



Solid-State Batteries for Air and Space: Pushing Boundaries with Materials Science

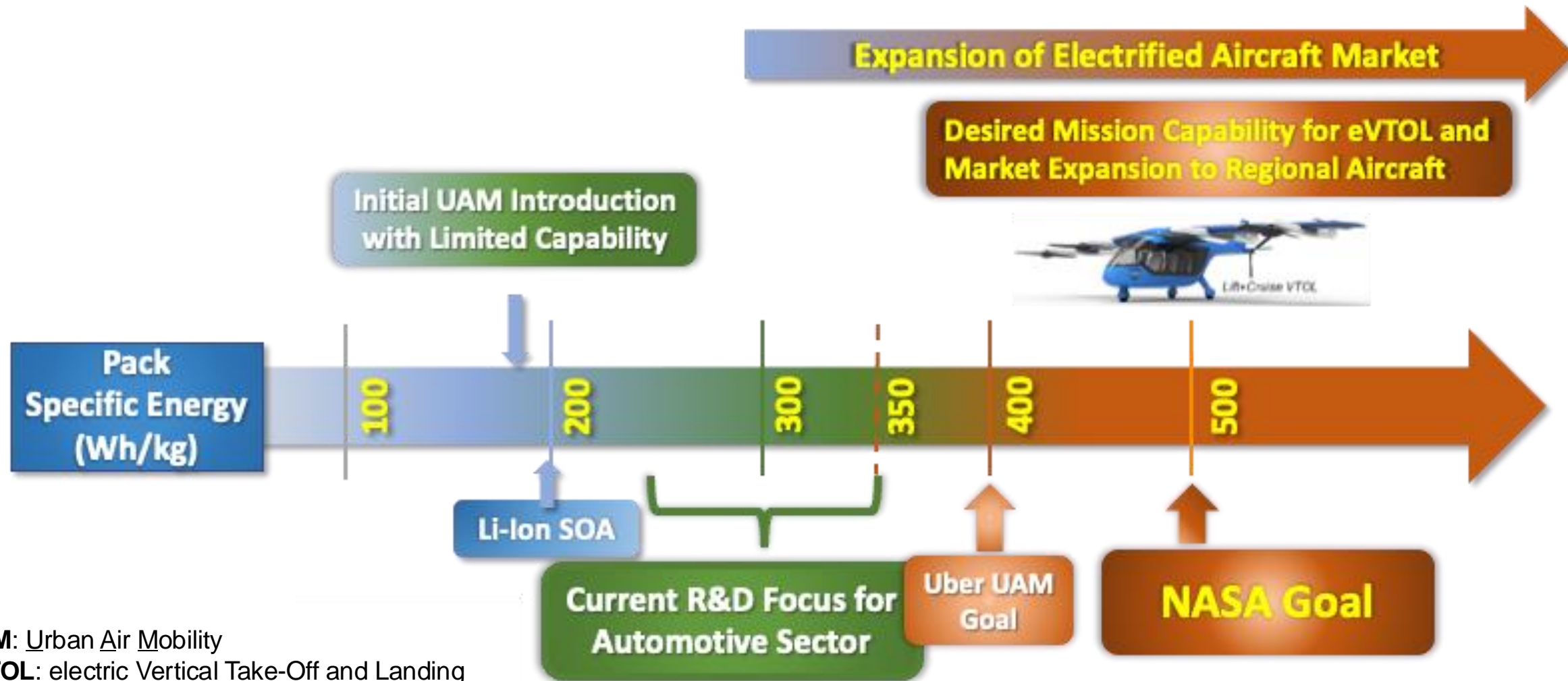
Yi Lin

Advanced Materials & Processing Branch, NASA Langley Research Center, Hampton, VA 23681

**The 49th International Conference and Exposition on Advanced Ceramics and Composites
(ICACC)**

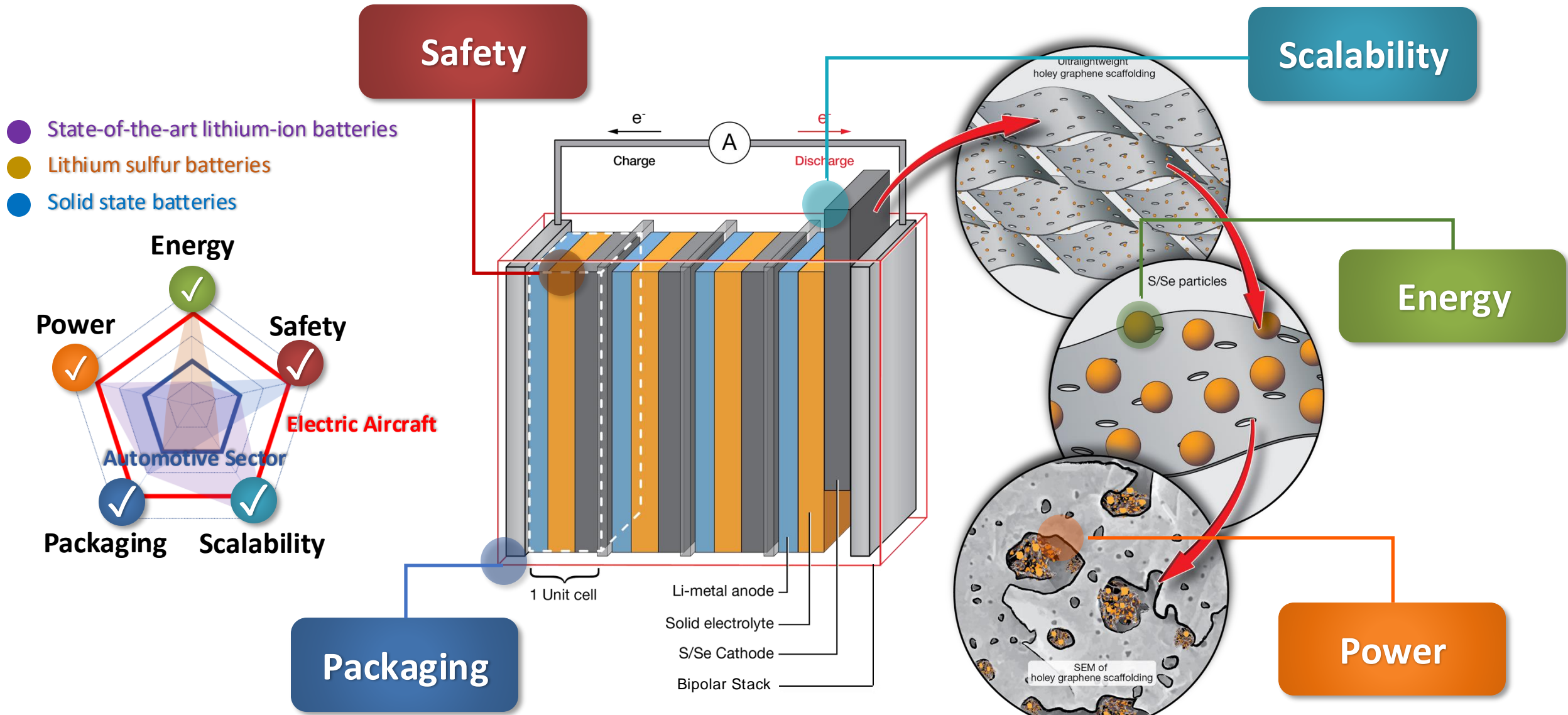
**Daytona Beach, FL
January 28, 2025**

NASA's Interest in High Performance Batteries



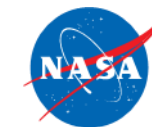
UAM: UrbAiMobility
eVTOL: electric Vertical Take-Off and Landing
SOA: State-of-the-Art
R&D: Research & Development

NASA SABERS Concept



SABERS: Solid-state Architecture Batteries for Enhanced Rechargeability and Safety

Why Lithium-Sulfur (Li-S) Solid-State Batteries?



Energy

- ❑ Sulfur has ultra-high theoretical specific energy (2510 Wh/kg)



Safety

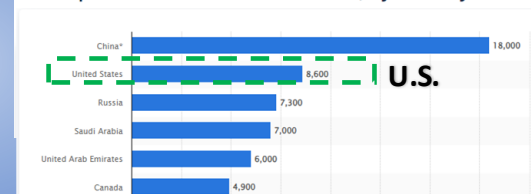
- ❑ Solid-state batteries are made from non-flammable components



Supply Chain

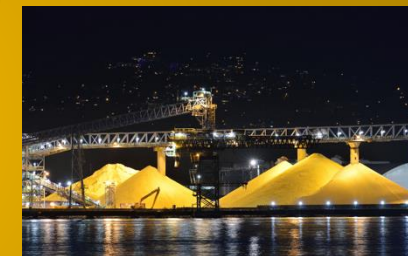
- ❑ Sulfur is abundant and inexpensive in the U.S.

Sulfur production worldwide in 2022, by country



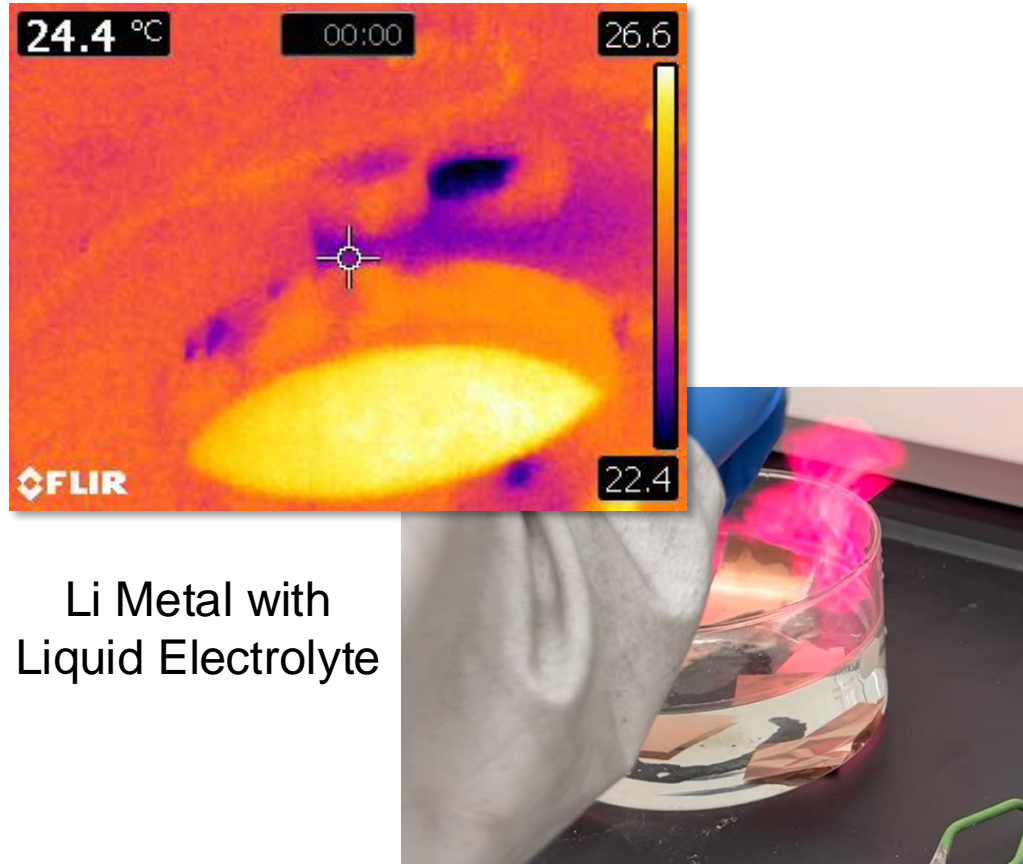
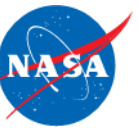
Sustainability

- ❑ >80% of the sulfur supply is a waste product, extracted from fossil fuels



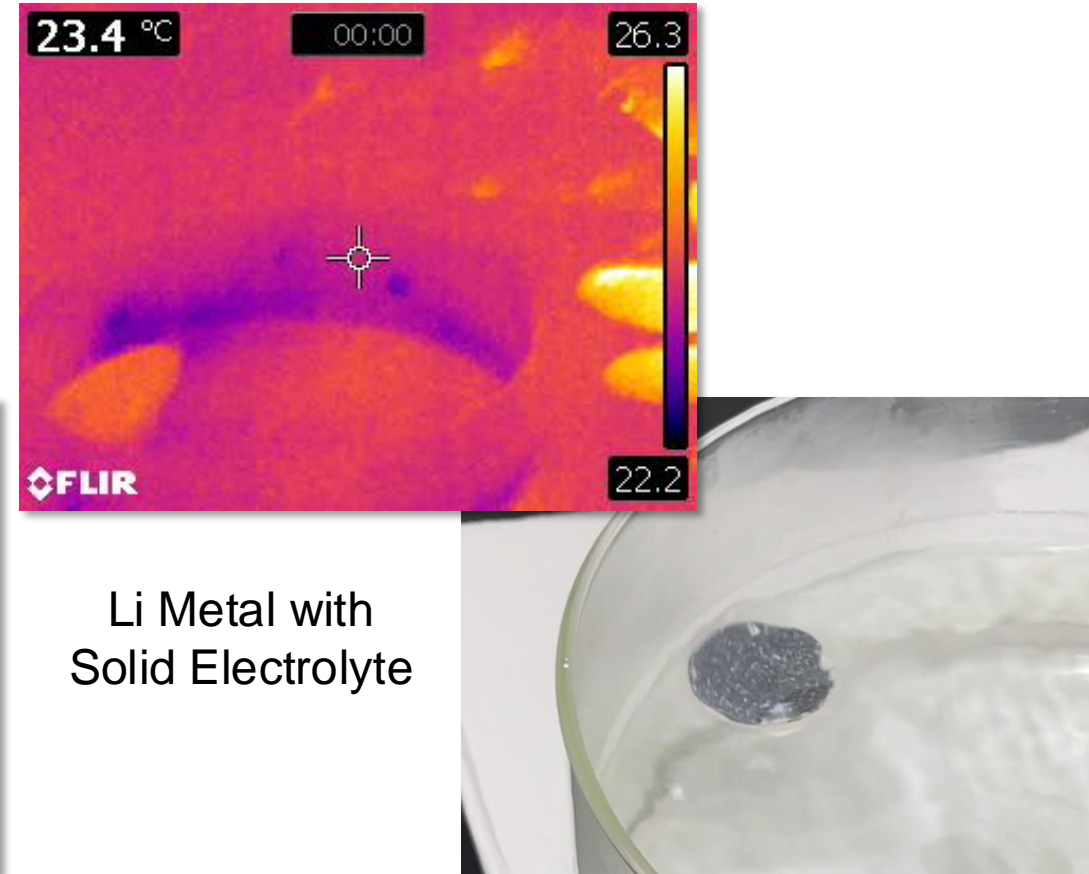
- ❑ SABERS aims for high performance and safe aviation batteries to power future electric aircraft and beyond

Solid Electrolytes Are Non-Flammable



Li Metal with
Liquid Electrolyte

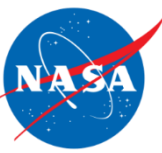
- ❑ Reaction of Li metal and water resulted in local temperature exceeding the flash point (<math><40^{\circ}\text{C}</math>) of organic solvents that catch fire.



Li Metal with
Solid Electrolyte

- ❑ Reaction of Li metal and water resulted in local temperature increase and hydrogen release, but no flammable material to catch fire.

