Batteries for Electric Aviation

Ratnakumar Bugga, Charlie Krause, Marshall Smart, William West and Erik Brandon

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Pasadena, CA

February 12, 2020

Jet Propulsion Laboratory
California Institute of Technology

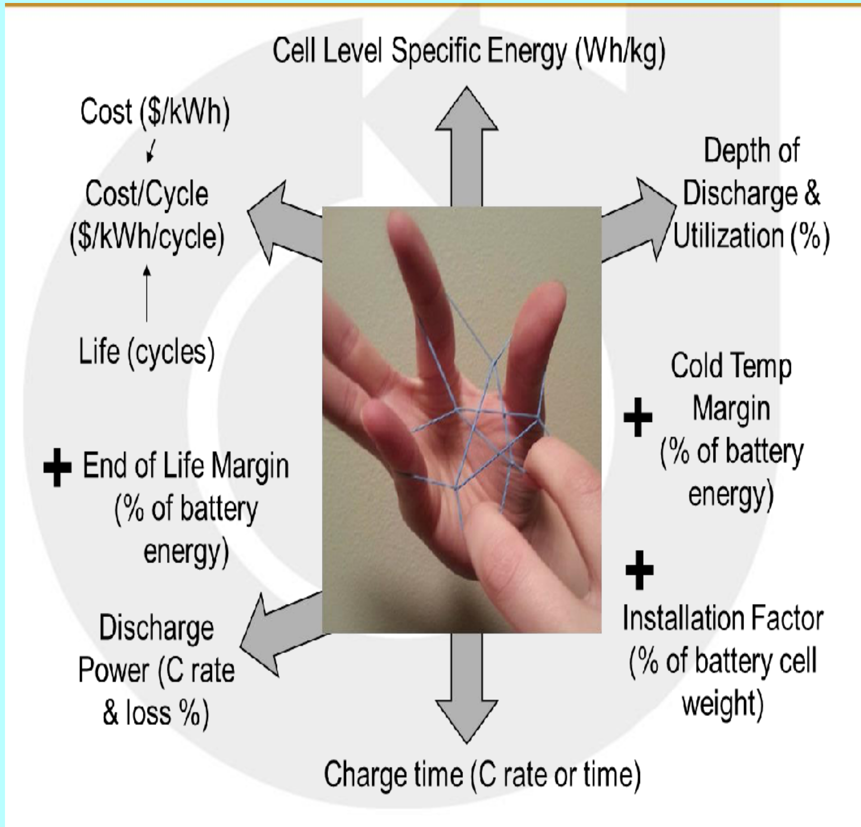
Benefits and Challenges for Electric Aviation

Benefits

- Environmental
  - Reduced Noise
  - Reduced Emissions
- Unique Configurations
  - BLI Distributed propulsion
  - Urban Mobility
- Operational Flexibility
  - Multiple power schedules (Efficient, quiet, low-emission modes)
- Potential for Reduced Costs
  - Energy and Maintenance

Challenges and Issues

- Low Specific Energy
  - Limited mission capability (payload, range and endurance)
  - Weight critical (not cost or volume)
    - One lb of jet fuel =14 x 1 lb battery
- Low Power Density
- Safety
  - High Voltage & Thermal Management
- Operational (ground)
  - Battery Swap / Charging
- Certification
  - New Technology and New Standards



- Installation, margins and reserves are reducing available energy more than anticipated.
  - Thermal safety protection, depth of discharge limits battery life preservation, aging battery performance large mission range/endurance margins

Opportunities for Electrified Aircraft Market with Advanced Batteries

Battery Pack Specific Energy	Potential Missions	Potential Market Introduction
SOA (150 – 170 Wh/kg)	  	Initial commercial introduction possible for all-electric with limited range and payload, extended capability with hybrid-electric
300 Wh/kg	 	All-electric eVTOL urban air mobility with 4 passenger and 50+ mile range; 20-passenger all-electric commuter
400 Wh/kg Sweet spot for eVTOL	  	Desired capability for all-electric eVTOL urban air mobility, long-range all-electric commuter, Initial version of small hybrid-electric regional
500 Wh/kg	 	Expansion to various classes of hybrid-electric regional aircraft, short-range 150 Passenger, single aisle hybrid-electric aircraft
> 700 Wh/kg	 	Single aisle, 150 passenger single-aisle aircraft, long range

Specific Power is Critical

Component Performance Requirements from National Academies Report

	Electric System [a]		Battery [b]
Aircraft Requirements	Power Capability (MW)	Specific Power (kW/kg)[c]	Specific Energy (Wh/kg)
General aviation and commuter			
Parallel hybrid	Motor <1	>3	>250
All-electric	Motor <1	>6.5	>400
Turboelectric	Motor and generator: <1	>6.5	n/a
Regional and single aisle			
Parallel hybrid	Motor 1-6	>3	>800
All-electric [b]	Motor 1-11	>6.5	>1,800
Turboelectric	Motor 1.5-3; Generator 1-11	>6.5	n/a

[a] Includes power electronics.
[b] Total battery system and usable energy for discharge durations that are relevant to commercial aviation flight times, nominally 1-10 hours. Values shown are for rechargeable batteries; primary (nonrechargeable) batteries are not considered relevant to commercial aviation.
[c] Conversion factors: 1 kW/kg = 0.61 HP/lb; 1 kg/kW = 2.2 lb/kW = 1.64 lb/HP.

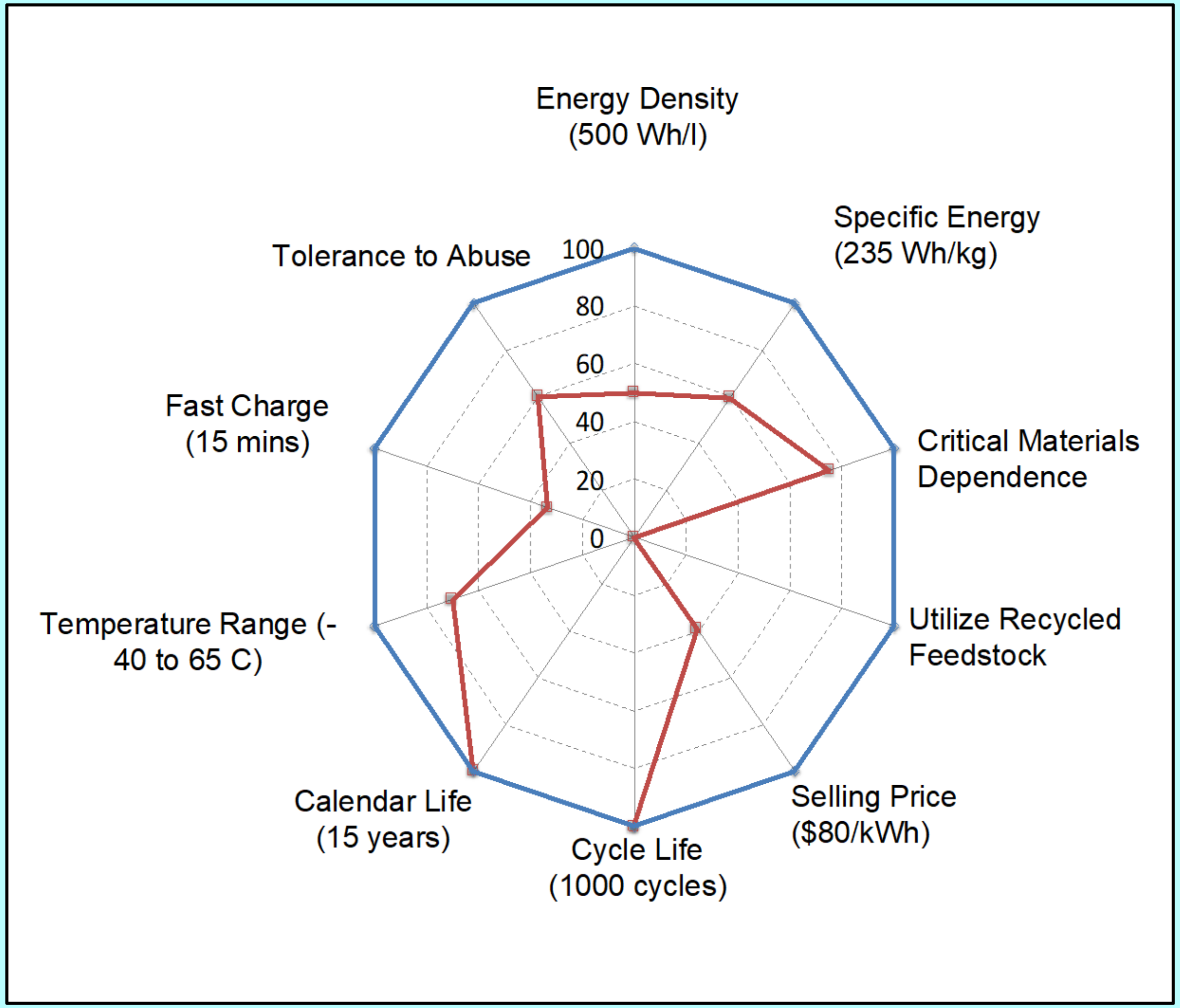
Source: National Academies Report 2016 (Bradley)

From AIAA Short Course – Design of Electrified Propulsion Aircraft

- In addition to specific energies, power densities are challenging. High power densities reduce realized energy density and also pose thermal issues.
- Charge times either have to be fast (less than 1 hour), to allow flights to “turn” quickly at the gate, or be rapidly replaceable and charged overnight when electricity cost is low. High charge rates lead to faster capacity degradation and also possible Li plating.

