Technology Innovation Blast – Wednesday PM

July 13, 2023

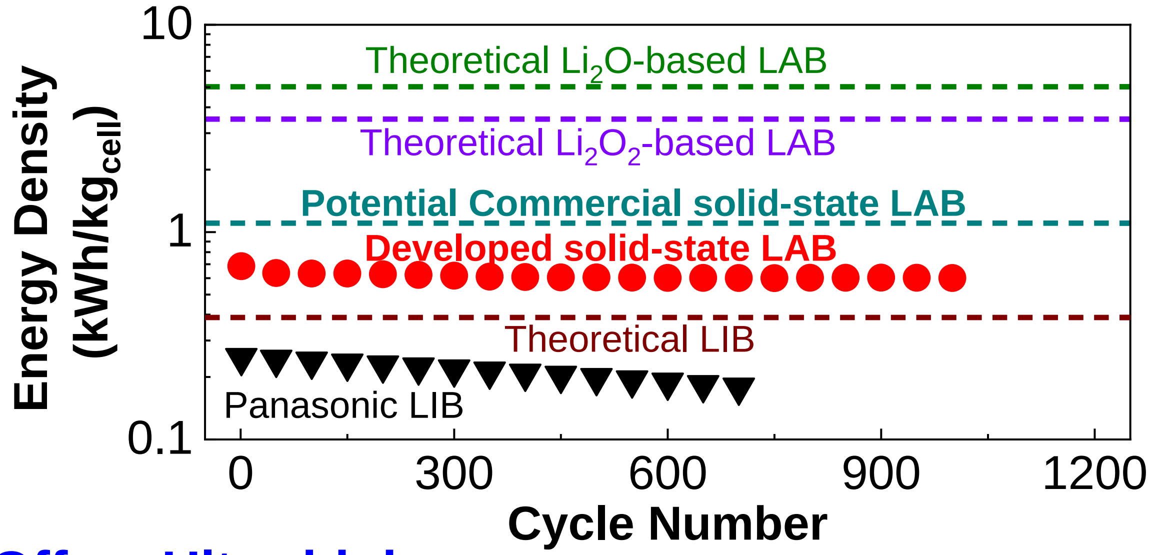
Why This Solid-State Li-Air Battery Is Unique?!

1 kWh/Kg
Closer than ever before?!!

- Use of solid electrolyte drives reaction to Li_2O product offering much greater energy density compared to state-of-the-art Li-ion batteries.
- Runs on air at room temperature.
- Cyclable up to 1000 @ 1C rate and tested to work up to 5C rate.
- Power to energy ratio of > 1

Opportunity

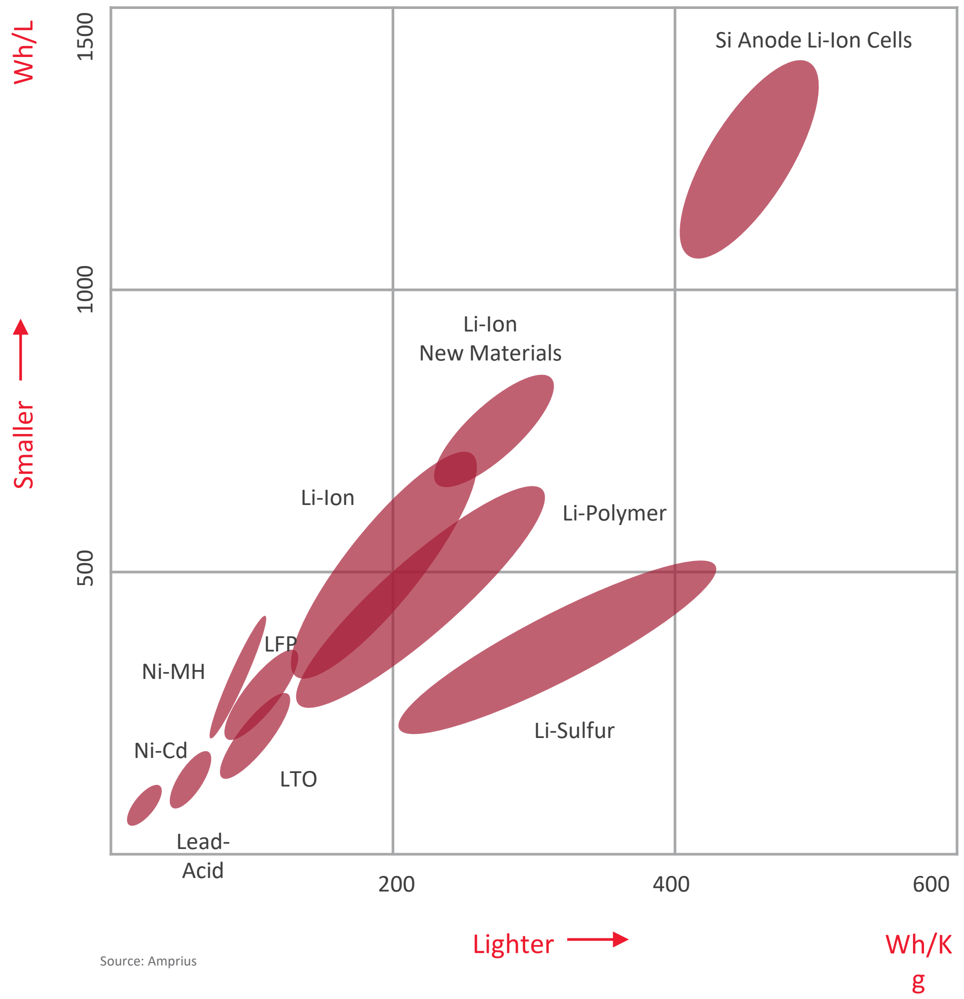
- Gravimetric energy density of >1200 Wh/kg and volumetric energy density of >1000 Wh/L.
- Low cost: <75$/kWh.
- Avoids safety problems with liquid electrolytes.
- Could enable electrifying heavy-duty transportation e.g., aviation, marine, trucking, etc.



