Persistent Solar Powered Airplanes: Energy Storage

MIT Course,16.82 SP20

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Dr. Lovelace Background

MIT Undergrad
- BS ME

GE Aircraft Engines
- Digital & analog engine controls
- Cockpit interfaces

MIT Automotive Research Consortium
- High voltage systems & component R&D
- MS ME/EECS, TPP Minor, EECS Ph.D.

SatCon Technology
- Mechatronics R&D
- Electric machines, mag bearings, propulsion, generation, distribution, & actuation systems

Free Flow Power
- hydrokinetic turbine & array technology
- project development

XL Fleet
- fleet electrification & connectivity
- Hybrid electric powertrain platform product development

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- Hybrid & electric power systems R&D
- Urban air mobility

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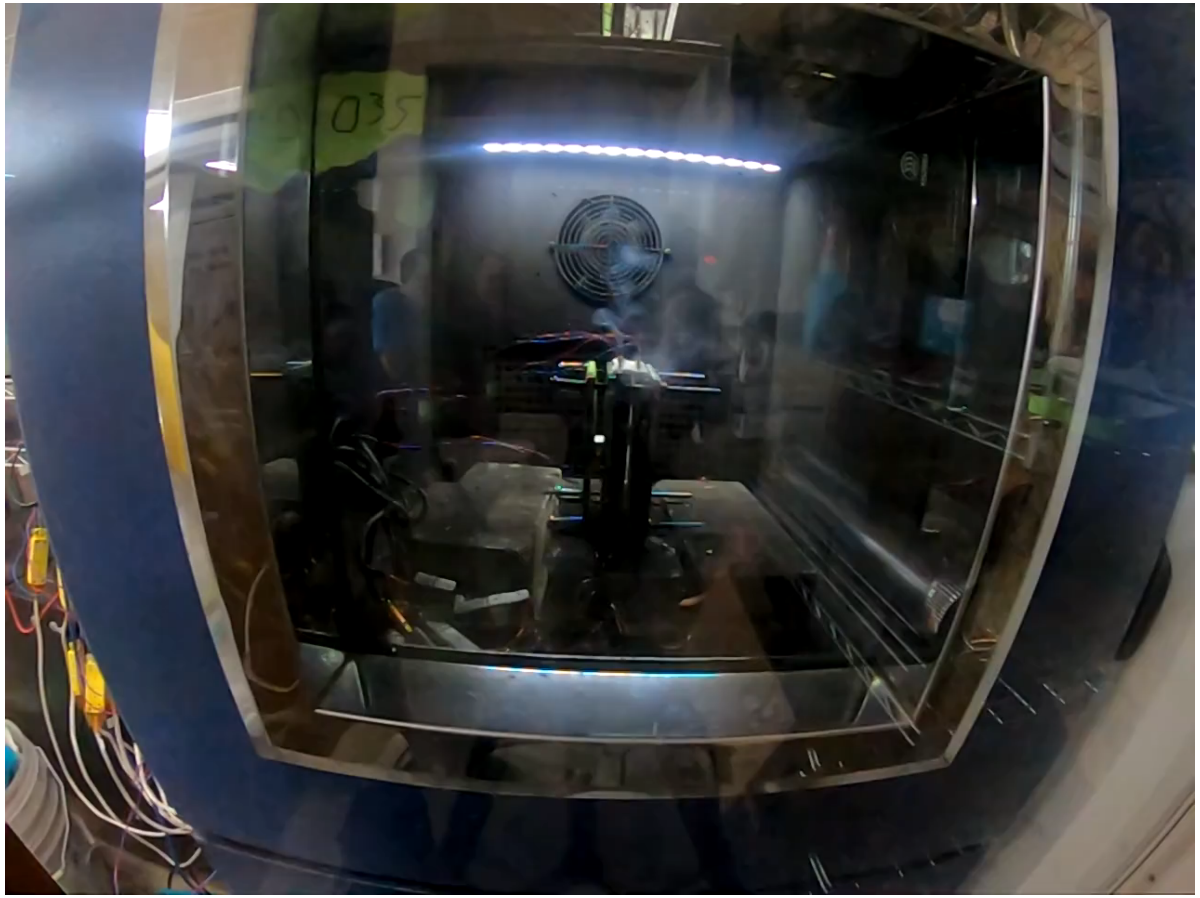
Topics

- Safety First
- Powertrains for Solar Aircraft
- Storage Requirement
- Storage Options
    - Fuel Cells
    - Batteries
- Battery Topics
    - Anatomy
    - Chemistry
    - Modules
    - Temperature & Pressure Management
    - Packs
    - Vehicle Interfaces
    - Safety Hierarchy
- Q&A

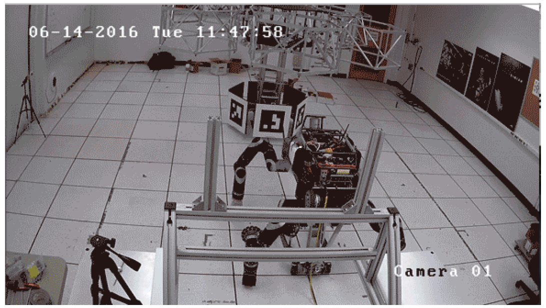
Safety Warning: Energy Release in Thermal Runaway Can Be Significant

Example 1: single overheated <20Wh cell



Example 2: NASA Robosimian thermal event

11:47:58



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https://www.wired.com/2016/10/samsung-isnt-one-lithium-ion-problems-just-ask-nasa/

