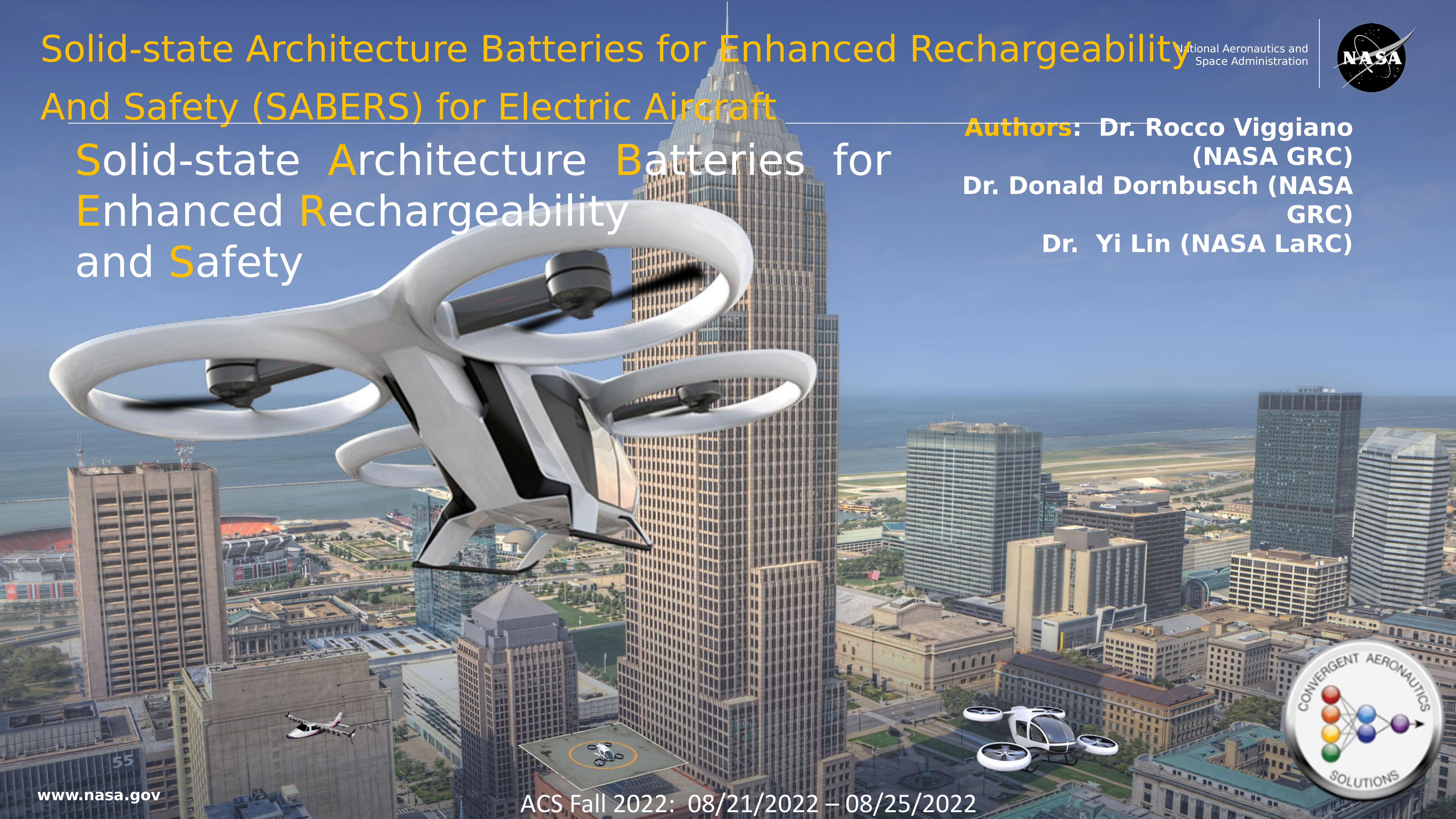

Solid-state Architecture Batteries for Enhanced Rechargeability And Safety (SABERS) for Electric Aircraft

National Aeronautics and Space Administration

Solid-state Architecture Batteries for Enhanced Rechargeability and Safety

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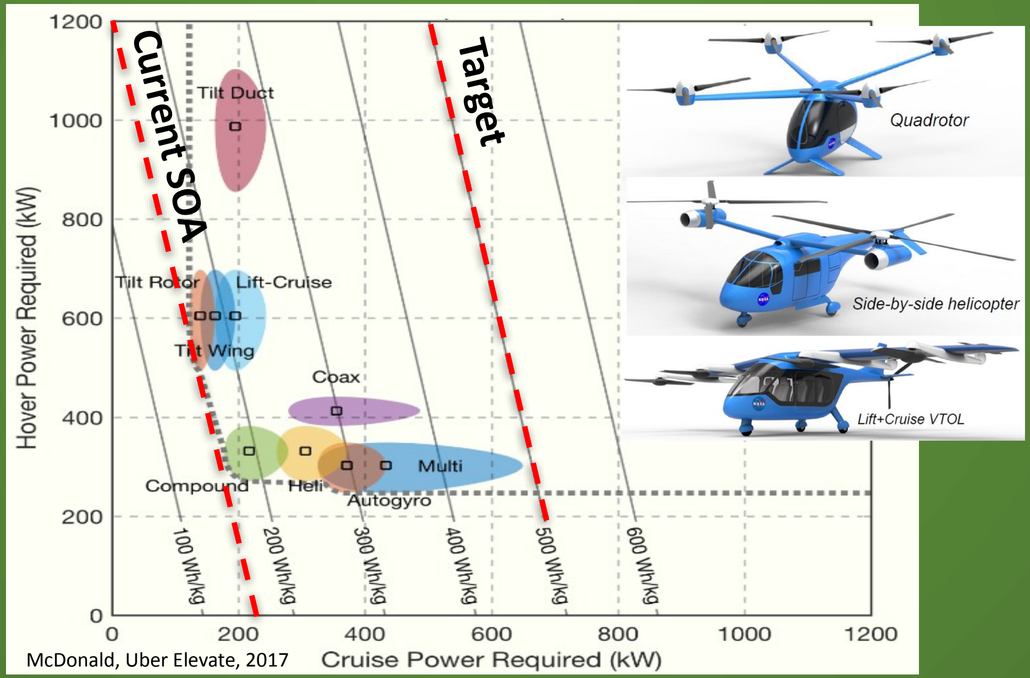
www.nasa.gov

ACS Fall 2022: 08/21/2022 – 08/25/2022

The Problem

Battery Performance Requirements

- NASA Battery Workshop 2017 and industry representatives state "The primary barrier to electric aviation is battery performance"
- SOA lithium ion batteries do not meet energy density requirements needed to enable electric aircraft designs
- Unique flight critical metrics (e.g. high power) required



McDonald, Uber Elevate, 2017

Vehicle Performance & Efficiency

Battery Safety Requirements

- Current SOA lithium-ion batteries utilize highly flammable organic liquid electrolytes
- Their highly flammable nature have caused a number of safety incidents on aircraft
- Safety is required for aerospace applications
- Parasitic weight from excess packaging and cooling is undesirable since it will impact flight performance