Assessment of Today's Li-ion Batteries for EV

Characteristic	Goal or Requirement	Curent Level, %
Specific Energy, Wh/kg	235	60%
Energy Density, Wh/l	500	50
Cycle life	1000	100
Calendar life	15	100
Temperature Range	-40 to 65C	70
Cost, $/kWh)	80	40
Critical Materials	-	80
Recycled batteries	-	0
Fast Charge	15 min	0
Abuse Tolerance	No TR	60



From the DoE report

- Low energy densities, poor safety and low temperature performance and high cost

Cathode Materials in Li-ion Cells

Cathode	Specifc capacity (mAh/g) and mid-point volage	Company	Target application	Benefit
Lithium Nickel Cobalt Manganese Oxide (NMC or LiNiCoMnAlO2)	155 mAh/g, and 3.6 V	Nissan Motor, Microvast Inc., LG Chem	Electric vehicles, power tools, grid energy storage	good specific energy and specific power density
Lithium Nickel Cobalt Aluminum Oxide ("NCA", LiNiCoAlO2)	180 mAh/g and 3.7	Panasonic, Saft Groupe S.A., Samsung	Electric vehicles, power tools, grid energy storage	High specific energy, good life span
Lithium Manganese Oxide ("LMO",LiMn2O4)	120 mAh/g and 4.0 V	LG Chem, NEC, Samsung, Hitachi, Nissan/AESC	Hybrid electric vehicle, cell phone, laptop	Good life span
Lithium Iron Phosphate ("LFP", LiFePO4)	160 mAh/g and 3.2 V	Hydro-Québec, Phostech.,Valence, A123 Systems	Segway Personal Transporter, power tools,	Low specific energy but high power
Lithium Cobalt Oxide (LiCoO2, "LCO")	155 mAh/g and 3.6 V	Sony first commercial production	Broad use, laptop	High specific energy, good life span

High Capacity Cathodes

Material	Specific Capacity (AH/kg)	Improvement over NMC 111 (%)
NMC 111	155	
NMC 532	167	8
NMC 622	175	13
NMC 811	203	31
NCA	185-190	23

- Lower cobalt (and higher nickel) lowers cost and raises capacity
- Cathode stability becomes an issue with Ni-rich formulations, as Co and Mn contents are lowered
- Anode is a carbonaceous material, either graphite, natural graphite, hard carbon etc.

Commercial Cells are Continuing to Get Better

- Commercial manufacturers have traditionally focused on small cells (cylindrical 18650 , 21700 and pouch cells).
- With improved cell designs (dense electrodes, thin separators), many commercial manufacturers have achieved significant energy improvements.

Characteristic	LG MJ1	Samsung 35E	Panasonic GA	Sony VC7
Capacity at C/10 at RT, Ah	3.41	3.49	3.34	3.5
Energy, Wh	12.46	12.7	12.16	12.72
DC Internal Resistance, mOhm	33	35	33	31
Mass, g	46.9	46	47	47.4
Specific Energy, Wh/kg	266	276	259	269
Energy Density, Wh/l	720	733	704	735

Commercial (18650) Li-ion Cells

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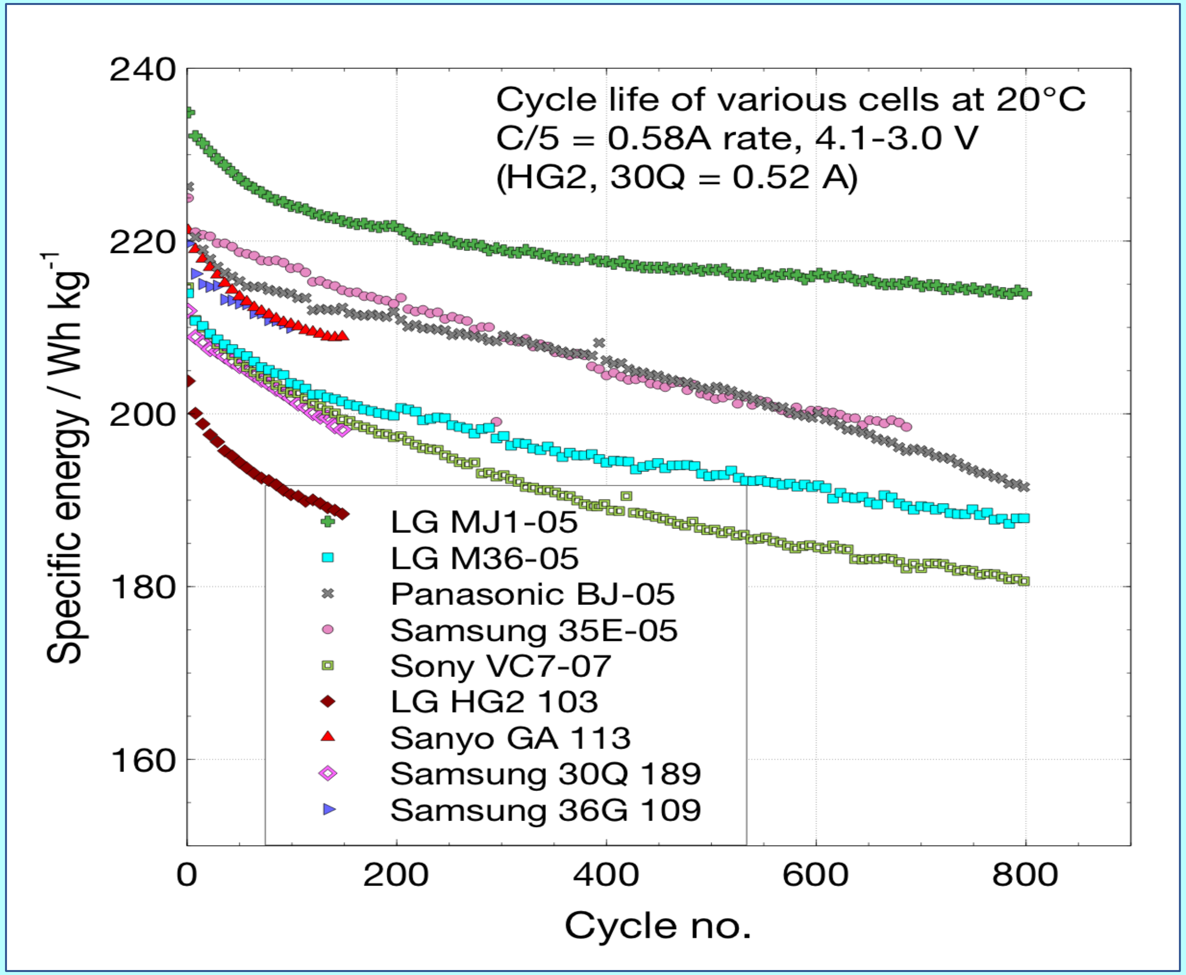
	Anode	Cathode
LGMJ1	graphite	$Ni_{0.81}Co_{0.13}Mn_{0.06}$ by EDX*
SA35E-10	graphite, ~2% Si by EDX	$Ni_{0.83}Co_{0.15}Al_{0.02}$ by EDX
PBJ-10	graphite	$Ni_{0.81}Co_{0.16}Al_{0.04}$ by EDX
LM36-10	graphite (less crystalline)	$Ni_{0.86}Co_{0.12}Al_{0.02}$ and $LiMn_2O_4$ (95:5)*
SOVC7-10	graphite (least crystalline)	$Ni_{0.90}Co_{0.08}Al_{0.02}$ by EDX$

