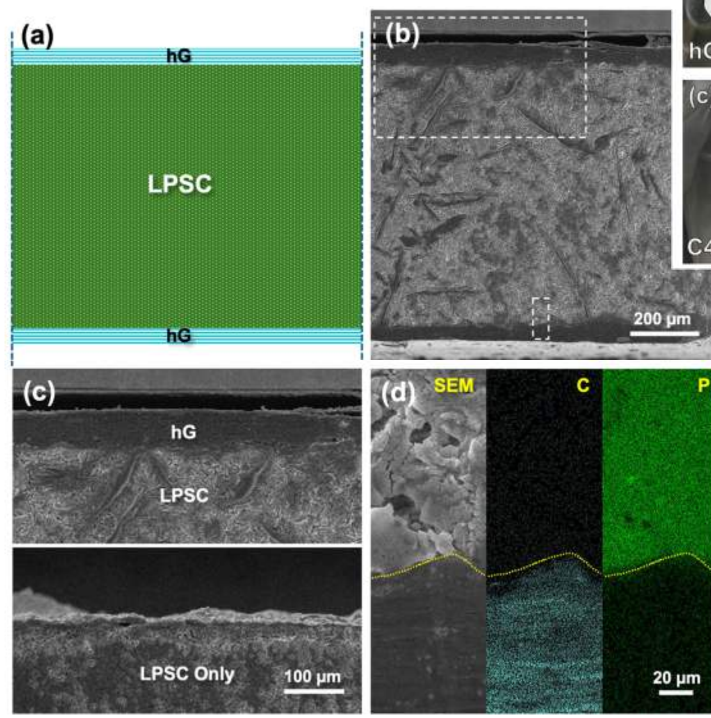
Challenge 1: Solid Electrolyte Ionic Conductivity

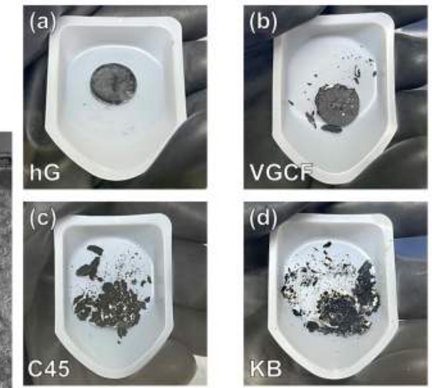
- ❑ **Solid electrolyte ionic conductivity is pressure dependent. But to what extent?**
- ❑ **Can coin cells be used for reliable ionic conductivity measurements?**



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

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



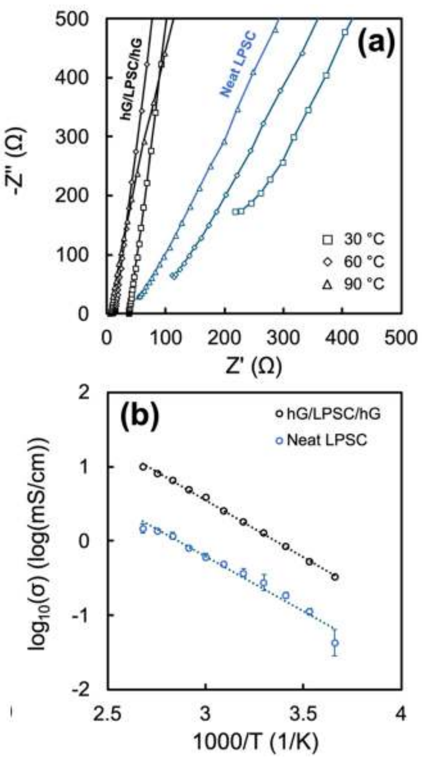


- ❖hG: Holey graphene
- ❖VGCF: Vapor grown carbon fiber
- ❖C45: Super-P C45 (carbon black)
- ❖KB: Ketjen black