Novel Chemistry Offers Ultra-high Energy and Power Density Batteries to Decarbonize Transportation.

"A Room Temperature Rechargeable Li_2O-based Lithium-Air Battery Enabled by a Solid-State Electrolyte" Science, 2 Feb 2023, Vol 379, Issue 663, pp. 499-505

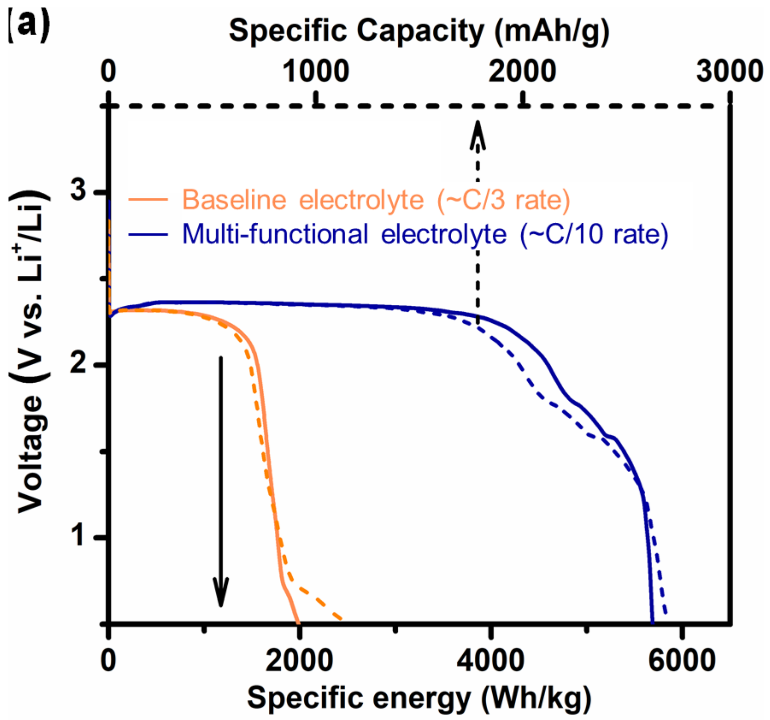
Aviation's Role in Achieving 1K Batteries



Source: Amprius

magniX

Converting the Primary Batteries into the Secondary Batteries: Li/CFx



Discharge behavior of primary Li/CFx in functional electrolyte

 unpublished

Lithium/Water Batteries for Marine Applications

Lithium-Air batteries 3.45V to 4.27V	800 Wh/kg demonstrated (US gov testing) 1000 Wh/kg possible 1200 Wh/kg possible w/acidic electrolyte
Lithium-Water batteries 2.60V to 3.45V	2000 Wh/kg & 1900 Wh/l possible 1300 Wh/kg demonstrated
Lithium-aqueous sulfur batteries	1000 Wh/kg possible
Lithium-new aqueous redox systems	TBD

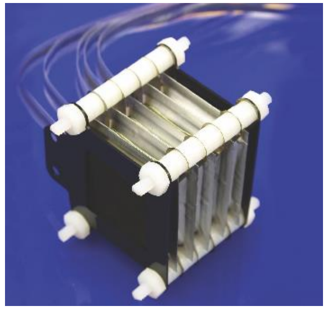
(The theoretical specific energy of a Li-Water battery is 3800 mAh/g x 3.45 V = 13,000 Wh/kg)

Lithium/Seawater Cell Reactions:

$4Li + O_2 + 2H_2O = 4LiOH$ **E=3.45V**

$2Li + 2H_2O = 2LiOH + H_2$ **E=2.60V**

The theoretical specific energy of Li/Water is 3800 mA/g x 3.45 V ~13,000 Wh/kg



1"x 1" cube 1300 Wh/kg

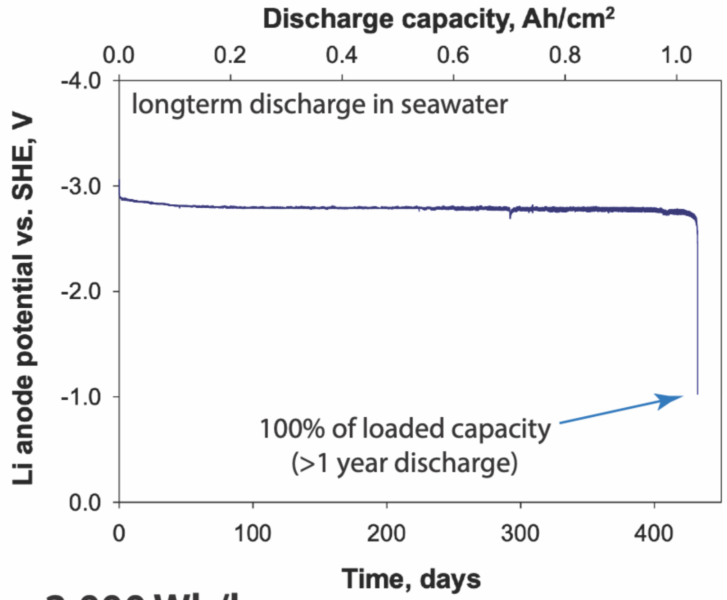
↑

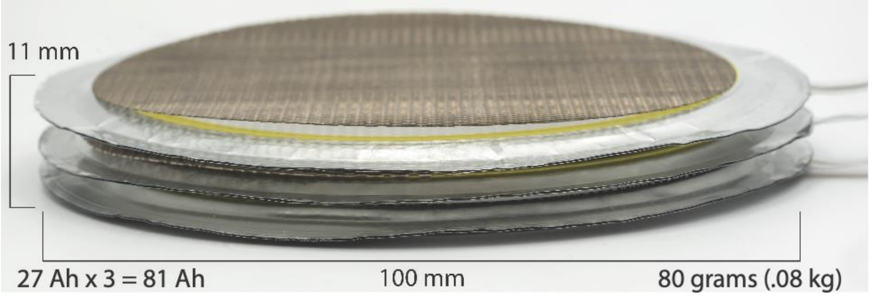
12.5 Ah Li/Water battery ($4Li + O_2 + 2H_2O = 4LiOH$)

81 Ah Li/Water battery ($2Li + 2H_2O = 2LiOH + H_2$)

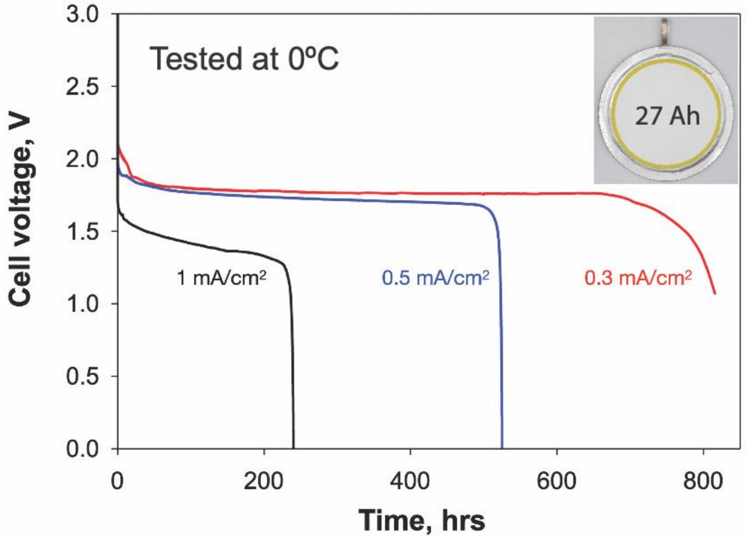
↓

162 Wh ÷ .08 kg = 2,000 Wh/kg





- Highest energy density ever achieved
- 2000 Wh/kg & 1900 Wh/l
- Competitive with fossil fuels
- Self discharge rate = 0
- Safe & Environmentally benign
- Pressure tolerant (tested at > 10,000 psi)
- Neutrally buoyant



PAVING THE WAY FOR RAM THROUGH BATTERY 1K

Aurora FLIGHT SCIENCES
A Boeing Company

Why Al-Air Battery?

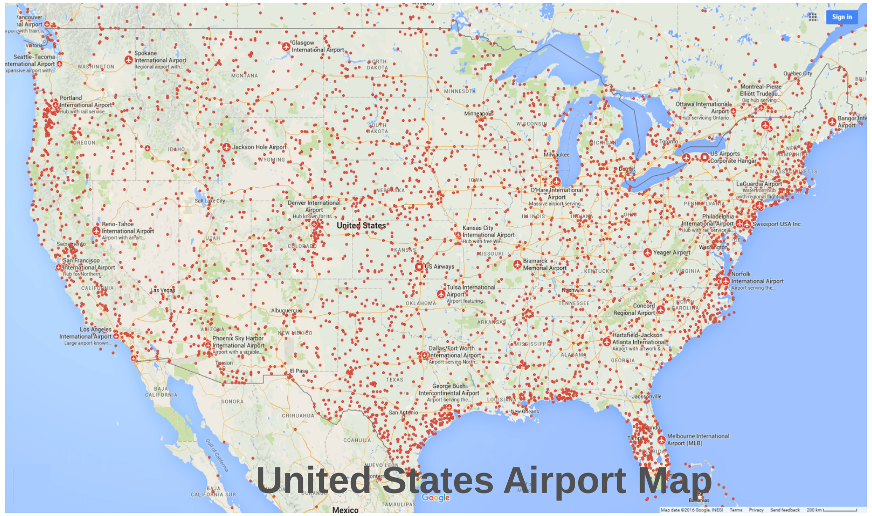
- Among high-energy battery chemistries targeting a system-level specific energy of 1000 Wh/kg, the Aluminum Air battery is a standout. Aluminum, as the safest, most abundant, recyclable, and lowest-risk element in the supply chain, makes this possible.
- Current market size of Al-Air battery is small, with the best system level specific energy of 160 Wh/kg with < 0.1 C power capability.
- Specific energy > 750 Wh/kg[1)] and ~2 C power capability are required to enable all electrical regional air mobility.
- Five times specific energy increase with 20 times specific power increase.