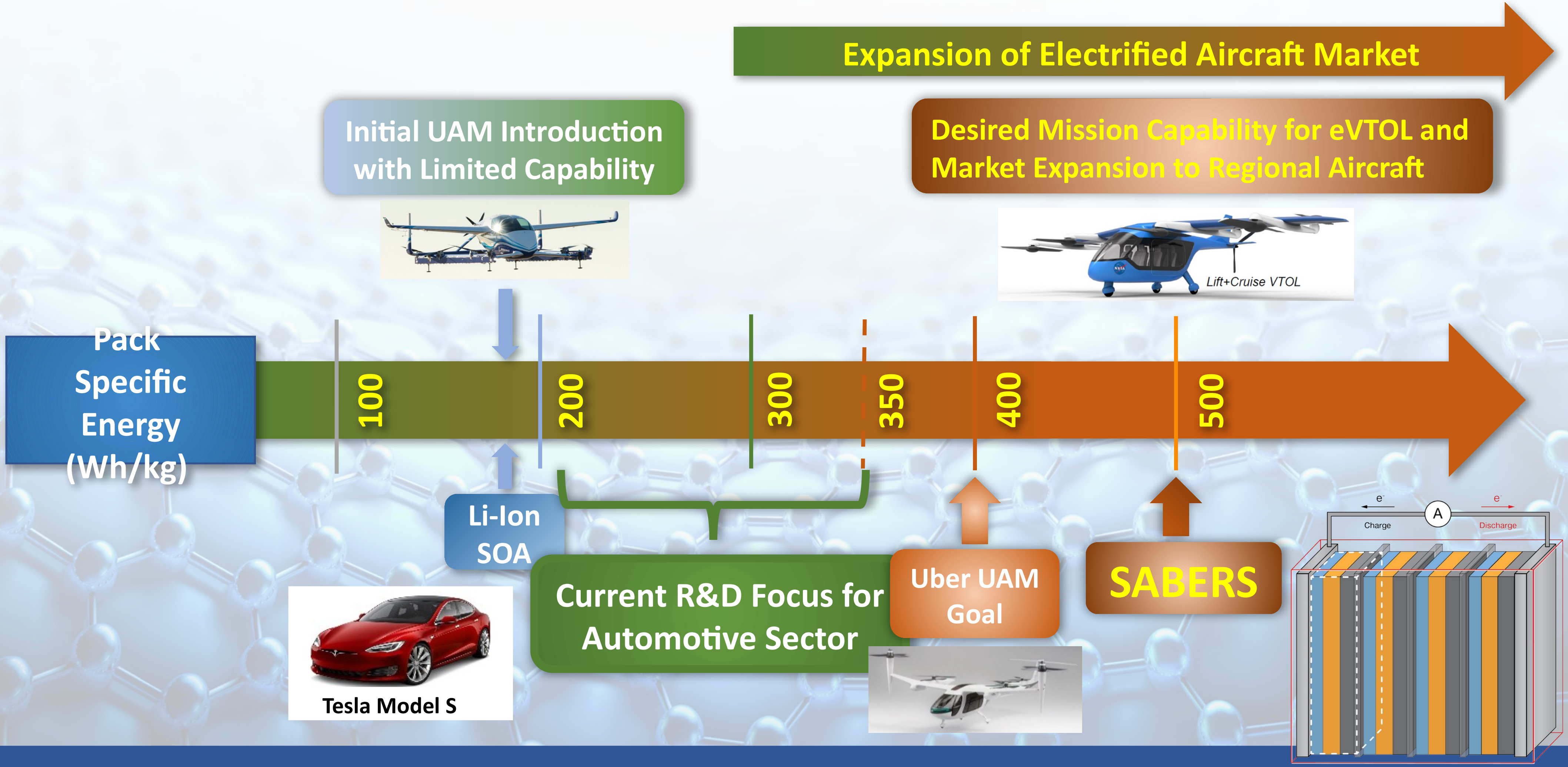
"... LITHIUM-ION CELLS ARE FLAMMABLE AND CAPABLE OF SELF-IGNITION ..."

Tesla Li-Ion Battery Fire

2006 UPS Cargo Flight Grounded

Boeing 787 Li-Ion Battery

SABERS Focused on Electric Aircraft



Expansion of Electrified Aircraft Market

Initial UAM Introduction with Limited Capability

Desired Mission Capability for eVTOL and Market Expansion to Regional Aircraft

Pack Specific Energy (Wh/kg)

Li-Ion SOA

Current R&D Focus for Automotive Sector

Uber UAM Goal

SABERS

Tesla Model S

- Current performance targets for the automotive sector are a battery pack with 250 – 300 Wh/kg

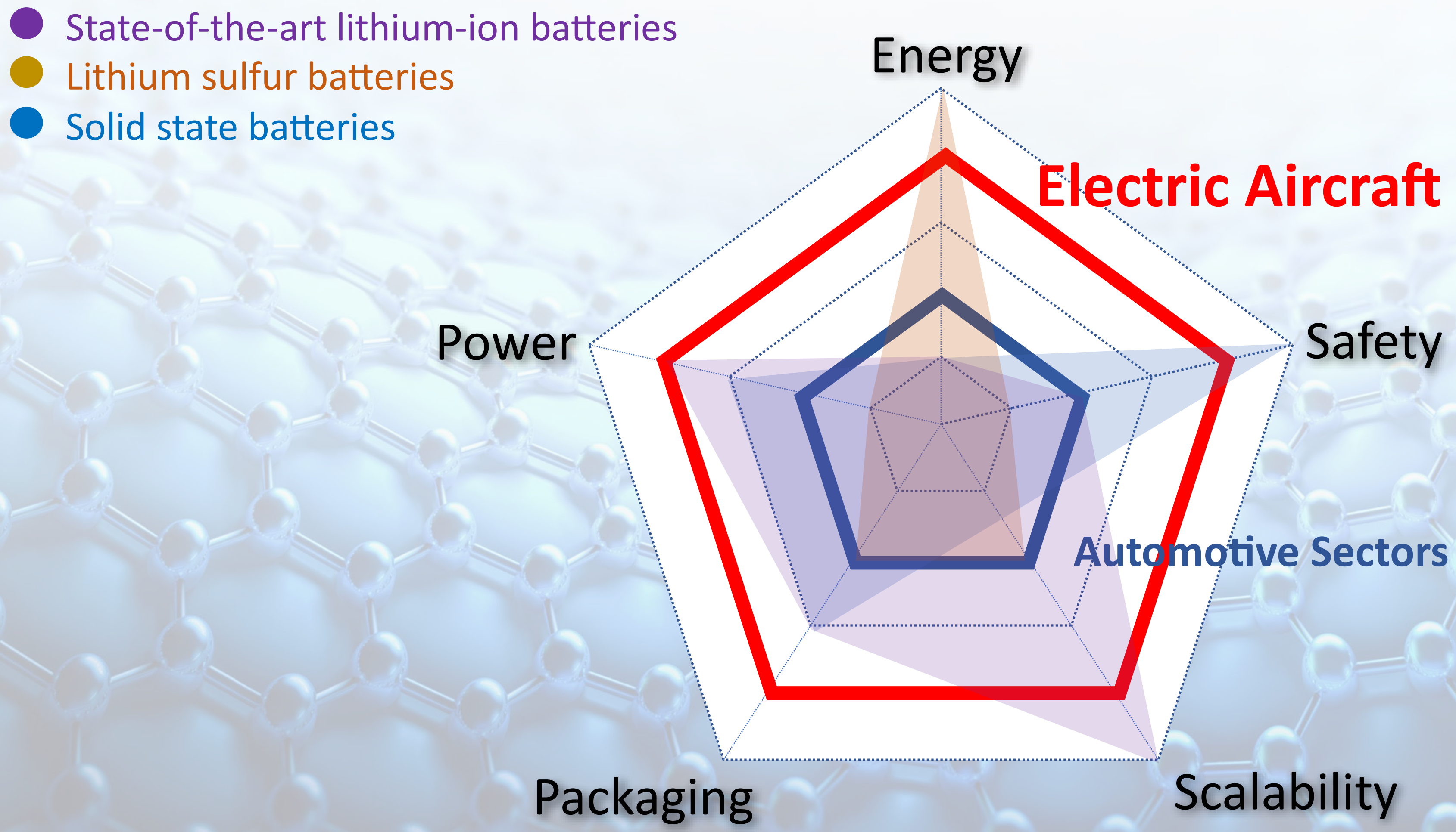
Aeronautics Challenges

- Can a battery be designed for electric aircraft, following system level analyses, that provides the combination of required properties?
  - Safety
  - Energy density
  - Discharge rate
  - Packaging design for minimal weight
  - Scalability


SABERS Concept: Design a battery using system level analyses to guide target properties, combine existing materials technologies, and a bi-polar stack design.

