Next Generation Batteries for Electric Aviation and Space

Donald A. Dornbusch[1], Yi Lin[2], William Huddleston[3], Vesselin Yamakov[4], Rocco P. Viggiano[1]

[1] - NASA Glenn Research Center, 21000 Brookpark Rd., Cleveland, OH 44135, USA

[2]- NASA Langley Research Center, Hampton, VA 23681, USA

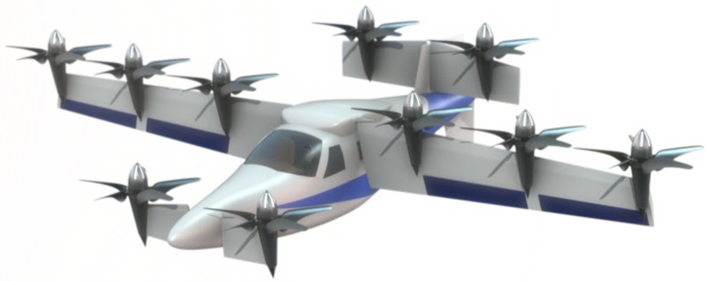
[3]-NASA NPP/Oak Ridge Associated Universities, USA

[4] – Analytical Mechanics Associates Inc, Hampton, VA 23666

48th International Conference and Expo on Advanced Ceramics and Composites

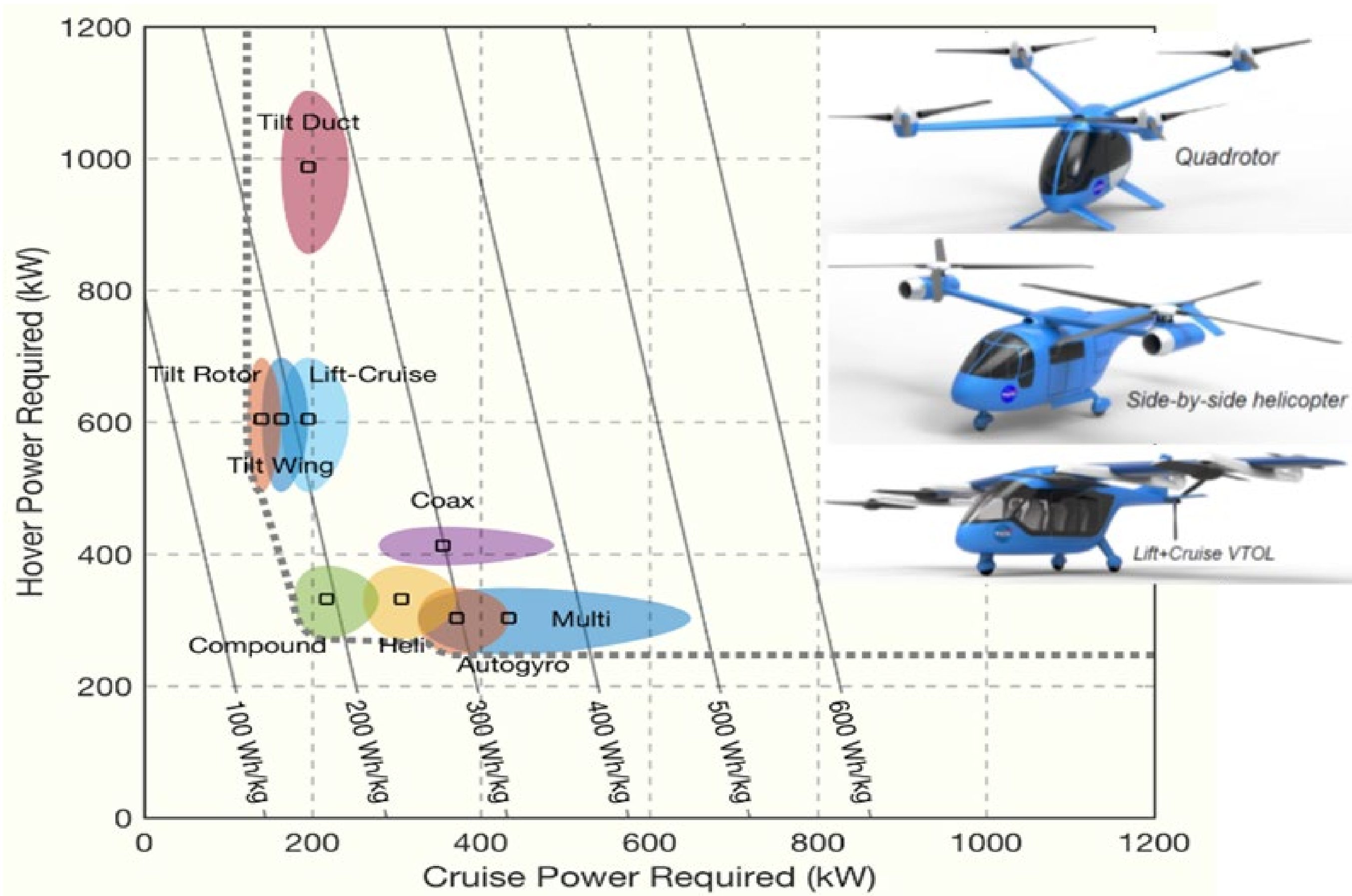
Presenter:
Dr. Donald A. Dornbusch-NASA GRC
donald.dornbusch@nasa.gov

Introduction – Electrified Aviation



- Electric and hybrid electric aircraft systems can lead to higher efficiencies, safer designs, and quieter operation
- Current battery technology is insufficient to achieve the requirements for electric aviation:
  - Energy, Power, and Safety
- Higher energy density batteries and current flammable liquid electrolytes lead to safety concerns

Aircraft Requirements



- Aircraft design significantly impacts power requirement
- Current battery energy limited to ~200 Wh/kg

Solid-State Electrolytes

Advantages:
- Solid-state electrolytes = low volatility
- Wide temperature tolerance

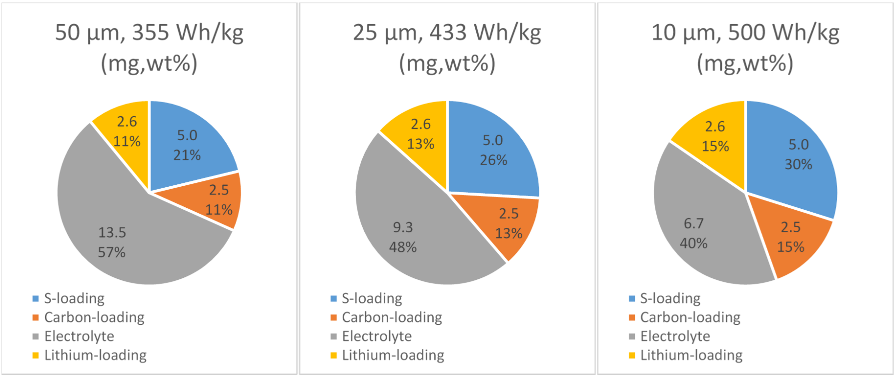
Disadvantages:
- Difficult to manufacture
- Interface issues
  - Solid-Solid contact vs Liquid-solid
- High density vs liquid (g/cm3)

