BATTERIES FOR MORE ELECTRIC AIRCRAFT & EXTREME ENVIRONMENTS

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Roger Brewer, Lockheed Martin

LM Fellow
(817) 762-2482

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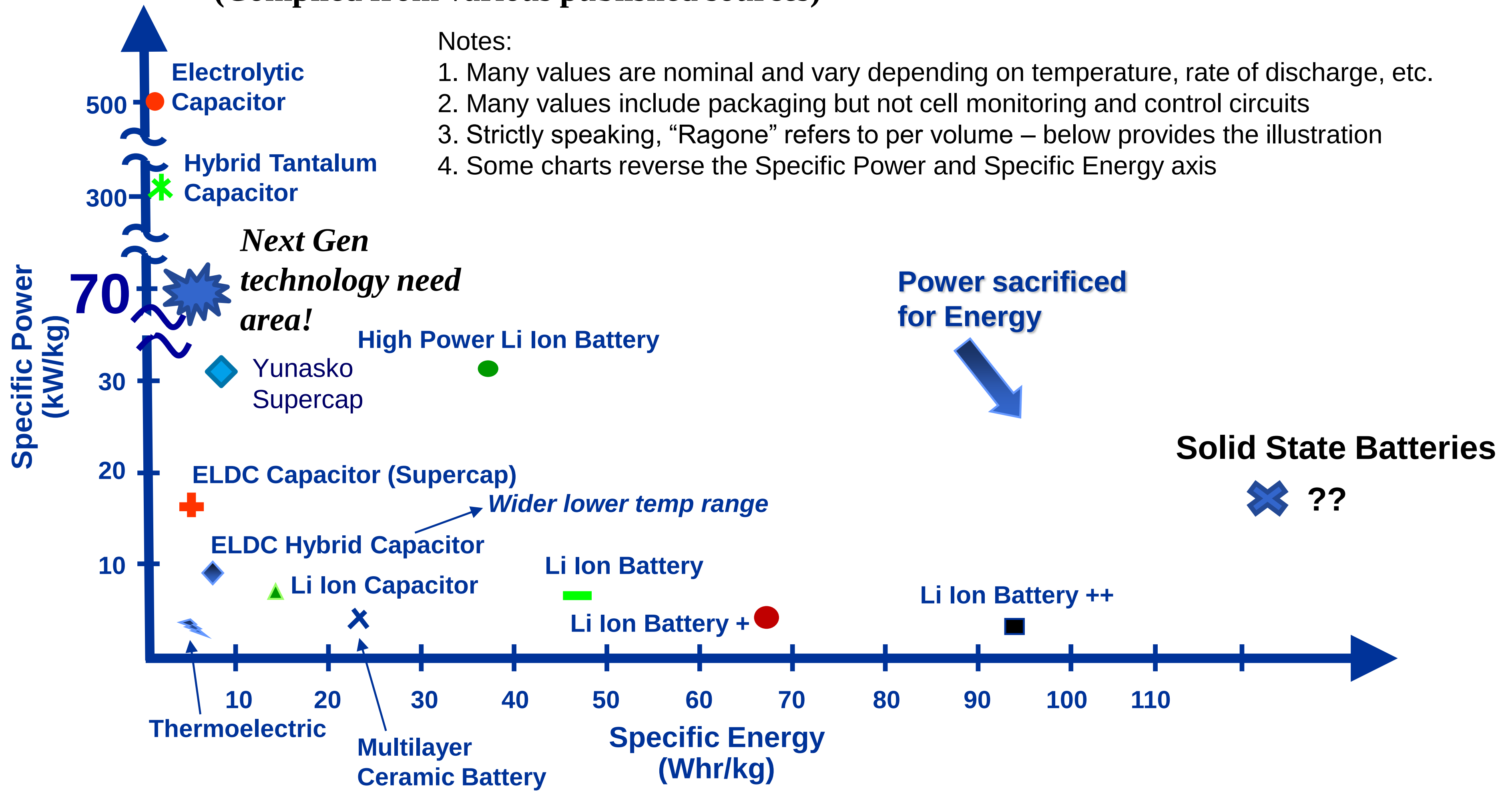
Aircraft Energy Storage “Wish List”

- **The Aircraft Operating Profile (typical of existing platforms) drives several needs**
  - Low temperature (-20->-40 deg.) in combination with high power
  - “Lithium Ion like” energy density with much faster recharge capable rate (i.e. 5-10x existing)
  - “Lithium Ion like” energy density with improved safety (less susceptibility to thermal runaway)
  - More energy density is always better (Whrs./kg), but not always at the sacrifice of power density (kW/kg)
  - Cells able to absorb regenerative energy (“backfeed”) from the bus (Capacitor like performance with battery like energy density)
- **The Role of Capacitors?**