POC: Lu Yang, Yang.Lu@Aurora.aero

1) Bills et. al. ACS Energy Letters 2020 5 (2), 663-668
2) Antcliff et. al. https://ntrs.nasa.gov/citations/20210014033

Why Regional Air Mobility?

- In the past 20 years, China's GDP increased 12x; its high-speed rail (HSR) system (~26100 mi, ~$19M/mi) is one of the key enablers of growth (transport ~6.3M passengers/day).
- HSR may not be suitable for the US (e.g., LAX to SFO: 800 mi, 2008-2033, $33.6B to $98B, $123M/mi), but with over 5,000 underutilized regional airports[2)], there is huge potential for electric regional aircrafts.



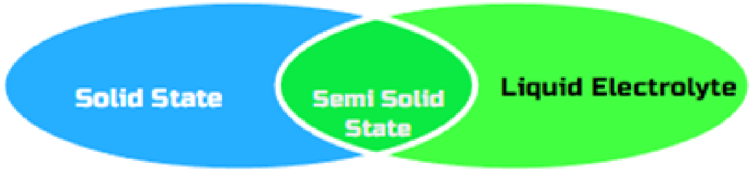
United States Airport Map

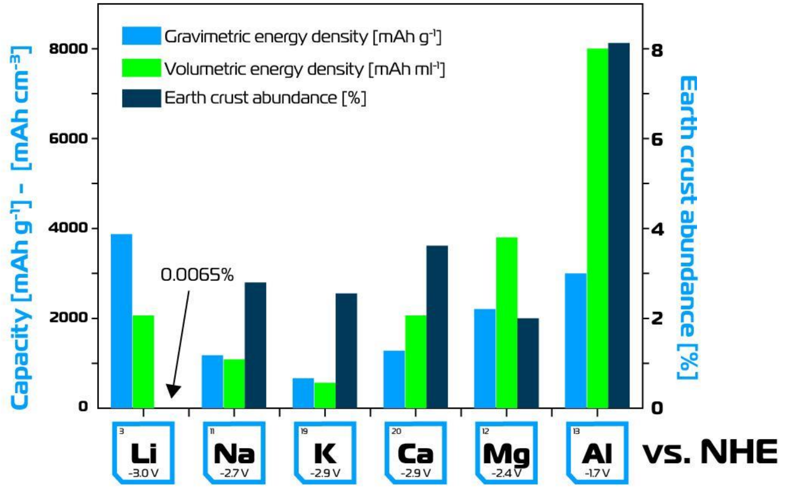
Why Aurora Flight Sciences?

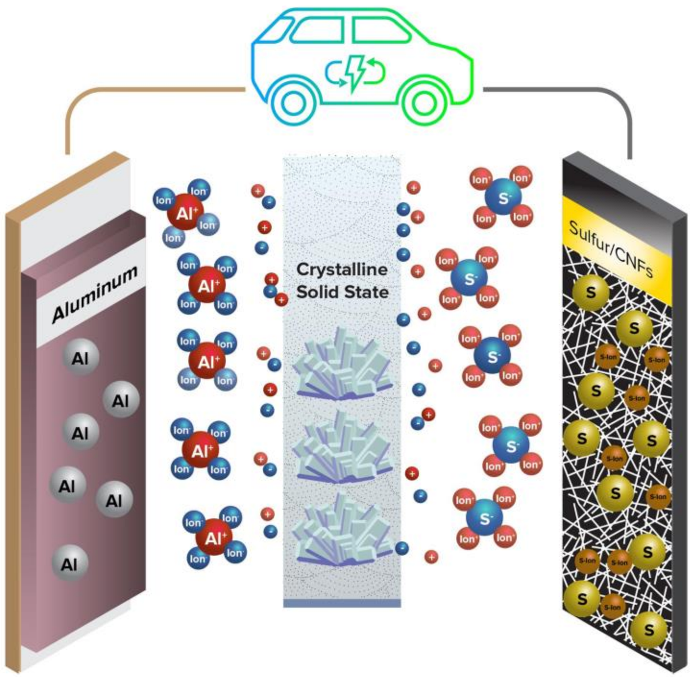
- Aurora is working at the forefront of electric flight technology, pioneering advances for sUAS, UAM, HAPS, and hybrid-electric aircraft.
- Aurora can leverage expertise in both batteries and aircraft to help shape and mature a platform-agnostic Battery 1K solution for applications including long-lead aviation.
- By collaborating across government, academia, and industry, we can drive innovation forward.