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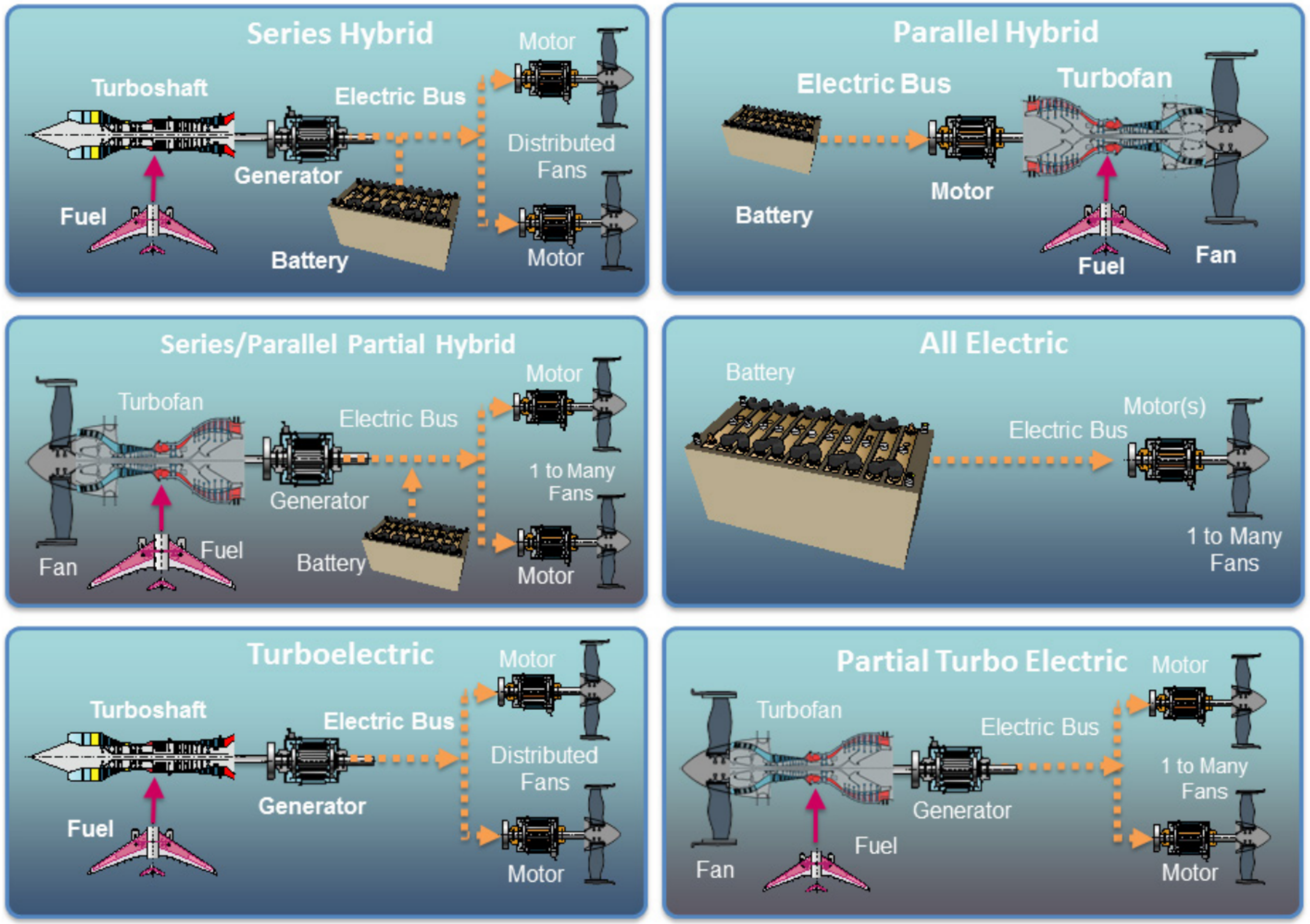
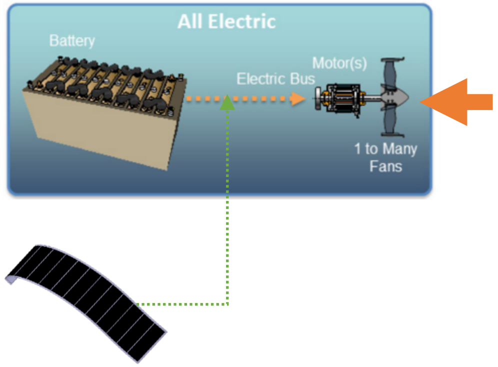
Electrified Propulsion Aircraft Architectures

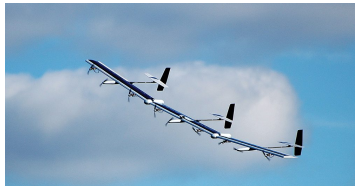
NASA Description of Architectures



w/renewable electricity



Solar Program



distributed DC propulsion

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Solar Aircraft w/ Energy Storage & DC Distribution

Varying voltage storage

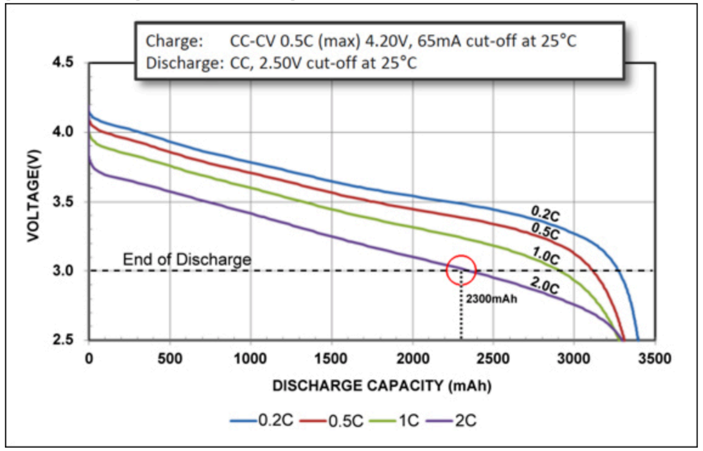
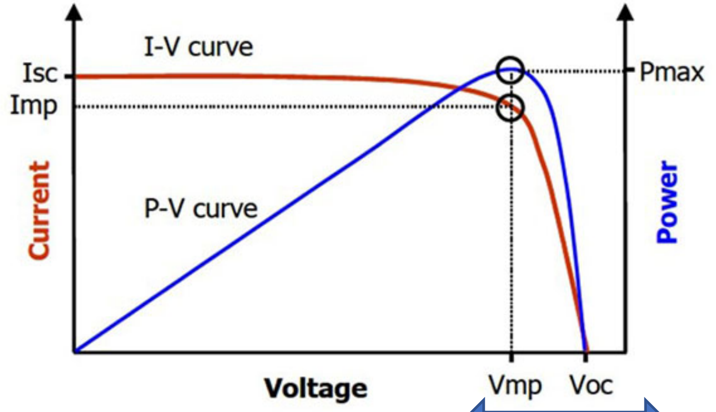
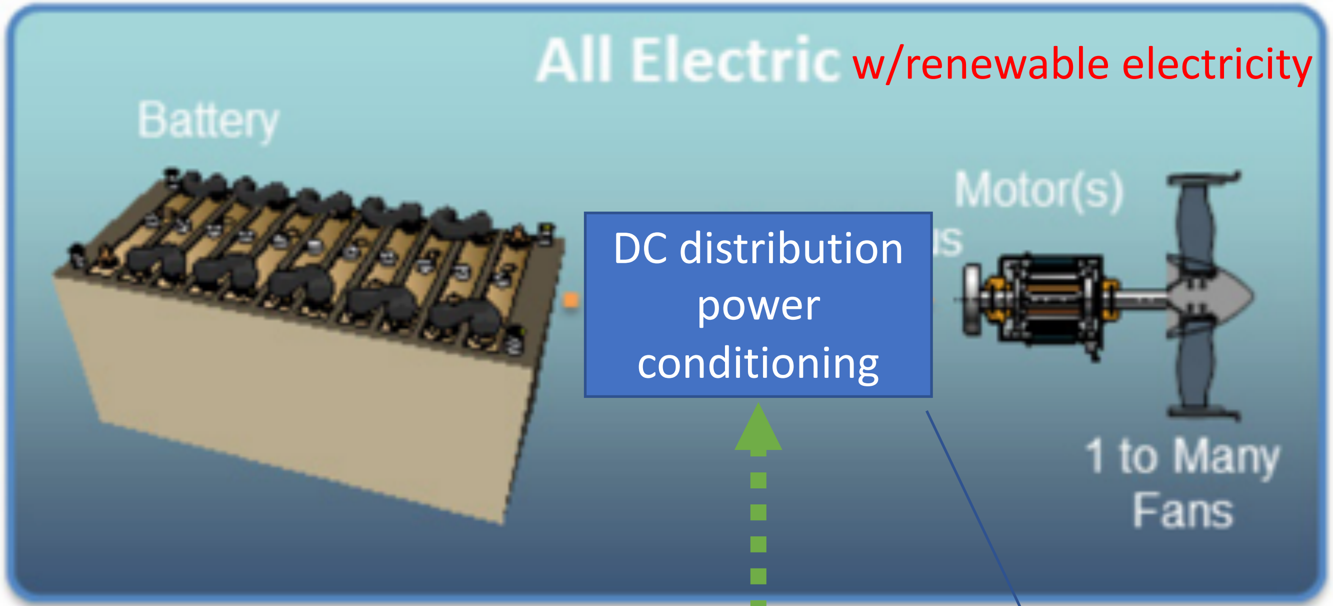
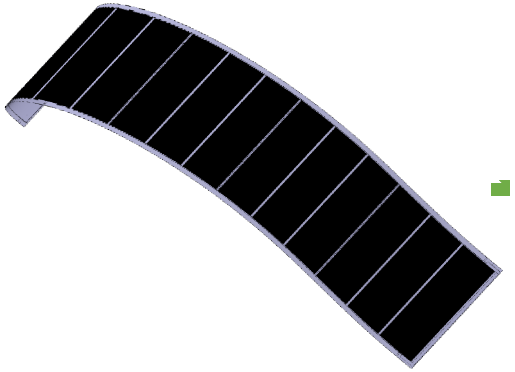