Materials in SABERS Batteries



“Fuel” - Electrochemical energy source:

❑ Cathode – **Sulfur**

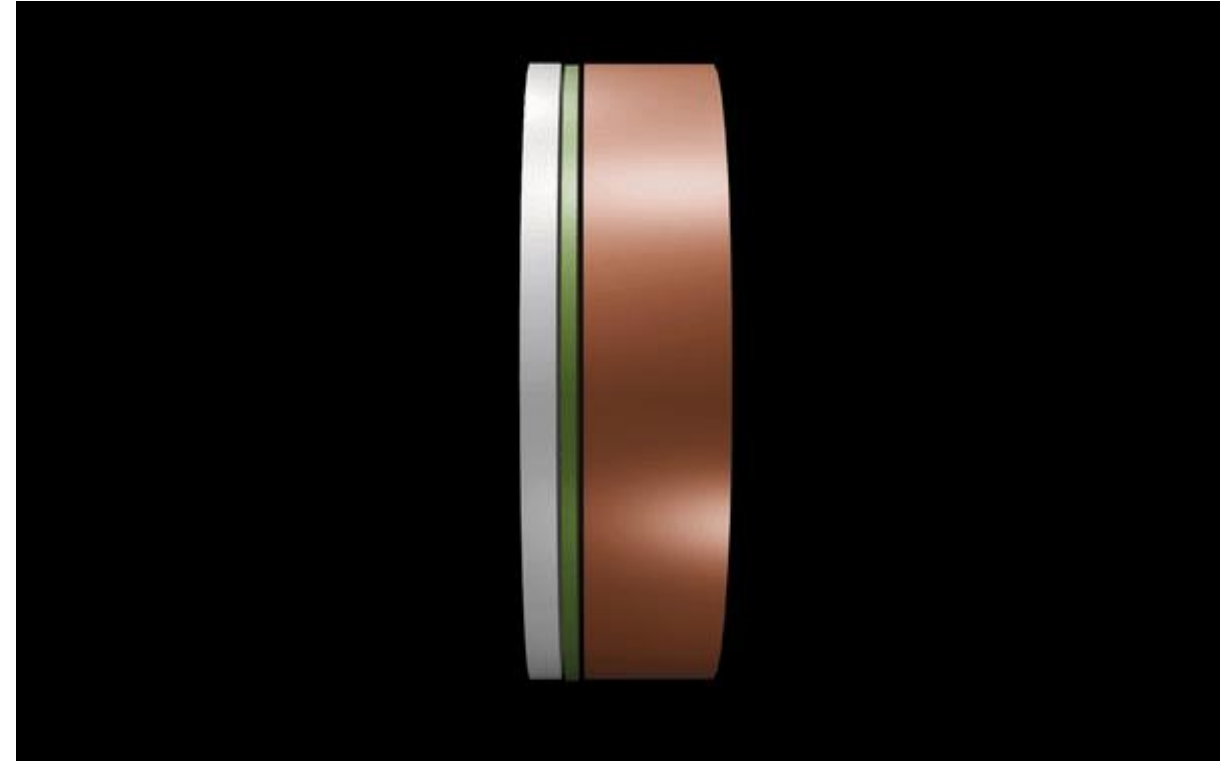
- Insulating to both Li and electrons
- A sustainable choice
- Need additives (“composite cathode”)
 - ❑ Carbon: electron conductor
 - ❑ Solid electrolyte: Li ion conductor
 - ❑ Binder: mechanical strength

❑ Anode – **Lithium**

- Conductive to both Li and electrons
- Could be directly used but may need engineering to perform better

❑ **Solid electrolyte:**

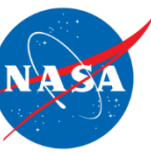
- Nonflammable
- Li ion conducting (but electron insulator)
- Uses: (1) separates cathode and anode
(2) Li ion conductive additive for cathode



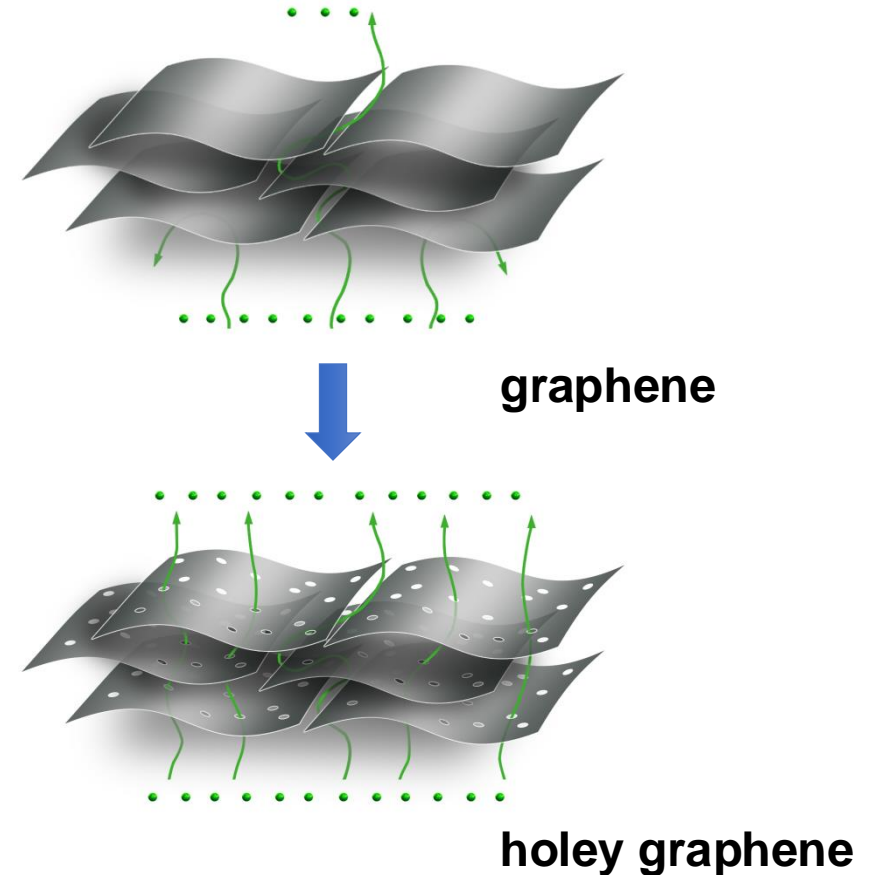
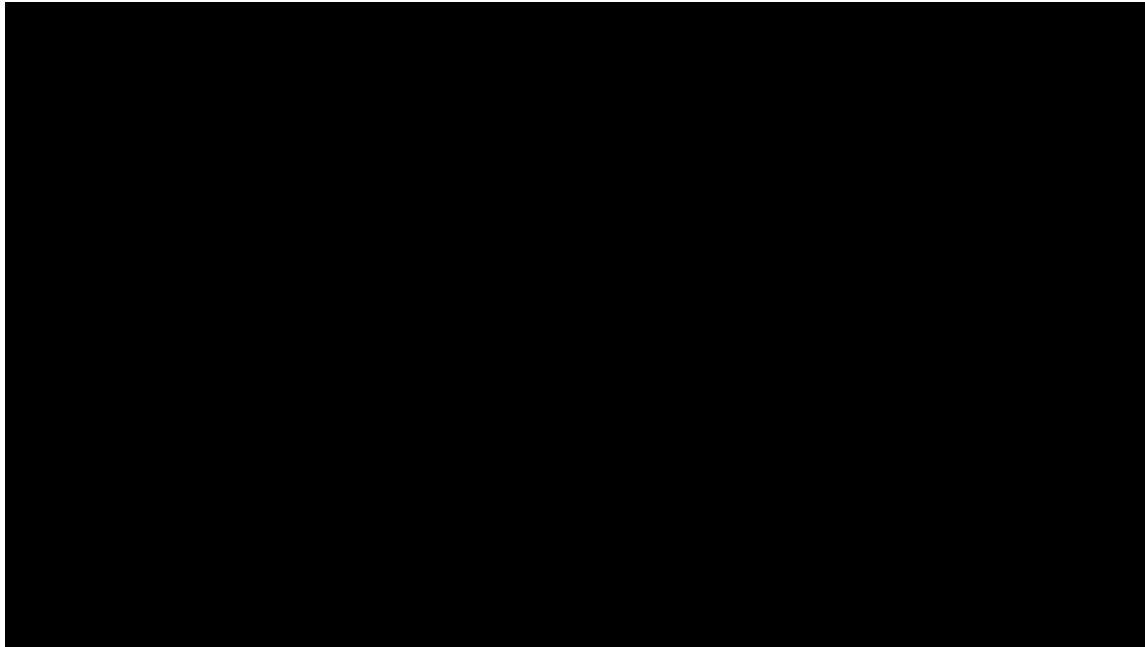
❑ **Other components:**

- Current collectors
- Bipolar plates (separate solid-state unit cells)

Holey Graphene (hG)



Improved ion transport path at high stacking density



Full version*: <https://www.youtube.com/watch?v=OGyn2PjBTN0>

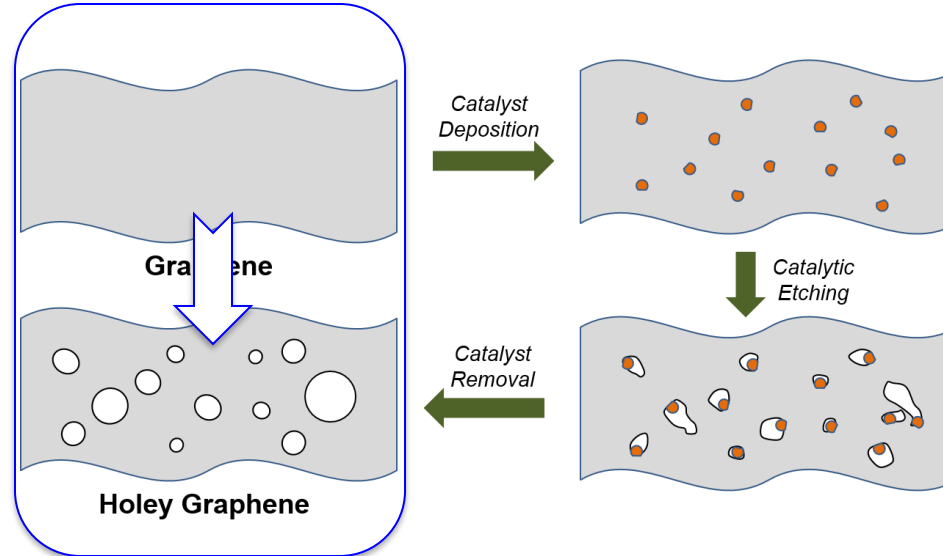
*NASA's holey graphene introduction and webinar videos are available online.

- ❑ Holey graphene retains most geometrical (two-dimensional), electrical, and mechanical advantages of intact graphene, but with improved ion transport path and thus accessible surface area
- ❑ Holey graphene is a unique electrode material for enhanced battery performance

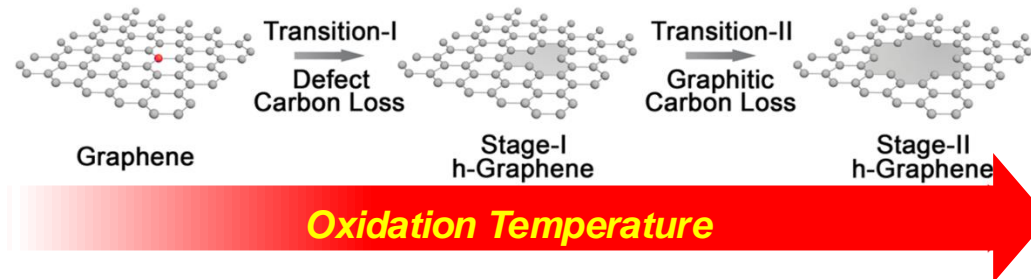
Synthesis of hG



Nanoscale 2013, 5, 7814.



“Generation II”



Single Step + Catalyst-Free = Highly scalable!

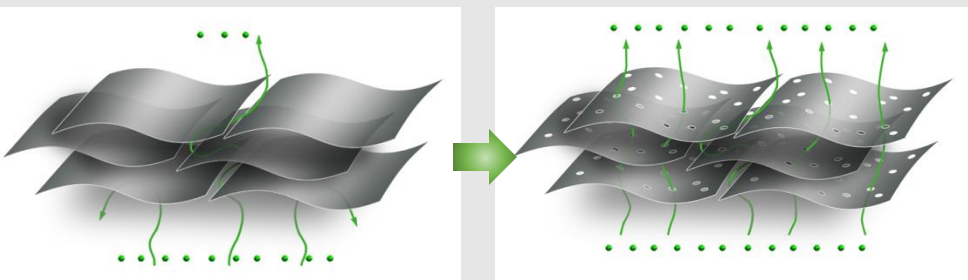


ACS Nano 2014, 8, 8255; Adv. Func. Mater. 2015, 25, 2920.

hG for Advanced Electrodes



Supercapacitors



Intact Graphene

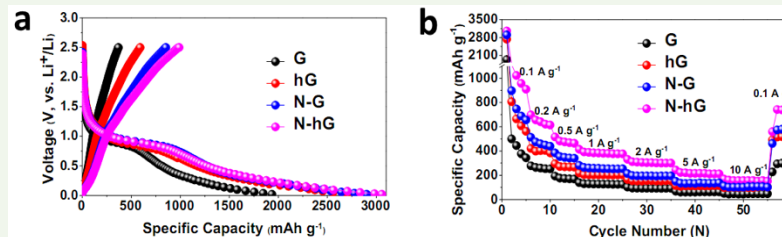
Holey Graphene

ACS Nano 2014, 8, 8255.

As-Prepared hG

Liangbing Hu
(U Maryland)

Li-Ion Battery (Anode)

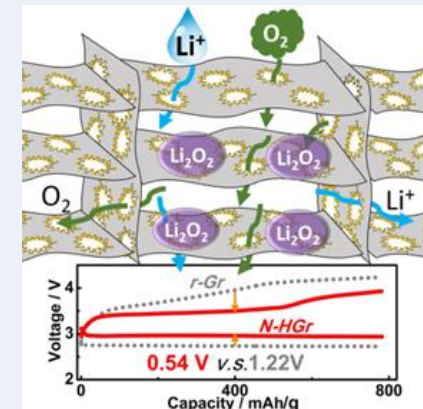


Small 2015, 11, 6179.

N-doped hG

Liming Dai
(CWRU)

Li-Oxygen (O₂) Batteries

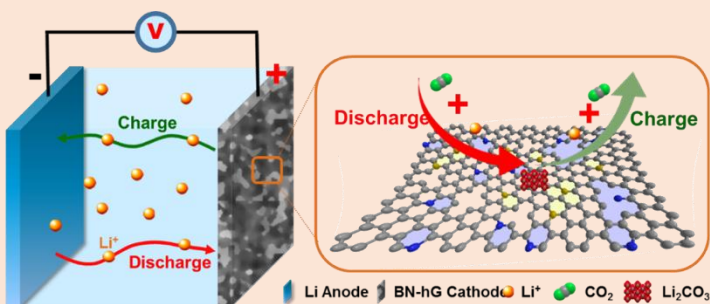


ACS Energy Lett 2016, 1, 260.