Material Selection

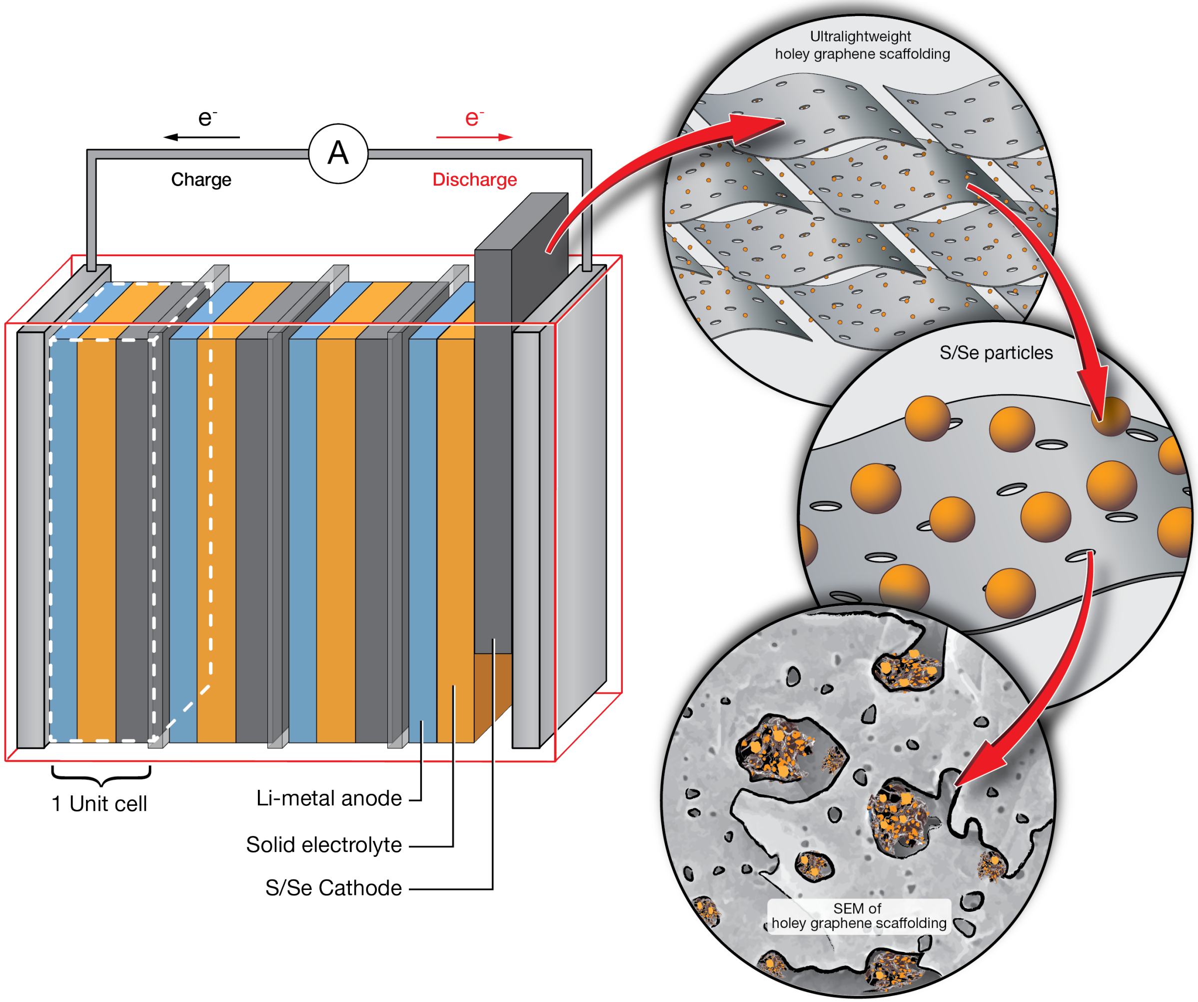
- Lithium-Sulfur
  - Lithium metal is an ideal anode material
    - Lightweight (3860mAh/g), low potential, metallic
  - Sulfur has high capacity (1675mAh/g)
    - Reasonable potential above lithium (~2V)
    - Dissolution prevented in a solid-electrolyte
- Solid-Electrolyte → 25 μm separator:
  - Polymer ~1.2g/mL → 3 mg/cm2
  - Sulfide ~1.7 g/mL → 4.25 mg/cm2
  - Oxide ~5.6 g/mL → 14 mg/cm2

Oxides, such as LLZO, must be x3.3 times thinner than corresponding sulfide to achieve same weight penalty

- Impact of Solid-Electrolyte (Sulfide):
  - Substantial gains in energy by controlling separating layer thickness