Figure 1: Discharge characteristics of NCR18650B Energy Cell by Panasonic.

Varying voltage solar







+ Electrical loss
+ Heat
+ Weight

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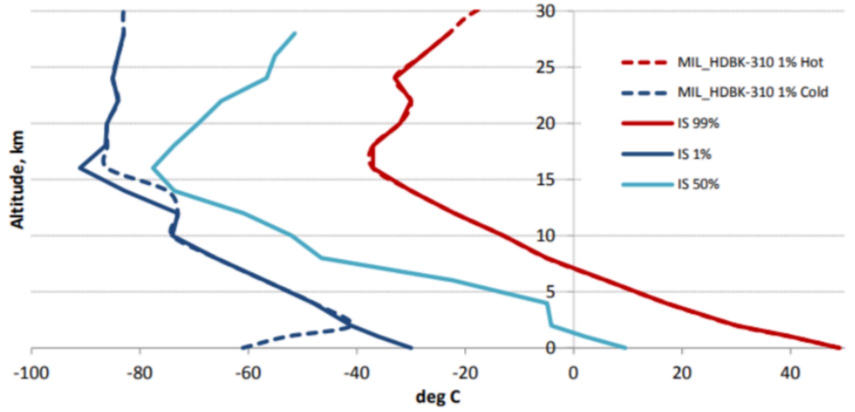
Top Level Requirements Impact on Storage

Attribute	Energy Storage Impact
Payload & Speed	Power (kW) required for climb and cruise
Endurance	Energy (kWh) required ~0.5-1 day with recharging from solar (battery or reversible FC)
Altitude	Low temperature (C) impact on battery recharging Low pressure (Pa) impact on battery swelling management Low oxygen impact on fuel cell fuel supply
Safety	TBD?
Life & Maintenance	Not for this project, but could affect future utility
Production Cost	Not for this project, but could affect future utility

Altitude		Air Temperature, deg C			Air Pressure
m	ft	IS 1%	IS 50%	IS 99%	mbar
0	0	-30	10	49	1013.25
1000	3281	[illegible]	[illegible]	[illegible]	
2000	656[illegible]				795.01
4000	1312[illegible]				616.60
6000	19685	-57	-22	6	472.18
8000	26247	-66	-47	-5	356.52
10000	32808	-74	-52	-13	265.00
12000	39370	-73	-61	-22	193.99
14000	45932	-83	-74	-30	141.70
16000	52493	-91	-78	-37	103.53
18000	59055	-86	-74	-37	75.65
20000	65617	-86	-69	-32	55.29
22000	72178	-84	-65	-30	40.47
24000	7[illegible]				29.72
26000	8[illegible]				21.88
28000	91864	-83	-51	-23	16.16

49C SL, hot day

-69C 65kft, ISA day



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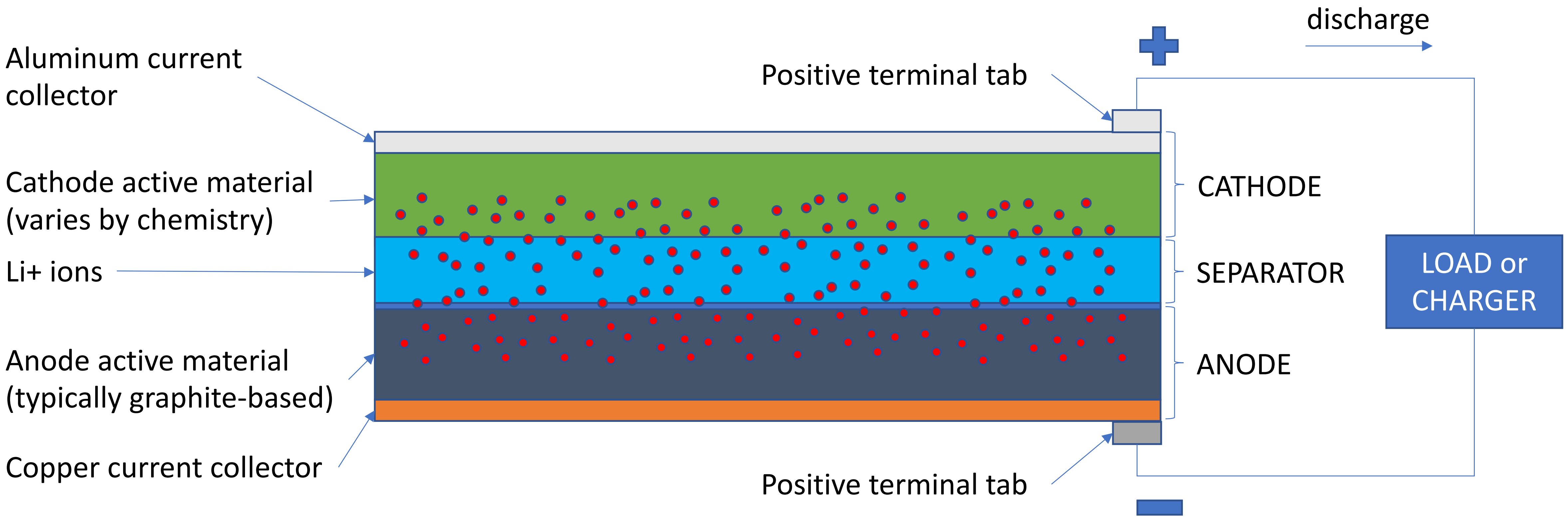
Energy Storage Options