N-doped hG

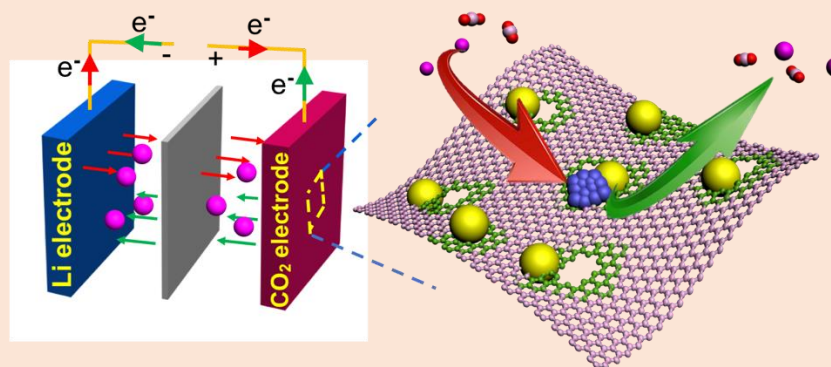
Liming Dai
(CWRU)

Li-Carbon Dioxide (CO₂) Batteries



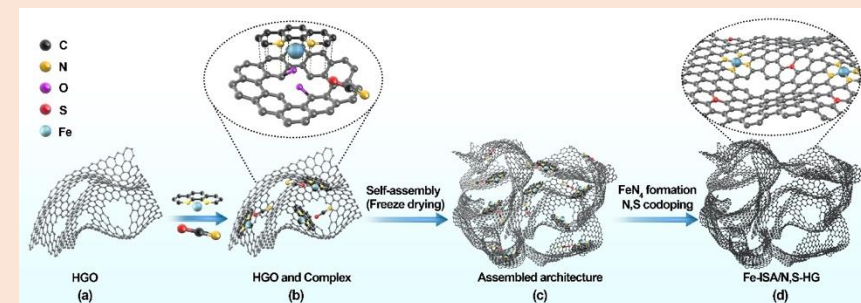
Angew. Chem. Int. Ed. 2017, 56, 6970.

B,N-codoped hG



Adv. Func. Mater. 2018, 28, 1804630

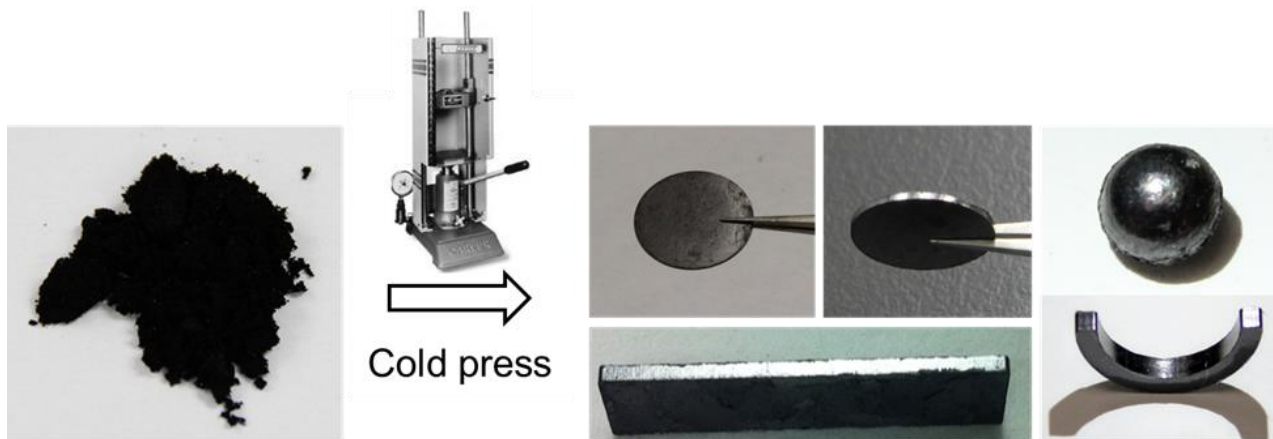
Carbon Dot-Supported on hG



Adv. Mater. 2020, 32, 1907436.

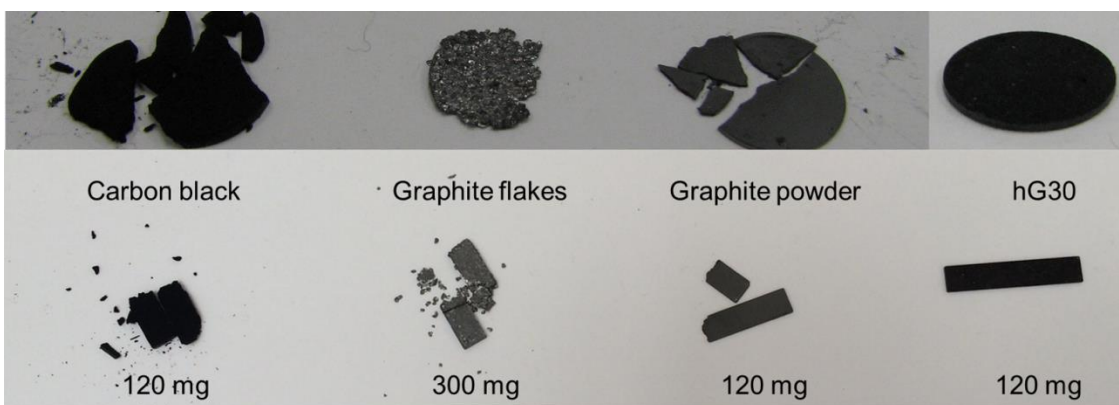
Single Fe Atom Catalysts Supported on hG

hG is Uniquely Dry Compressible



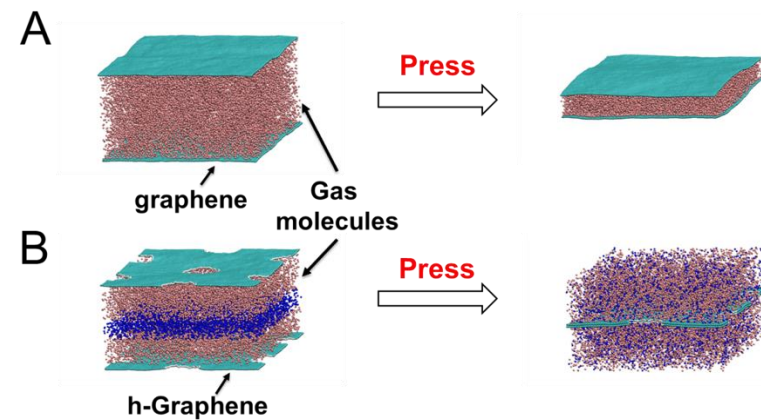
Holey Graphene Powder

Holey Graphene Monolithic Architectures

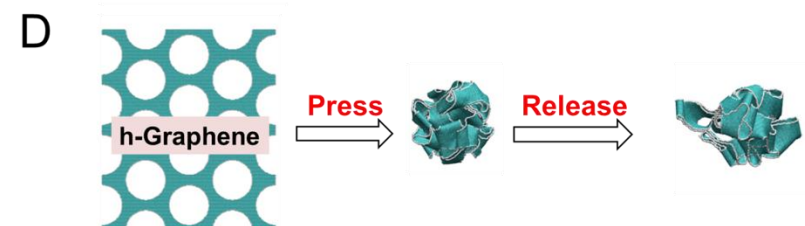
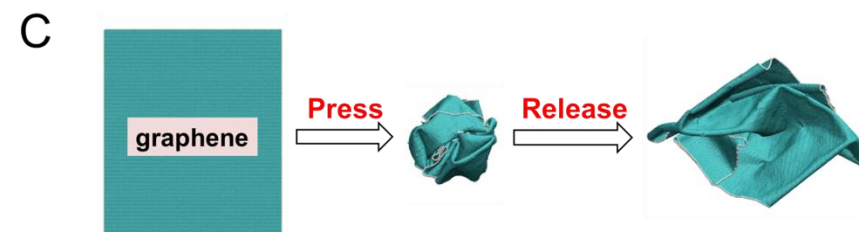


Drop from 36 cm

Drop from 36 cm, and then 110 cm



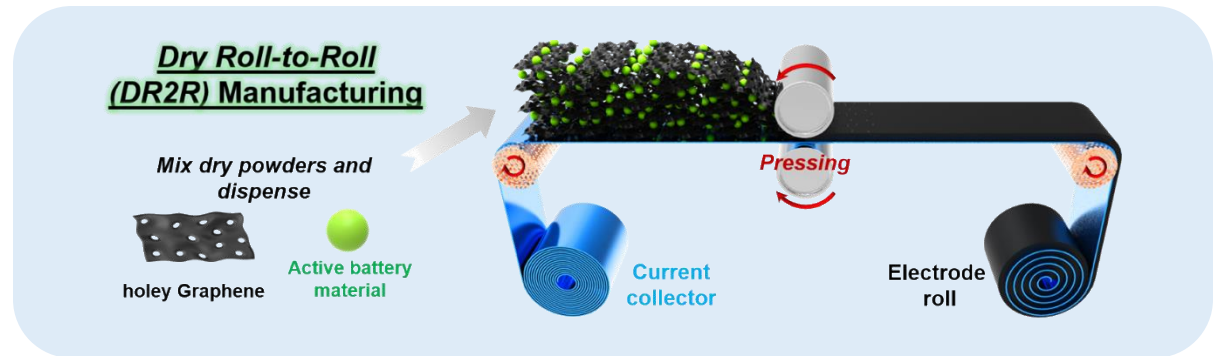
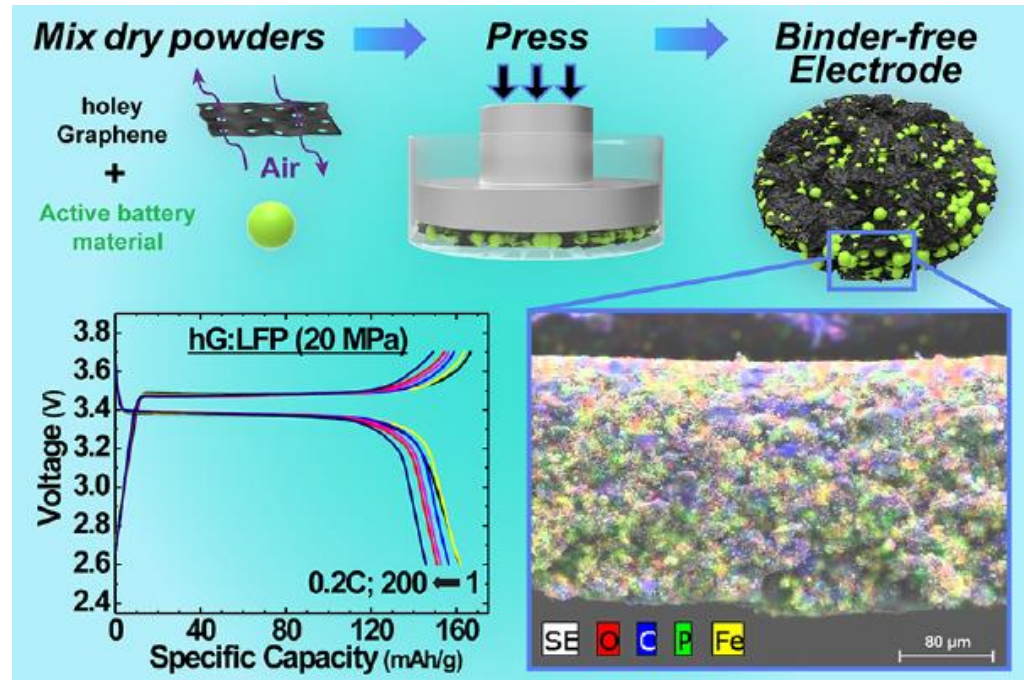
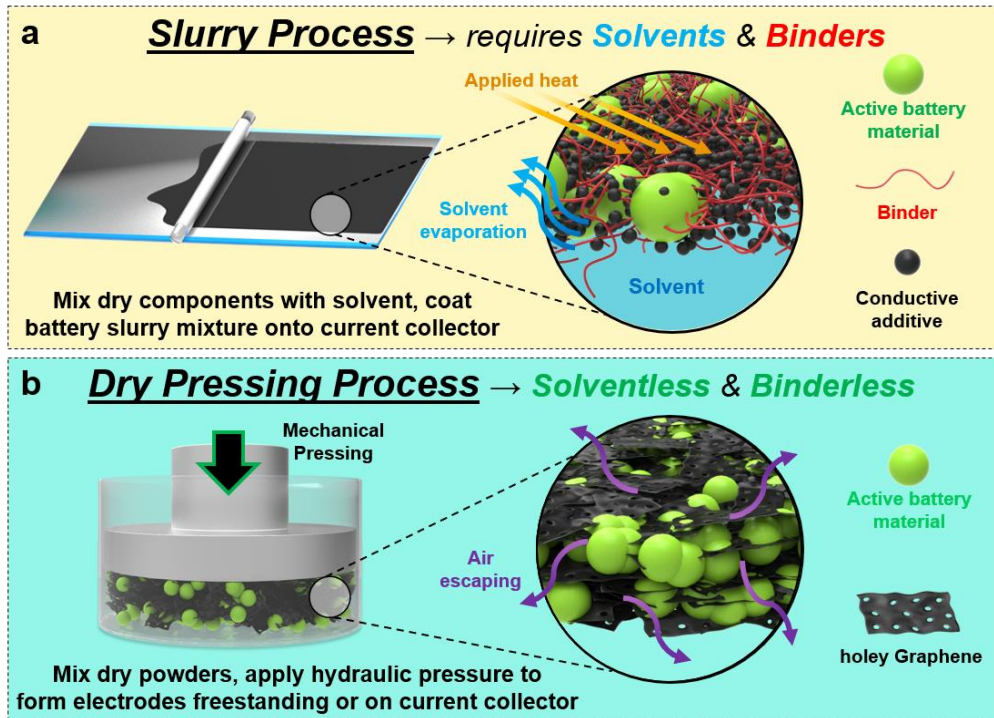
Facile air escape upon compression



Minimal volume rebound upon release

ACS Nano 2017, 11, 3189. (In collaboration with Prof. Liangbing Hu)

Dry Electrode Fabrication and Processing



ACS Appl. Energy Mater. 2019, 2, 2990.

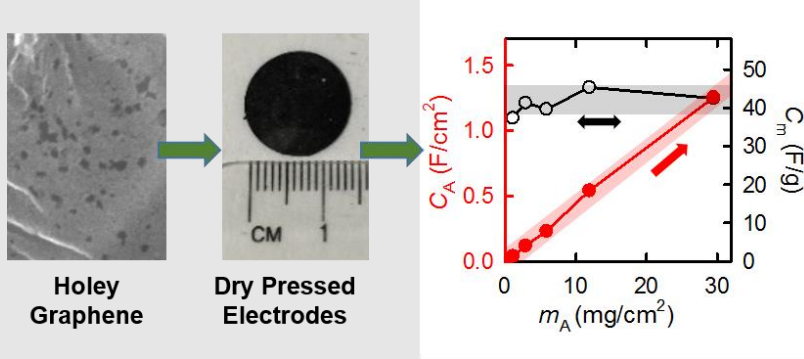
LFP: Lithium iron phosphate

A New Narrative in Electrode Preparation



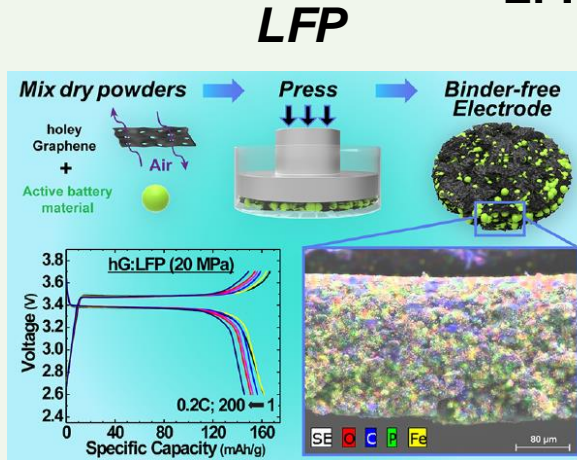
Dry-pressed hG is applicable in various energy storage platforms for ultrahigh areal capacities.