250 Wh/kg with graphite anodes and NCA or NMC cathodes

JPL Data

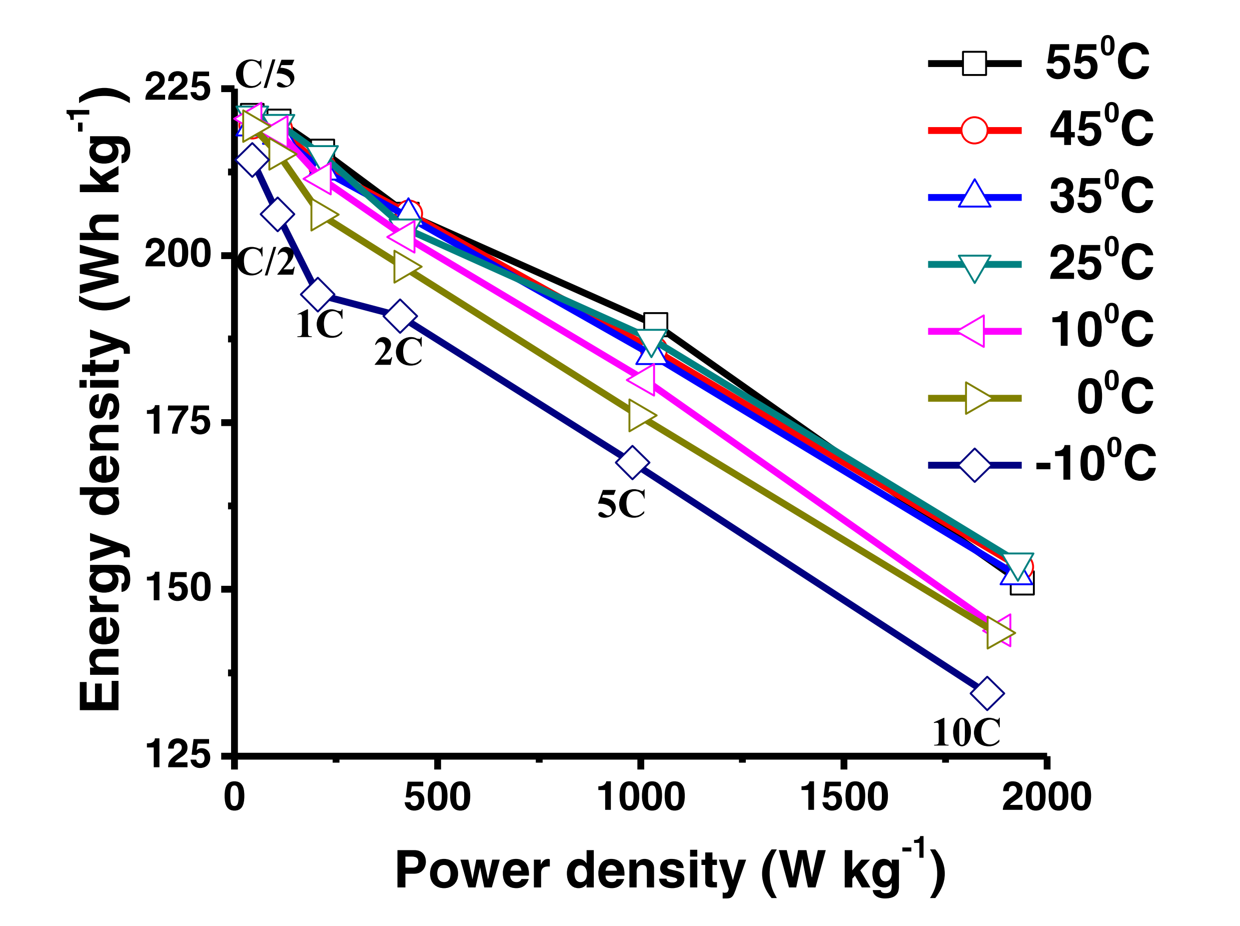


- Cells charged to 4.1 V have good cycle Life

Battery level energy densities are only 60-75% of the cell level energies, and even less if safety against thermal propagation is mandated

Power density vs. Specific Energy of 18650 Li-ion cells

Ragone Plot of Li-ion cells at Different Temperatures

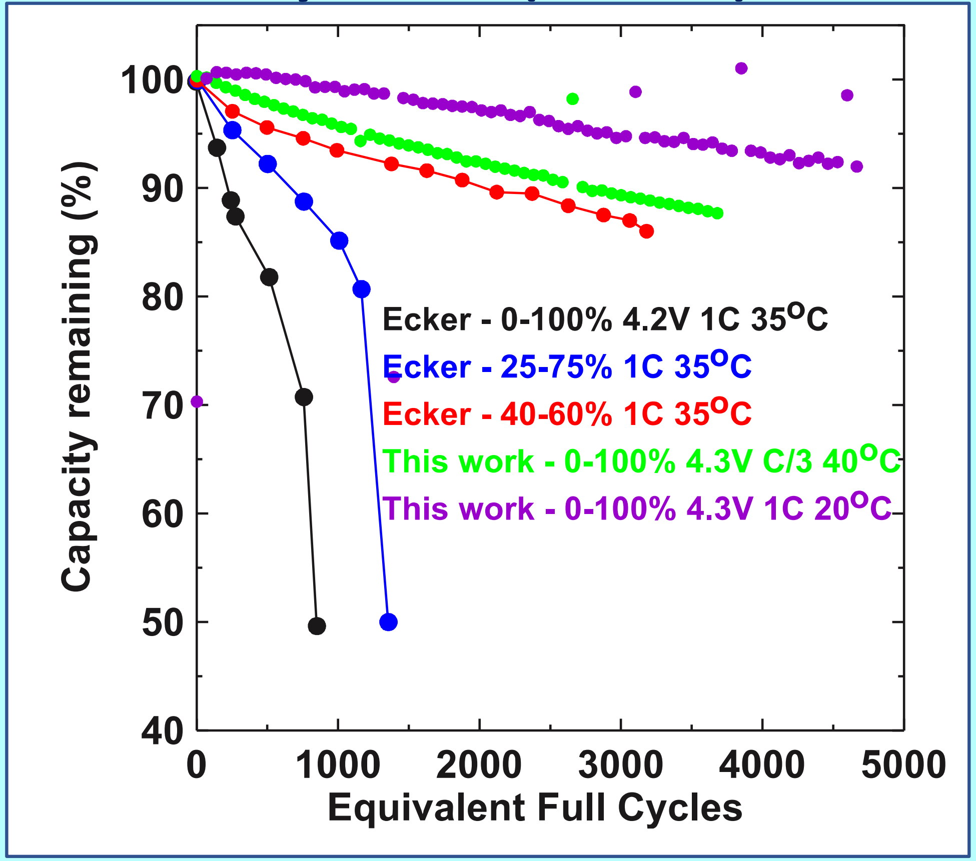


Krishna Kumar et al, J. *Electrochem. Soc.*, **165** (3) A674 (2018)

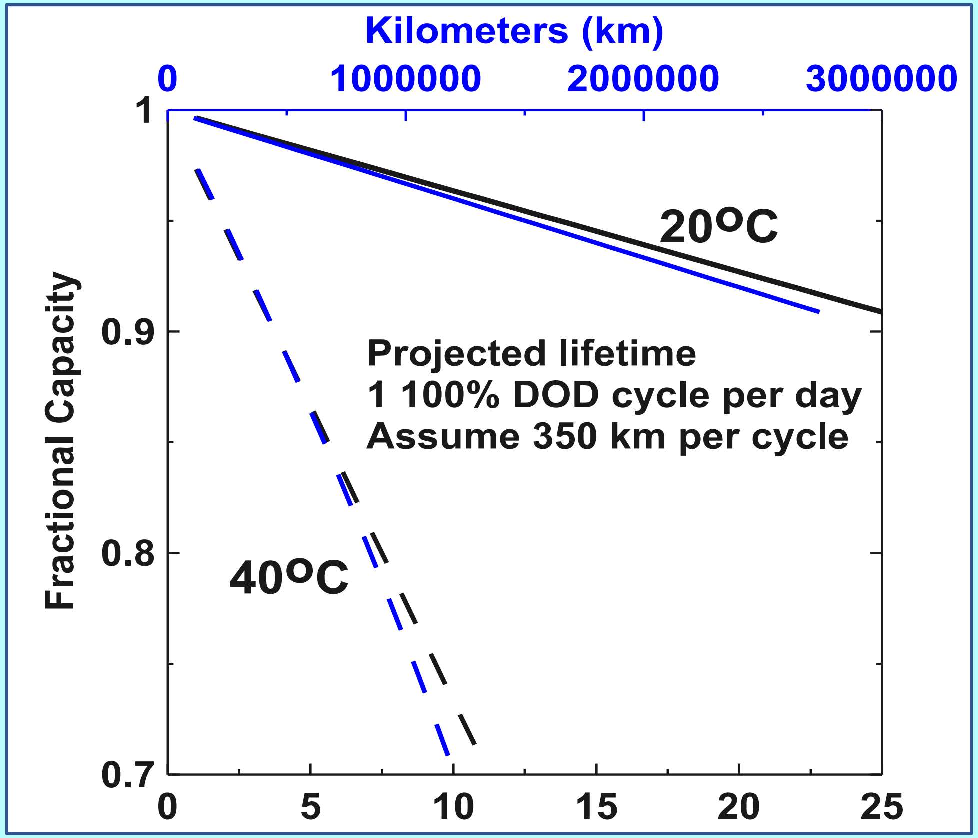
It is more challenging to to get high power density and also high specific energy especially at low temperatures

Cycle life and Calendar Life

Cycle Life (vs DOD)



Operational Life (vs T)