Attribute	Fuel Cells	Batteries
Fuel Energy Density	Including hydrogen & oxygen or regenerative	~1:4 plus does not decrease
Powertrain Efficiency	~65%	~85%
In Air Long Duration	Less mature R&D, regenerative or open loop	Regen from solar array
On Ground ”Refueling”	Fast	slow
Net Energy Density	TBD	TBD
Maintenance & Life	long	Adv. chem. degrades fast

Regenerative Fuel Cell R&D Examples

- Technologies
  - Solid-oxide (less mature)
  - PEM (more mature)
- Companies
  - Proton Onsite
  - Versa Power
  - MSRI
  - Giner

Cell Anatomy



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Cell Specifications

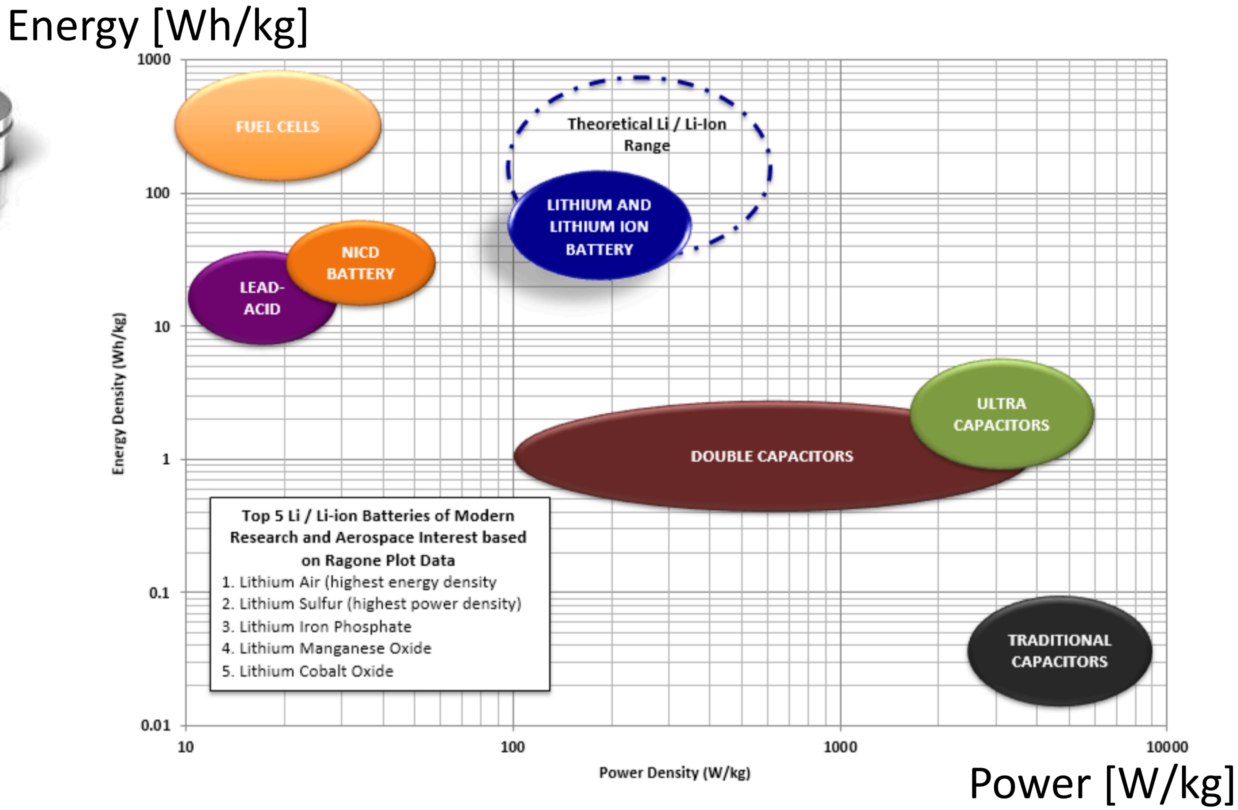
1. Cell Voltage (V) is driven by the two electrochemically dissimilar materials used for the electrodes
2. Cell energy (Ah or Wh=VxAh) is often driven by how thick the active material coatings are on the electrodes/current collectors
3. Cell power (W) is often driven by the surface area of the electrodes/current collectors
4. C-rating (C) is how fast the cell can be charged or discharged C = W/(Wh); note charging is usually much more constrained
5. Internal impedance measures the potential drop during discharge/charge and is often driven by thickness of current collectors and tabs
6. Operating temperature range
7. Physical weight and dimensions
8. Cycle life

Cell Basic Differences

- Primary Batteries: non-rechargeable
- Secondary Batteries: rechargeable
  - Chemistries
    - Lead-Acid Batteries
    - NiCAD
    - NiMH
    - Lithium – usually graphite anode, differentiated by cathode and electrolyte
      - Cathode – cobalt, iron, manganese, nickel
      - Electrolyte – liquid, gel/polymer, solid
    - Lithium sulfur and air – emerging tech
  - Properties – cost, energy, power, life, stability
  - Formats
    - Cylindrical
    - Prismatic
    - Pouch
    - Flow

Cell Packaging and Energy and Power Density Properties

LITHIUM-ION BATTERY FUNDAMENTALS: RAGONE PLOT



Ragone plot of energy storage device specific energy density vs. specific power density. Data adapted from the United States Defense Logistics Agency [36]