Supercapacitors



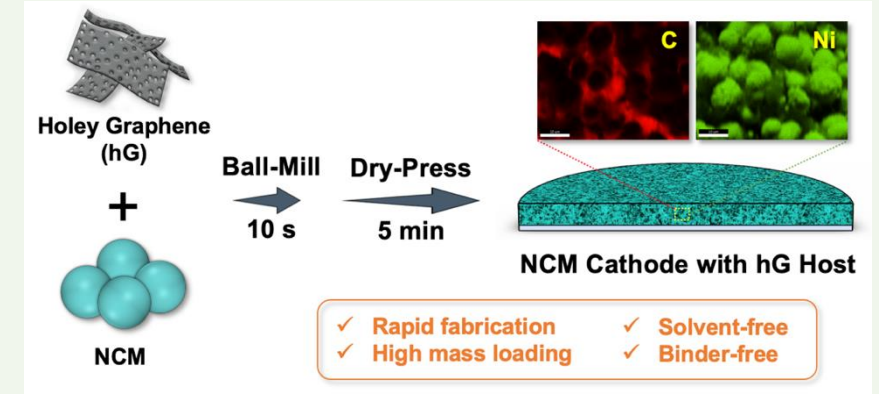
ACS Appl. Mater. Interfaces **2016**, 8, 29478.

Li-Ion Batteries



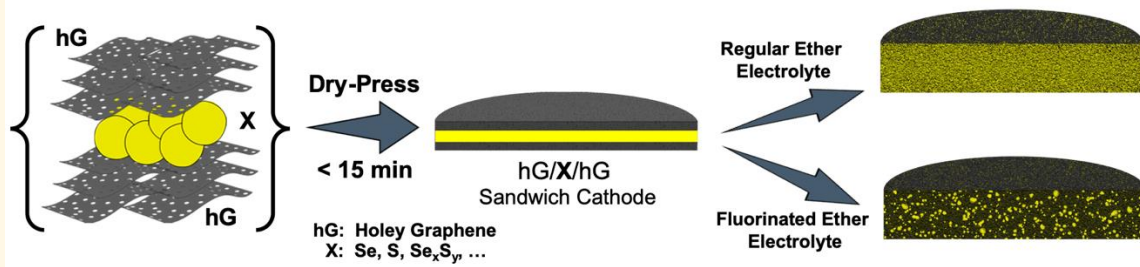
ACS Appl. Energy Mater. **2019**, 2, 2990.

NCM



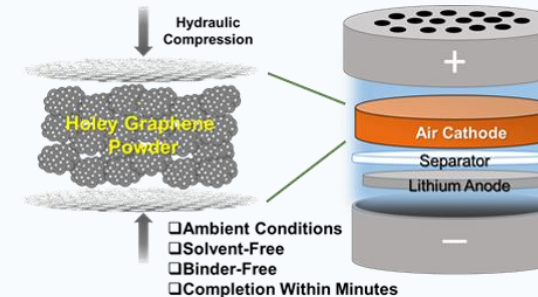
NCM: Lithium nickel cobalt manganese oxide
Electrochim. Acta **2020**, 362, 137129

Li-Sulfur/Selenium (Li-S/Se) Batteries

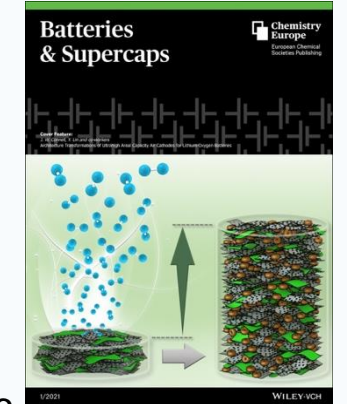


Batteries & Supercaps **2019**, 2, 774; ACS Appl. Energy Mater. **2020**, 3, 6374; Front. Energy Res. **2021**, 703676.

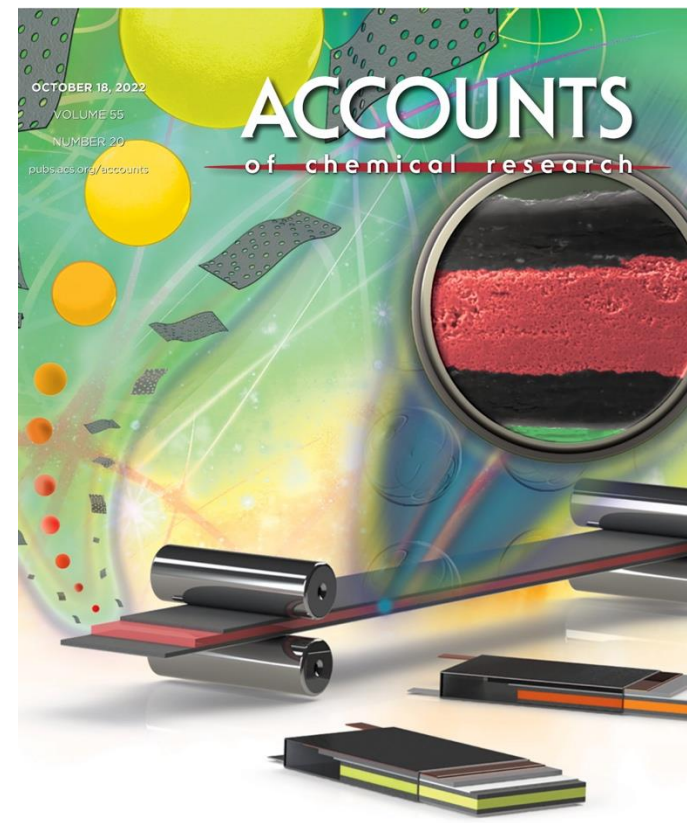
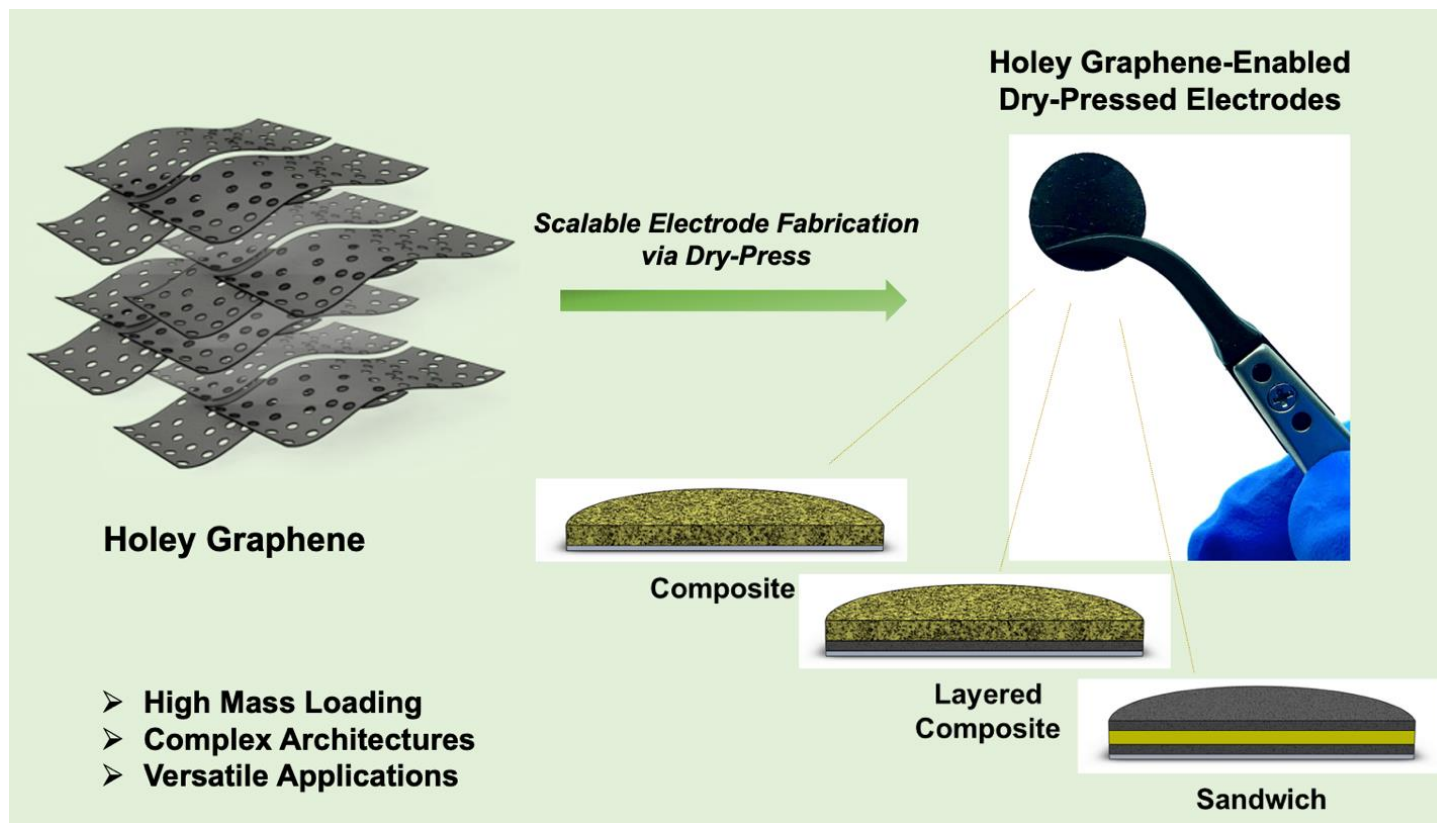
Li-O₂ Batteries



Nano Lett. **2017**, 17, 3252; Nano Energy **2017**, 31, 386;
J. Electrochem. Soc. **2020**, 167, 080522; Batteries Supercaps **2021**, 4, 120.



Dry-Pressible hG for Battery Electrodes



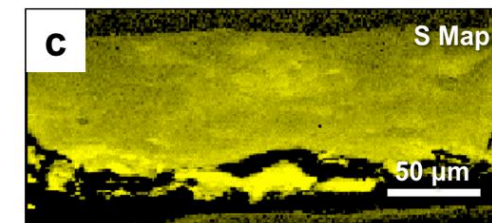
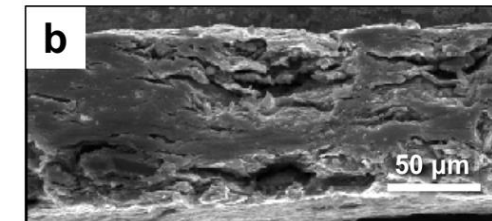
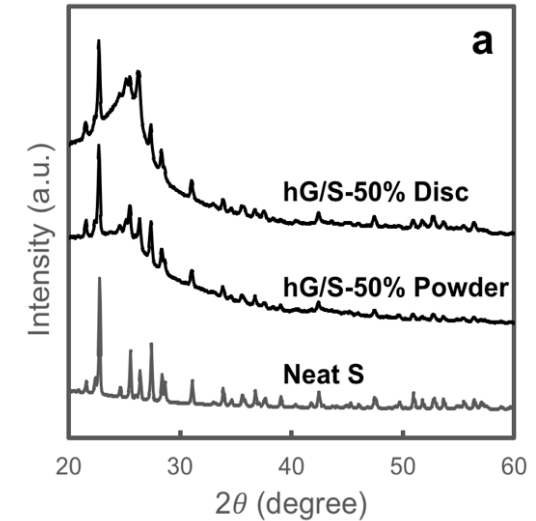
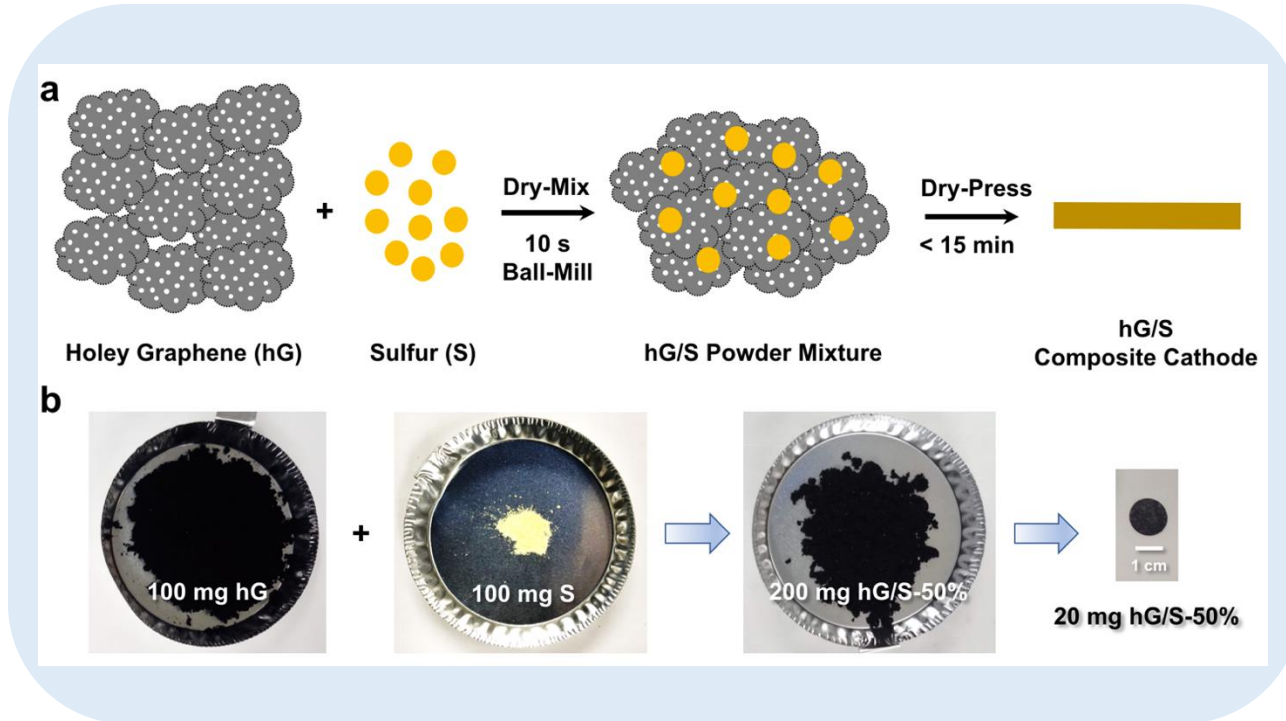
Acc. Chem. Res. **2022**, *55*, 3020-3031.