The Big Question

How do we meet ***ALL*** demanding battery needs of electric aircraft?



Next Generation Chemistries

Li-Ion cathode

- Pros
  - Higher Voltage
  - High density
  - Small volume change
- Cons
  - Low capacity

Sulfur Cathode

- Pros
  - High Capacity
  - Low cost, Abundant
  - High theoretical specific energy
- Cons
  - Lower Voltage
  - Low density
  - Low electronic conductivity*

“Carbon nanotubes for lithium ion batteries”
Brian J. Landi , Matthew J. Ganter , Cory D. Cress , Roberta A. DiLeo and Ryne P. Raffaelle
Energy Environ. Sci., 2009, 2, 638-654
DOI: 10.1039/B904116H

Voltage vs Capacity for different Lithium electrode chemistries.

- Blue = Lithium-Ion with lithium metal anode specific energy
- Green = Li-Sulfur specific energy from 50% carbon to theoretical*

NASA’s Interest in Solid-state Batteries

- Improved safety – Traditional liquid electrolytes are highly flammable

- High temperature stability

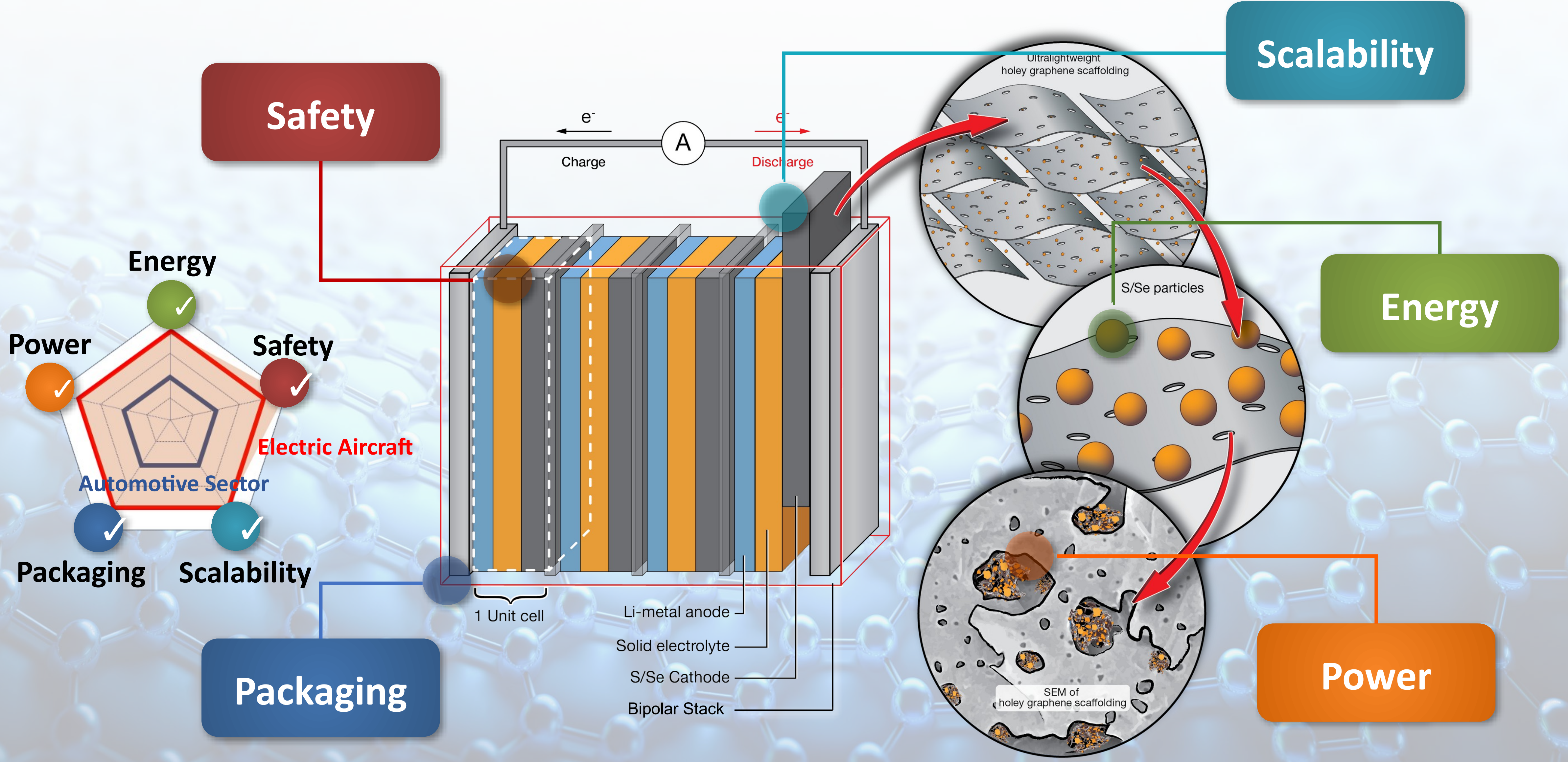
- Different electrolytes at each electrode – Compatibility tunable