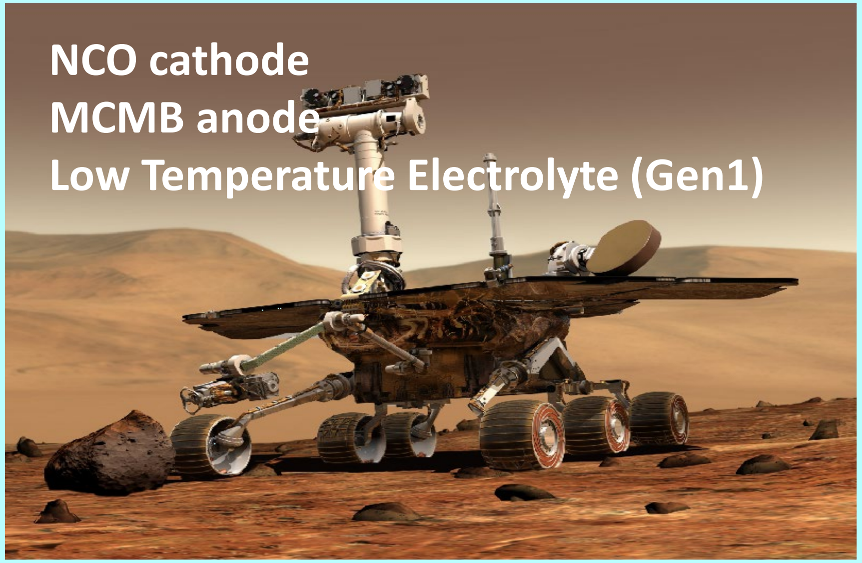


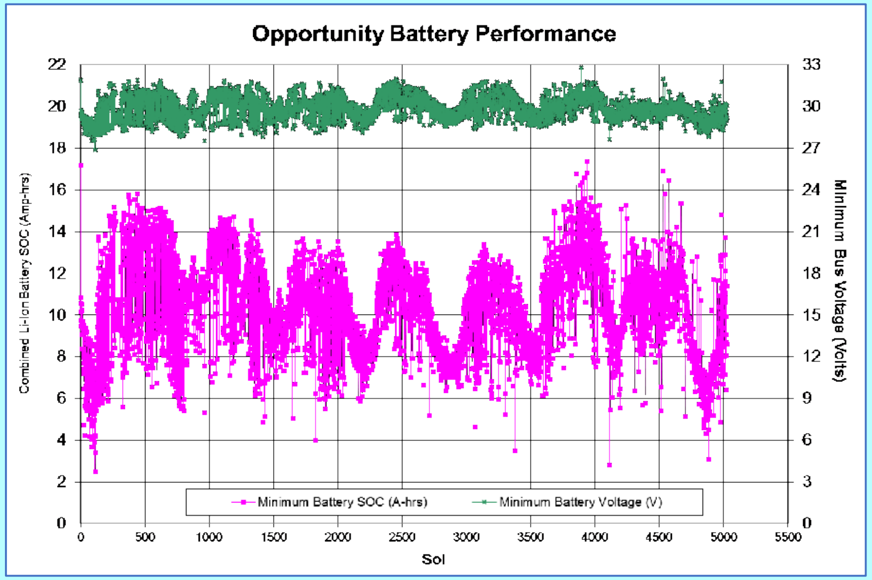
- Laboratory NMC/graphite pouch cells cycled to a charge voltage of 4.3 V. The data from Ecker et al., used 4.2 V as 100% state of charge
- Laboratory NMC/graphite pouch cells (with 2% VC and 1% DTD) at 20^{o}C and 40^{o}C. (6h 100% DOD cycle a day and 350 km driving range per cycle).

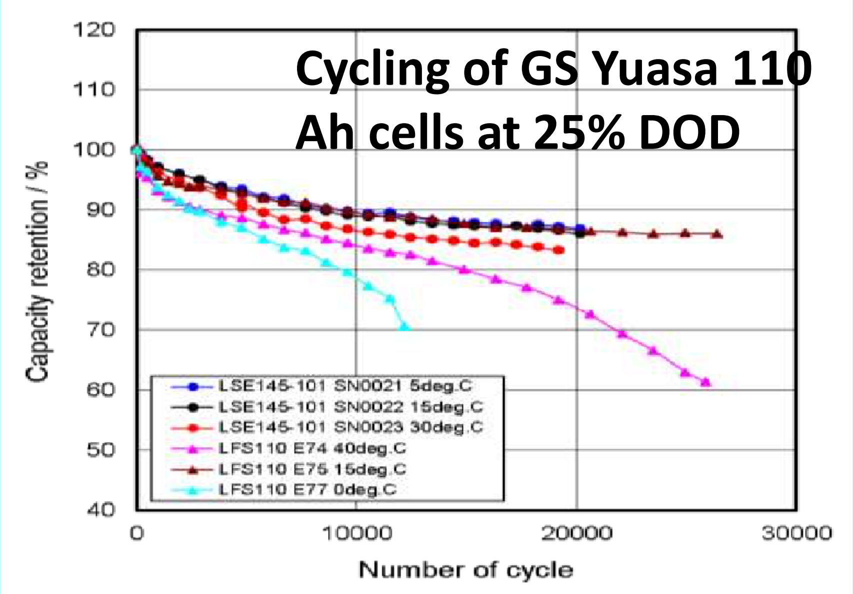
Jessie E. Harlow, …and J. R. Dahn, *Journal of The Electrochemical Society*, 166 (13) A3031-A3044 (2019)

- Li-ion batteries have adequate cycle life and calendar life for electric aviation