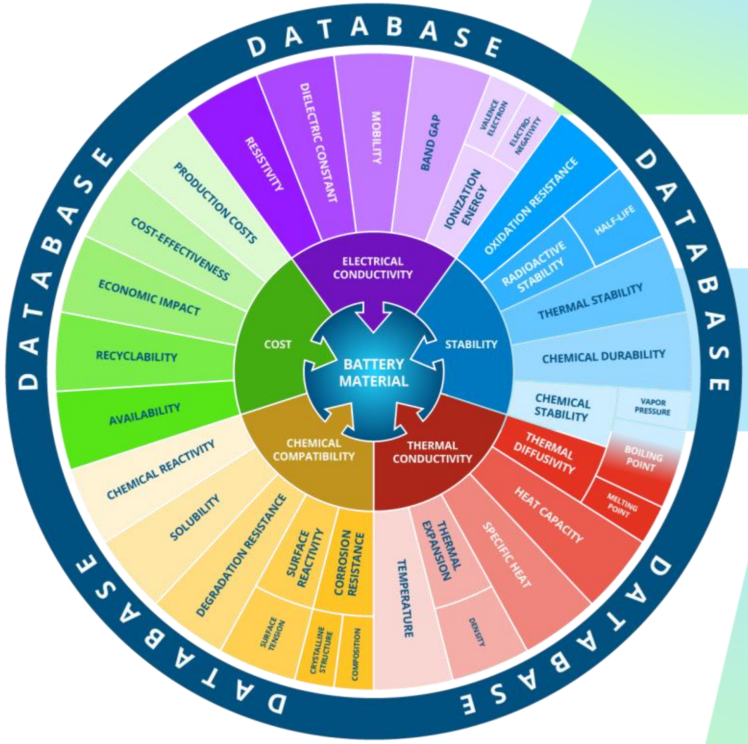
Regional Aircraft

Powerit - 2023 ARPA-E
Aluminum Battery Chemistry





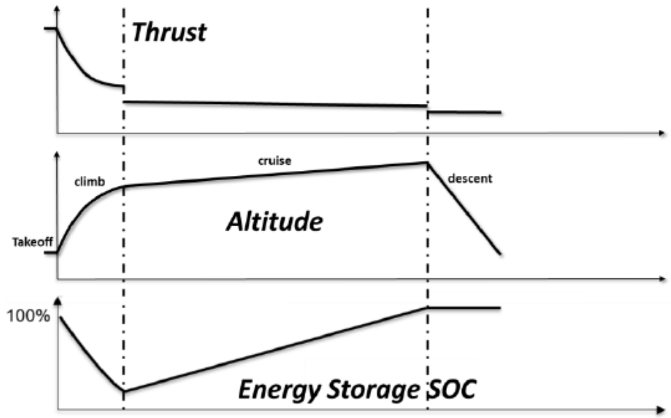




Contact: Dave Clark
dclark@powerit.com

A Hybrid Approach to Electrified Transport

- Transportation requires high power density for acceleration/takeoff and high energy density for range.
- No battery today can meet the specific energy density of liquid fuels needed for wide-body airplanes or long haul ground or sea transport
- Electrified propulsion provides opportunity for fuel-cell/battery hybrid energy storage to meet both power and energy demands:
  - -Fuel-cell and battery in parallel for high power demand
  - -Fuel-cell for cruising range and recharging battery as needed



Exemplary aircraft mission profile (thrust, altitude, energy storage SOC). Adapted from[26]

Fuel	Primary specific energy, kWh/kg	Primary energy density, kWh/L
Jet fuel*	12.04	9.68
Bio LNG	14.0	6.3
Synfuel	12.0	9.68
Biojet fuel	10.6	8.37
n-BuOH	9.17	7.43
Ethanol	8.33	6.57
Dimethyl ether	7.9	5.28
LH2	33.3	2.55

Renewable liquid fuels (ARPA-E REEACH DE-FOA-0002240)

Science AAAS

Lowering the Temperature of Solid Oxide Fuel Cells
Eric D. Wachsman, *et al.*
Science **334**, 935 (2011);
DOI: 10.1126/science.1204090

- We've developed high power density (2W/cm^2) low-temperature (650°C) Solid Oxide Fuel Cells (SOFCs) that compete with combustion engines on power density basis (3 kW/kg at stack level)
- For SOFCs like combustion engines energy density is based on fuel, but due to higher efficiency can provide greater range for same mass of fuel.

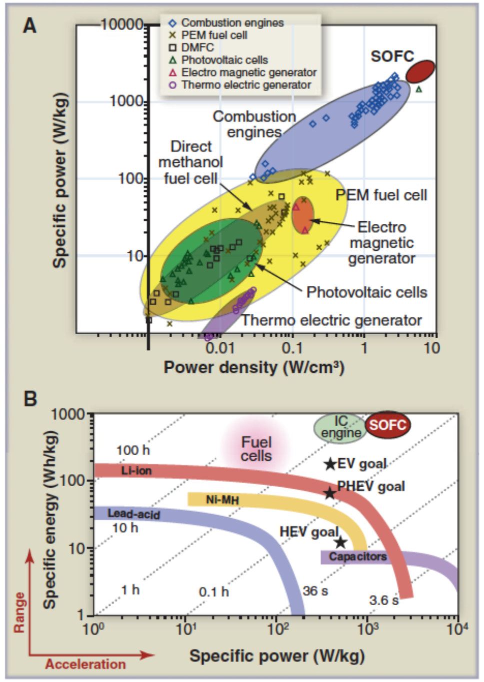
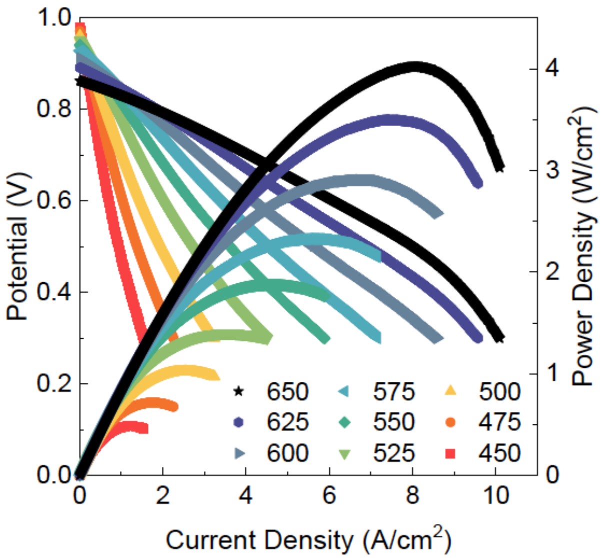


Fig. 4. (**A**) Comparison of specific power of the present ~2W/cm^2 SOFC at 650°C compared with various energy conversion devices as a function of power density (*23*). (**B**) Ragone plot (specific energy versus specific power) for various energy devices (*40*) compared with the present SOFC.