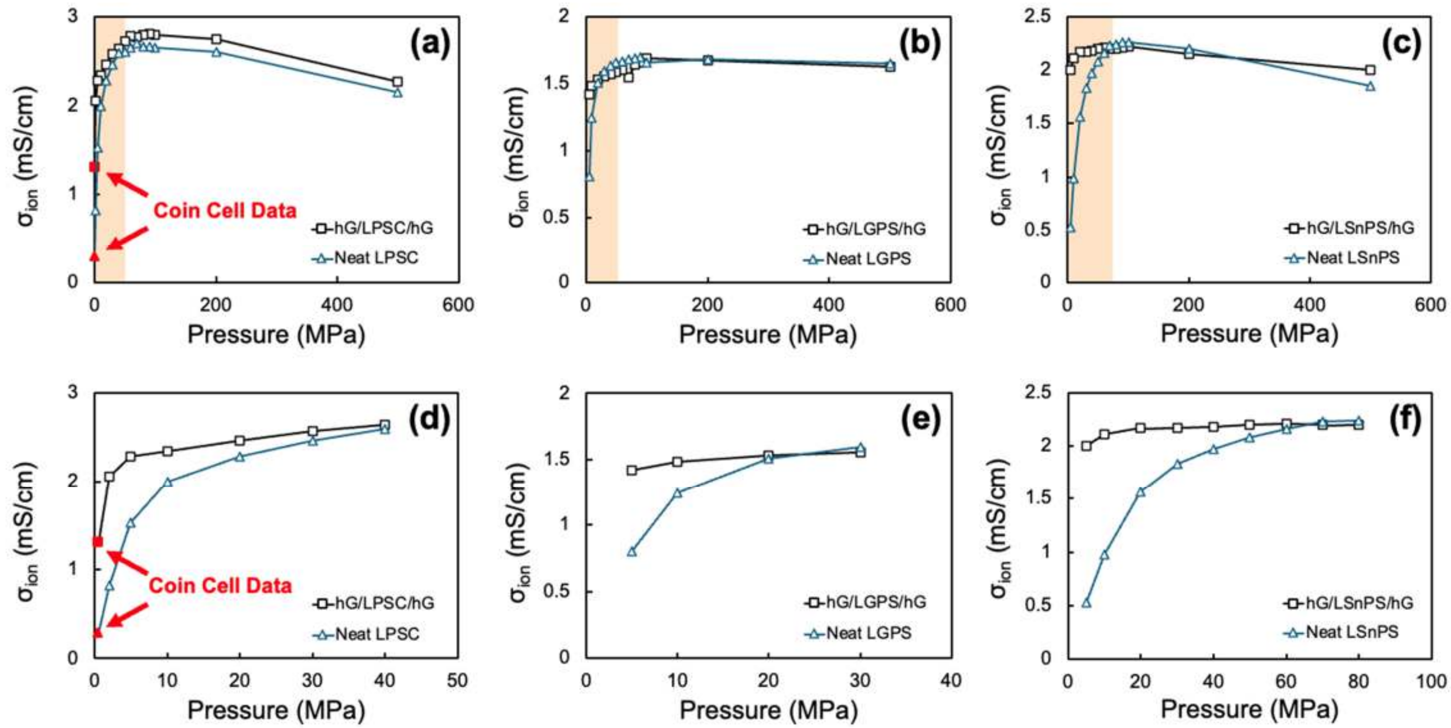
❑ Using dry-pressable hG as current collector electrodes allows consistent fabrication of robust, freestanding hG/solid electrolyte/hG sandwich discs, enabling reliable ionic conductivity measurements with coin cells

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

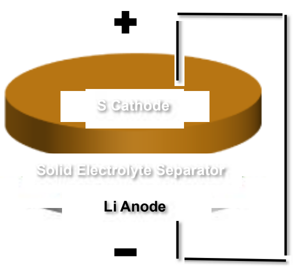
- ❖ LPSC: lithium phosphorus sulfur chloride
- ❖ LGPS: lithium germanium phosphorus sulfide
- ❖ LSnPS: lithium tin phosphorus sulfide