Impressive Life of Li-ion batteries in Aerospace



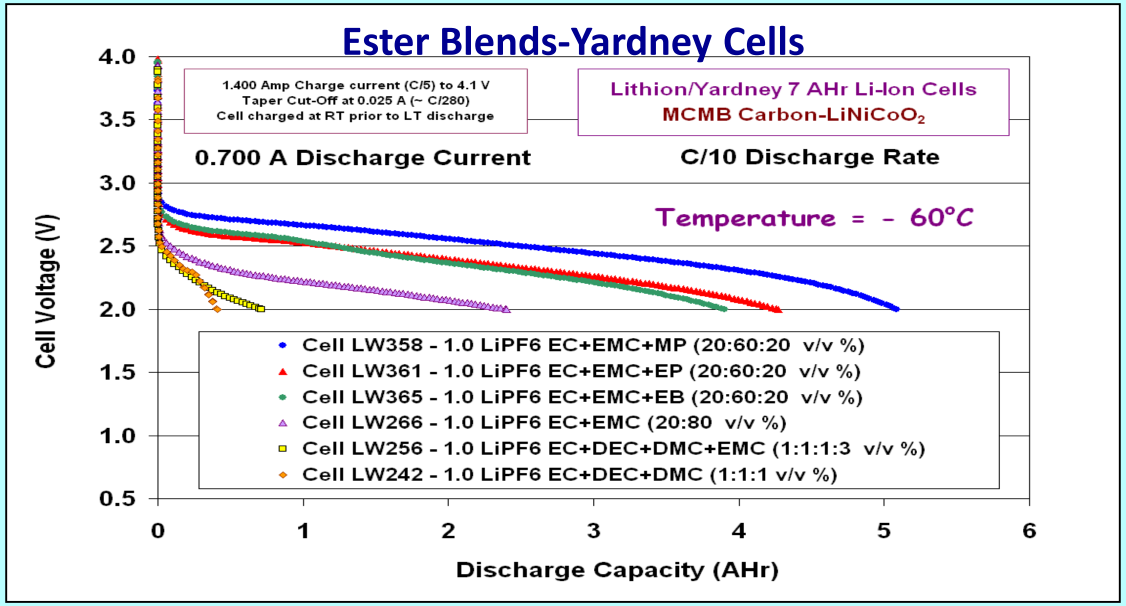


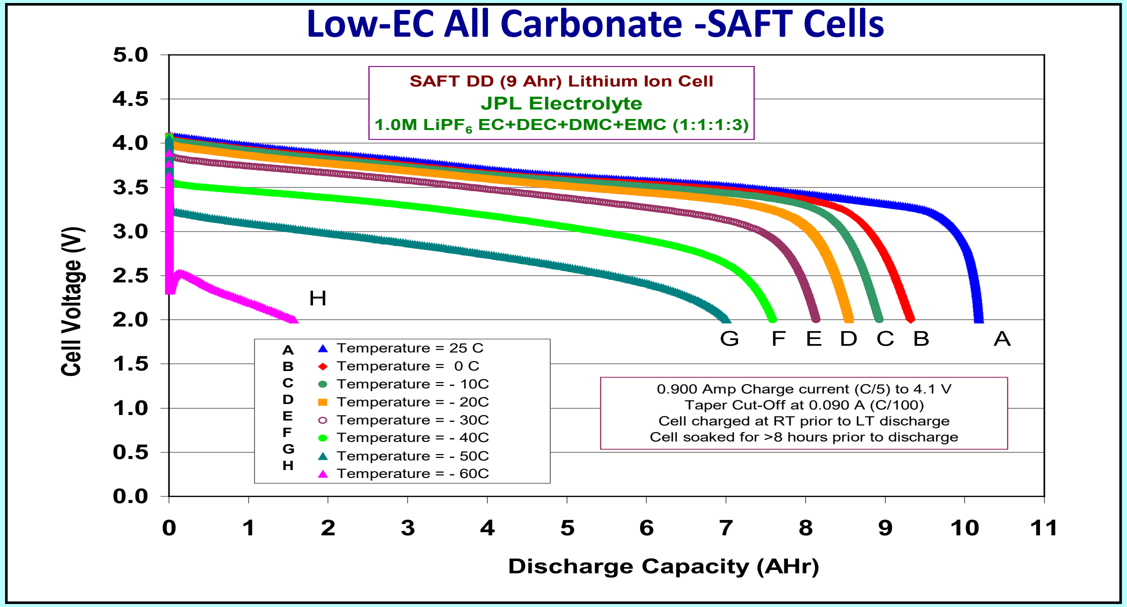


- Operated for 17 years
- 5500 sols and cycles

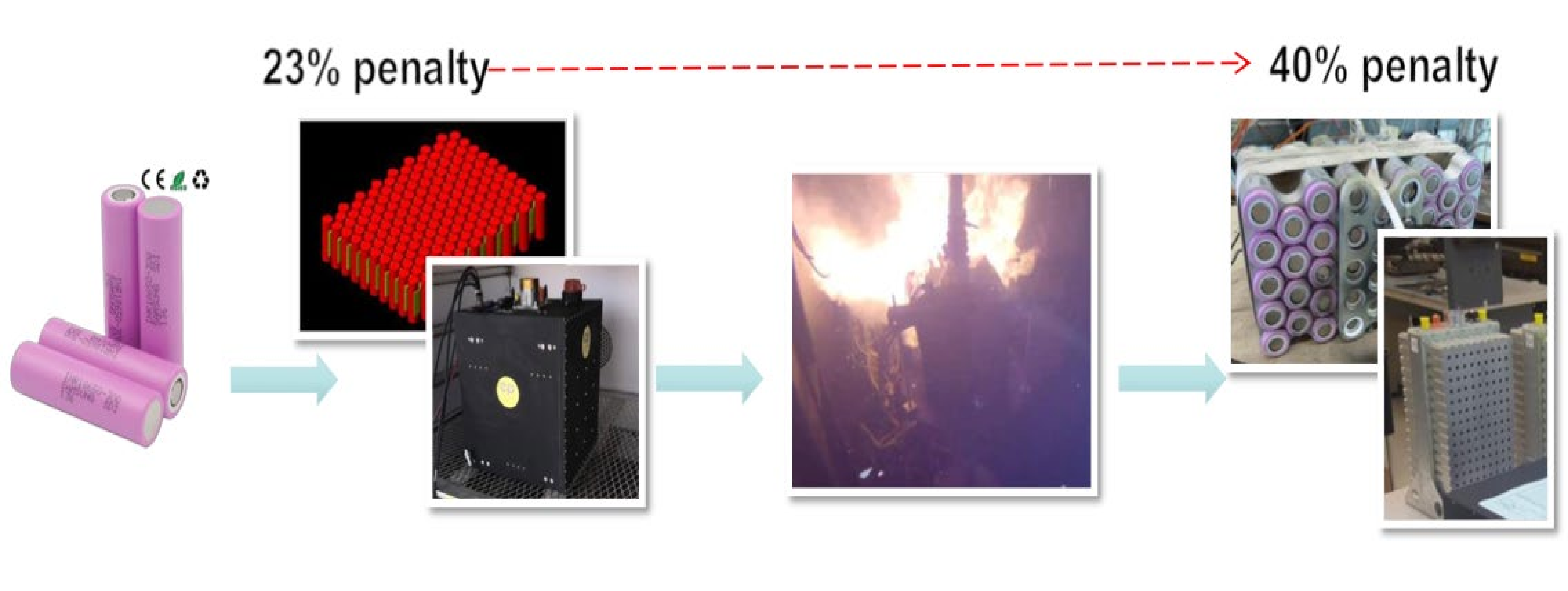
Performance Derating of Li-ion cells at Low Temperatures

- Electrolyte is the critical component for low temperature performance, by controlling the anode SEI characteristics and the bulk and interfacial diffusion of Li ions
- JPL developed several electrolyte formulations for improving performance down to -80°C.
    - Early Generation Ternary Electrolyte (-20 to +40°C)
    - Quaternary Carbonate-Based Electrolytes with low EC (-40 to +40°C)
    - Use of Ester-Based Co-Solvents (-60 to +40°C)
    - Use of Electrolyte Additives with Ester-Based Electrolytes
        - VC, VEC, LiBOB, FEC etc. to engineer the interfaces both at the cathode and anode
- Typically, the performance drops to 70% at -20°C, 50% at -40°C and ~40% at -60°C at discharge rates <C/5-C/10





Reduction of Specific Energy from Cell to Pack



- The specific energy of Li-ion batteries is only 50-60% of the specific energy at the cell level due to ancillary subsystems (thermal, electrical and mechanical).
- SOA Cell Specific Energy: 250 Wh/kg and the Battery Pack Specific Energy: $\leq$160 Wh/kg
- Safety or thermal propagation guidelines lower the specific energy and energy density further.

Battery Safety – Thermal Runaway and Propagation

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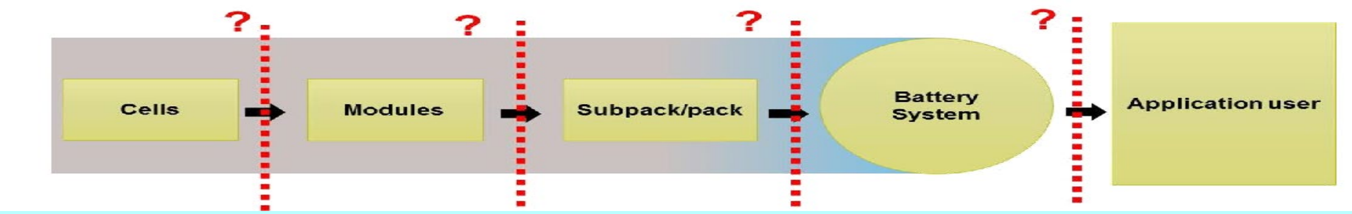
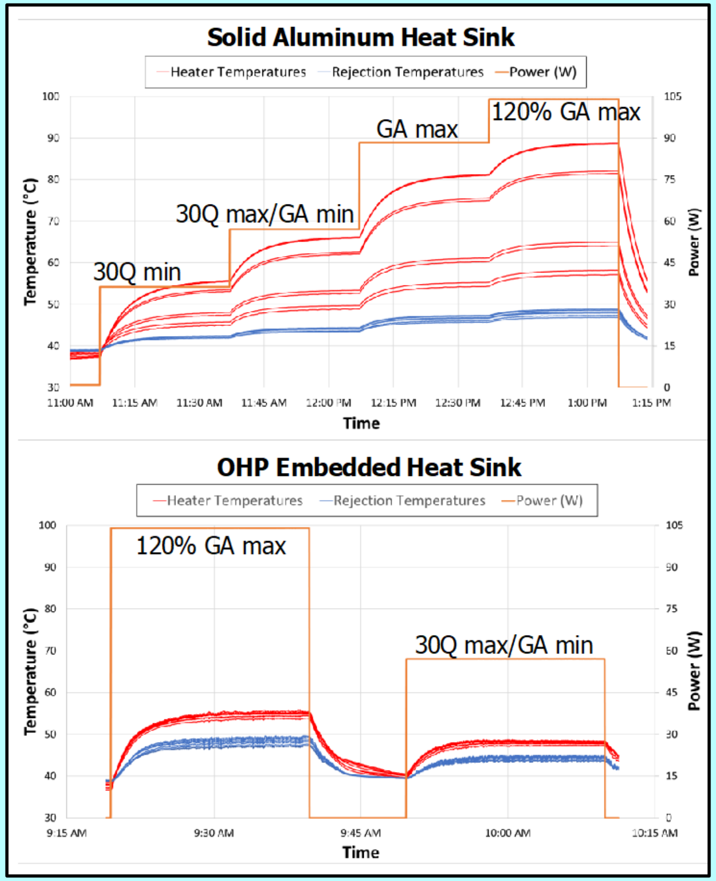
Propagation initiation and mitigation is possible at several levels

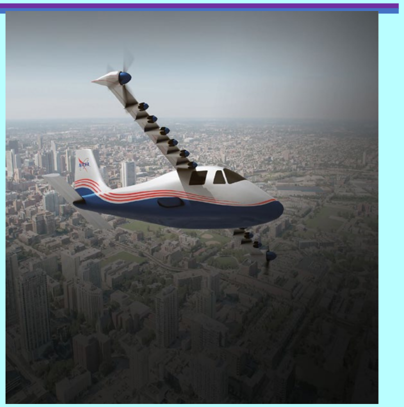


TR Propagation Resistant Design Guidelines (NASA-JSC)