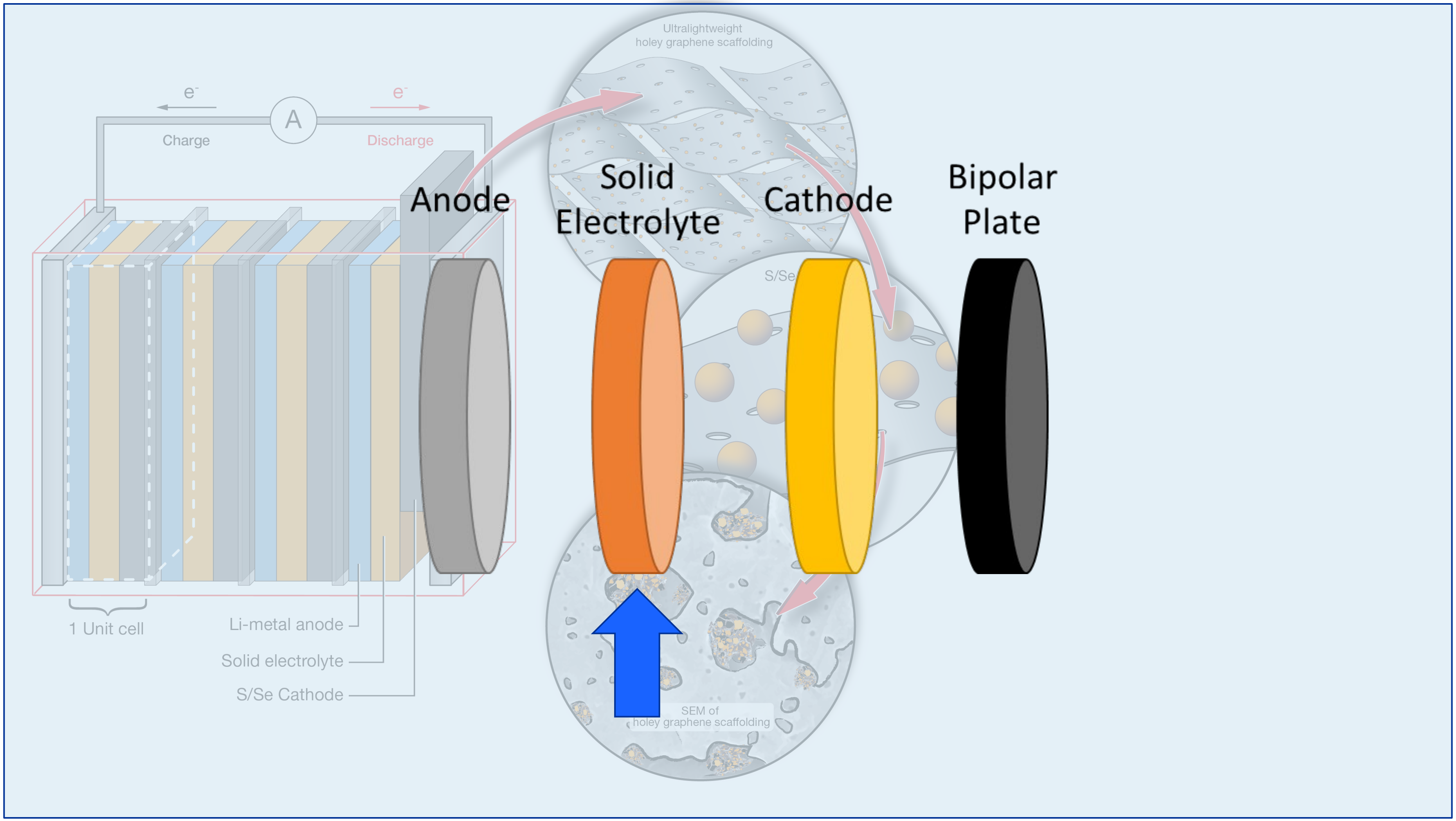


Cell Design



- Multilayered system
- Anode: Lithium Metal
- Separator:
  Solid Electrolyte-Polymer composite
- Cathode:
  Sulfur-Carbon-Electrolyte Composite

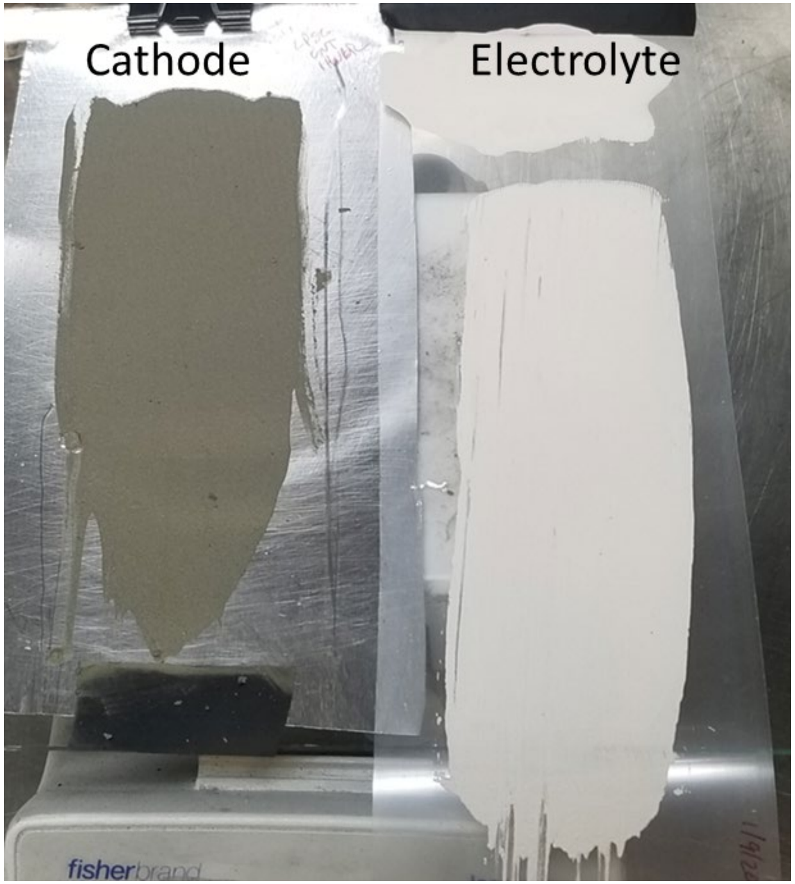
Cell Design


Ultralightweight
holey graphene scaffolding
e-
e-
A
Charge
Discharge
Anode
Solid
Electrolyte
Cathode
Bipolar
Plate
S/Se
1 Unit cell
Li-metal anode
Solid electrolyte
S/Se Cathode
SEM of
holey graphene scaffolding

Manufacturing Thin Electrolytes

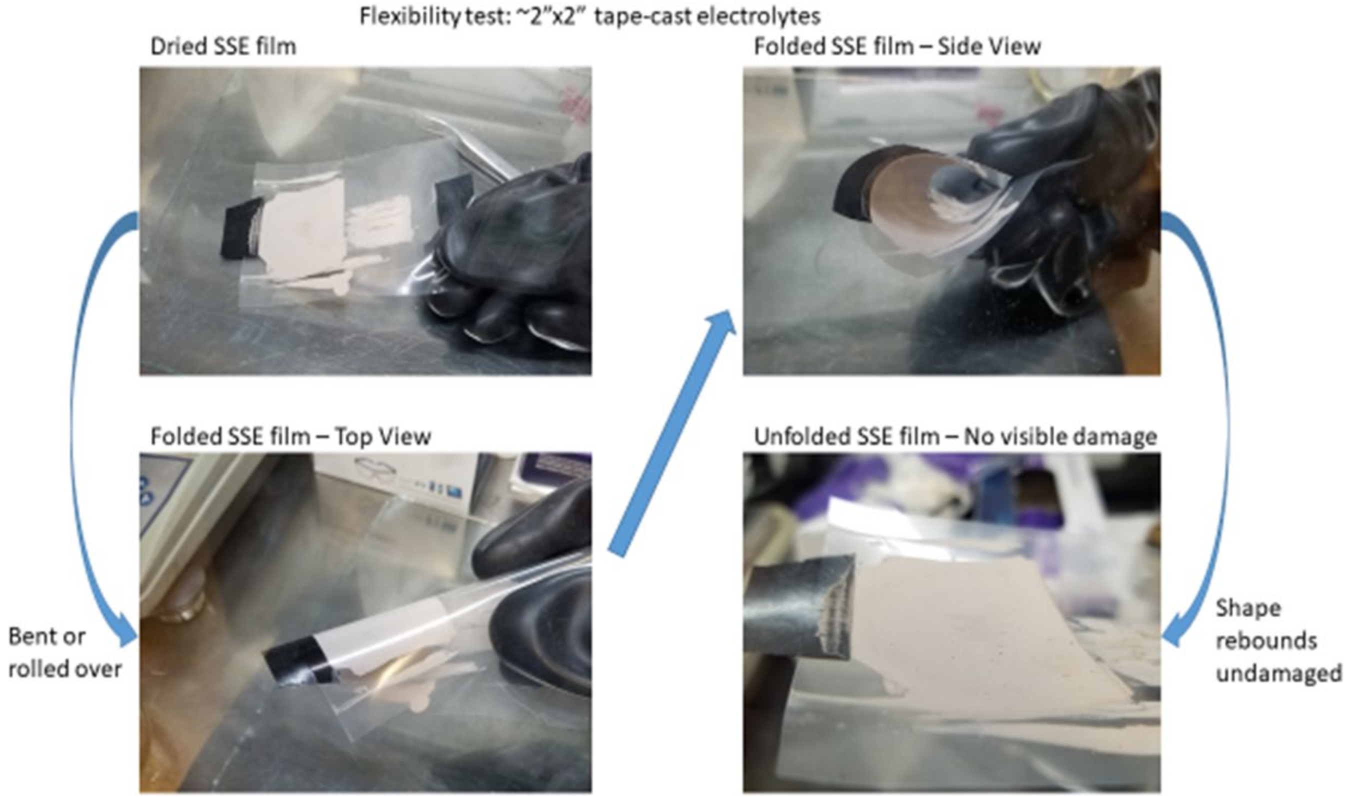
Sulfide (Li_6PS_5Cl)-Polymer Composites

- Tape-casting produces thin electrolytes
- Traditional lithium-ion manufacturing technique
- Utilizing inert binder (3-5wt%) to achieve well adhered films
- Capable of producing multi-phase cathodes
  - (Active-Carbon-Electrolyte-Binder)