- Allows different geometries – Reduced transport distances

- Avoids dissolution issues of sulfur intermediates

- Conductivity can meet or exceed liquid electrolytes

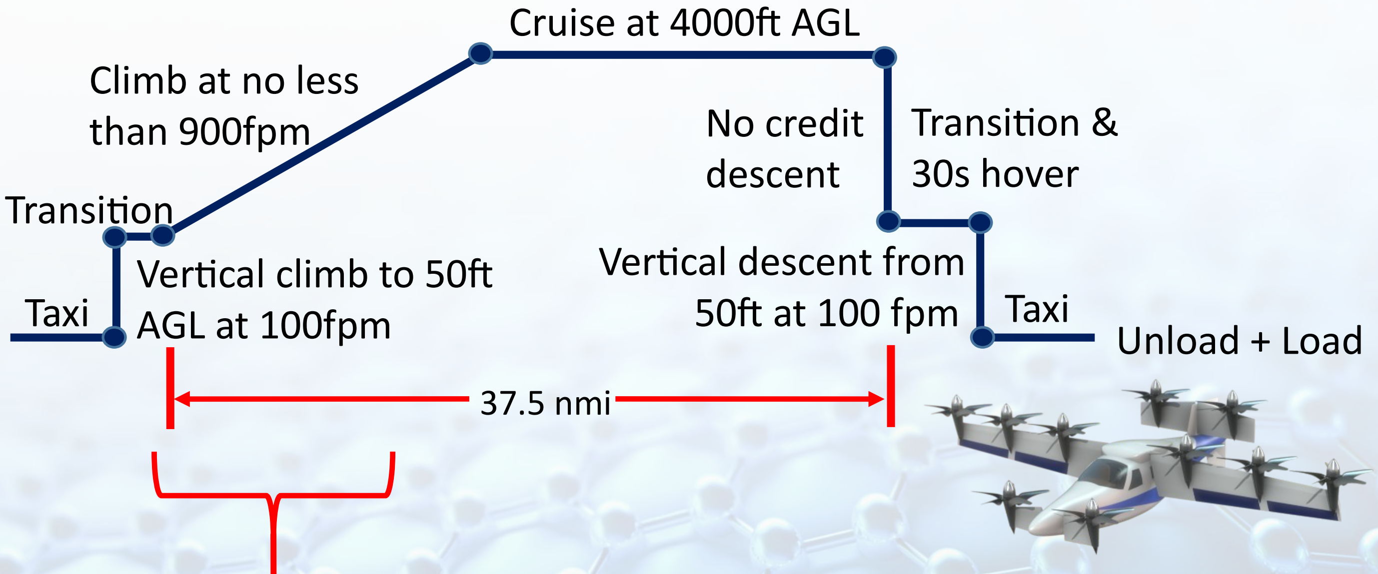
SABERS Transformative Technology



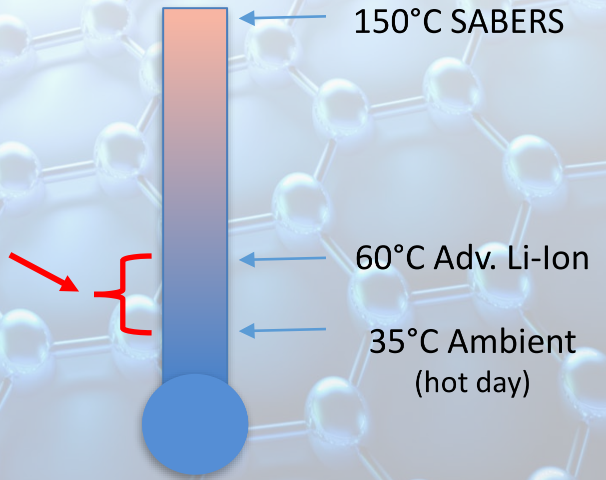
Combination of unique materials technologies to achieve performance goals

Thermal/Weight Systems Level Analysi

- **SABERS operating temperature (150°C) versus for Li-Ion chemistries (50-60°C)**
- **Thermal heat load well within SABERS temperature limits (simple passive system)**
- **Advanced Li-Ion batteries require:**
  - *Active system*: <u>adds 20-30% weight</u>, 30-50% volume, 1-3% of power used
  - *Semi-passive:* system with phase change material: 10-20% weight and volume penalty



Internal heat energy from high-power vertical takeoff / climb flight segments



<u>SABERS Bi-Polar Stack</u>

- ➢Effectively 10-30% less battery pack “overhead”
- ➢Improved specific energy and power
- ➢<u>Critical enabling technology for all-electric, battery vehicles/missions</u>

Solid-state Design Strategy to Maximize E

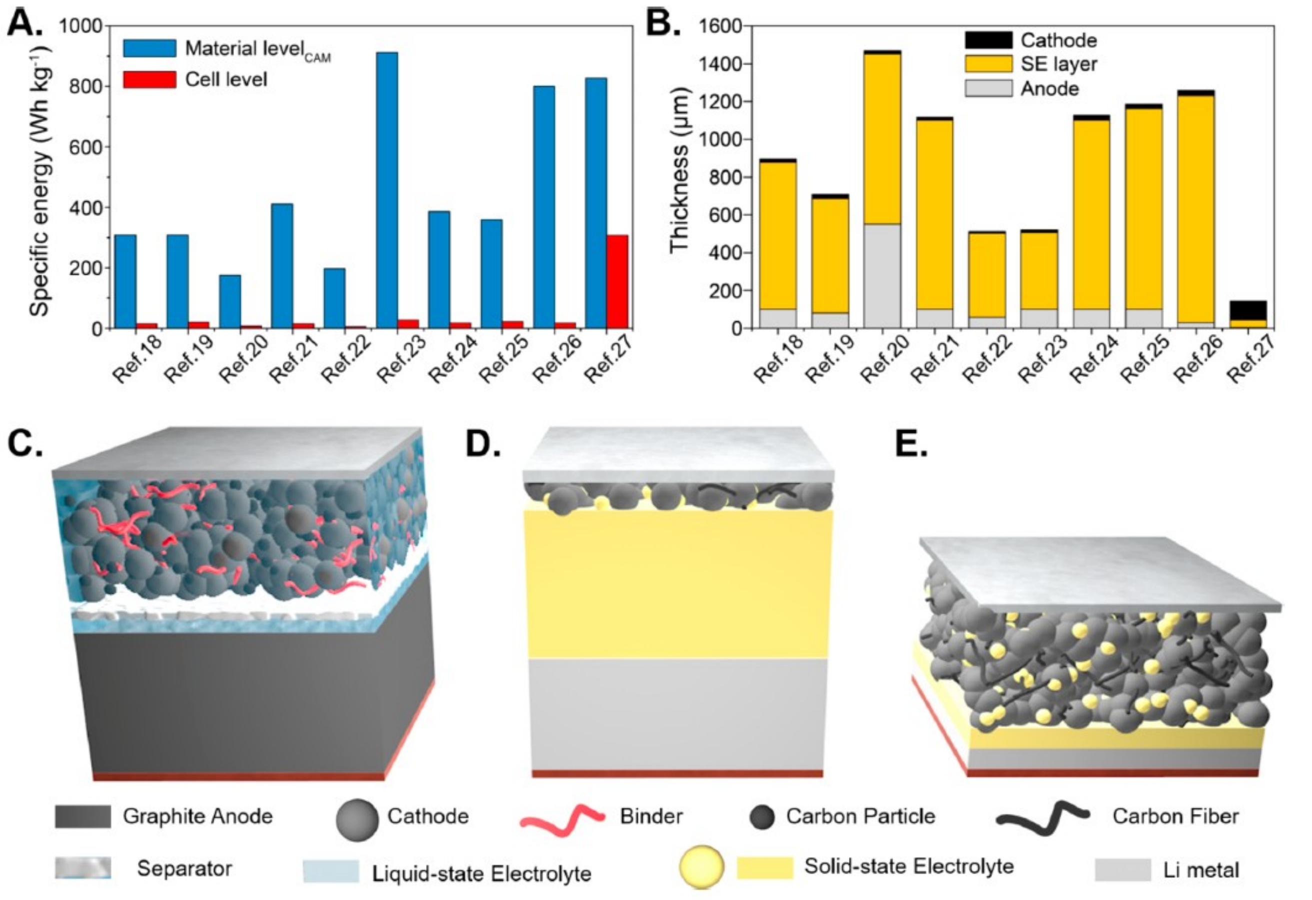
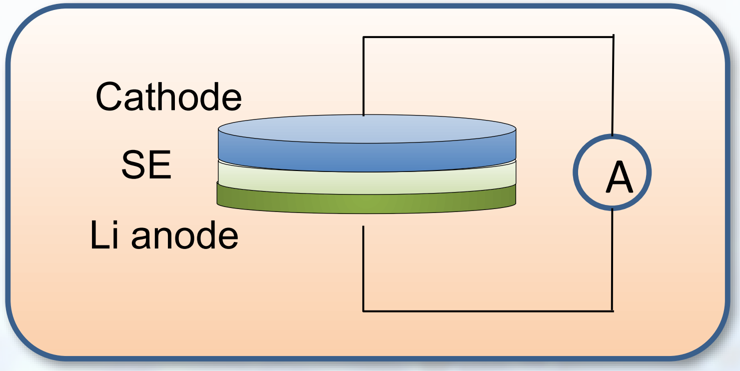


Figure 1. Relationship between cell configuration and cell-level energy in ASLBs. (A) Comparison in specific energy between active material level and cell level. (B) Thicknesses of each layer in reported ASLBs.[29] Data of Ref. 18–25 come from ref 29. Reproduced with permission from ref 29. Copyright 2020 Springer Nature. Data of ref. 26 and ref. 27 are combined and plotted. Typical configurations of (C) conventional LIBs, (D) current ASLBs, and (E) future high-energy ASLBs.