- Reduce risk of cell can side wall breaches
  - Without structural support cells may experience side wall breaching during TR
  - Minimize constrictions on cell TR pressure relief
- Provide adequate cell spacing and heat rejection
  - Direct contact between cells nearly assures propagation. Spacing required is inversely proportional to effectiveness of heat dissipation
- Individually fuse parallel cells
  - TR cell becomes an external short to adjacent parallel cells and heats them up
- Protect the adjacent cells from the hot TR cell ejecta (solids, liquids, and gases)
  - TR ejecta is electrically conductive and can cause circulating currents
- Prevent flames and sparks from exiting the battery enclosure
  - Provide tortuous path for the TR ejecta before hitting battery vent ports equipped flame arresting screens

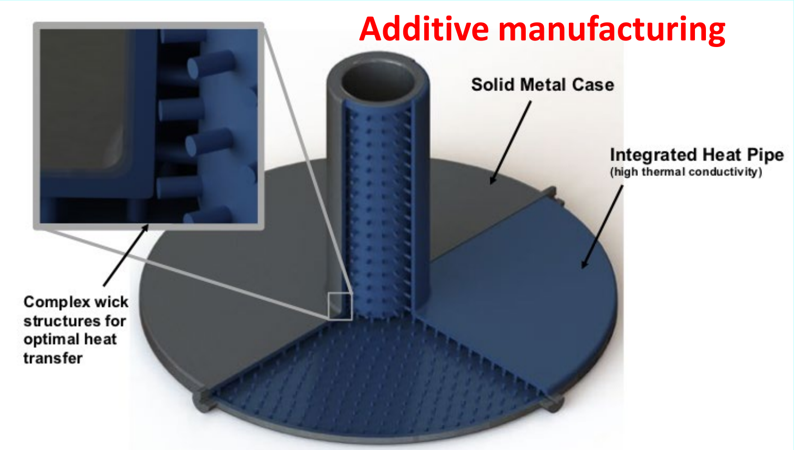
Thermavent's Oscillating Heat Pipes



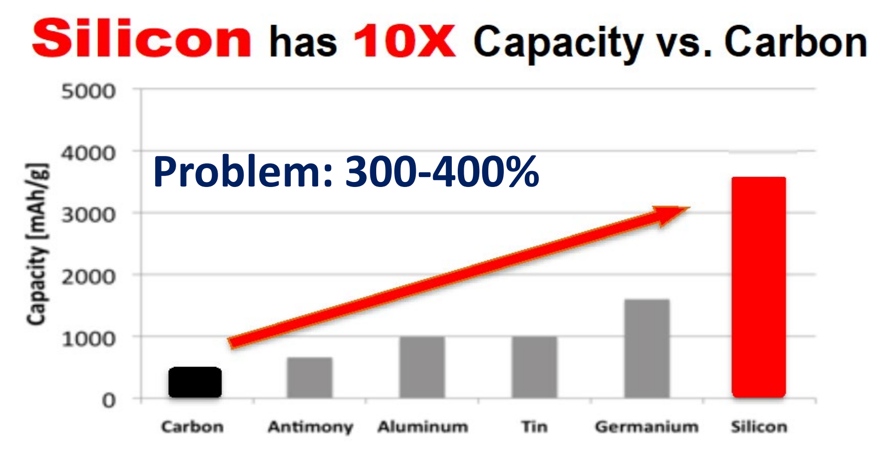


NASA's (Electric Power Systems)'s all-electric X-57 Maxwell airplane. The battery package houses thousands of COTS Li-ion cells and ensures no thermal propagation

JPL Concept



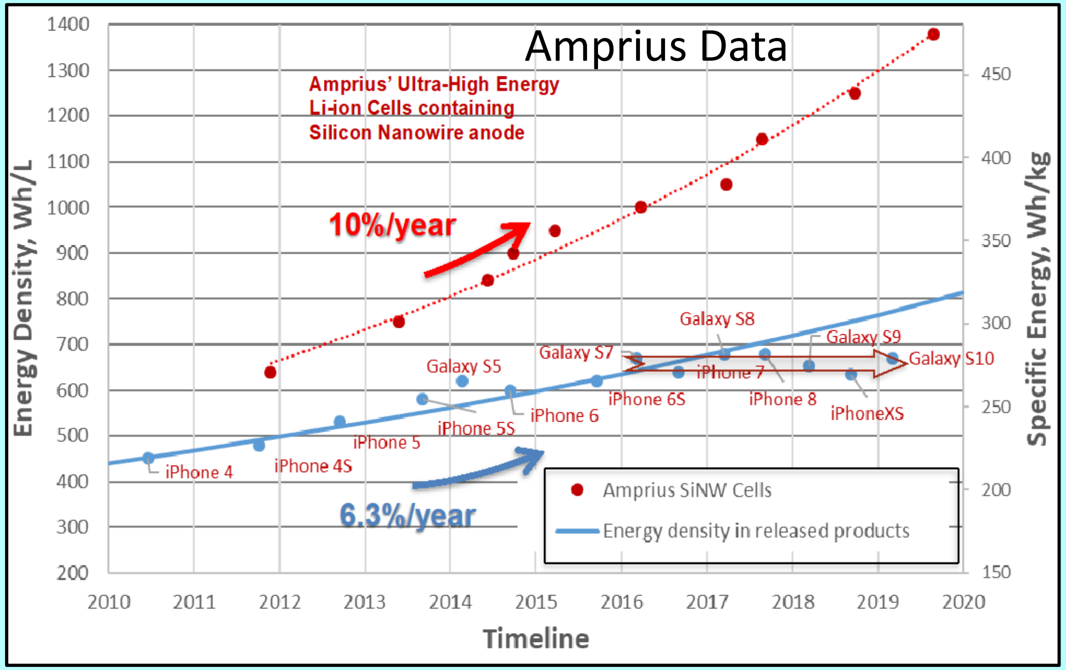
Li-ion Cells with Si anode



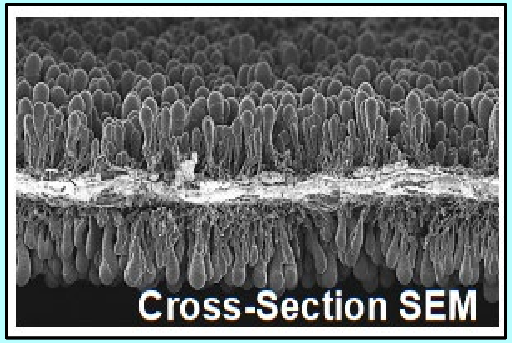
- New designs to mitigate expansion
  - Nanocrystalline Si (composite) anodes with graphite (3M, Sila Nanotechnologies, American Lithium Energy, Enevate)
  - Si Nanorods (Amprius, Sienza Energy)

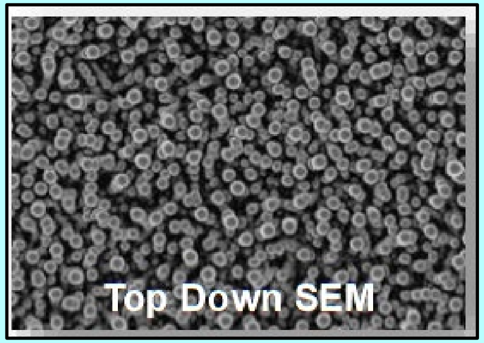
Realistic Goals

- >500 mAh/g
- 4 mAh/cm²
- Cycle Life: 500
- >1000 Wh/l

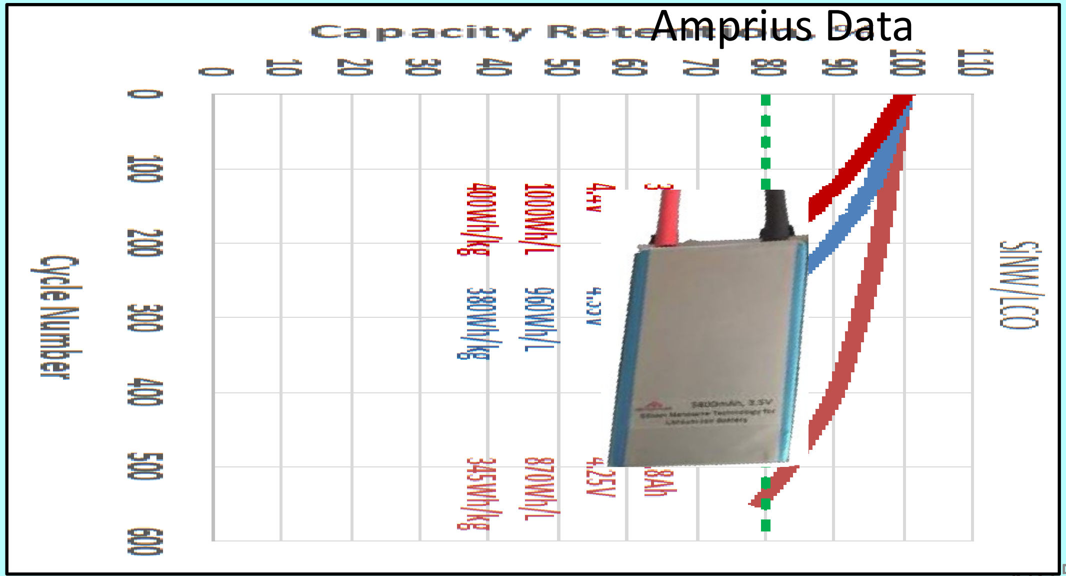


Si nanorods (Amprius)