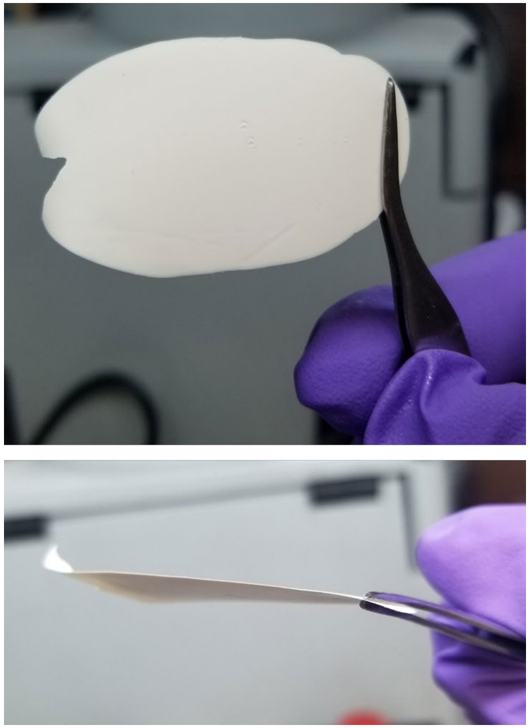


Improved mechanical properties

Mylar Supported

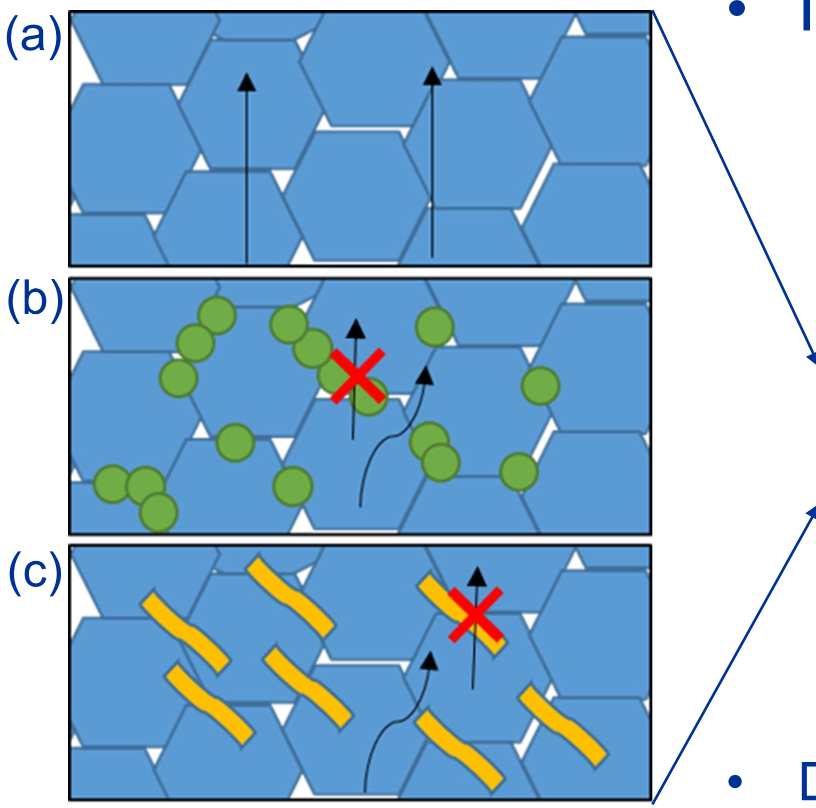


Free-standing



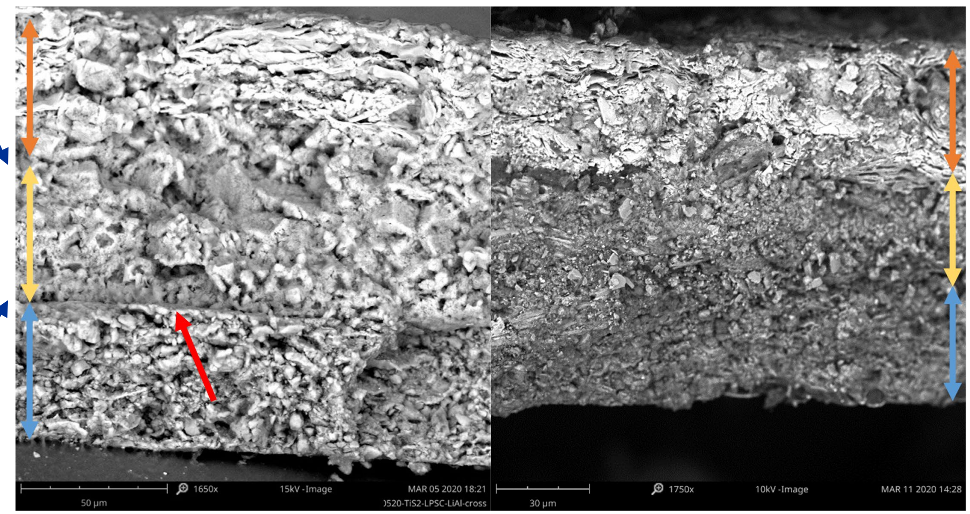
Substantially improved flexibility over pure glass electrolytes

Glass-Polymer Composite Electrolytes



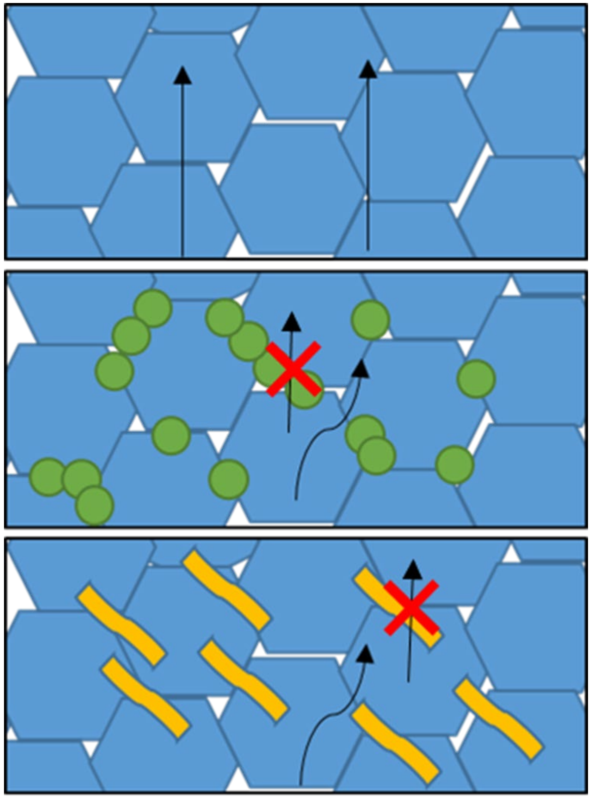
Depiction of Li transport through densified solid-state electrolyte for pure (a), composite with PTFE powder binder (b), and composite with solution deposited Styrene-Butadiene-Styrene (SEBS) rubber binder (c).