https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160010460.pdf

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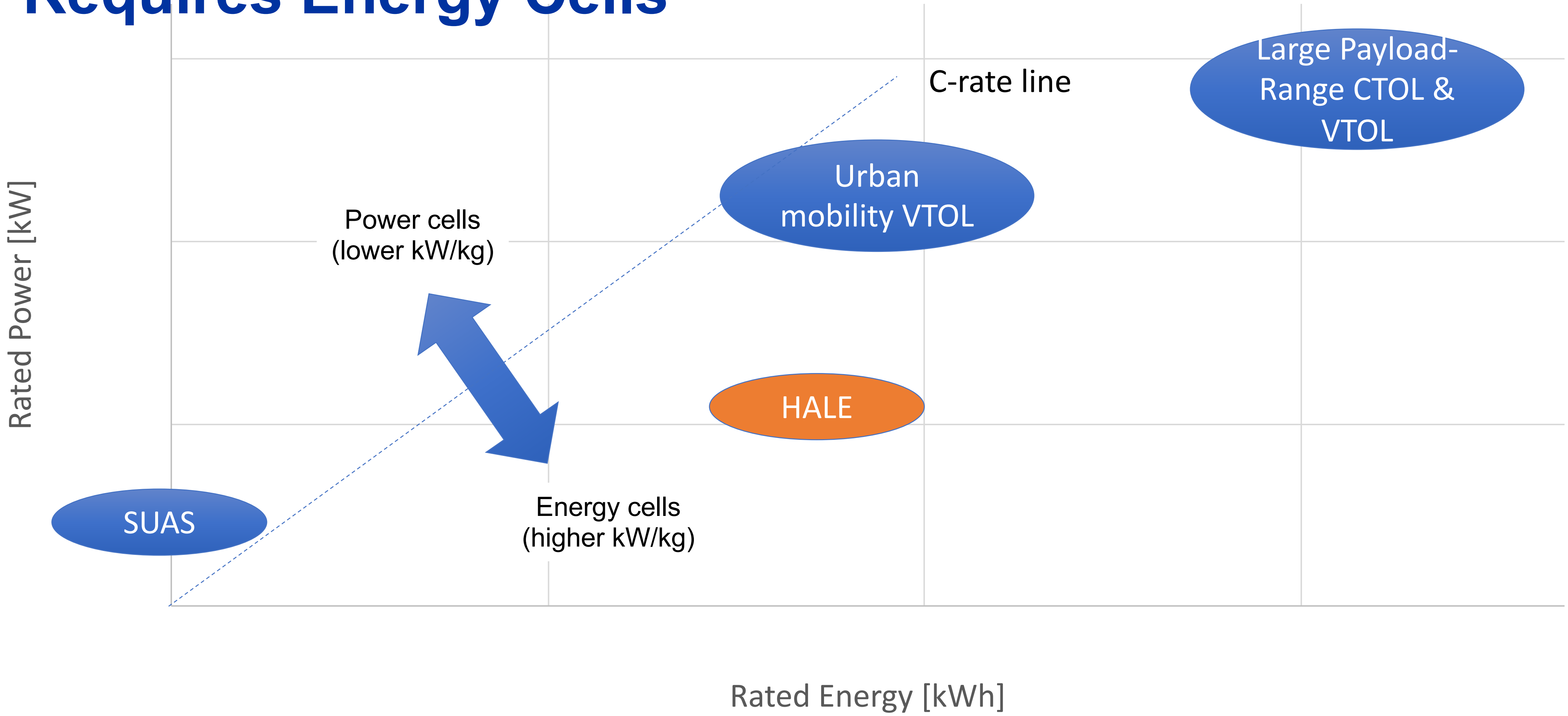
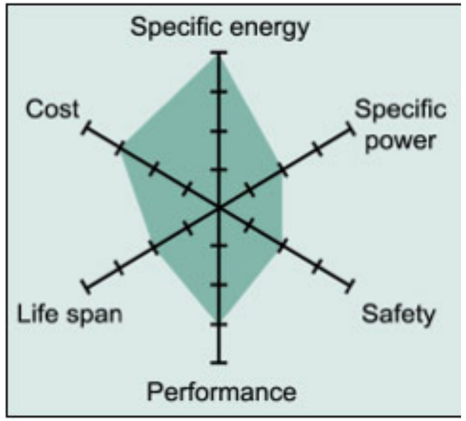
High Altitude Long Endurance (HALE) Generally Requires Energy Cells

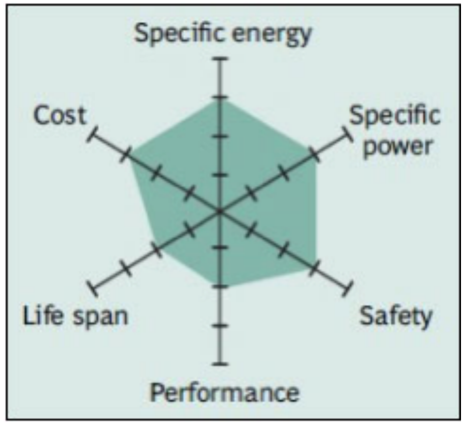


Comparison of Commercial Lithium Cell Chemistries

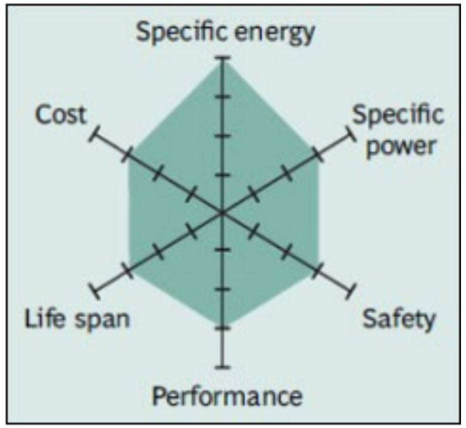
LCO (energy; electronics)



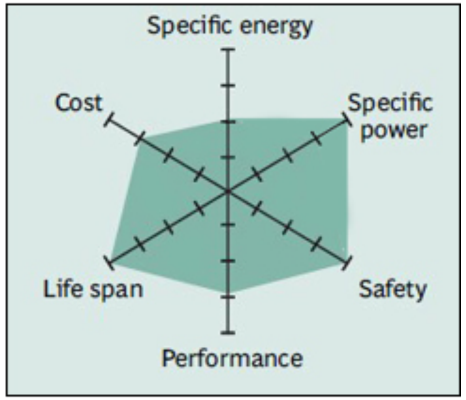
LMO (power, stability; power tools)



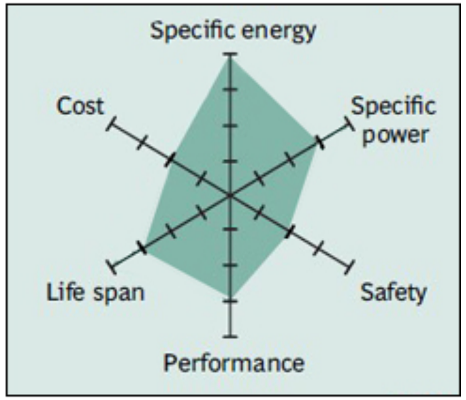
NMC (power, stability; hybrid vehicles)



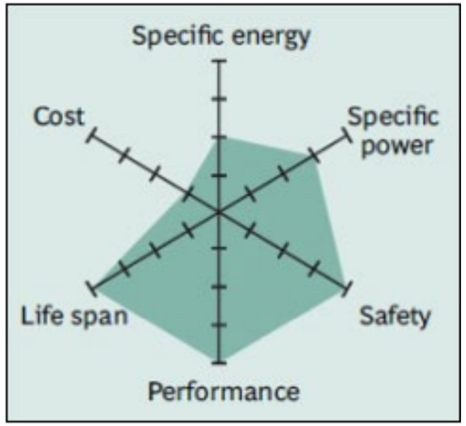
LFP (power, stability; grid)



NCA (energy; electric vehicles)