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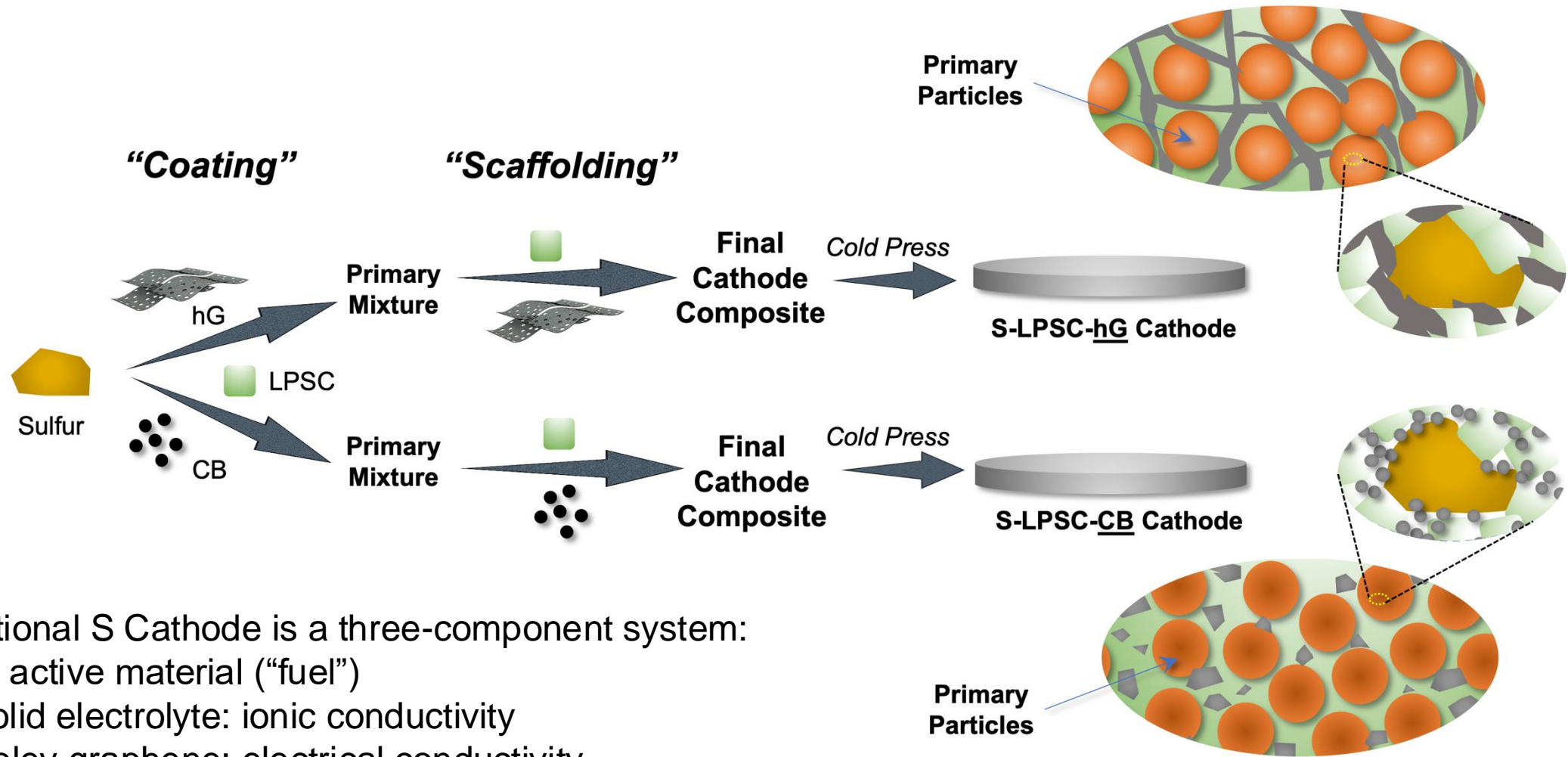
- ❑ Holey graphene is a unique conductive scaffold that can be **directly dry-pressed** into robust, high mass loading electrodes by itself or as a host for active battery materials.

Sulfur Cathode with Liquid Electrolytes



- ❑ Extremely facile preparation of high-performance, high S content, high mass loading S cathodes.
- ❑ **Two component** system: S + carbon (and binder if needed)
- ❑ **Liquid electrolytes** are added during cell assembly.

Solid-State Sulfur Cathodes



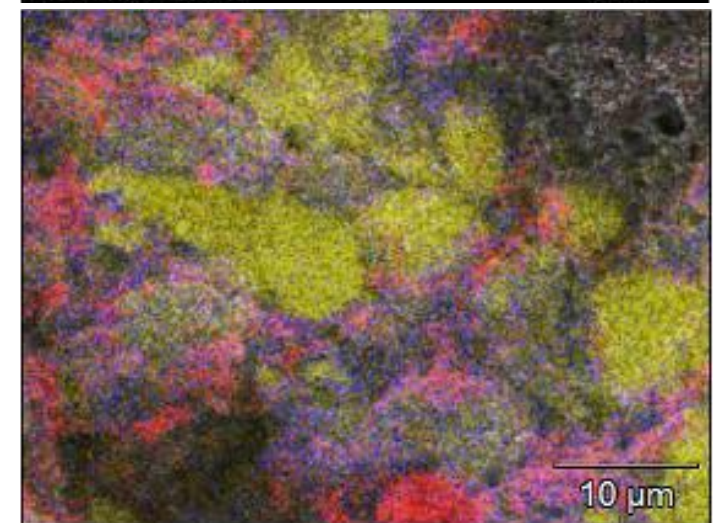
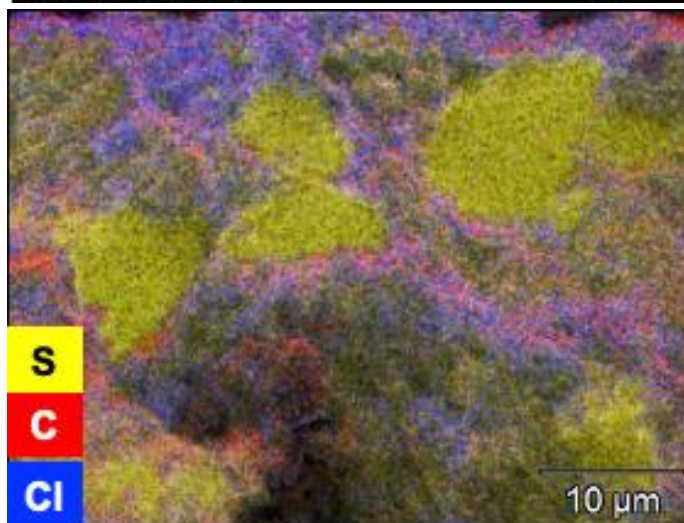
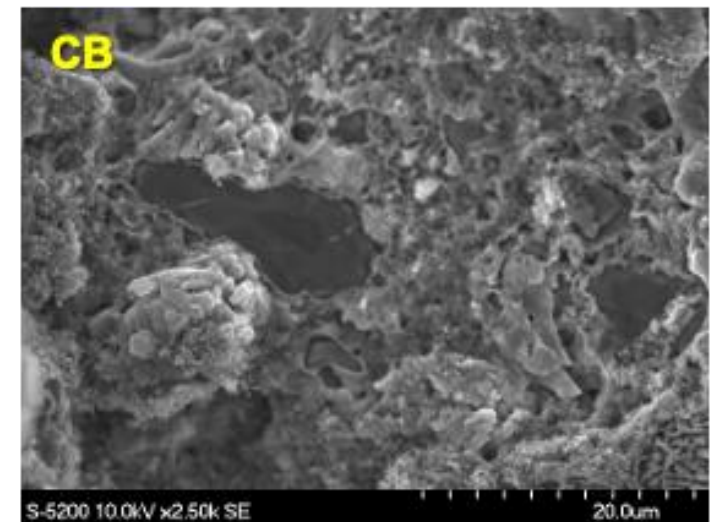
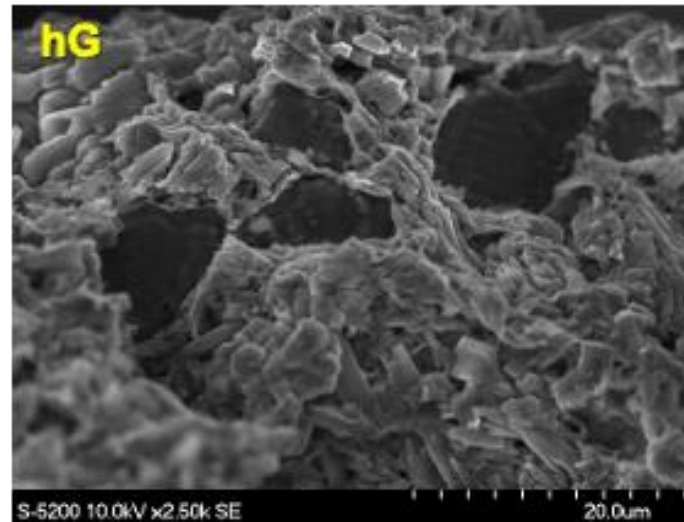
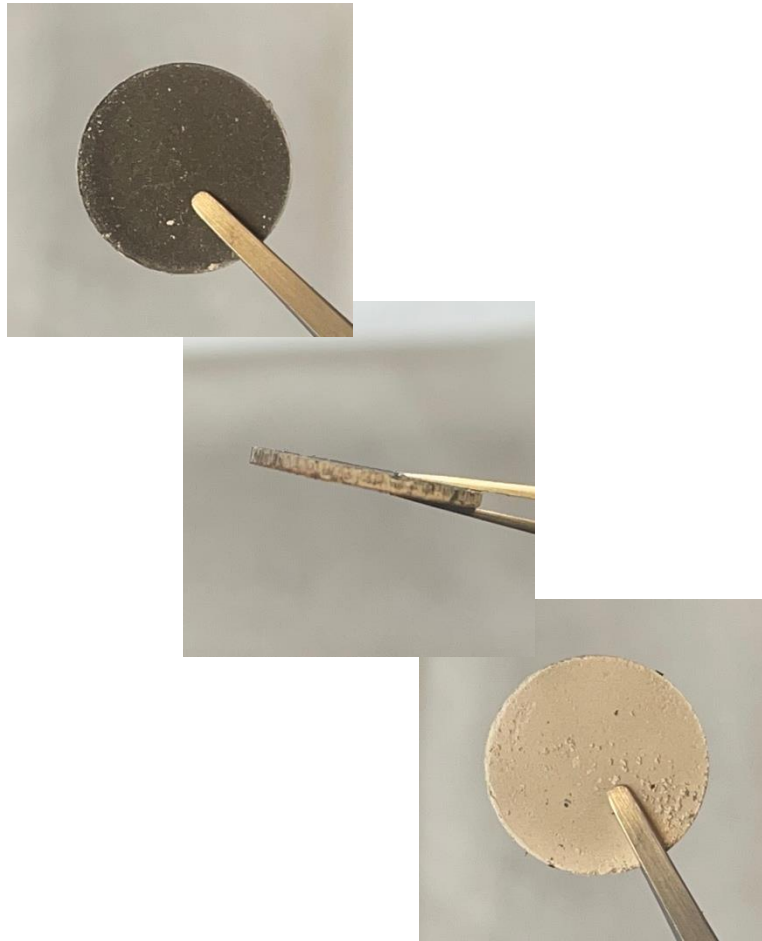
❑ A functional S Cathode is a three-component system:

- ✓ S: active material ("fuel")
- ✓ Solid electrolyte: ionic conductivity
- ✓ Holey graphene: electrical conductivity

❑ Material composition and processing are key to achieve best performance

- ❑ CB: carbon black
- ❑ Solid electrolyte: LPSC ($\text{Li}_6\text{PS}_5\text{Cl}$)

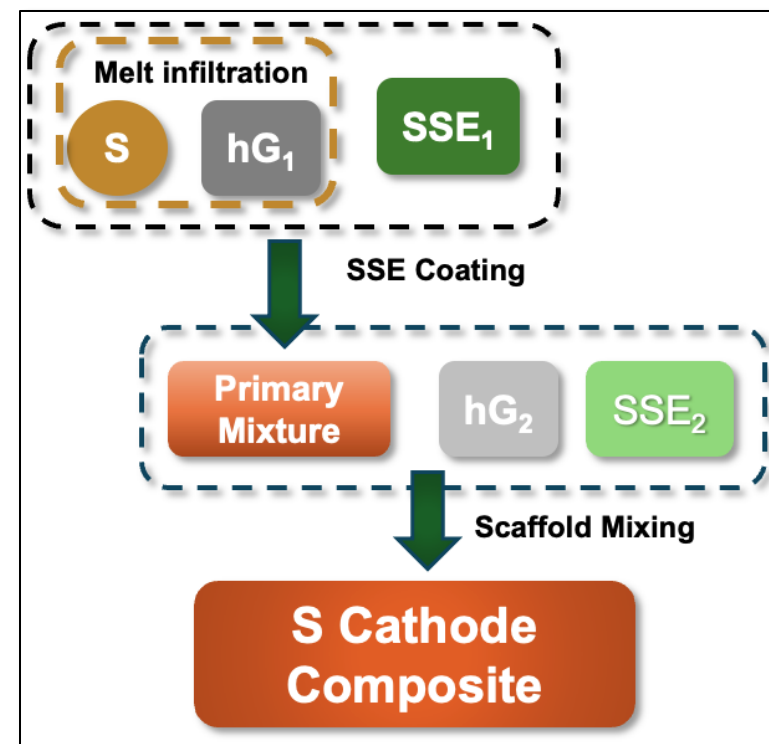
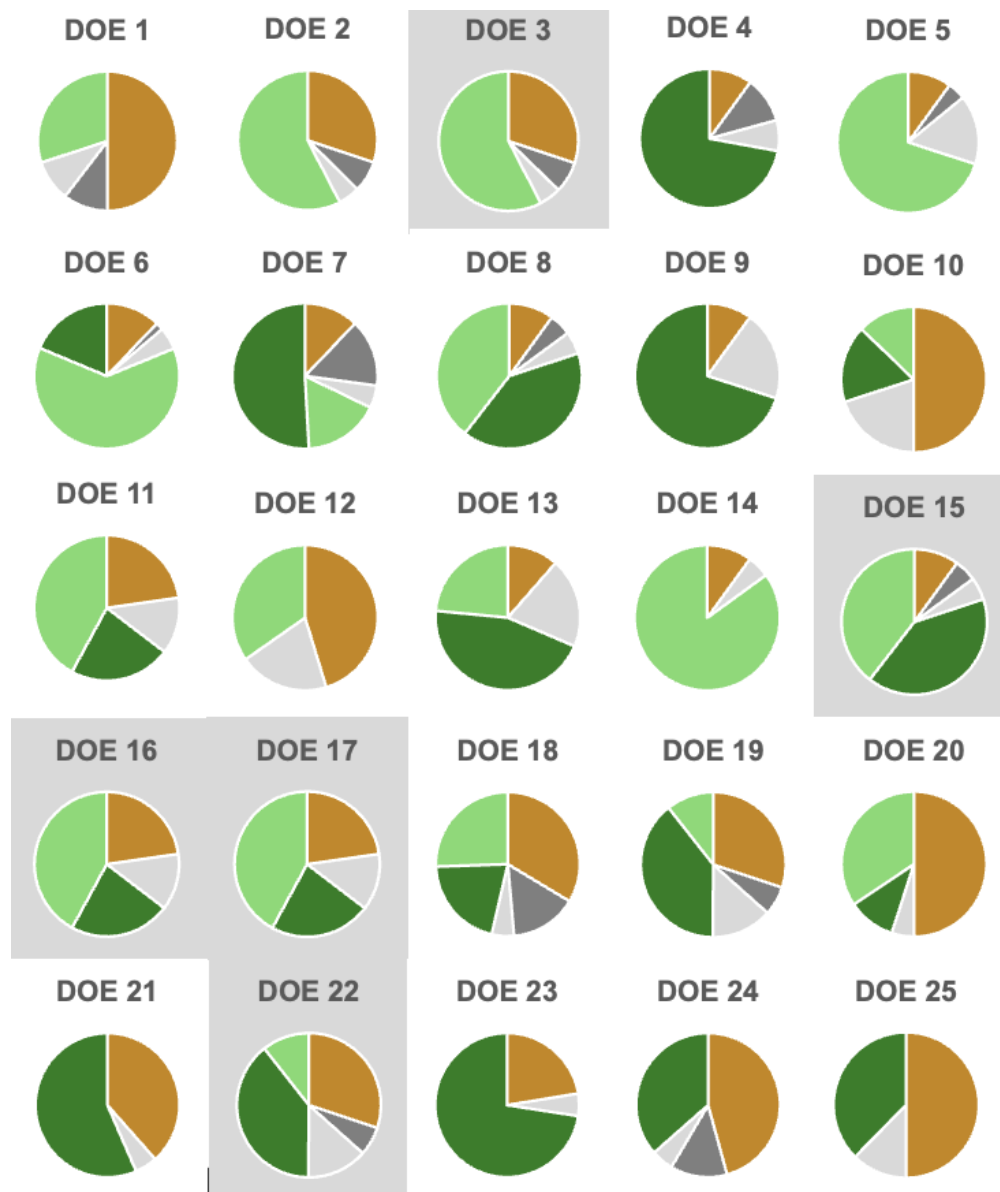
Dry-Pressed Cathode/SSE Bilayer Discs