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

Challenge 2: Sulfur Composite Cathode

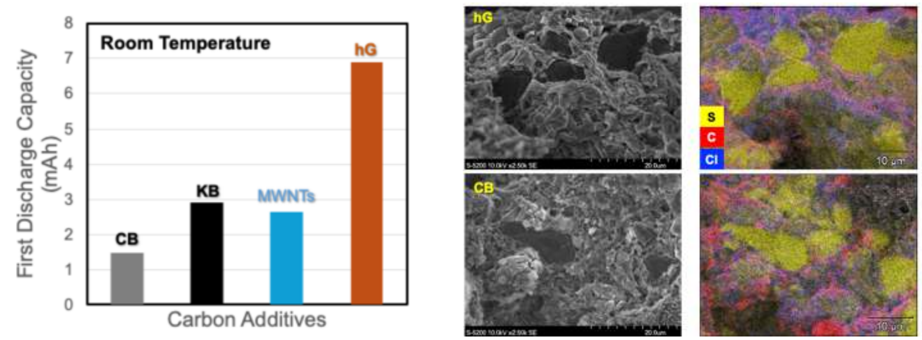
❑ How to overcome the intrinsic insulating properties of S?

A Solid-State Li-S Cell

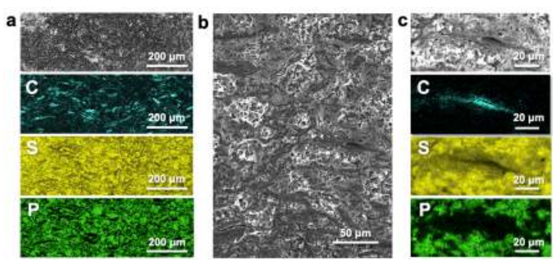


- **Cathode**: S *and* necessary additives to make it electrically (thus carbon) and ionically (thus solid electrolyte) conductive
- **Solid electrolyte (SSE) separator**: A solid layer that conducts Li ion but insulates electrons
- **Anode**: Li metal

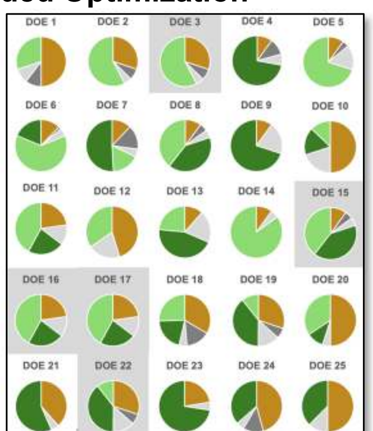
Holey graphene enabled solvent-free processing of S composite cathode with superior performance vs. other carbon additives.



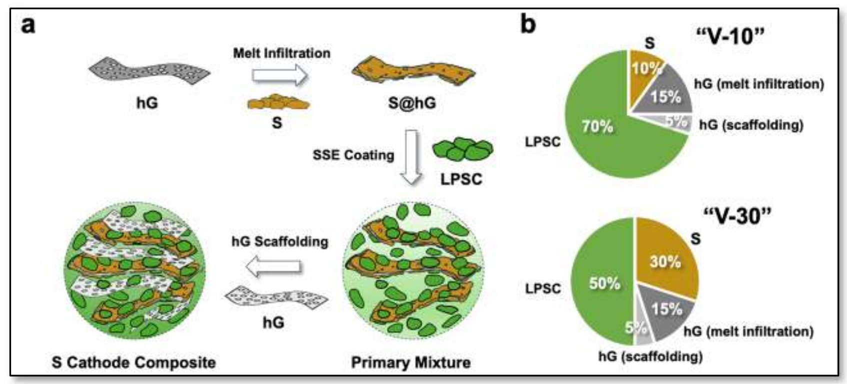
A Design-of-Experiment (DOE) Guided Optimization



Optimized cathode microstructures enabled maximal S utilization for battery reactions.



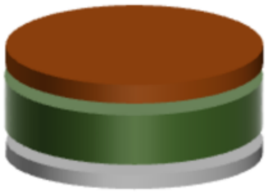
S Composite Cathode Fabrication and Compositions



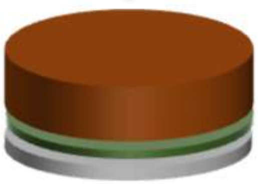
Small **2025**, *21*, 202409536.