- Under REEACH program we have since doubled the power density to 4 W/cm^2 which would provide even higher specific power
- The majority of the SOFC stack mass is the metal interconnects and our lower operating temperature enables use of lightweight alloys
- These may enable stack power densities of ~5kW/kg
- Integrated with battery could provide both power and energy needs for longer range electrified transport



MARYLAND ENERGY INNOVATION INSTITUTE

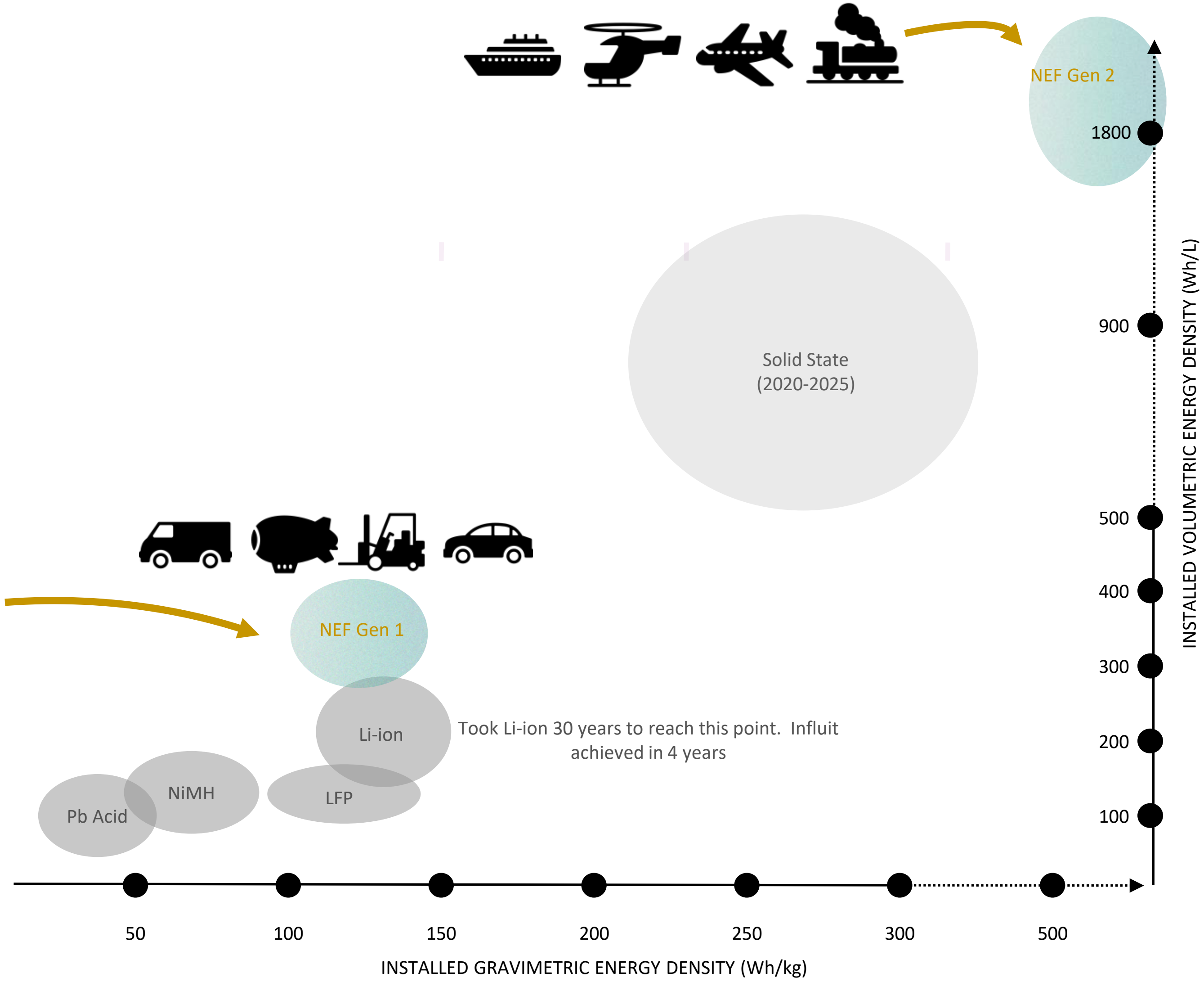
ewach@umd.edu

REEACH

First Demonstration of NEF-powered Electric Utility Vehicle

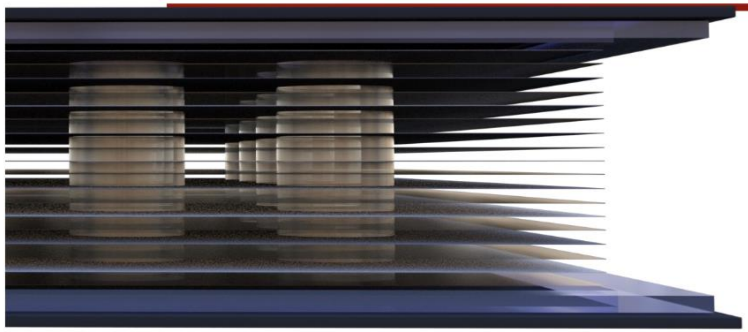
Tennant T12 Machine Alpha Test for T12 Mule