- Desirable high energy density cell structure
  - Thick cathode
  - Thin solid electrolyte
  - Thin anode

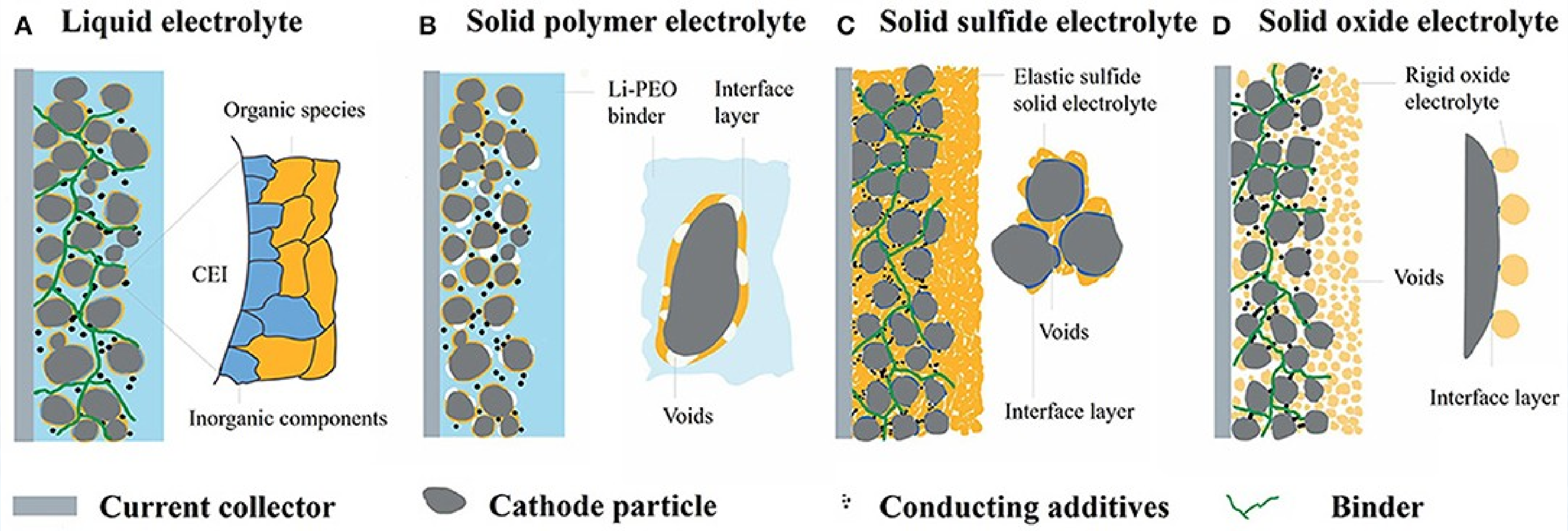
Reprinted with permission from “Processing Strategies to Improve Cell-Level Energy Density of Metal Sulfide Electrolyte-Based All-Solid-State Li Metal Batteries and Beyond
Daxian Cao, Yuyue Zhao, Xiao Sun, Avi Natan, Ying Wang, Pengyang Xiang, Wei Wang, and Hongli Zhu
ACS Energy Letters 2020 5 (11), 3468-3489
DOI: 10.1021/acsenergylett.0c01905

SABERS Cell Components



- Anode: Li or Li-based alloys
- SE: sulfide (thiophosphate) solid electrolytes
- Cathode:
  - – A mixture of three with optimal active material content, electrical conductivity from carbon, and ionic conductivity from solid electrolyte (SE); as well as optimal interfaces among three.
  - – Active material
    - Nonlithiated: S, Se, **SeS_x**
    - Lithiated: Li_2S, **$Li_2S_xSe_y$**
  - – SE: sulfide (thiophosphate) solid electrolytes (high ionic conductivity; soft and pressable)
  - – Carbon
    - Holey graphene (hG)
    - Other carbon additives: Ketjen black, Super P, carbon nanotubes, carbon nanofibers, graphene.

Solid Electrolyte Candidates



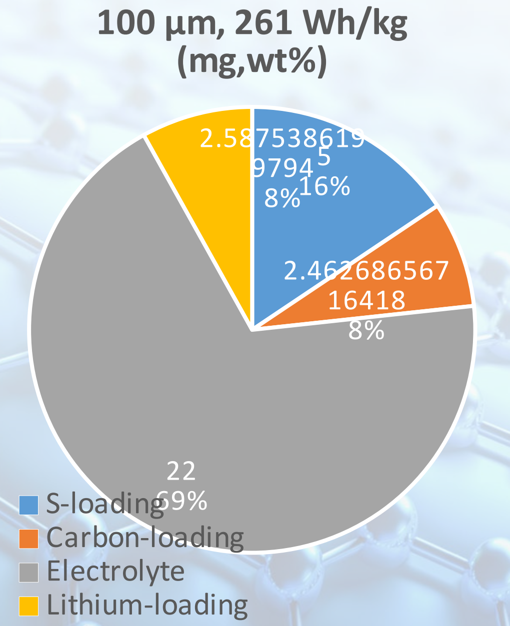
Front. Chem., 12 December 2018 Sec. Physical Chemistry and Chemical Physics : https://doi.org/10.3389/fchem.2018.00616

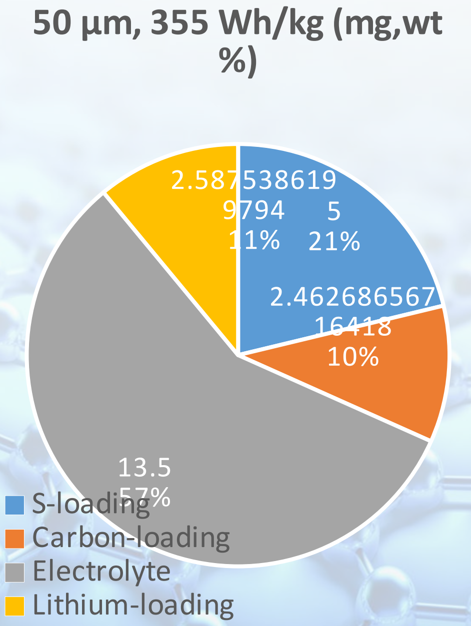
	Liquid	Polymer	Sulfide	Oxide
Process	Infiltration	Solution casting	Mechanical	Thermal Sintering
Physical Characteristics	Imbibed Film	Soft, Flexible Films	Soft, Glass	Hard, Rigid
Ionic cond. range (S/cm)	1E-3 ~ 1E-2	1E-4	1E-3 ~ 1E-2	1E-4 ~ 1E-3
Density (g/mL)	~1	1.2-1.5	1.5-1.8	5.5-6.5