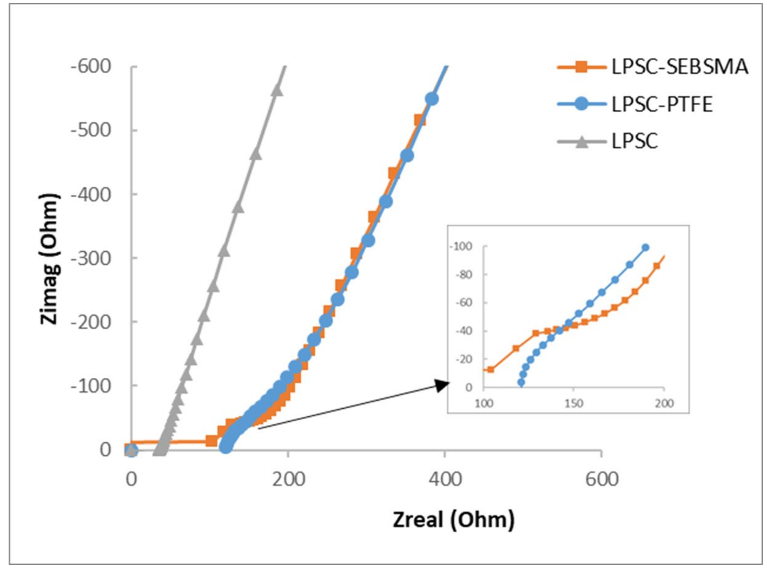
- Introduction of a passive phase
  - Conduction pathways change

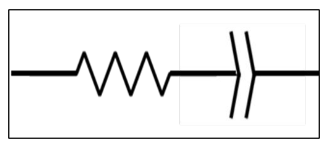


- Densification processing improvements lead to better sheet adhesion

Impedance Data







Electrolyte	Resistanc e (Ohm)	Conductivity (S/cm)
LPSC	35	1.36E-03
LPSC-PTFE	159	2.99E-04
LPSC-SEBS	168	2.83E-04

- Increase in impedance through electrolyte layer due to binder phase
- Ionic conductivity still retains ~20% of pure LPSC
- Binder type has less impact on performance loss

Limitations of binder-based systems

- Reactivity of LPSC with polar solvents forces the use of nonpolar solvents
  - Nonpolar solvents are limited to low polarity binders with weaker adhesion to polar LPSC surfaces
- Below 30μm films remain fragile

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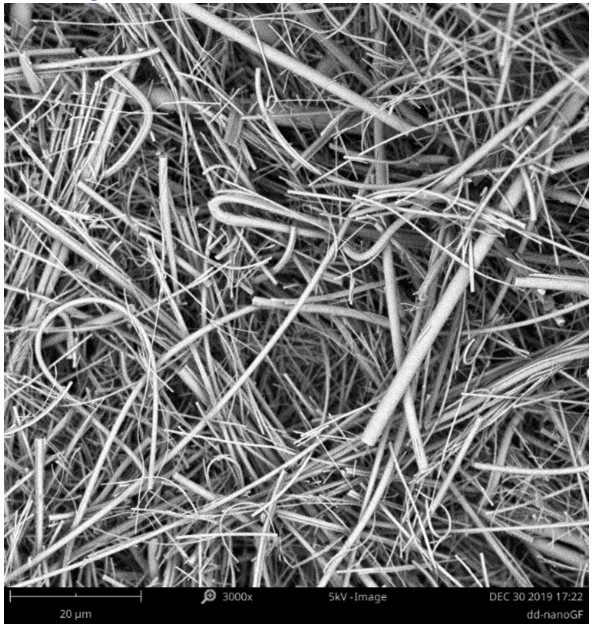
Possible solutions:

- Explore alternate binders/processing techniques
- ⇨ Introduce a filler material to further strengthen the composites

Fiber-based fillers

Polyaramid(Kevlar)

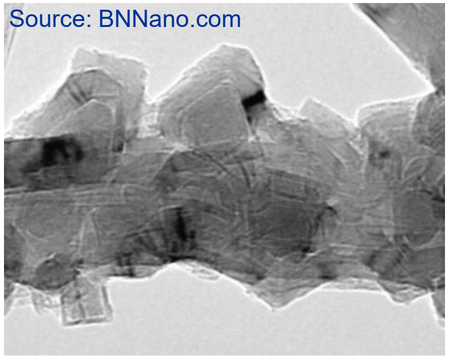
Nanoglass



NASA forcespun fibers

Boron Nitride Nanobarb™

Source: BNNano.com



Fiber candidates:

Kevlar – high strength polymer fibrils (wide distribution)

Nanoglass – high aspect ratio (700nm x 100's µm)

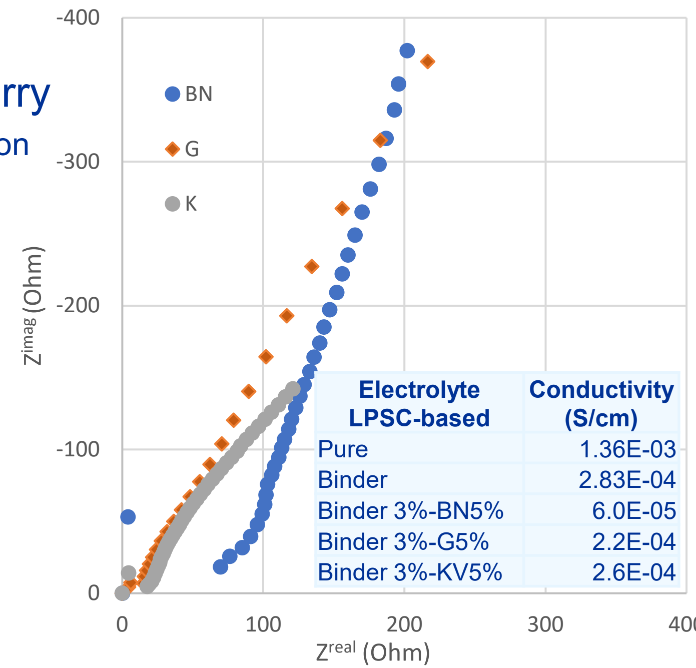
Forcespun polymers – high aspect ratio, polymer control

BNNanobarbs™ – insulating analog to CNT (very small, nm x nm)