❑ Robust electrode/electrolyte discs

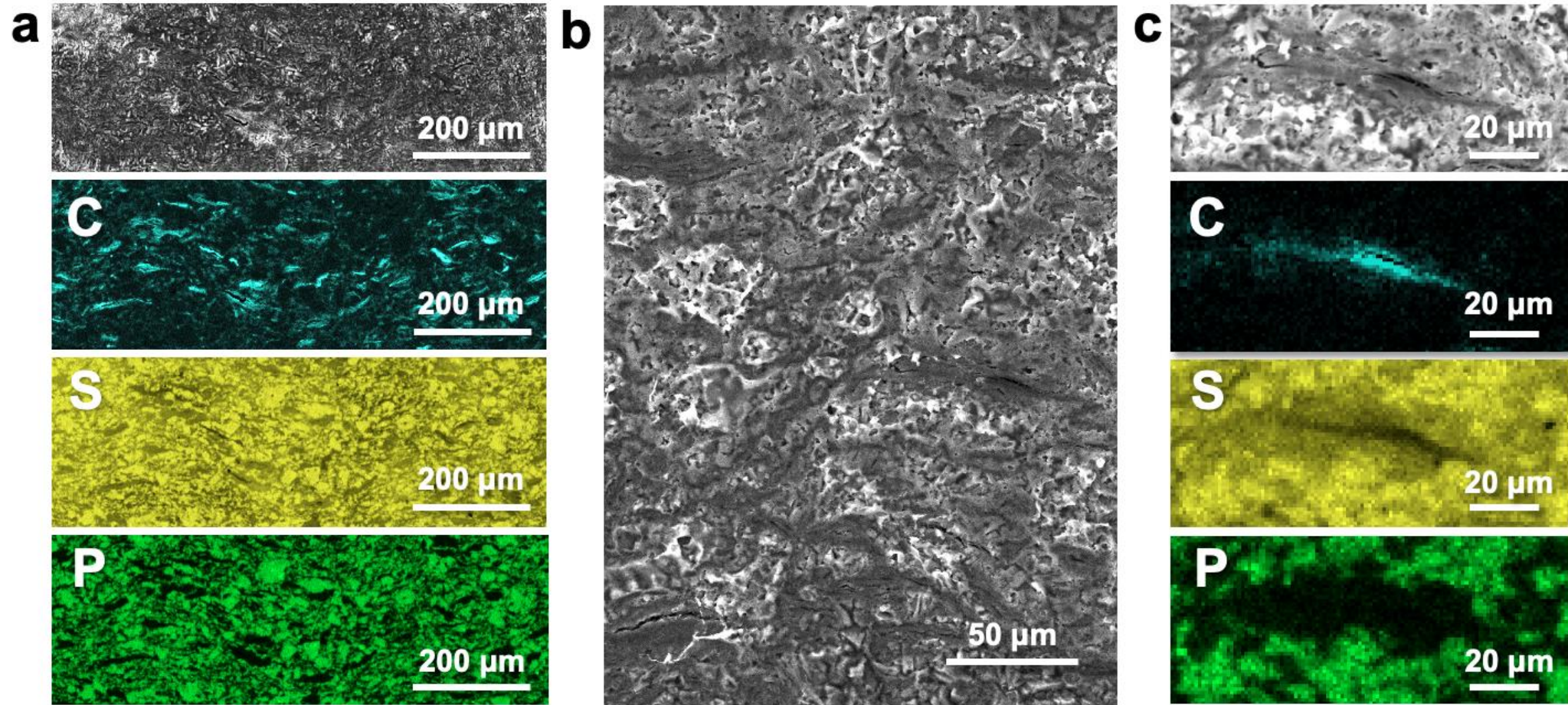
❑ hG-based cathode exhibited more even material distribution and less porosity, and thus better performance than CB-based cathode

Optimizing S Cathode Fabrication



- ❑ A Design-of-Experiment (DOE) study
- ❑ 20 unique compositions
 - ❖ S: 10-50%
 - ❖ hG_1+hG_2 : 5-20%; hG_1 : 0-15%; hG_2 : 0-20%
 - ❖ SE_1+SE_2 : 30-85%; SE_1 : 0-75%; SE_2 : 0-70%
 - ❖ No hG_1 = no melt infiltration

Solid-State S Cathode Design Principles



- ❑ Melt infiltration of S (at 160°C) onto hG sheets
- ❑ Maximal contact of S with both electrical (carbon) and ionic conductors (solid electrolyte)

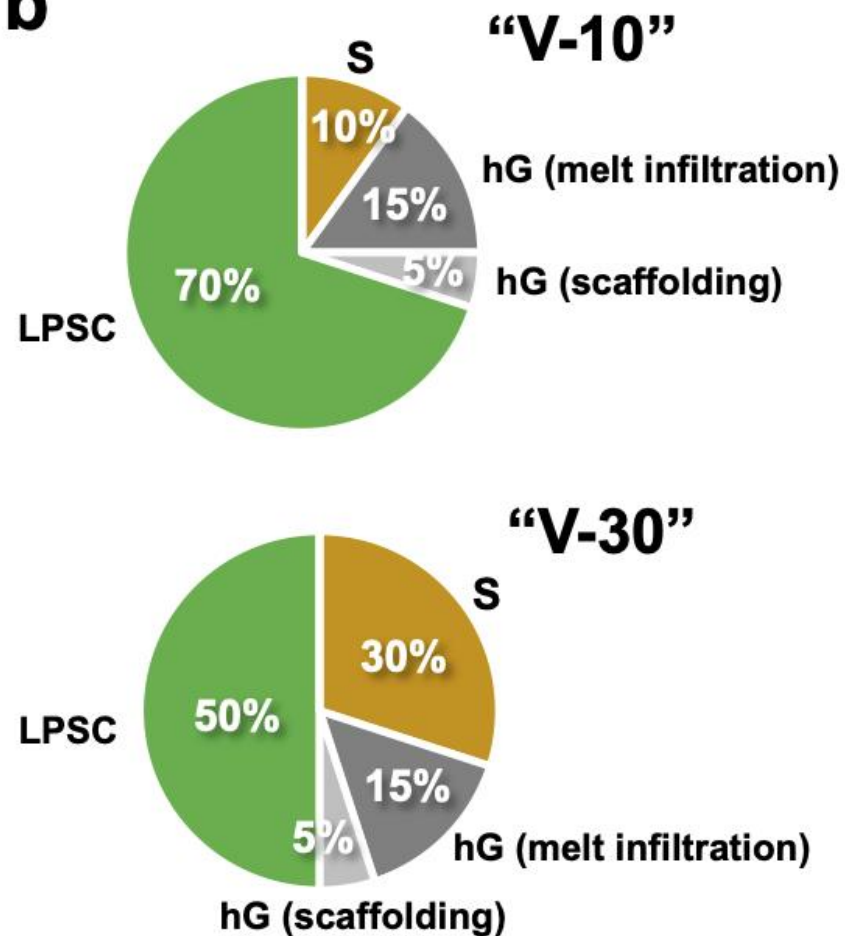
Optimized Solid-State S Cathode Fabrication



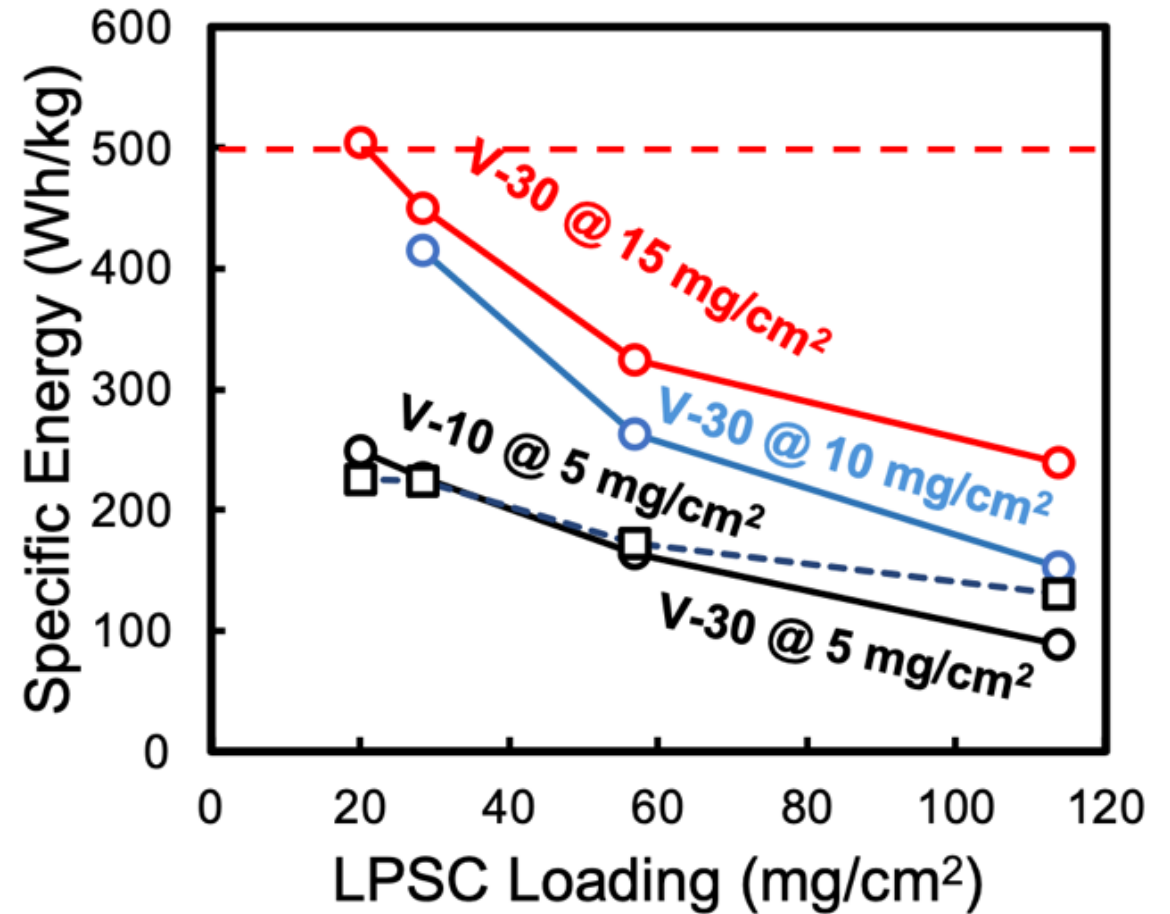
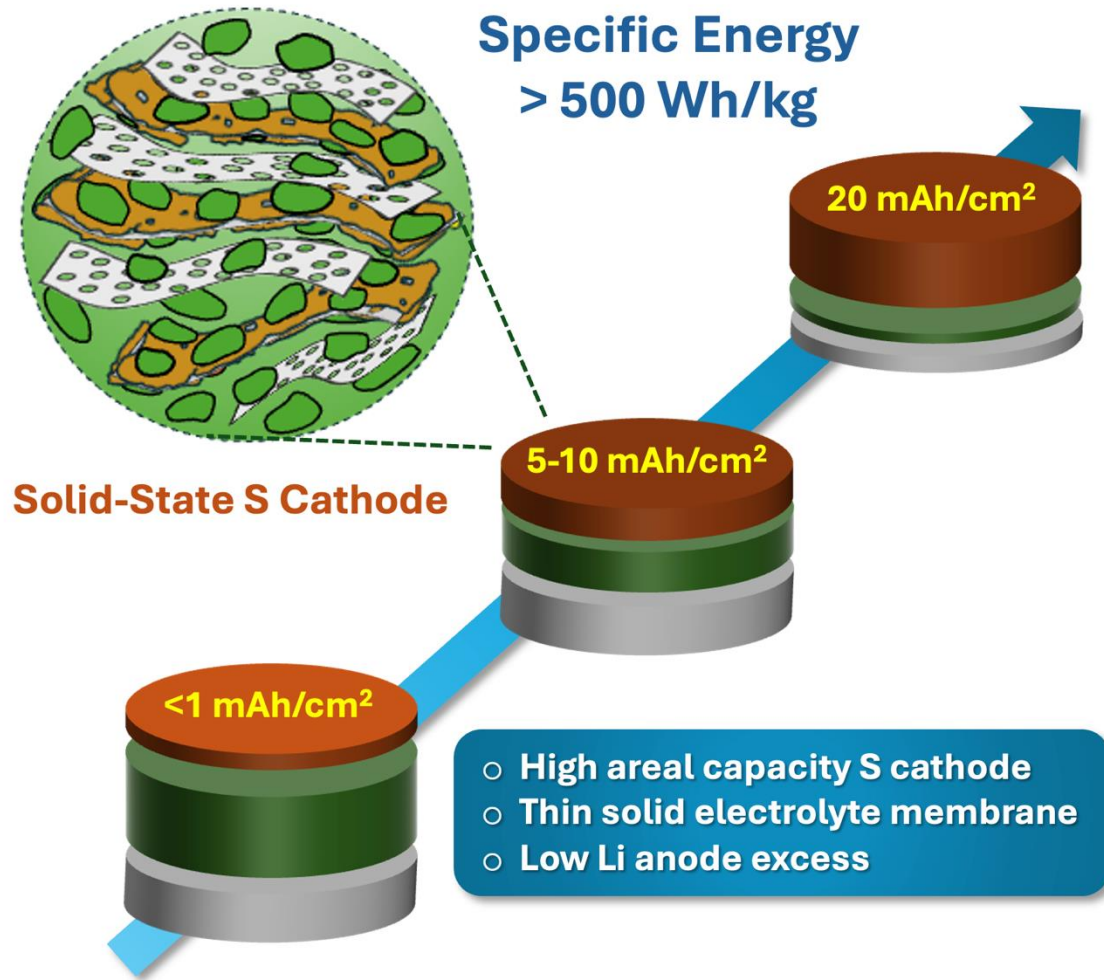
a