Challenge 2: Sulfur Composite Cathode

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

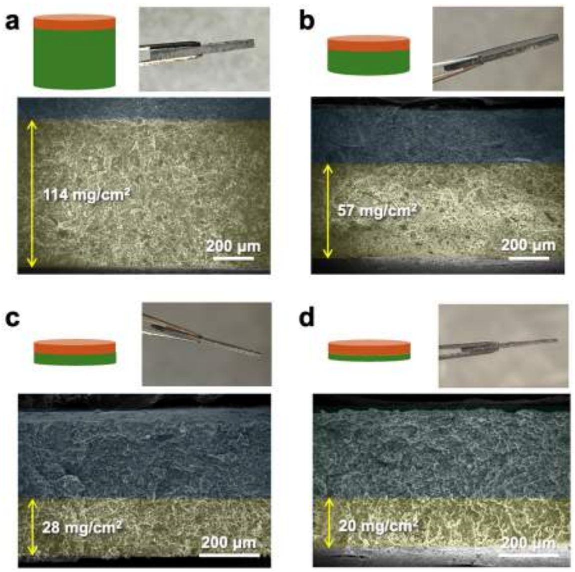


- **Thin** cathode (less S)
- **Thick** SSE
- Energy **inefficient**



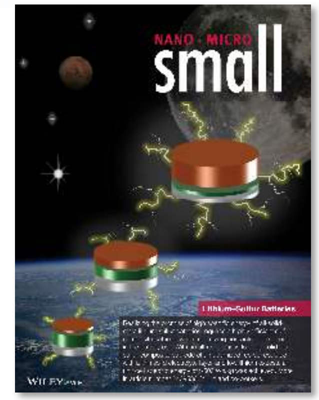
- **Thick** cathode (more S)
- **Thin** SSE
- Energy **efficient**

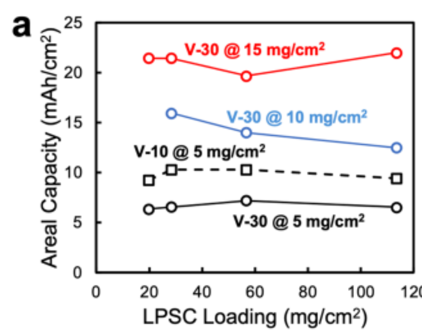
Thick S Cathode with Thin SSE Layer

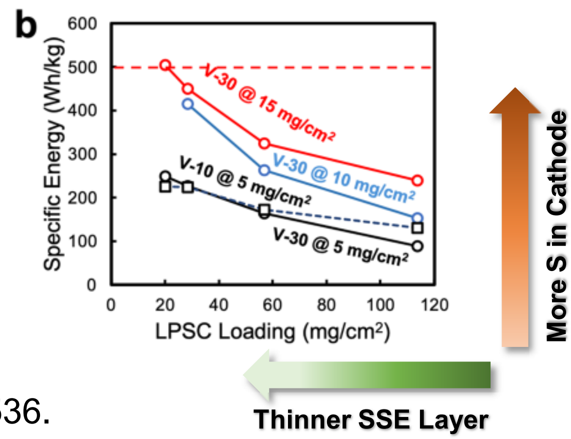


Thick SABERS S Cathode + Thin SSE enabled:

- >20 mAh/cm^2 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)







Small **2025**, *21*, 202409536.

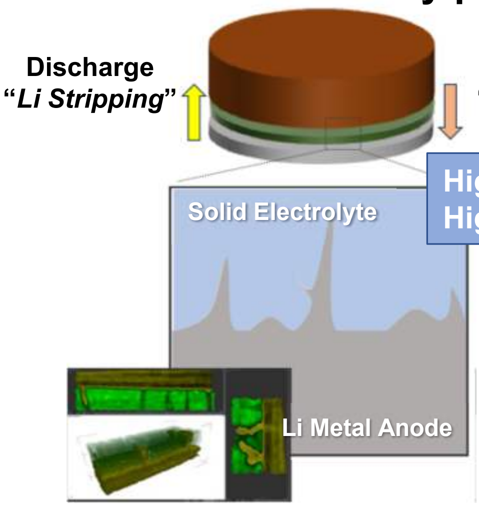
Solvent-free fabrication of thick S cathode exhibits excellent performance with optimized composition and processing