Demonstrated 6/2022



Technology Sponsors

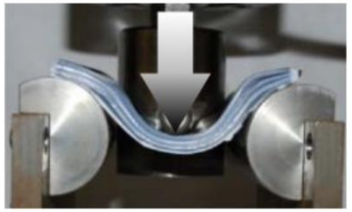
Multifunctional Energy Storage Composites (MESC)



PI: Fu-Kuo Chang
fkchang@stanford.edu
1(650)-7968899

Current Battery Research- Much focus on energy storage, but packaging is critical

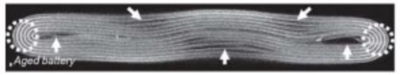
1) Prone to mechanical abuse



→ Short circuit
→ Combustible energy released
→ Fire, explosion

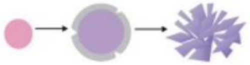
2) Undesirable volume expansion

- Today's graphite: 10%



New materials:

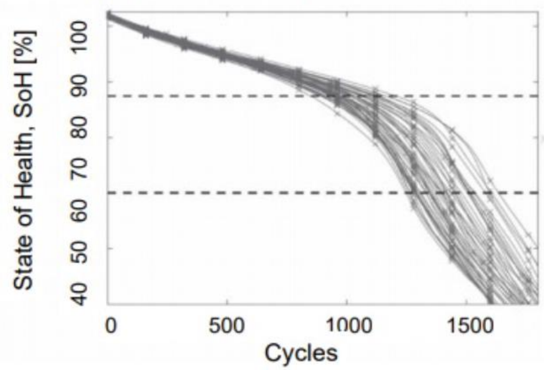
- Li_2S: 100%
- Silicon anode: 400%
- Li metal: ∞ %



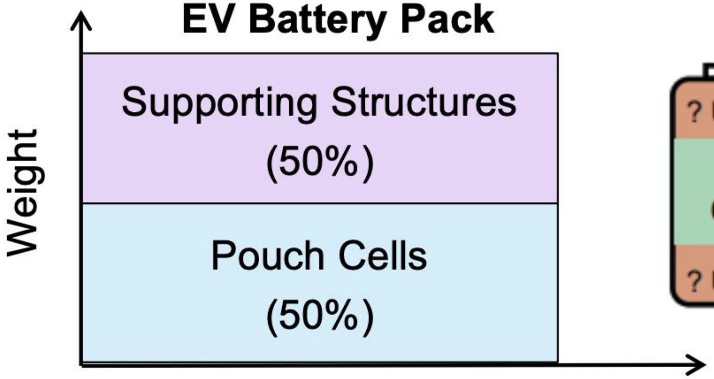
Silicon fractures

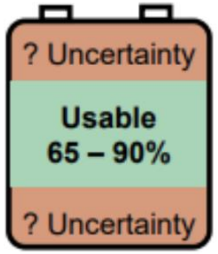
3) Battery health is difficult to predict