b

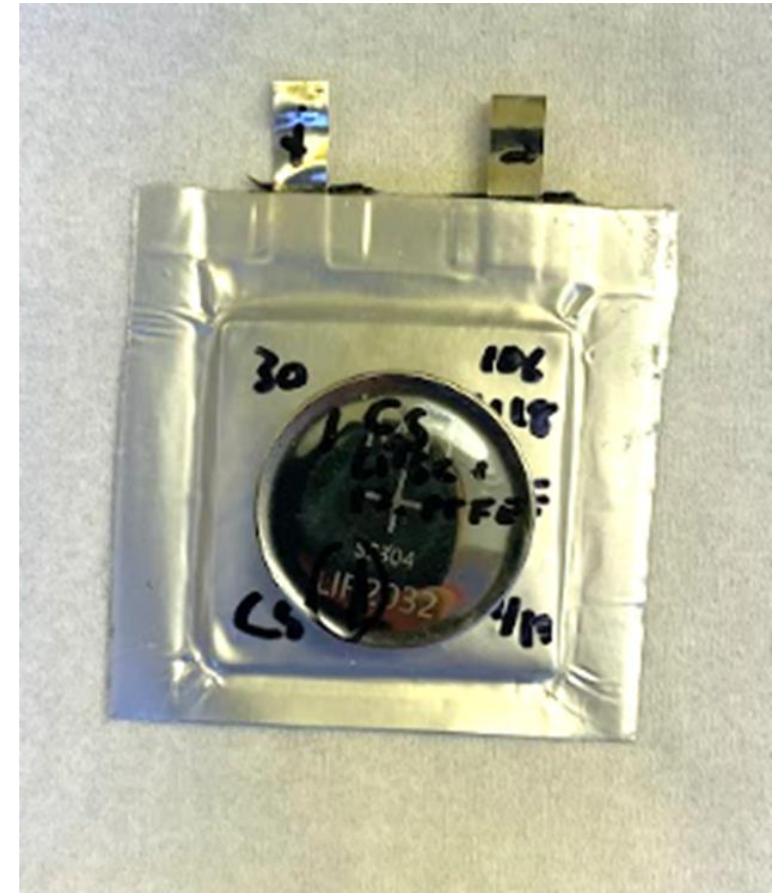
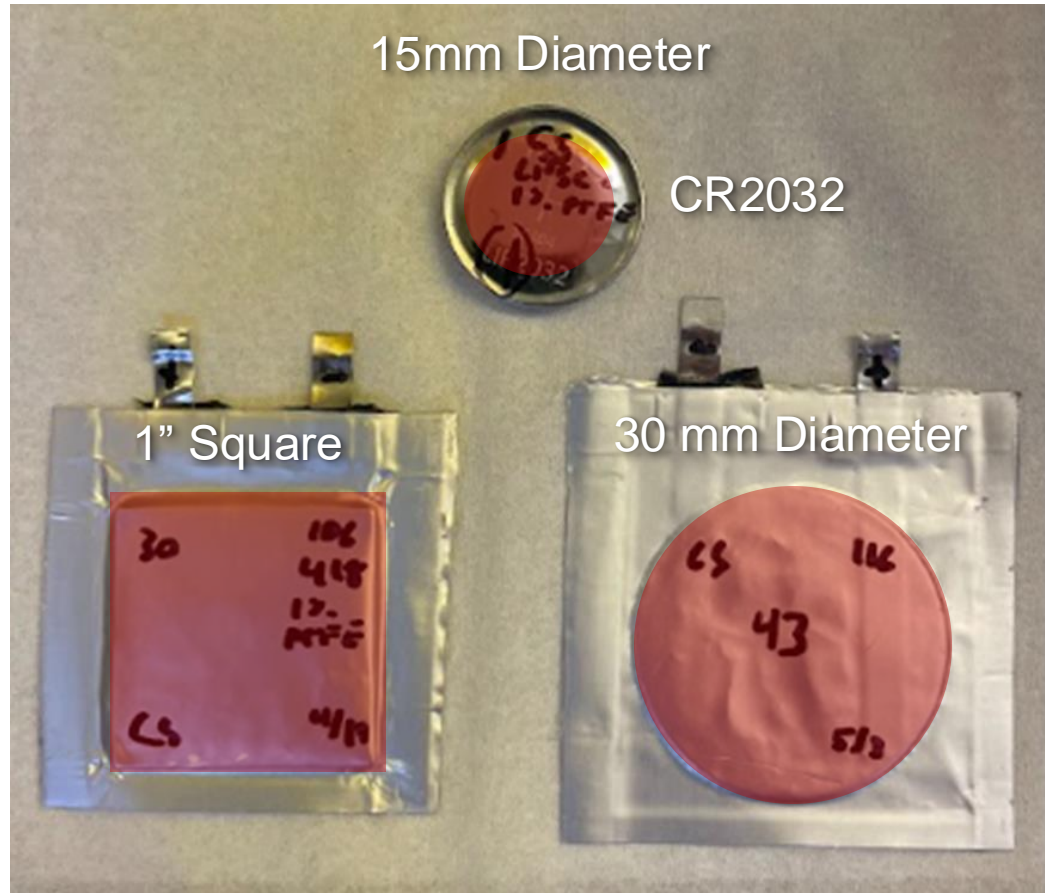


Cell Integration to Improve Specific Energy



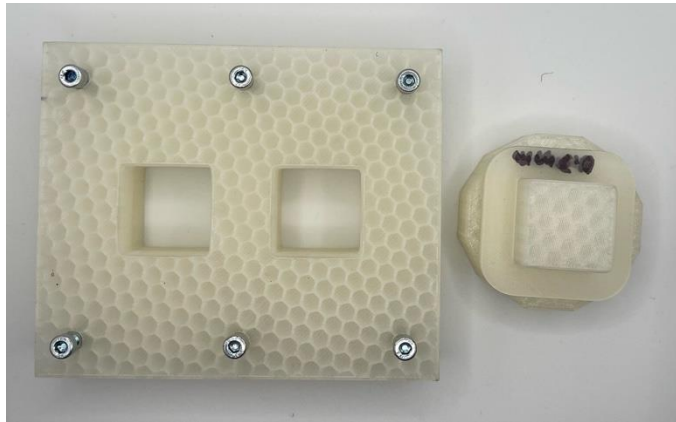
□ Optimized S cathode allowed significant improvement in specific energy

From Coin Cells to Pouch Cells

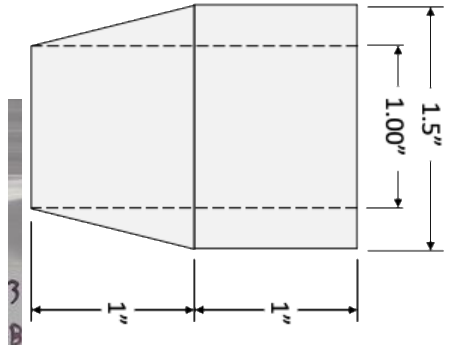


- Small format pouch cell allows scale-up materials engineering studies with (currently) costly chemicals conducted at an affordable scale

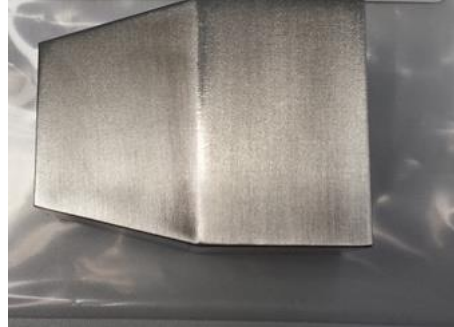
Fabrication Tools and Parts for Pouch Cells



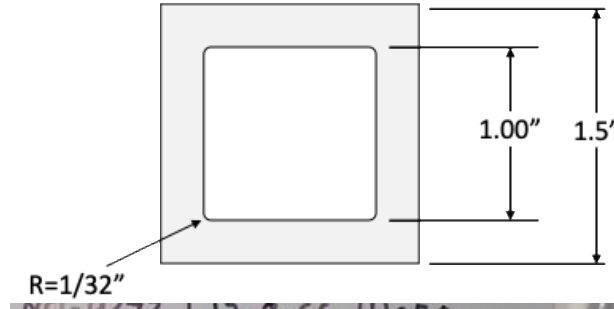
Pouch Formation Tool



NSI-4372 | 13-8 SS H1050



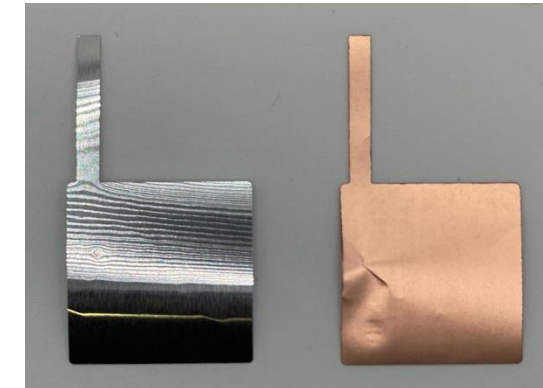
Electrode/Electrolyte Cutting Tools



NSI-4372 | 13-8 SS H1050

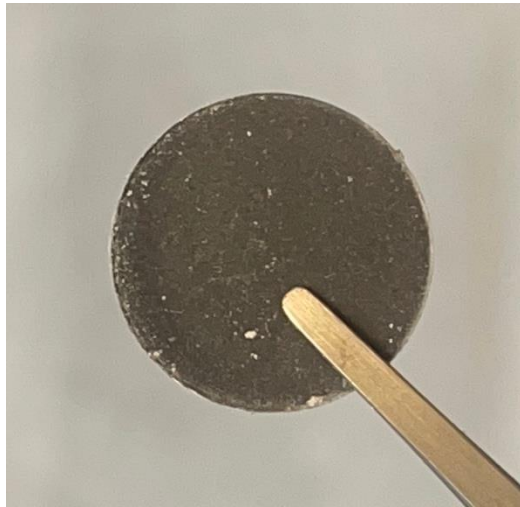


Compression Die



Laser-Cut Current Collectors

Scaling Up is NOT Straightforward

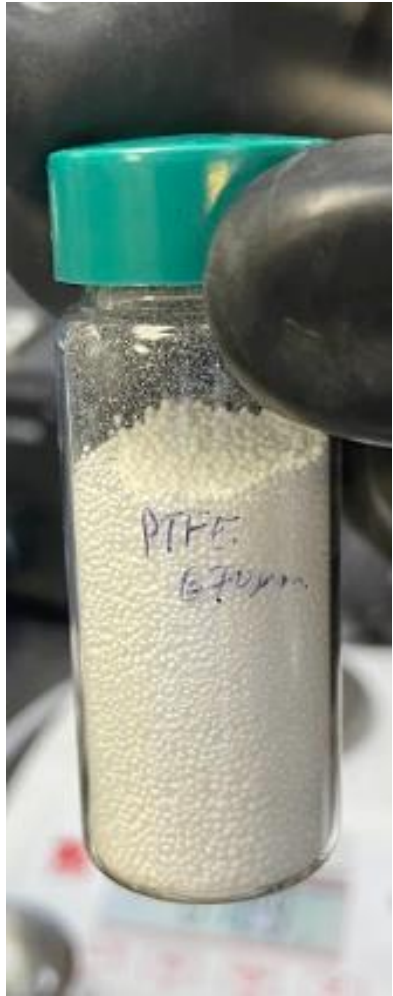
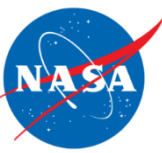


Cathodes for Coin Cells

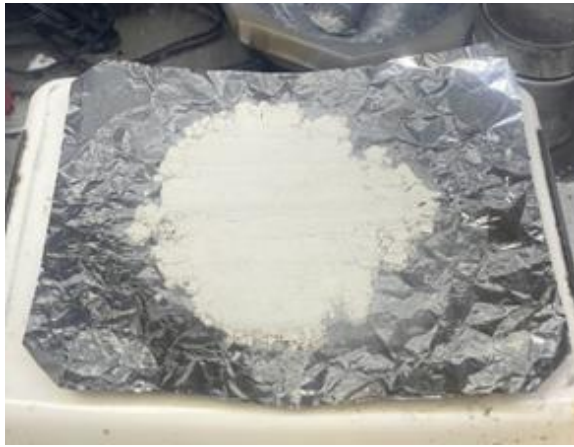


Cathodes for Pouch Cells

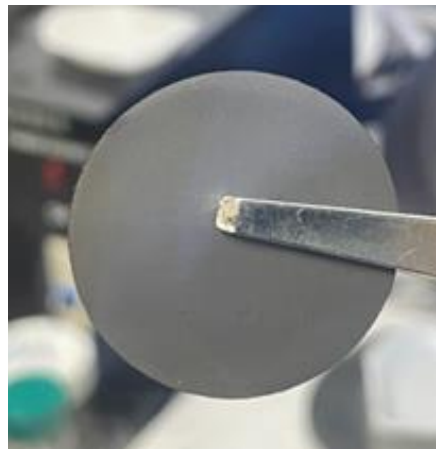
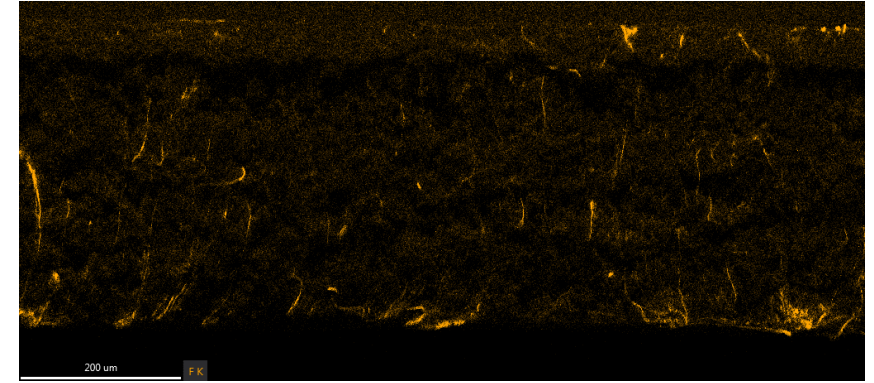
Polymer Binder for Improved Processing



PTFE
(polytetrafluoroethylene)



Solid Electrolyte Film with Binder



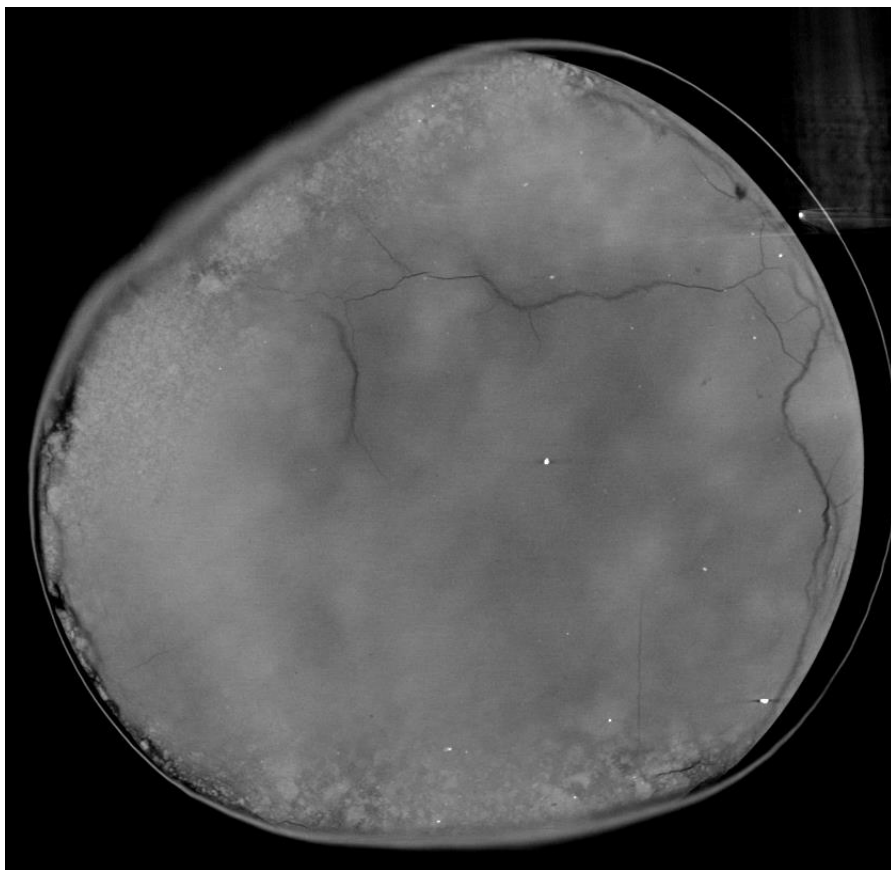
Cathode Film with Binder

- ❑ The use of a polymer binder significantly improved the processibility of cathode and electrolyte films
- ❑ Microscopy investigations showed that the polymer binder fibers evenly distributed through the layers