LTO (life; UPS)



https://batteryuniversity.com/

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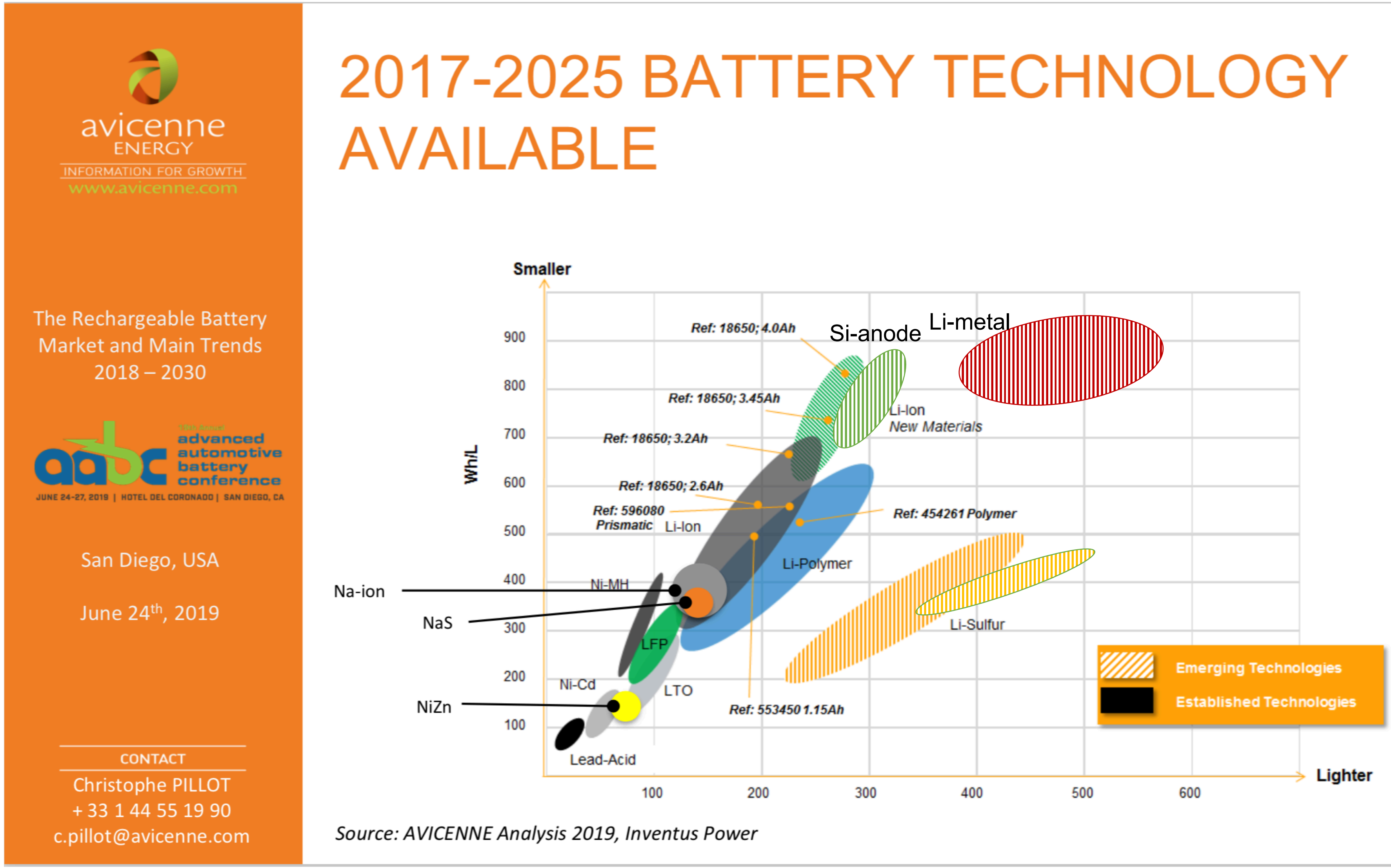
Comparison of Pre-Commercial Cell Chemistries



Examples
Amprius (Si-anode)
Cuberg (Li-metal)
Oxis (Li-S)

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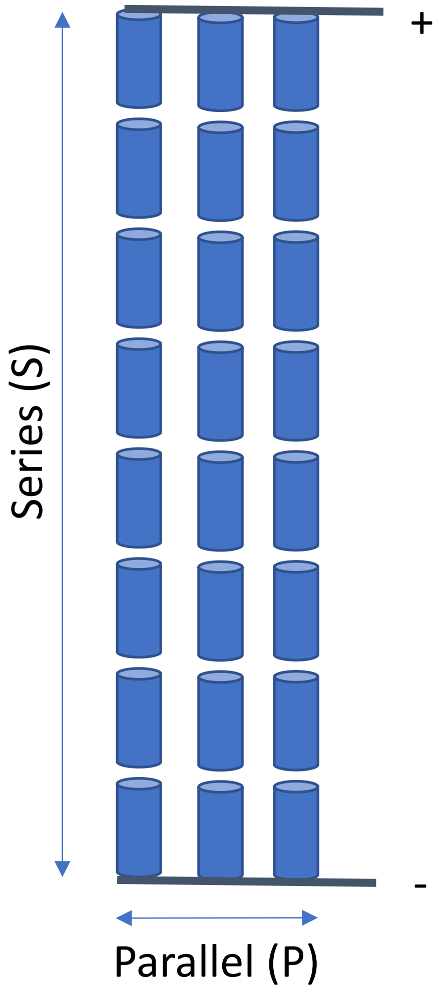
Cell “String” Specifications



Pack Design Example:
36S2P string of NCA 6Ah cells

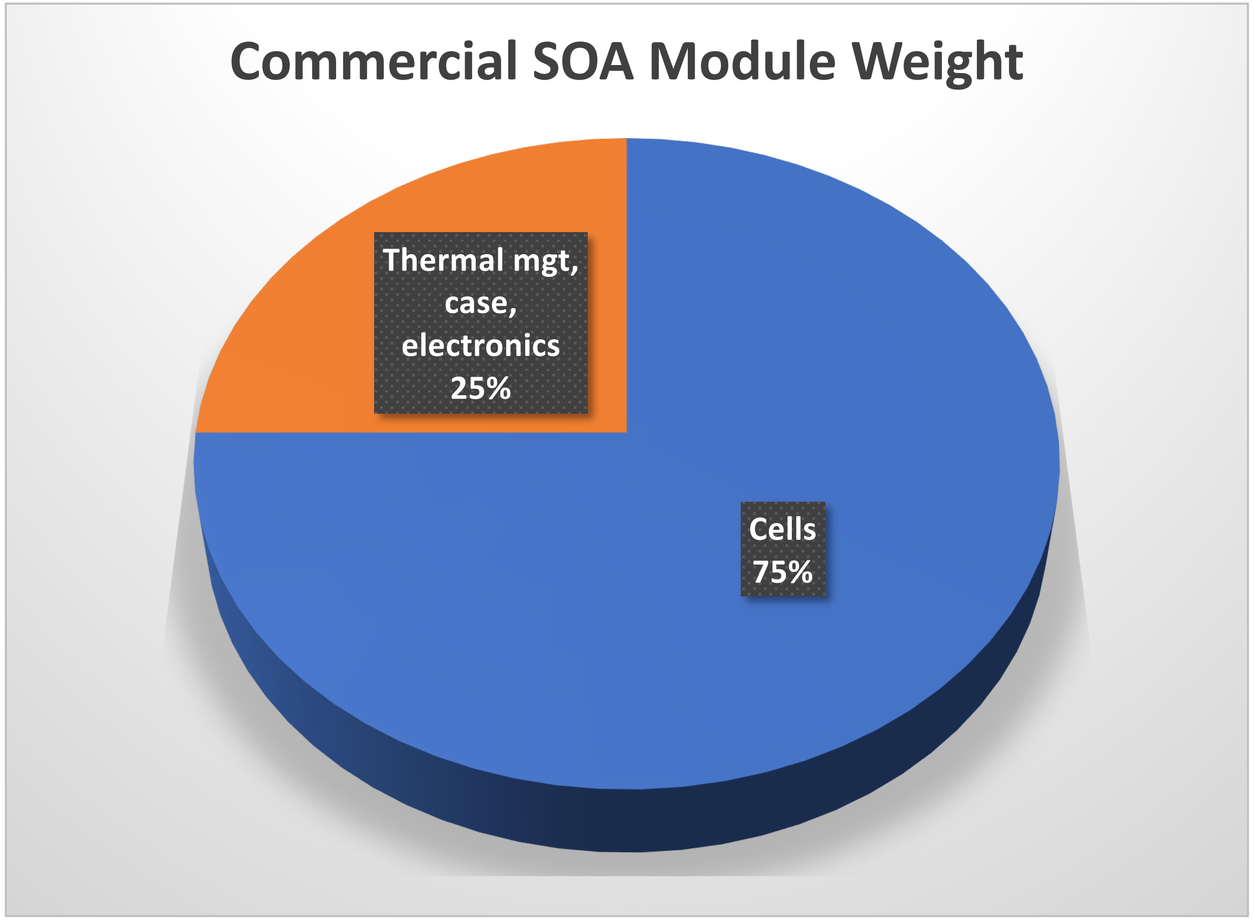
NCA chemistry generally has a rated voltage of 3.6V and a peak C rate of 30C