- 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

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

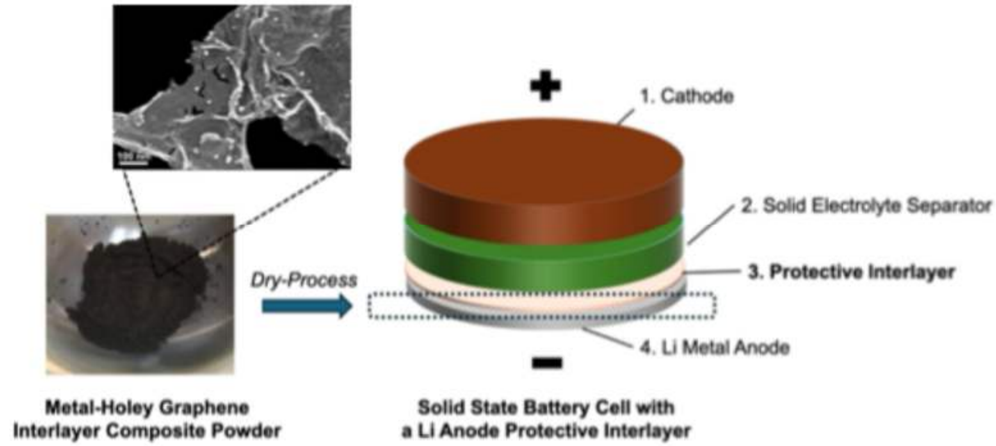
Challenge 3: Anode - Solid Electrolyte Interface

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

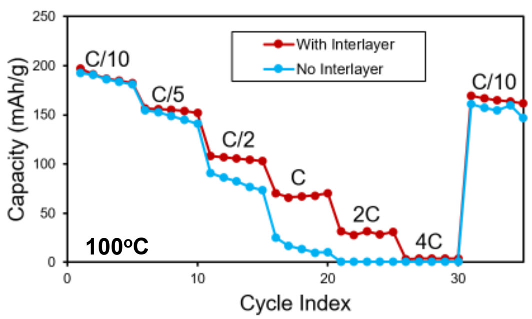


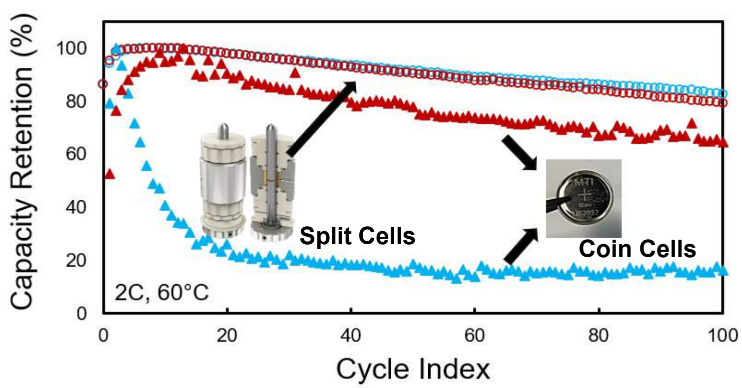
High energy = More Li movement
High rate = Faster Li movement

- Li surface roughening upon cycling
- Li dendrite resulting failure
- SSE– Li interface worsened at high energy and/or high power



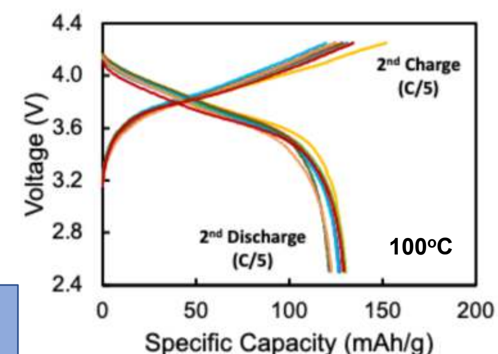
Improved Power/Rate Performance





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

Dry-Pressed Interlayer Allowed for Consistent Cell Fabrication



ACS Appl. Energy Mater. **2026**, DOI: 10.1021/acsaem.5c02931.