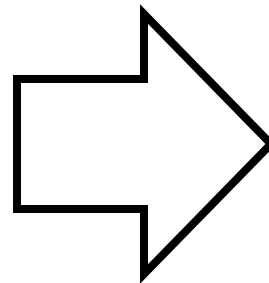
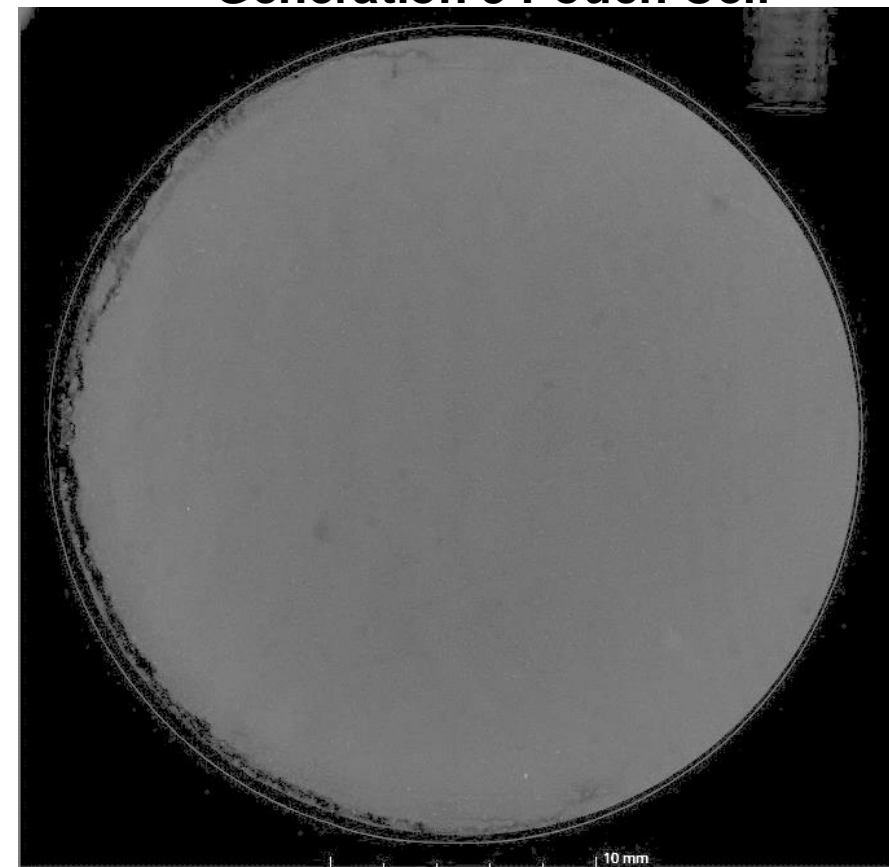
Improved Pouch Cell Fabrication



Generation 2 Pouch Cell



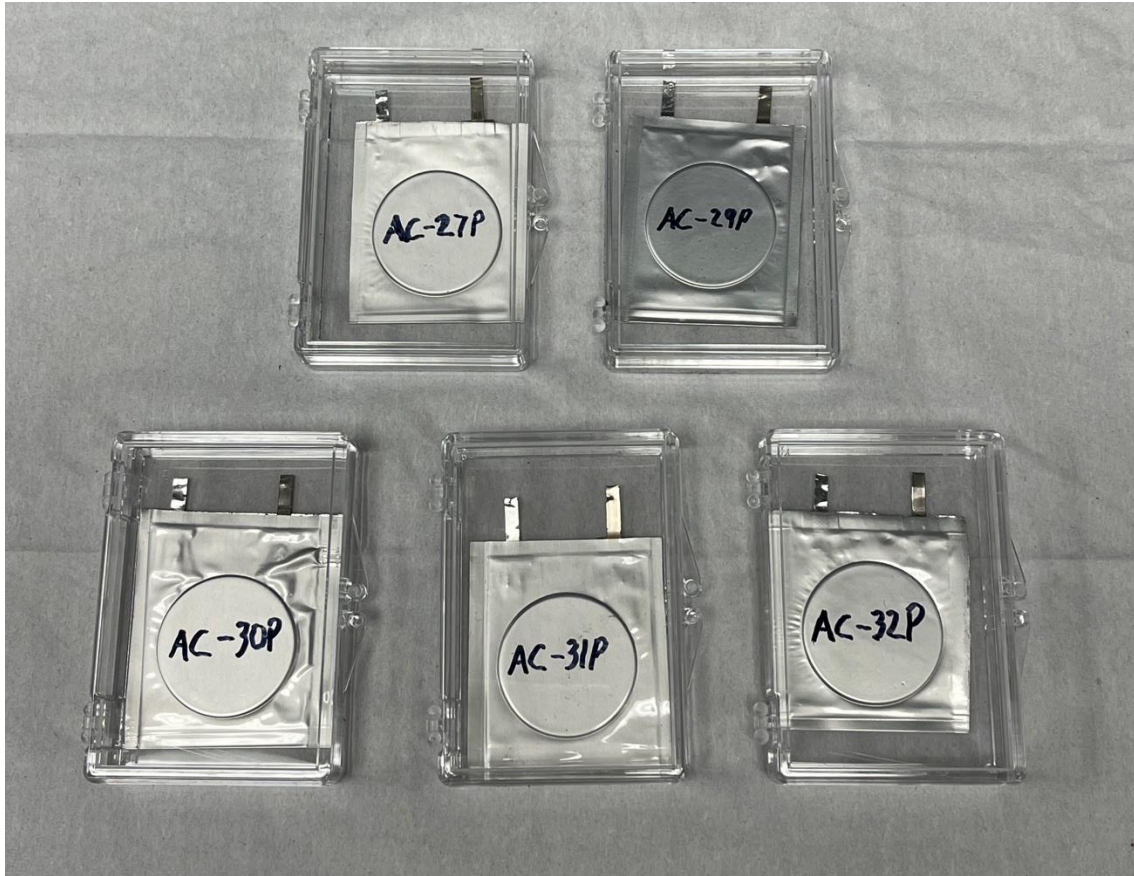
Generation 3 Pouch Cell



❑ Discs are all 3 cm in diameter

Courtesy: Dan Perey
NASA Langley Research Center (LaRC)

SABERS Pouch Cells

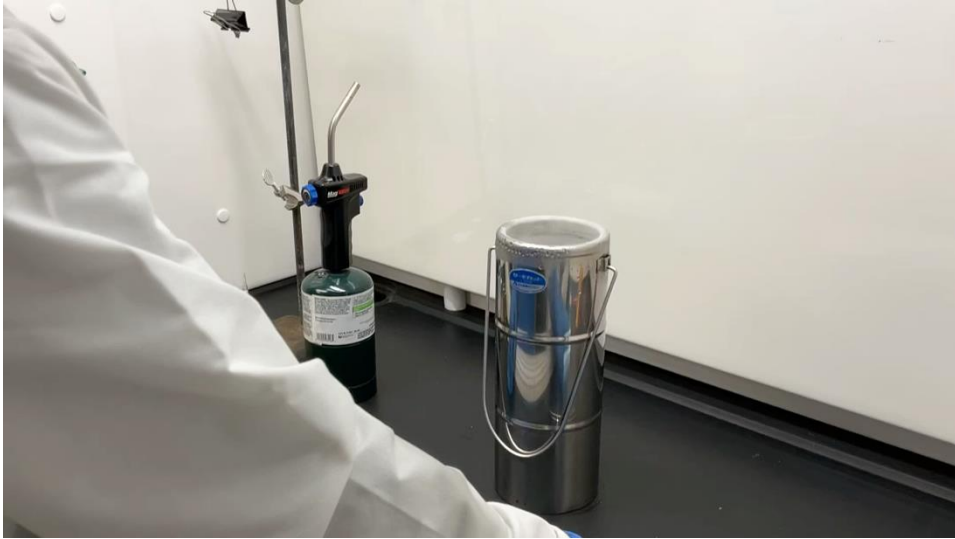


SABERS “Cookie” Cells

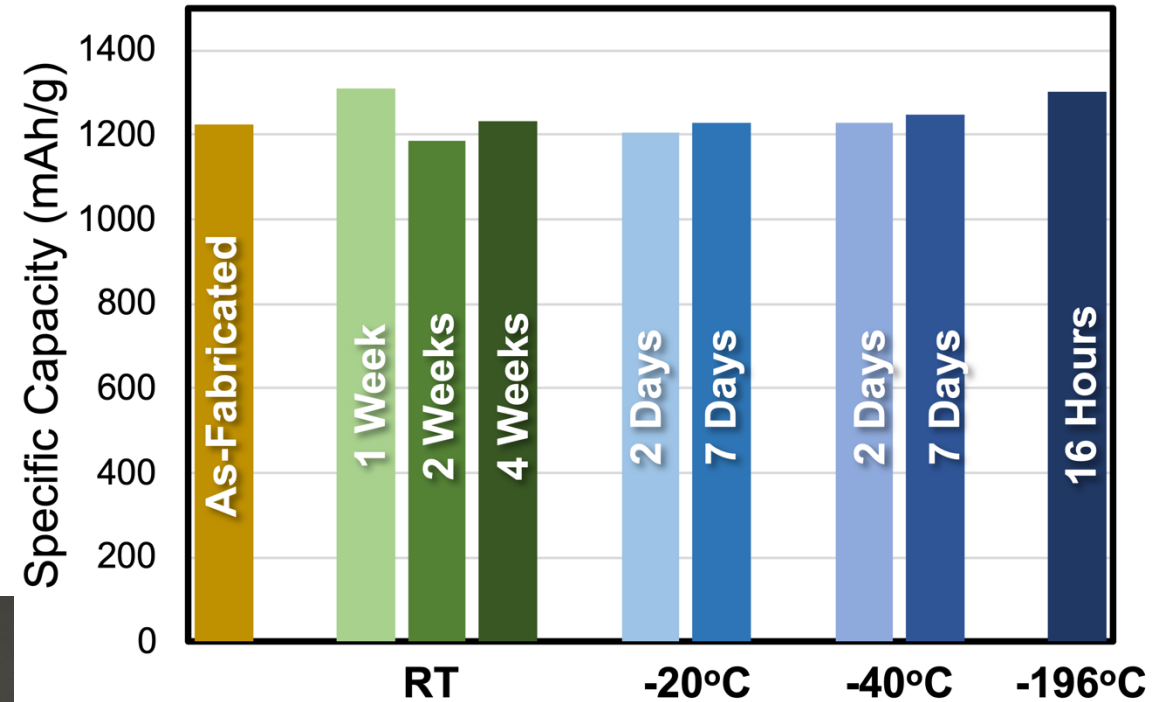


- ❑ Routine fabrications of high quality, small format all-solid-state pouch cells

Shelf Life and Low Temperature Storage



SABERS Cells Removed from Liquid Nitrogen Reservoir

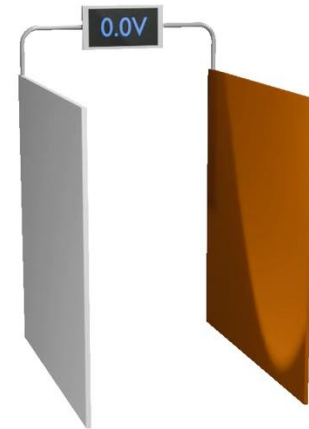


- ❑ SABERS all-solid-state battery cells exhibit excellent shelf life and survive from low and extremely low temperatures (exhibit normal functions after warming up).

Summary



- ❑ Materials science research is key for advanced battery development
- ❑ Holey graphene is an advanced electrode material with a variety of applications
- ❑ All-solid-state battery cells are being routinely fabricated and tested for applications toward air and space
- ❑ Research efforts at the materials level are still required for improved battery cell performance



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- Rocco Viggiano (GRC)
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- Vesselin Yamakov
- Ji Su
- Jin Ho Kang
- Dan Perey
- Rodolfo Ledesma
- Glen King
- Lopamudra Das
- John Hopkins



- NASA Convergent Aeronautics Solutions (**CAS**) Project



- NASA Transformational Tools and Technologies (**TTT**) Project



On-Site

- ❑ **2019-2021:** Christian Plaza-Rivera, Elizabeth Barrios, Brandon Walker
- ❑ **2022:** Daniel Caicedo, Abigail Durgin, Bona Kim, Ashley Lam, Rehan Rashid, Lucy Somervill
- ❑ **2023:** Melissa Chang, William Dai, Sayyam Deshpande, Prasun Kolhe, Shane Lindsey, Claudia Lopez, Alanis Matias-Perez, Abraham Nicolson, Coby Scudder, Aoife Zuercher
- ❑ **2024:** Autum Avery, Alan Cancel, Hanjing Chen, Kelsey Crawford, David Forslof, Ashley Gomez, Alison Kavanagh, Jason Packard, Vergil Schreiber, Daniel Thornton

Virtual

- ❑ **2020:** April Rains
- ❑ **2021:** Malik Satterwhite-Austin
- ❑ **2022:** Prabhat Jandhyala; Thomas Neufus; Luis Valdez
- ❑ **2023:** Sophie Kiley; Ethan Higginbotham; Amol Gupta
- ❑ **2024:** Kelton McGrath



2019

2020-2022

1293-C
6A West Taylor Street
Summer 2022

Fall 2022

Lucy Somerville
09/2022



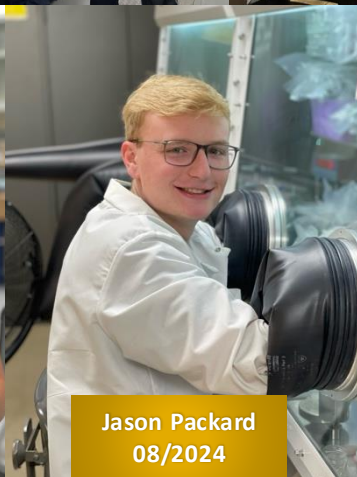
1293-C
West Taylor Street
Spring 2023

Coby Scrudder
02/2023

Summer 2023

Fall 2023

Spring 2024



Hanjing Chen
05/2024

Summer 2024

Autumn Avery
06/2024

Jason Packard
08/2024

Fall 2024

Alan Cancel
10/2024

❑ The LaRC team has a total 38 student interns since 2019: 9 virtual, 29 on-site (26 since Summer 2022)