So the pack specs are:

V = 36 x 3.6 = 129.6V
E = 36 x 2 x 3.6 x 6 = 1,555 Wh
W = 30 x 1555 = 38,880 W

1. If you want higher voltage put more cells in series
2. If you want more energy put in more cells in total (SxP)
3. If you want higher peak power capability choose the right chemistry (tradeoff is usually energy density, cost, and life)

Module Design Considerations



(Module Wh/kg) = (packing factor) x (Cell Wh/kg)

- Cell Wh/kg
  - Advanced chemistries can take this up to 500+ Wh/kg
  - Need to manage potential increased operational and thermal runaway heat, negatively impacting packing factor
- Packing factor [%] = Cells/Module weight
  - Module SOA is ~75% for large packs
  - Is thermal runaway inhibited? negative p.f. impact
  - What is the thermal mgt technology? Negative p.f. impact

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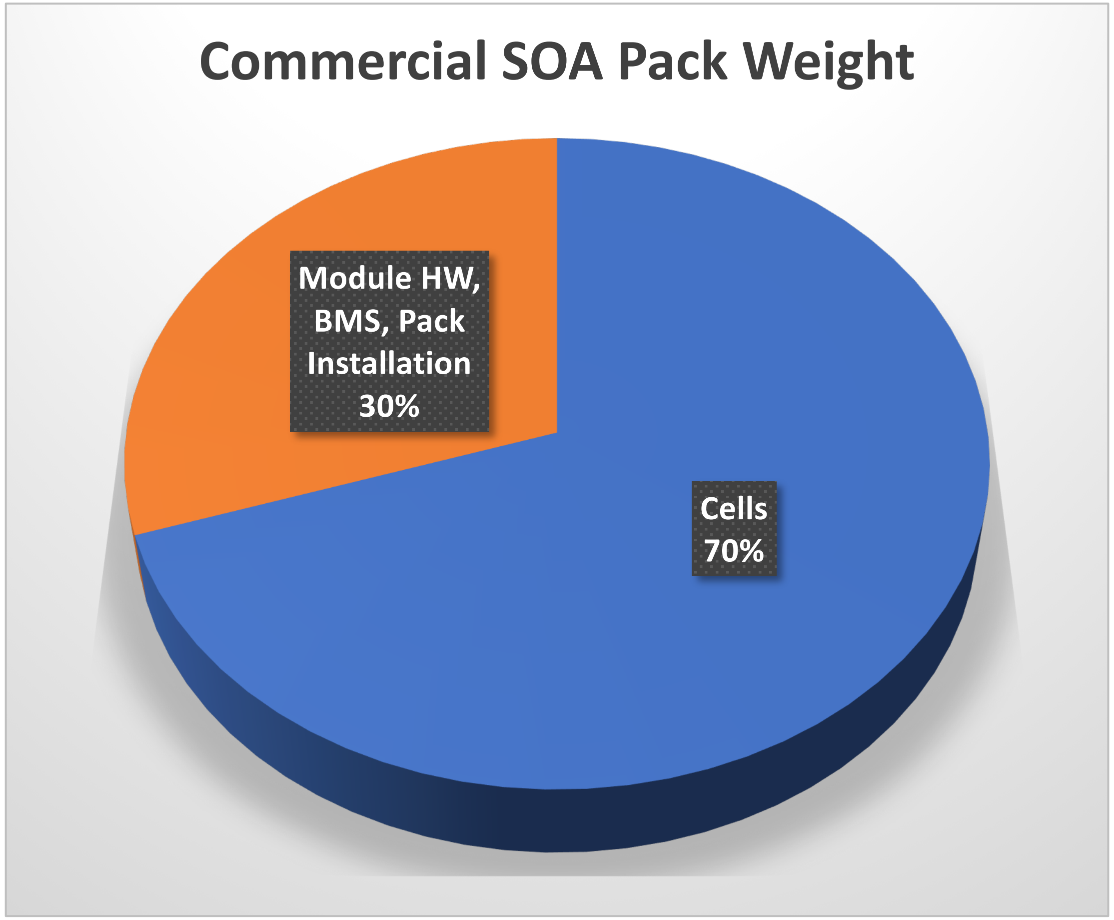
Thermal and Pressure Management at Altitude (cells don't like extremes)

- High temperature limits
  - Typically 60C operational limit
- Low temperature limits
  - Operational limit varies
    - 0C is a pretty typical min charging limit
    - Discharging can be lower
  - Charging/discharging cells will produce heat and warm the module
  - In charging specifically, premature degradation and increased thermal runaway risk
  - At 65kft, a heating mechanism will be needed
- Cells need to be in an assembly that maintains pressure
  - Cells produce gas and swell
  - Module design must allow some swelling
  - Module design must apply some pressure to prevent separation of materials (degradation and thermal runaway risk)