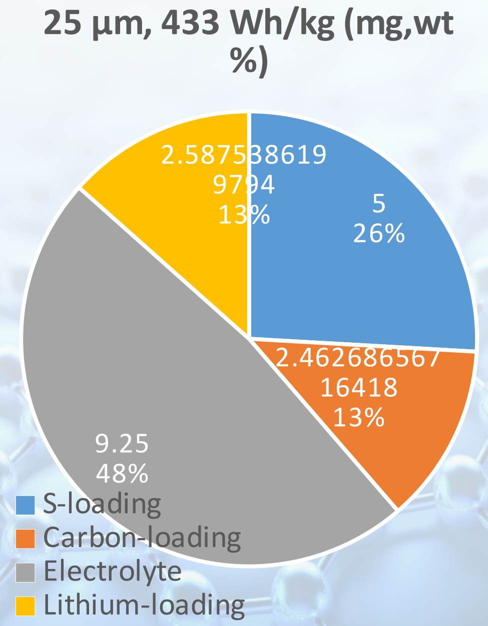
Increasing Temp tolerance →

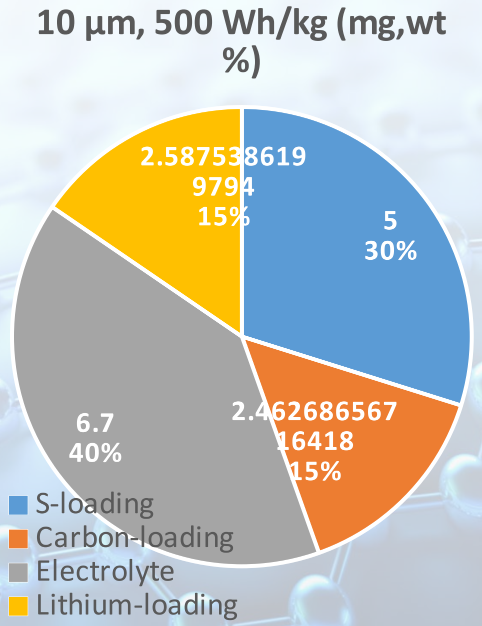
Projected Cell Energy Density (Tape-ca

- S:E:C = 2:2:1
- S mass loading = 5 mg/cm^2
- 1.2x Li excess
- LPSC electrolyte


100 µm, 261 Wh/kg (mg,wt%)


50 µm, 355 Wh/kg (mg,wt %)


25 µm, 433 Wh/kg (mg,wt %)

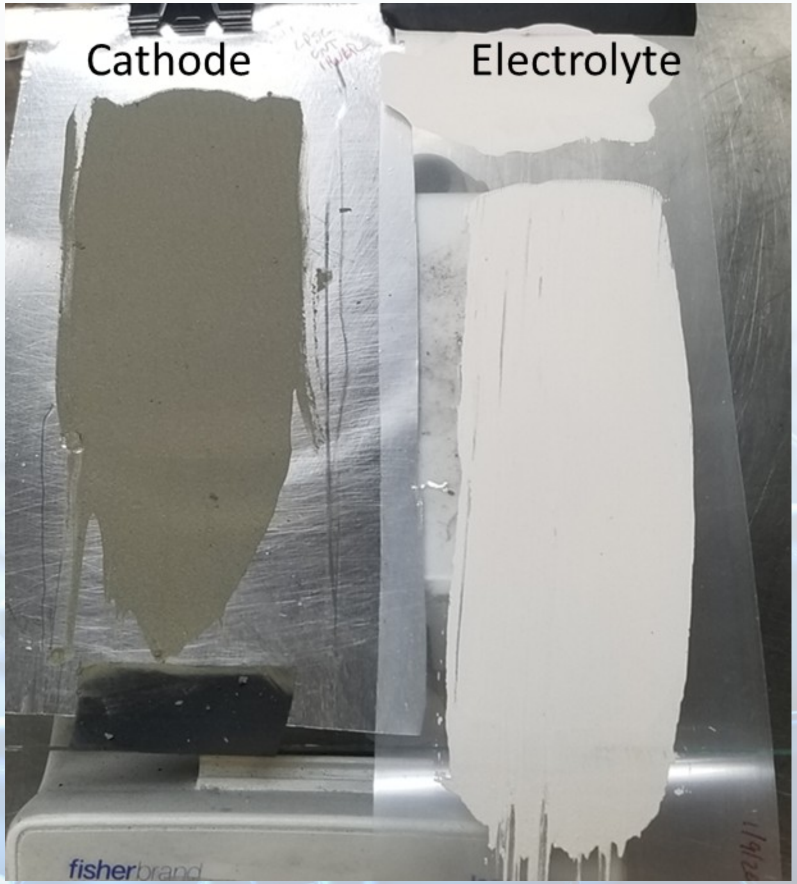

10 µm, 500 Wh/kg (mg,wt %)

Maximize cathode loading while **minimizing electrolyte** thickness to achieve highest specific energy

Electrochimica Acta Volume 403, 20 January 2022, 139406 : https://doi.org/10.1016/j.electacta.2021.139406

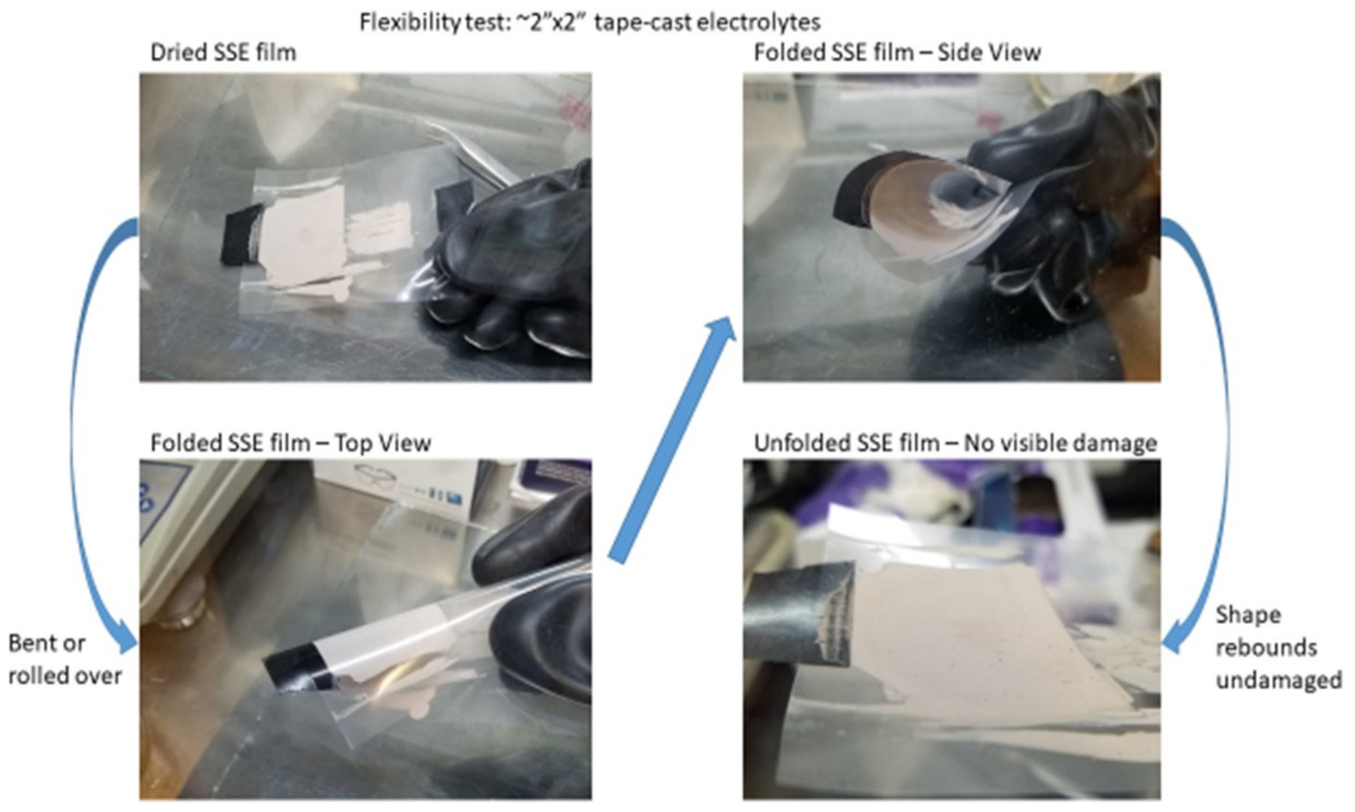
Manufacturing Thin Electrolytes

- 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)