From Amprius data



Lithium-Sulfur Rechargeable Batteries

Promise

- High capacity of sulfur (~8-10x of Li-ion cathodes)
- Inexpensive, abundant and non-toxic

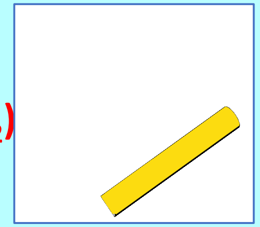
Problems

- Polysulfides soluble in electrolyte forming Redox shuttles affecting cycle life, efficiency, anode

Strategies

New cathode designs to sequester sulfur products within the cathode

- Carbon nanostructures as hosts
- **Metal sulfide blends (TiS_2, MOS_2)**
- Coated separators (JPL)
- Electrolyte Modifications
- Protected Li anode

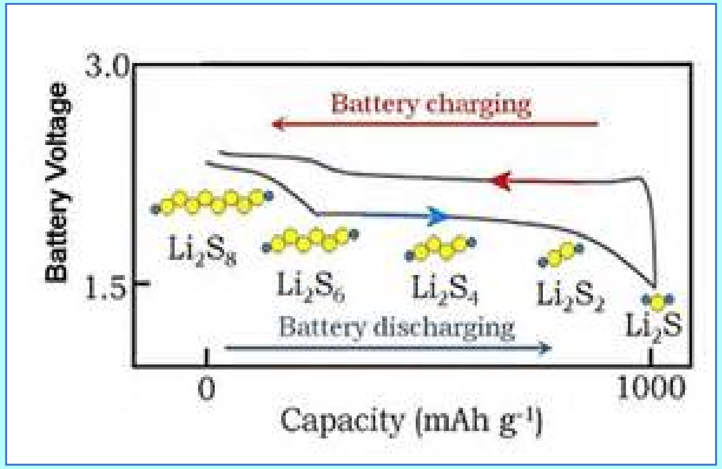


Active players

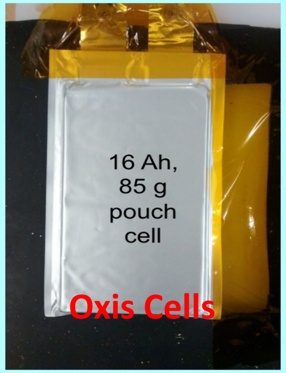
- Oxis Energy, Sion Power, Navitas, DoE, JPL

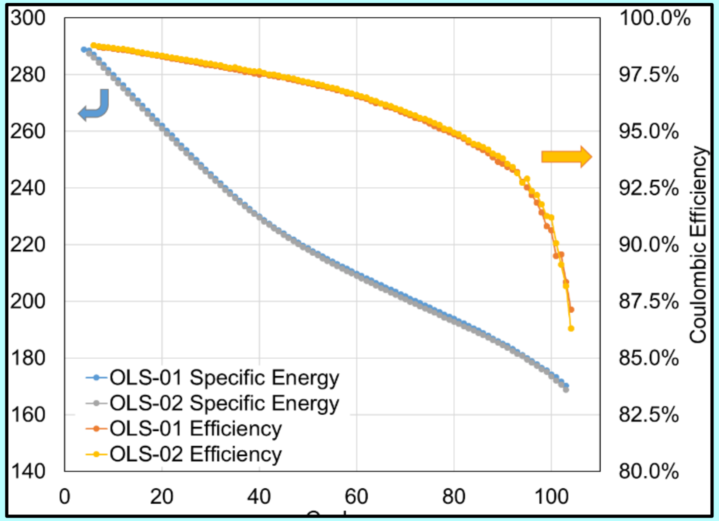
Realistic Goals

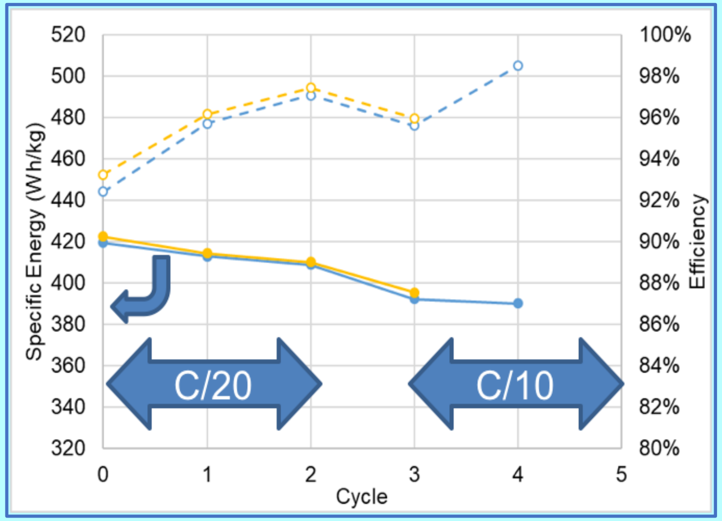
- **>800 mAh/g**
- **8 mAh/cm²**
- **< 9ml/g of S**
- **Cycle Life: 500**
- **>400 Wh/kg**



1st cycle C/20 specific discharge energy: **420** Wh/kg







OXIS Energy is close to achieving 500Wh/kg and is targeting 600Wh/kg with Solid State Lithium Sulfur technology

OXIS Energy has successfully tested its cell prototypes at 471Wh/kg and is confident of achieving 500Wh/kg in the next 12 months.

Lithium-Metal Oxide Batteries

Promise

- Higher anode capacity >2x vs carbon even with excess Li
- Higher voltage

Challenges

- Li dendrites upon cycling (premature failure)
- Dead Li reducing the capacity
- Morphological change leading to pyrophoric Li

Strategies

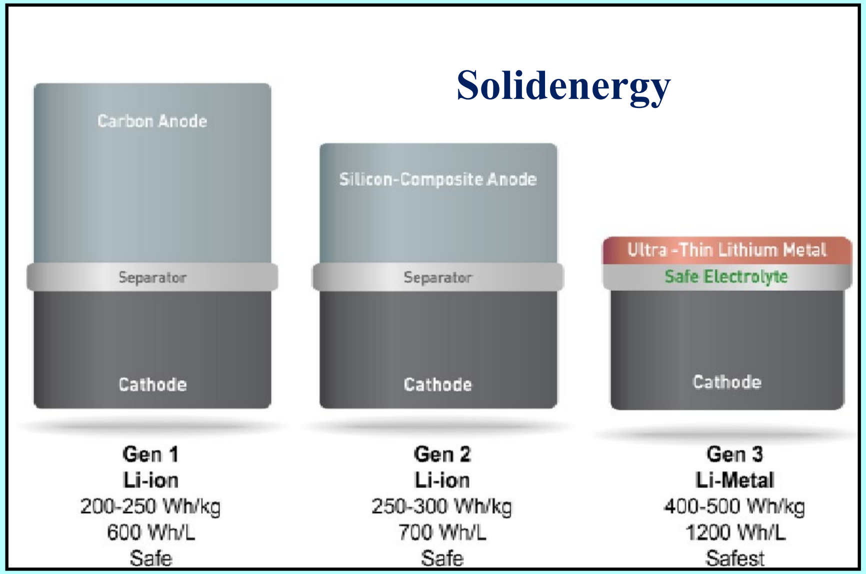
- Liquid electrolyte with selective additives
- (Gel) Polymer electrolytes
- Ionic Liquids
- Protected Li