Aging of 48 nominally identical batteries



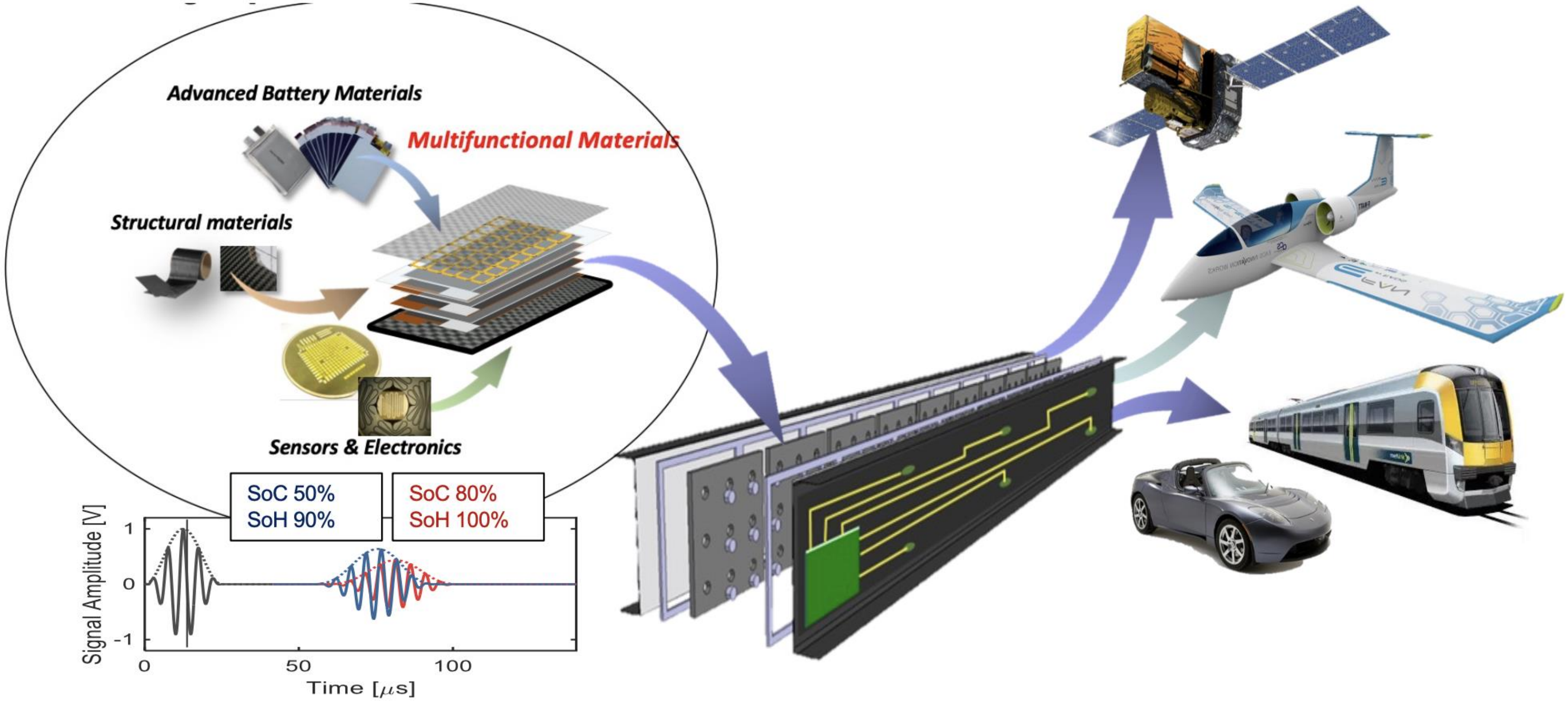
Mechanical protection





10 – 50% buffer capacity for uncertainties

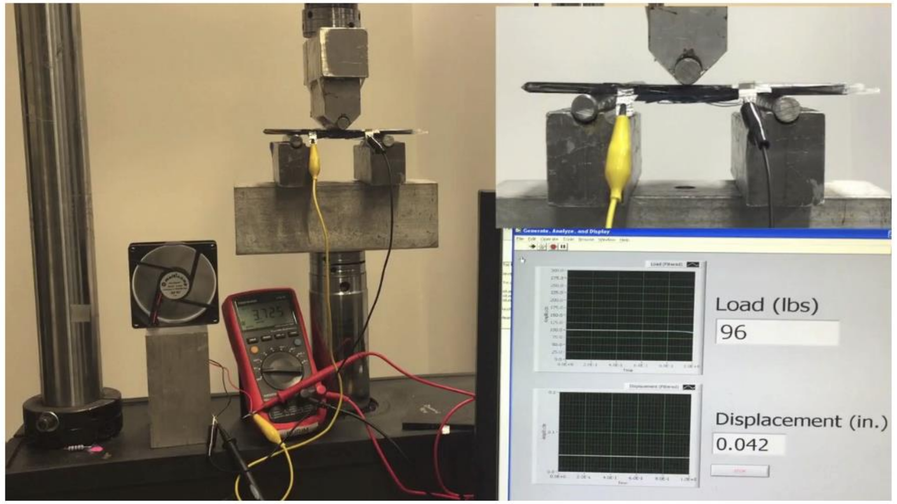
Multifunctional Energy Storage Composites (MESC)



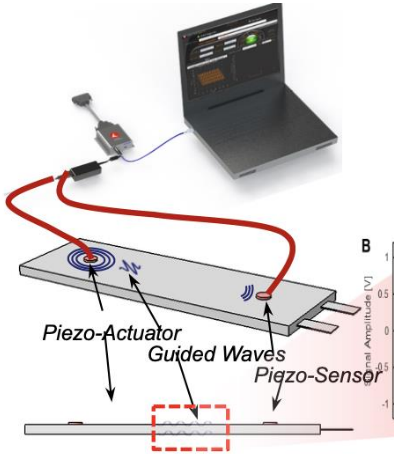
"GANTRIFY: *To Combine Mechanical Structure with Electrochemical Function*"

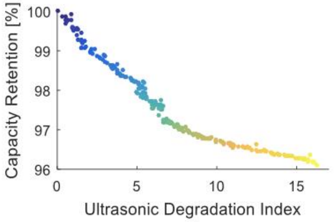
MESC Proof of Concept

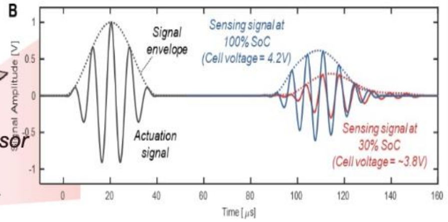
Cyclic Load Tests



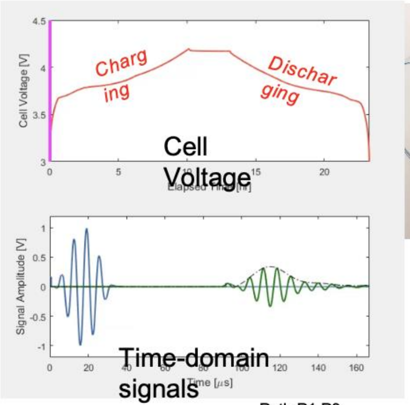
Electrochemical Degradation





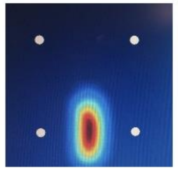


Acousto-ultrasonic waves



Path P1-P3, 175 kHz

Structural Damage



MESC Benefits

- 30% weight saving in structures
- 40% additional volumetric space
- 50% range extension
- Online real-time battery SOC and SOH prediction
- Built-in battery and structural health monitoring