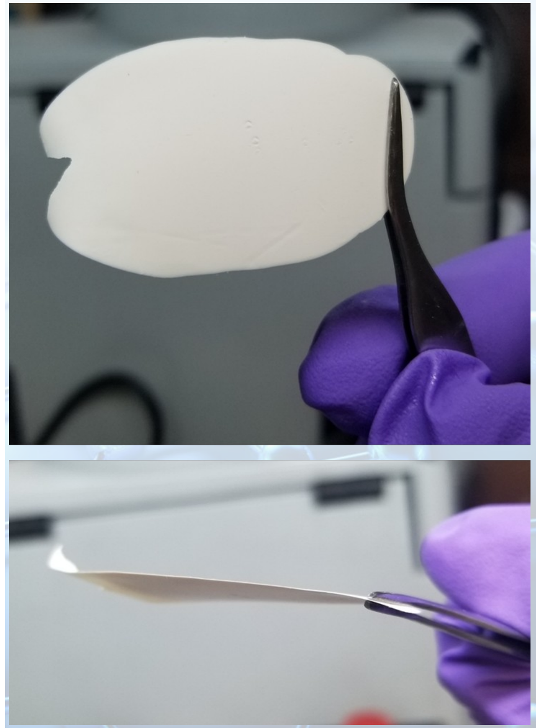


Improvement in Mechanical Properties

Mylar Supported

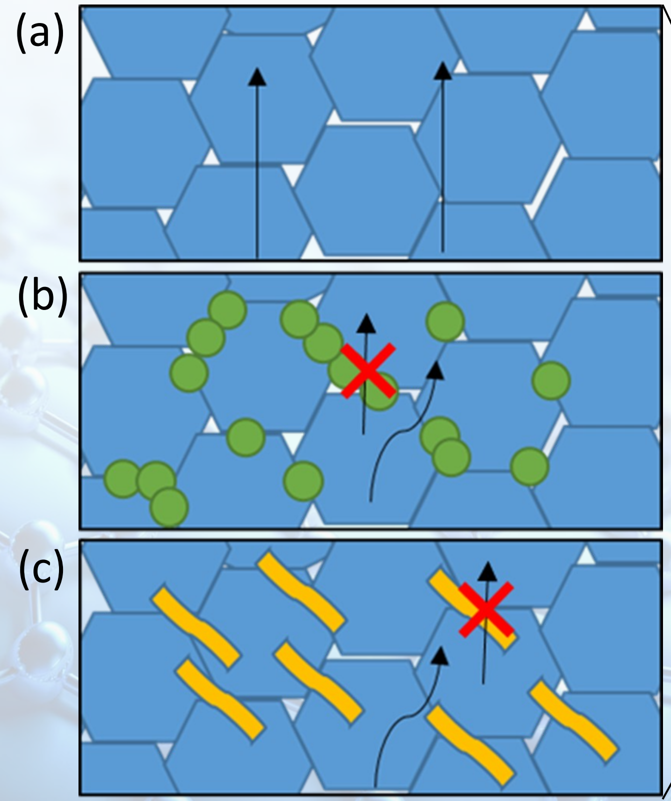


Free-standing



Substantially improved flexibility over pure glass electrolytes

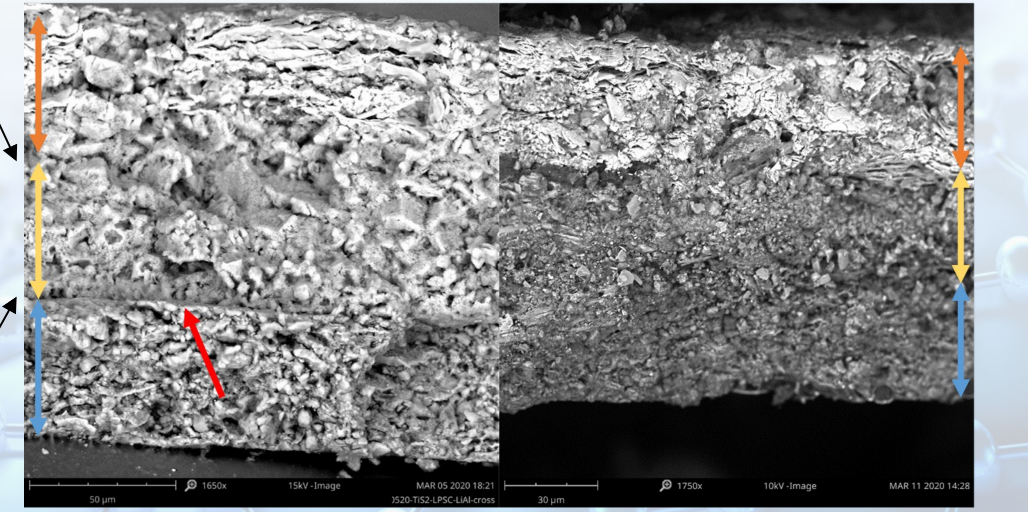
Glass-Polymer Composite Electrolyte



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).