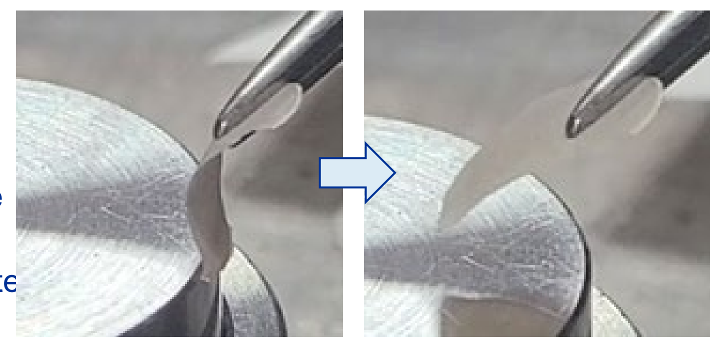
Filler Results

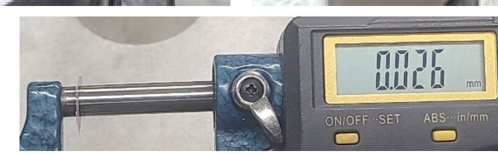
- Fillers were added at 5wt% to LPSC-Binder-Toluene slurry
  - Alternating centrifugal mixing and sonication to ensure even dispersion
  - Tape cast onto mylar substrate
  - Dried at 60°C

- Fibrous additives dramatically increased the slurry viscosity
  - Viscosity ranged from BN < Nanoglass < Kevlar
  - Kevlar viscosity greatly increased after sonication
    - Bundle unwrapping and/or stronger interaction with binder
- Impact on conductivity
  - Largest drop observed for BN, which suggests stronger interference between electrolyte particle-particle contacts within the composite.
  - Larger fibers retained more conductivity, close to filler-free composite indicating less contact interference between LPSC particles.
- Mechanical stability
  - All three materials showed substantially improved stability
  - The samples even showed flexibility after densification.



Electrolyte LPSC-based	Conductivity (S/cm)
Pure	1.36E-03
Binder	2.83E-04
Binder 3%-BN5%	6.0E-05
Binder 3%-G5%	2.2E-04
Binder 3%-KV5%	2.6E-04



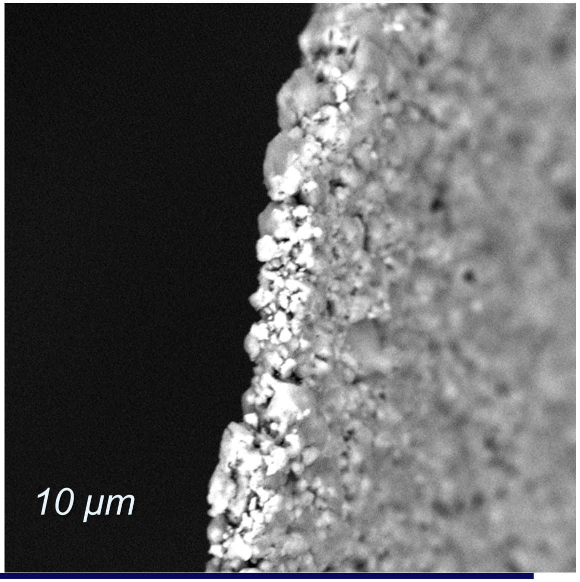


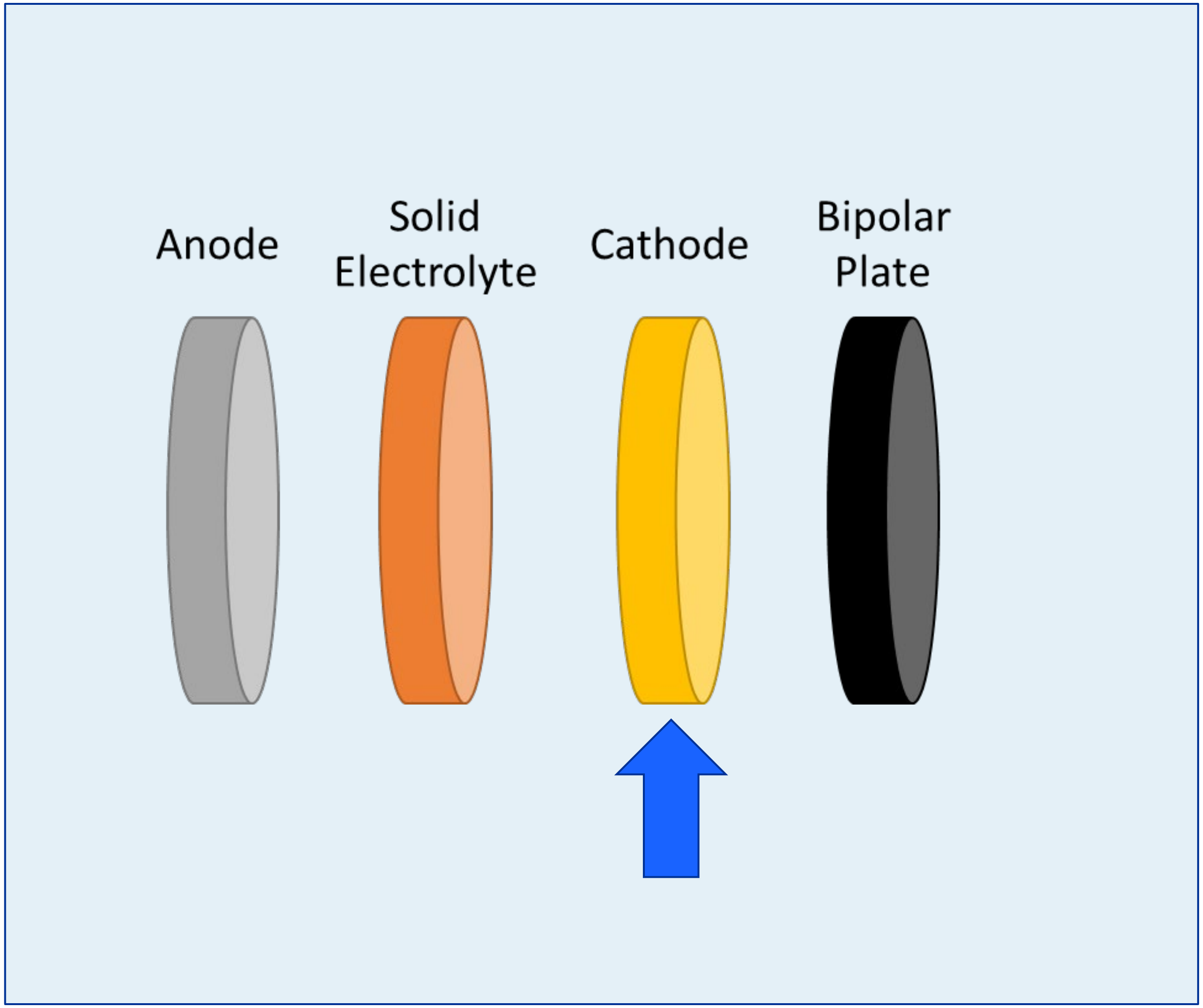
Conclusions

- Lithium conducting Li_6PS_5Cl composite electrolytes could be manufactured with thicknesses between 25-50 µm through a scalable process.
- Achieved thicknesses were in the practical range to make the chemistry competitive with current lithium-ion cells.
- Binder and filler impacted conductivity, but ~20% was retained.
  - Significant reduction in thickness will lead to overall improvements in energy and power capability.
  - Length-scale of filler influenced conductivity losses