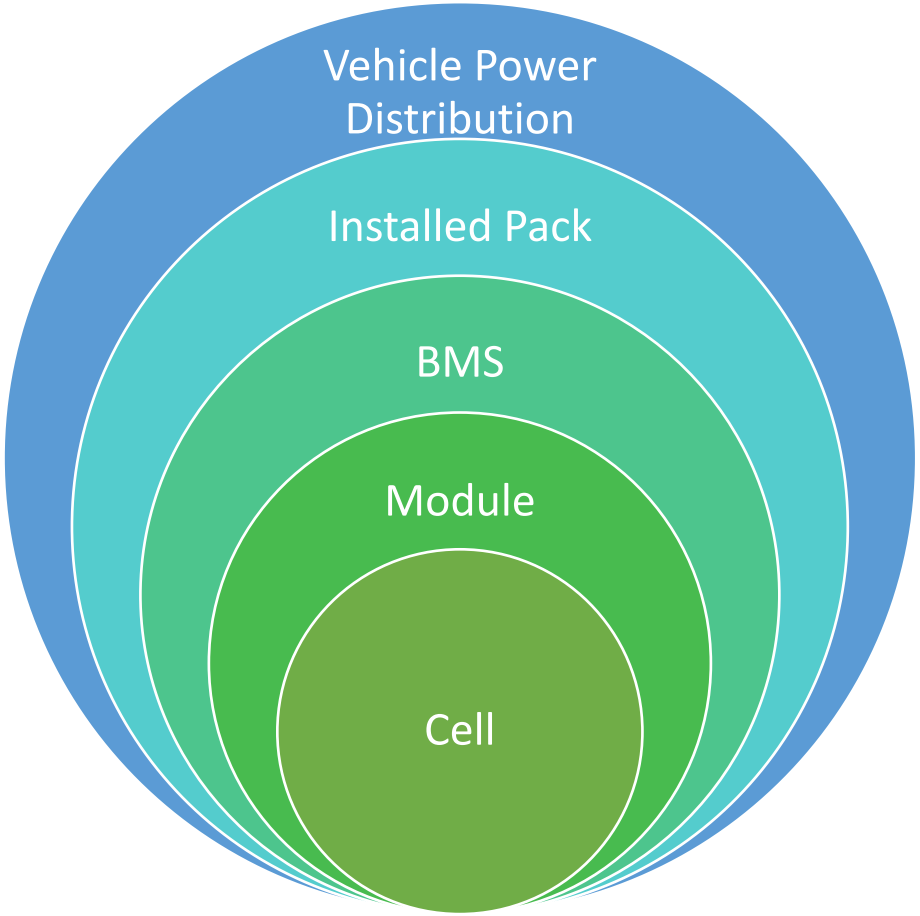
Pack Design Consideration



(Pack Wh/kg) = (pack packing factor) x (Cell Wh/kg)

- Easier to achieve higher packing factor in larger vehicles with more energy stored
- Often a tradeoff between accessibility and weight
    - Opportunities for structural integration
- For large multi-rotor aircraft, energy storage may be central or distributed
    - Again, a trade off of energy distribution flexibility, power distribution weight, and aircraft weight distribution
- Need to consider thermal sink/source
    - Heat transfer to/from cells

Safety Hierarchy Design



- Safety strategy flows down from aircraft level requirements
- Detectable Hazards
  - Pro-active mitigation strategies
  - Example: increased sensed temperature => reduce demanded load
- Undetectable Hazards
  - Some cell defects cannot reliably be sensed/predicted before failure
    - continuing R&D field
    - assume a single cell thermal runaway event can happen
  - Aircraft level requirements will dictate operational design and fault accommodation throughout the safety hierarchy

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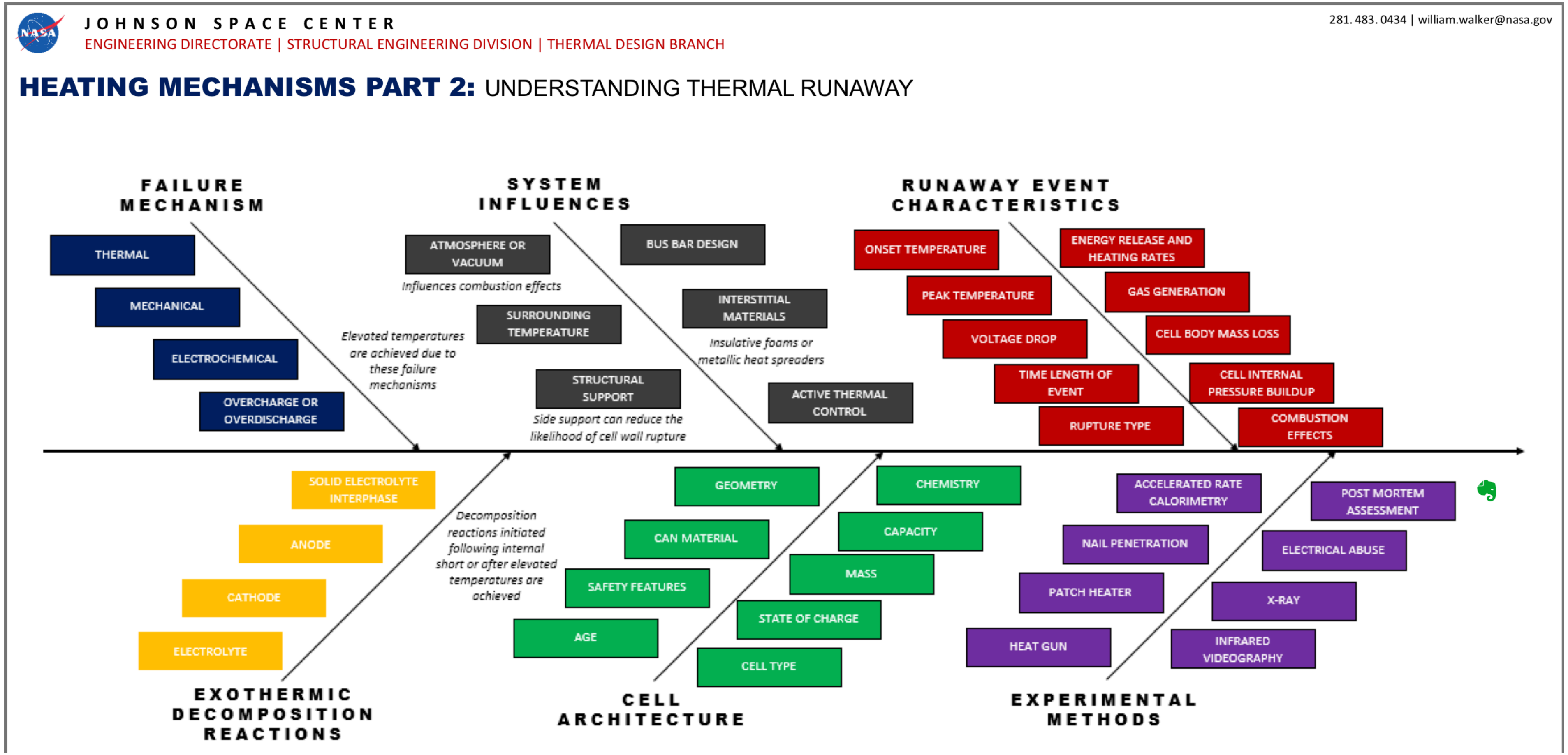
Thermal Runaway Considerations



https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160010460.pdf

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Thank you!
Questions?
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