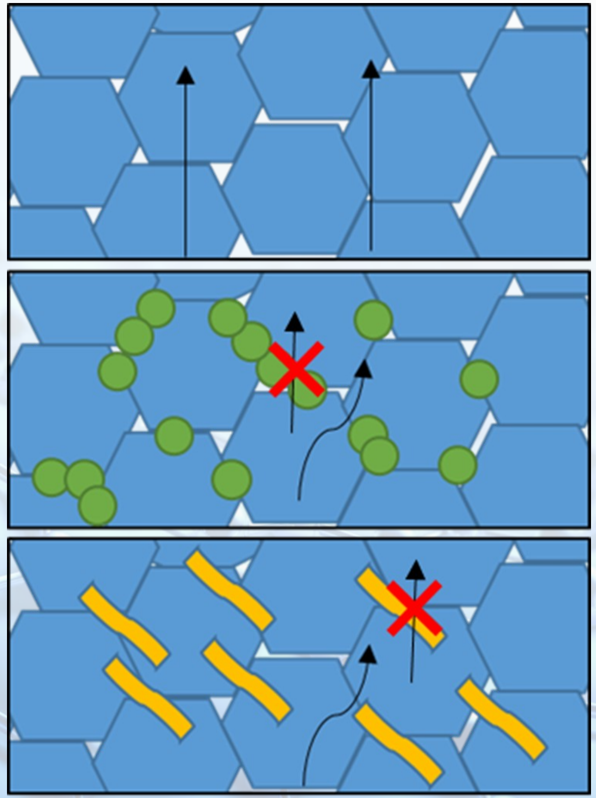
Introduction of a passive phase

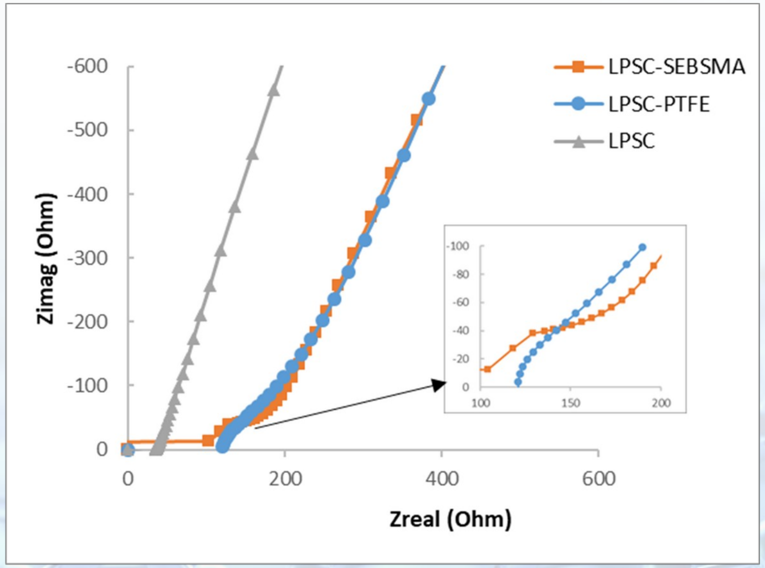
Conduction pathways change

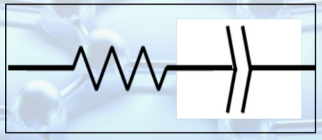


Densification processing improvements lead to better sheet adhesion

Impedance Data







Electrolyte	Resistance (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

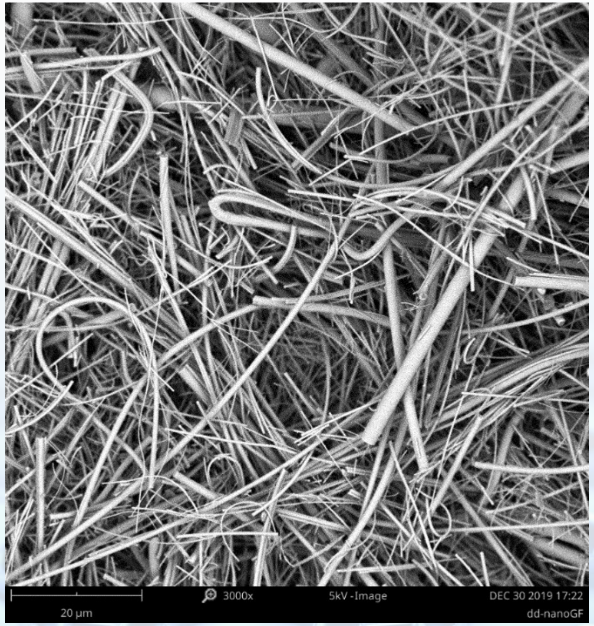
Ionic conductivity still retains ~20% of pure LPSC

Binder type has less impact on performance loss

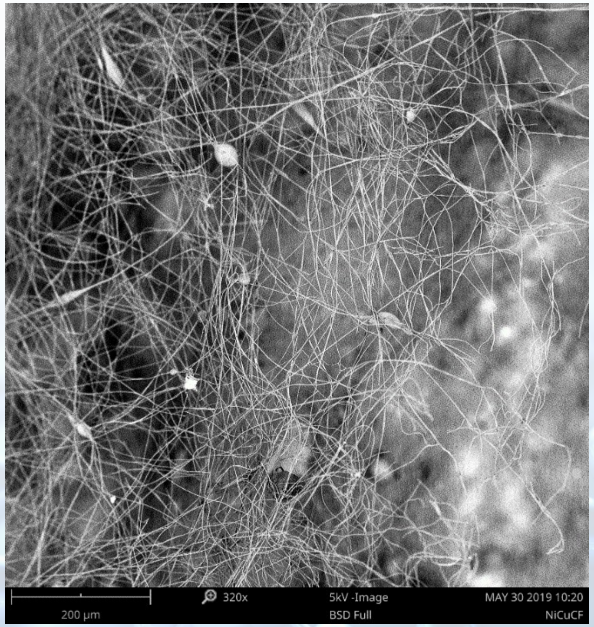
Fiber-based Filler Candidates

Polyaramid(Kevlar)

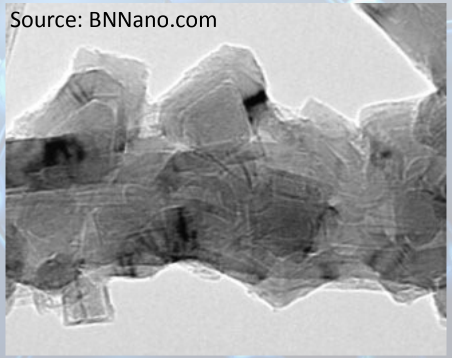
Nanoglass



NASA forcespun fibers



Boron Nitride Nanobarb™



Source: BNNano.com

Fiber candidates:

Kevlar – high strength polymer fibrils (wide distribution)

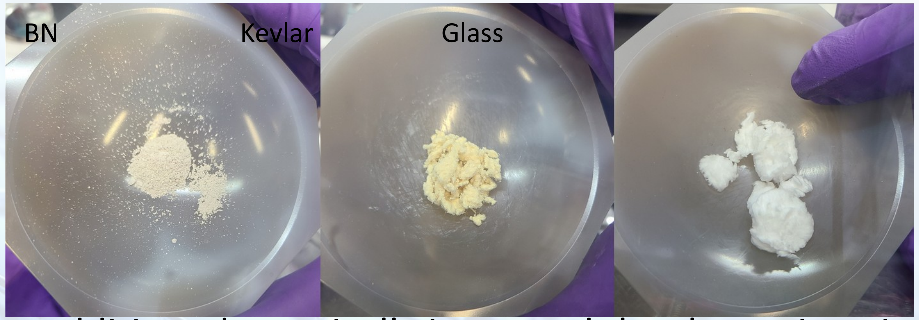
Nanoglass – high aspect ratio (700nm x 100’s μm)

Forcespun polymers – high aspect ratio, polymer control

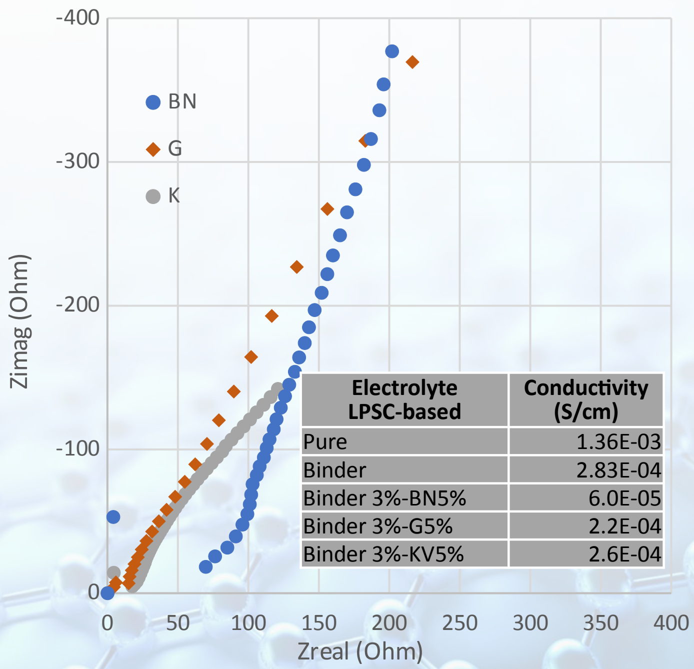
BNNanobarbs™ – insulating analog to CNT (very small, nm x nm)

Impact of Filler Reinforcement

- 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 composites, 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

Summary

- Commercial electric flight will not be possible with current SOA Li-Ion batteries due a lack of performance and safety
- Beyond Li-Ion technologies, including Li-S and solid-state architectures, are promising from a performance and safety standpoint, but require critical advances to meet the strict performance metrics to enable electric aircraft
- There are several material classes of solid-state electrolytes, each with advantages and drawbacks
- The thiophosphate solid electrolytes have thus far shown the best balance of properties to enable the SABERS goals
- 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

Thank You For Your Attention!

The researchers on the SABERS team would like to gratefully acknowledge funding for this research from the NASA Convergent Aeronautics Solutions (CAS) project within the Transformative Aeronautics Concepts Program (TACP)