Future Direction

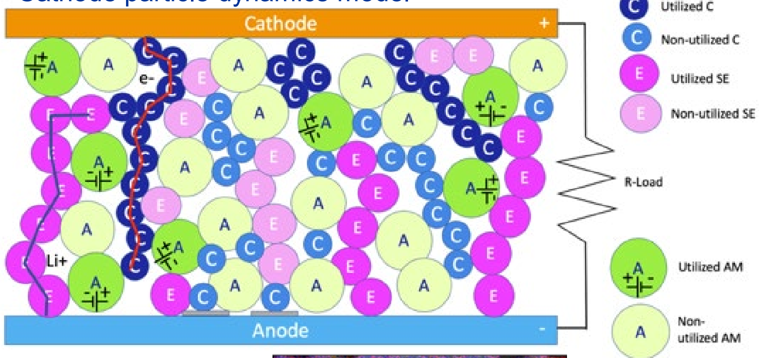
- Optimization of polymer and filler loadings to improve conductivity and mechanical stability
- Validate feasibility & reliability of thinner films

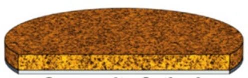


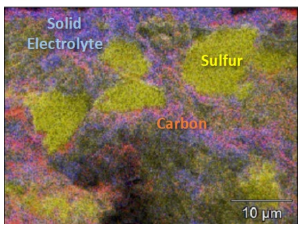

Anode
Solid Electrolyte
Cathode
Bipolar Plate

Cathode - Experimental & Computational Development

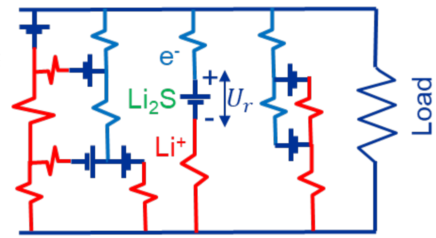
Cathode particle dynamics model





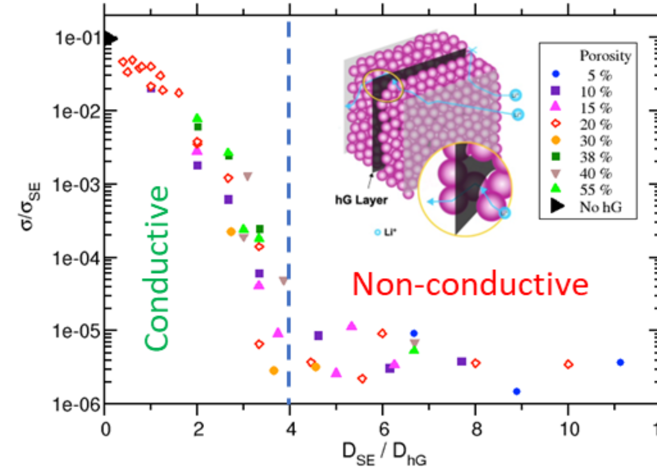


Convert to electric circuit model



U_r- reduction potential

Li-ion transport through holey graphene (hG) pores

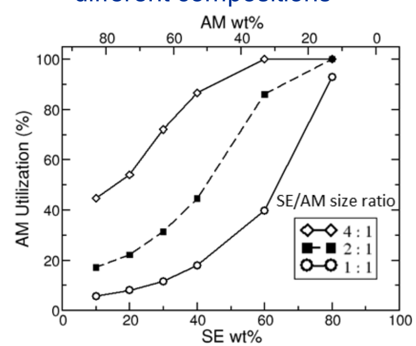


E. Barrios et al., ACS Appl. Mater. Interfaces 2022, 14, 21363−21370

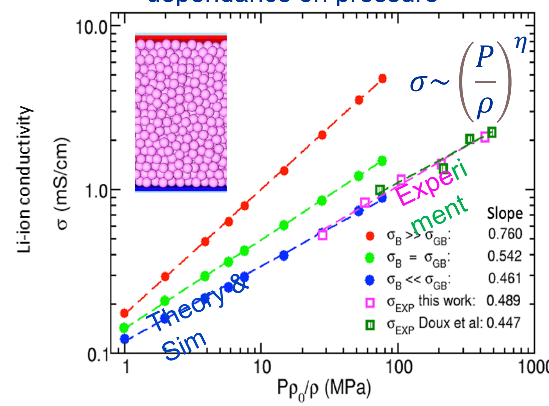
Optimization

- Effect of holey graphene porosity on Li-ion conductivity in the electrolyte
  - Li ion can conduct through hG holes if the holes are at least 25% the size of the SE particles.
- Effect of pressurization on the electrolyte conductivity
  - Pressure dependance of Li-ion conductivity is dependent on the surface properties of the electrolyte particles.
- Effect of cathode composition and particle size on active material (AM) utilization

Sulfur utilization at different compositions



Li-ion conductivity dependance on pressure



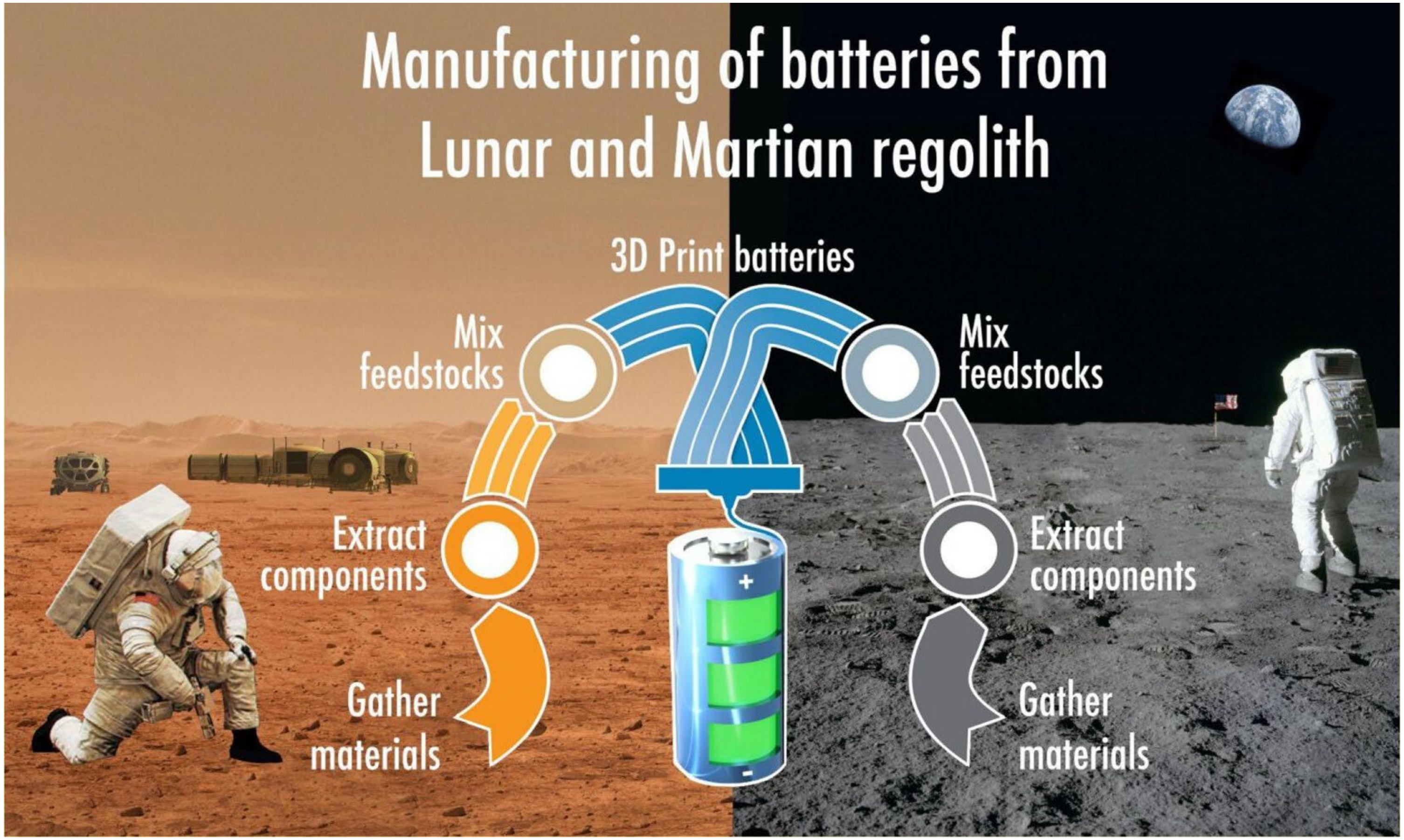
V. Yamakov et al., ACS Appl. Mater. Interfaces 2023, https://doi.org/10.1021/acsami.3c01279