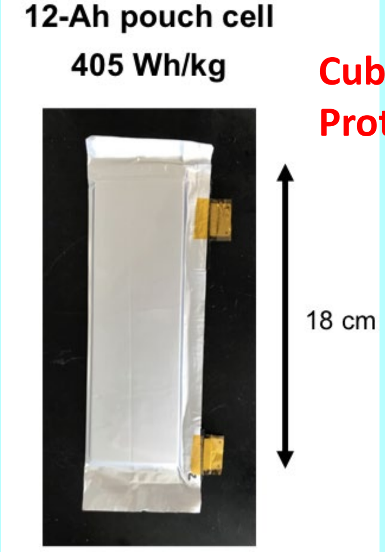
Active Players

- Solidenergy,
- Cuberg,
- Sion Power

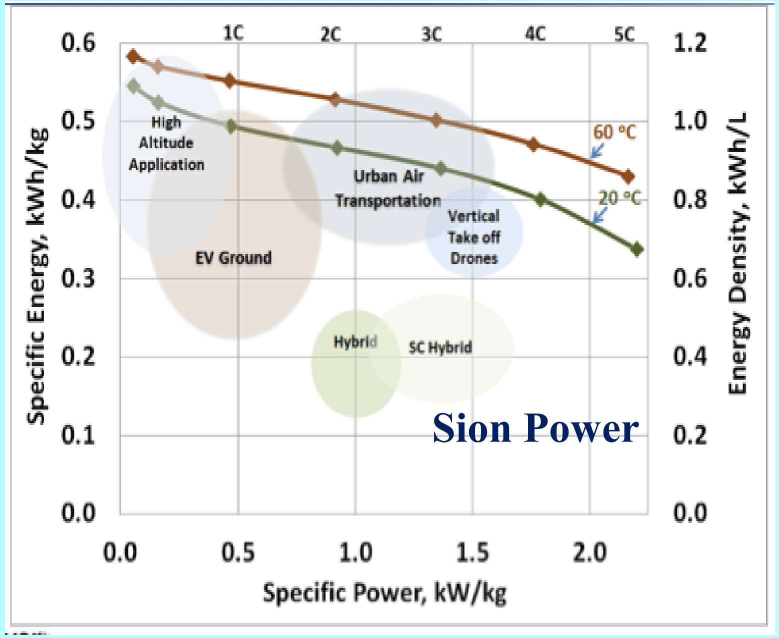
Realistic Goals

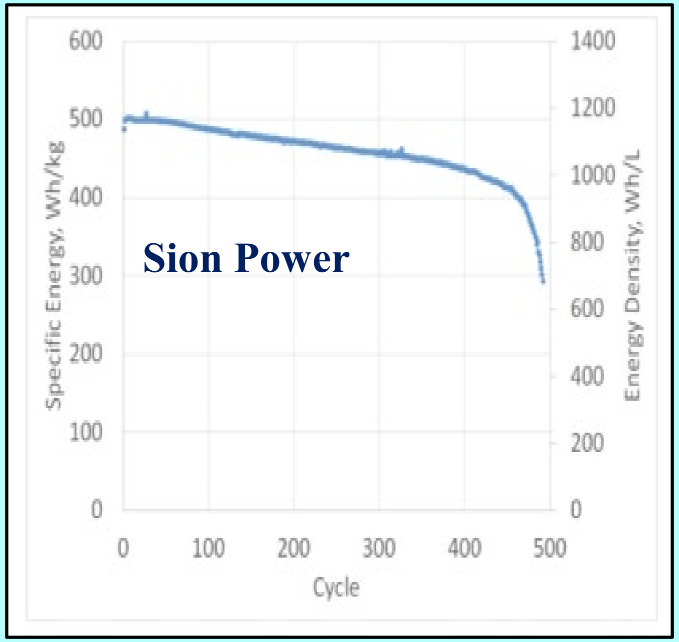
- **Cycle Life: >200**
- **>450 Wh/kg**





Cuberg Prototype





Solid State Rechargeable Batteries

Technology Status

- New Solid electrolytes being developed
  - Garnet Oxides.
  - LATP (Lithium Aluminum Titanium Phosphate)
  - LIPON
- Coin cells & Small format laboratory cells

Advantages:

- Improved safety (no runaway),
- Long cycle life and calendar life
- Good high temperature resilience,

Applications

- Low-power applications (sensors),
- Long-life (calendar life and cycle life)
- Extreme environments

Challenges

- Interfacial stability
- Poor rate capability
- Difficult to scale up to high capacity cells
- Poor low temperature performance
- Manufacturability

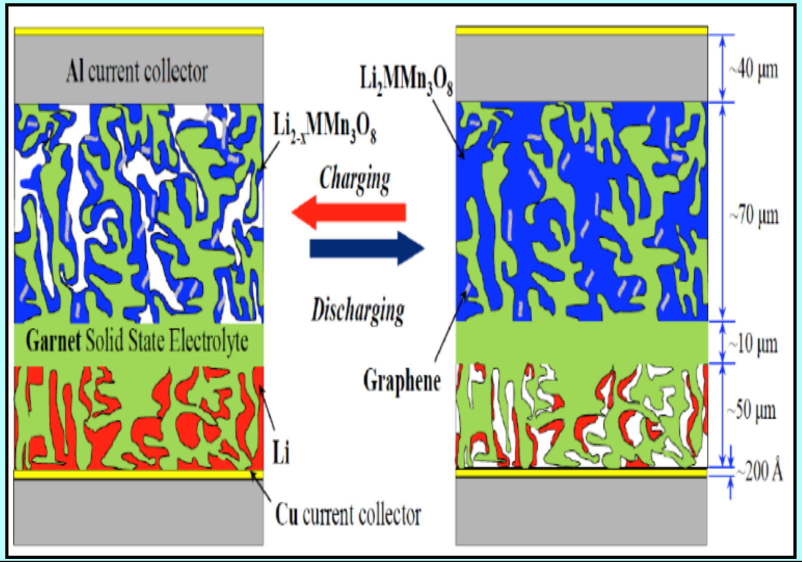
Active Players

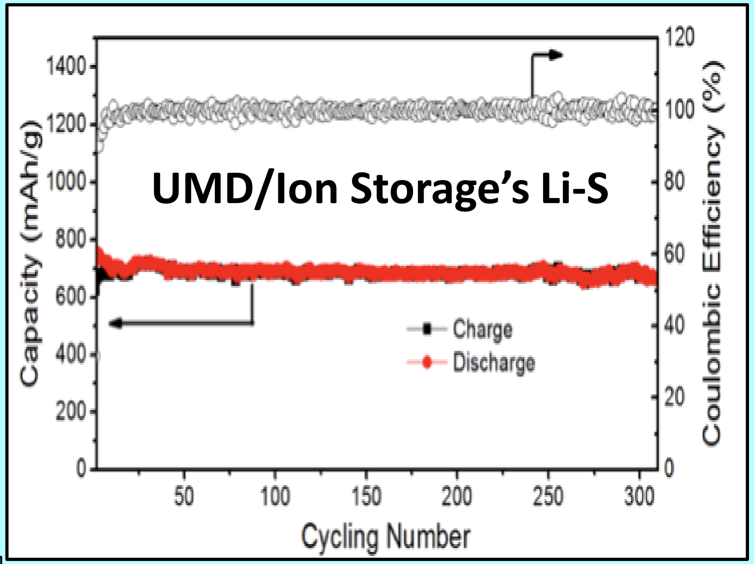
- Poly Plus, Front Edge, Univ. of Maryland, Solid Power, DoE, Solid Power, Toyota, Terrawatt

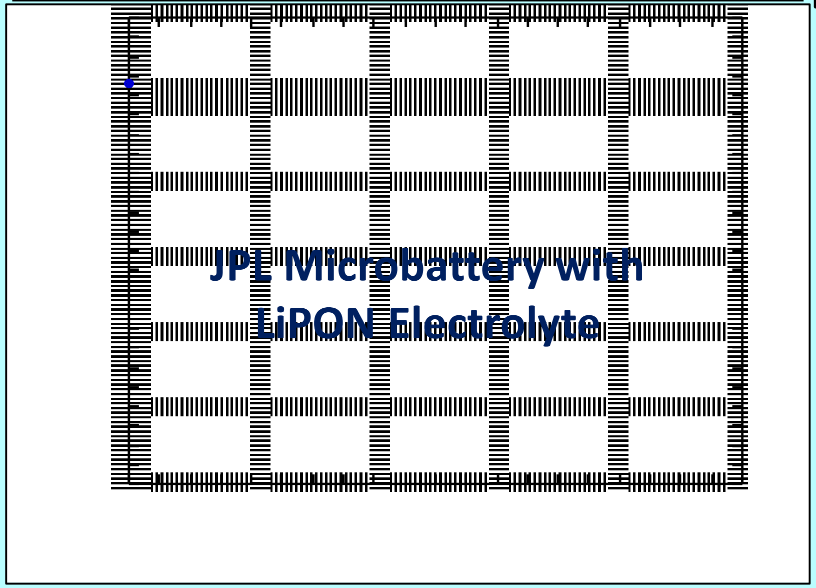
Realistic Goals

- **Sp. Energy: 400 Wh/kg**
- **Cycle Life: >1000**
- **Timeline: 3-5 years**

Univ. Maryland







Toyota will debut at the Tokyo Olympics a people-mover concept vehicle powered by solid-state batteries. To begin mass production around 2025.

Summary and Perspective

- With the current mature Li-ion technologies, specific energy of 200 Wh/kg at the pack level is achievable.
  - Need to optimize chemistries and cell structure to simultaneously achieve high specific energy and high power density for eVTOL applications
  - Battery performance need to be demonstrated under aircraft mission cycles
  - Safety challenges for high specific energy battery with liquid electrolyte needs to be addressed. If needed, ultra-safe propagation-resistant designs may be developed with <10% additional penalty on the energy densities
- Specific energies of >300 Wh/kg at the pack level are possible with newer chemistries
  - A few technical challenges exist related to chemistry, materials, cell engineering, and manufacturing and technology validation
    - Li(Si)-NMC
  - Significant challenges for the advanced chemistries with >500 Wh/kg at cell level and 400Wh/kg at pack level
    - Lithium-sulfur
    - All solid state battery likely to be the preferred choice both for higher energy densities and safety
    - EV industry is currently investing in this technology. Any augmentation from electric aviation applications ?
- Comprehensive system analysis with multiple scenarios needed to identify opportunity space for hybrid-electric regional and large, single-aisle aircraft.

The work described herein was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with National Aeronautics and Space Administration (NASA), and supported by NASA NESC Program.

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