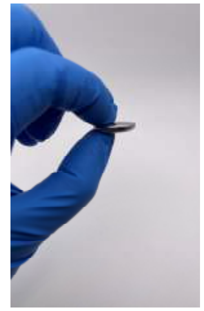
Challenge 4: Scale Up Engineering

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

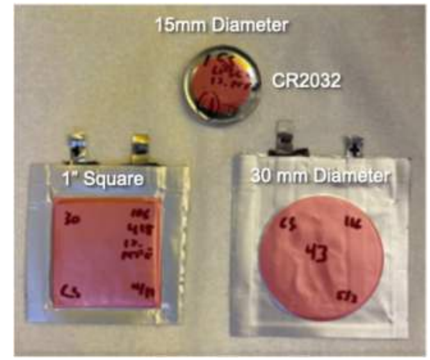
	Split Cells	Coin Cells	Pouch Cells
Stack Pressure Control	**Excellent**	Low	**Excellent**
Industry Standard Casing	No	**Yes**	**Customized**
Part Availability	Moderate	**Yes**	**Yes**
Cost	High	**Low**	Moderate
Field Testing Capable	No	**Yes**	**Yes**
Practical Applications	No	Moderate	**Yes**

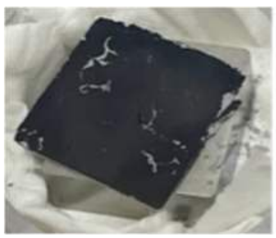
Split Cell

Coin Cell

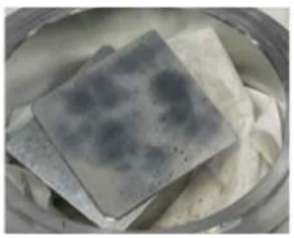


Pouch Cell

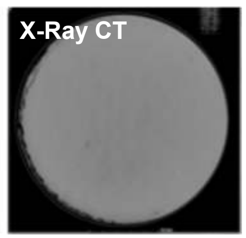




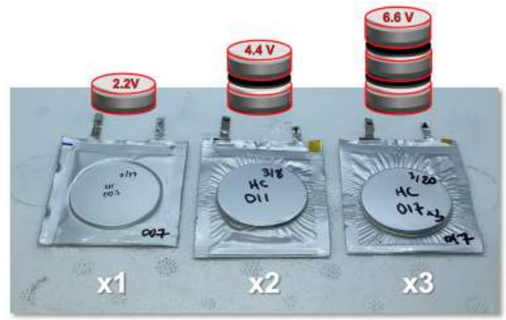
Generation 1
All Powder Processing

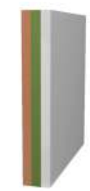


Generation 2
Binder in SSE Layer



Generation 3
Binder in Both SSE Layer and Cathode

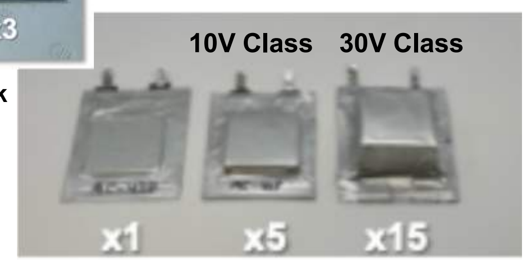




Single- and Multilayer Bipolar Stack "Cookie" Pouch Cells

- 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 microfibrous 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 "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
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- NASA Game Changing Development (**GCD**) Program

Current Team Members:

- Ji Su
- Vesselin Yamakov
- Dan Perey
- Sang-Hyon Chu
- Hailey Moore
- Joe Smith
- Jin Ho Kang
- Godfrey Sauti
- Rocco Viggiano (GRC)
- Donald Dornbusch (GRC)
- Seth Schisler (ARC)

Retirees:

- John Connell (retired)
- John Hopkins (retired)
- 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 Somervill, 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