Aeronautics Summary

- Ultra-high performing batteries required to compete with commercial aviation fuels

- Energy, Power, Cycle Life, and Safety advances beyond current state-of-the-art technologies required as EA needs are well beyond EV requirements

Beyond Aeronautics: Space



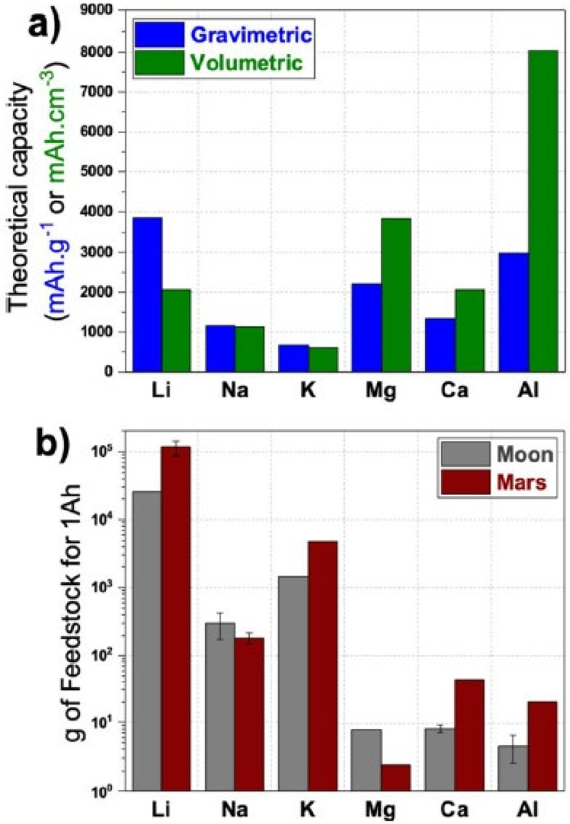
ACS Energy Lett. 2023, 8, 1042−1049

- Lunar derived materials for sustained habitation on the moon and mars

Lunar & Martian Abundance

Table 1. Bulk Composition of Lunar, Martian, and Terrestrial Soil[a]

Element	Moon (refs 17–19)	Mars (refs 20, 21, 24)	Earth (refs 25, 26)
Li (ppm)	10	1.8–3	18
Na (ppm)	2000–3000 (average); 5000 (Maria region)	5770	23 600
K (ppm)	1000	309	21 400
F (ppm)	70	20–30	525
Cl (ppm)	50	30	472
P (ppm)	800	675	757
V (ppm)	130	130	98
Mg (wt%)	5.5	18.5	2.2
Ca (wt%)	10 (highland); 8 (Maria Region)	1.7	3.9
Fe (wt%)	26 (highland); 15 (Maria region)	14.1	4.3
Mn (ppm)	200 (highland); 2000 (Maria region)	2250	716
Al (wt%)	13 (highland); 5 (Maria region)	1.6	8.0
Cu (ppm)	8	2	25
Si (wt%)	21	20.5	28.8
Ni (ppm)	200	330	56
Co (ppm)	40	71	24
Ti	1 wt% (average); 5 wt% (Maria region)	832 ppm	4010 ppm (0.4 wt%)
Zr (ppm)	100–400	7.5	203
C (ppm)	<100	2960	200–1990



- Elemental abundance driven material discovery
- Different geological processes affect elemental distributions
- *Make it don't take it*

Conclusions

- NASA has many unique considerations when developing energy storage devices
- Electric aviation demands ultra-high performing next generation batteries
- Sustained habitation on the moon and mars need alternate chemistries based on elemental availability
  - Environmental extremes vary greatly compared to Earth
- Safety and reliability remain critical

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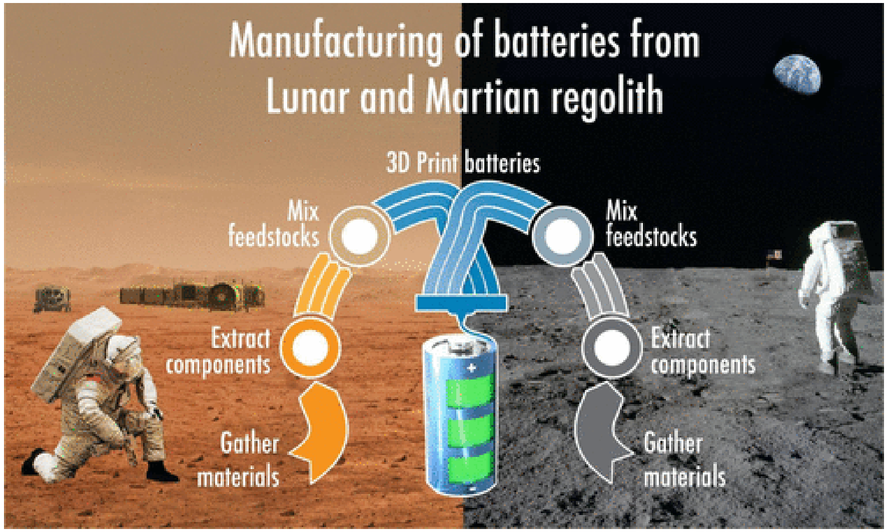
Acknowledgements

Convergent Aeronautic Solutions (CAS)
Transformational Technologies & Tools (TTT)
Early Career Initiative (ECI)
GRC Team, LaRC Team, MSFC Team



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