Nominal "Ragone" Chart

(Compiled from various published sources)

Notes:
1. Many values are nominal and vary depending on temperature, rate of discharge, etc.
2. Many values include packaging but not cell monitoring and control circuits
3. Strictly speaking, "Ragone" refers to per volume – below provides the illustration
4. Some charts reverse the Specific Power and Specific Energy axis



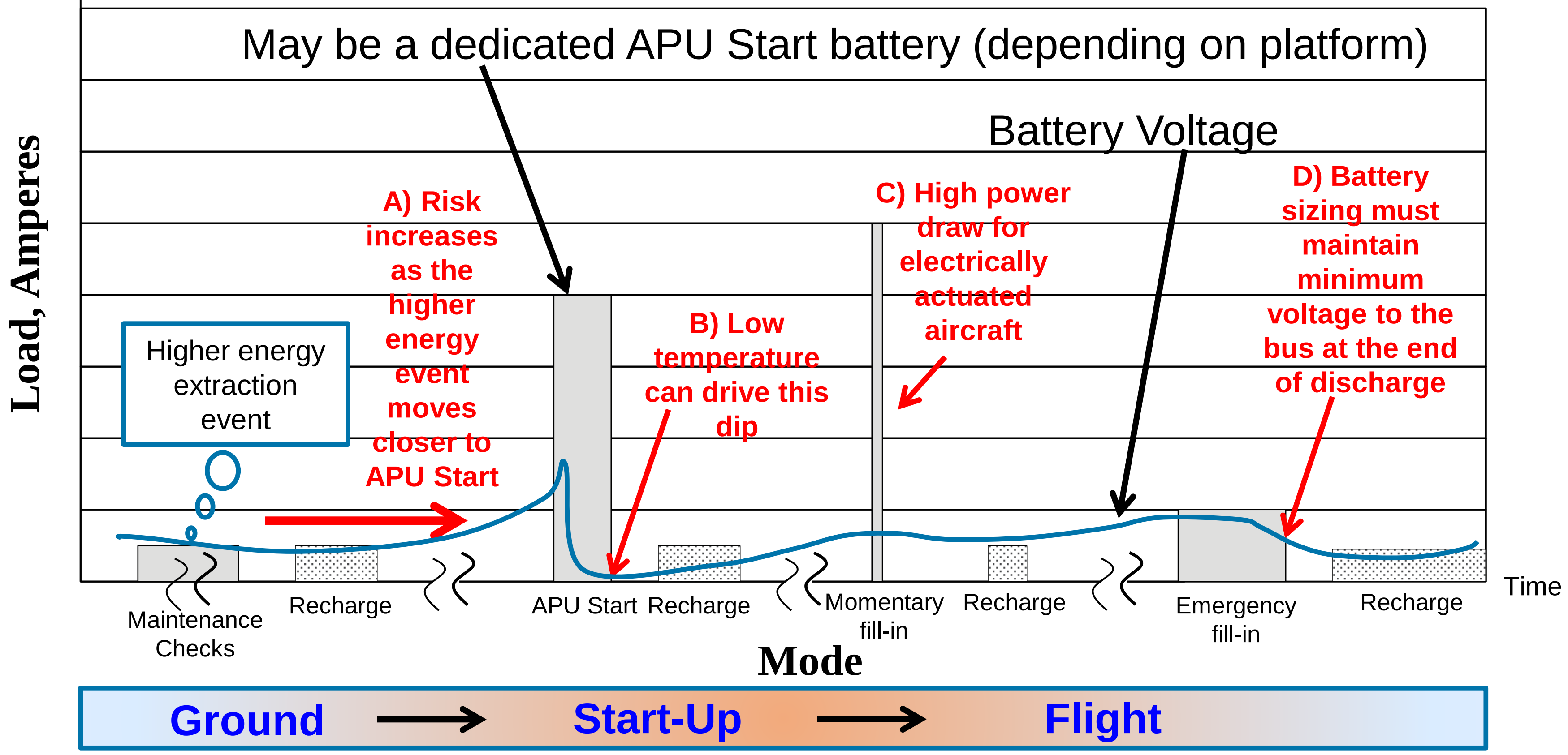
Impacts of BMS packaging & temperature exposure will shift points

Notional Battery Load Profile: Where are the operating point risks?

Not intended to represent any specific aircraft-values relative

Red = Risk Areas/Design Drivers

(And the risks vary with Battery Chemistry … see Next slide for thoughts)



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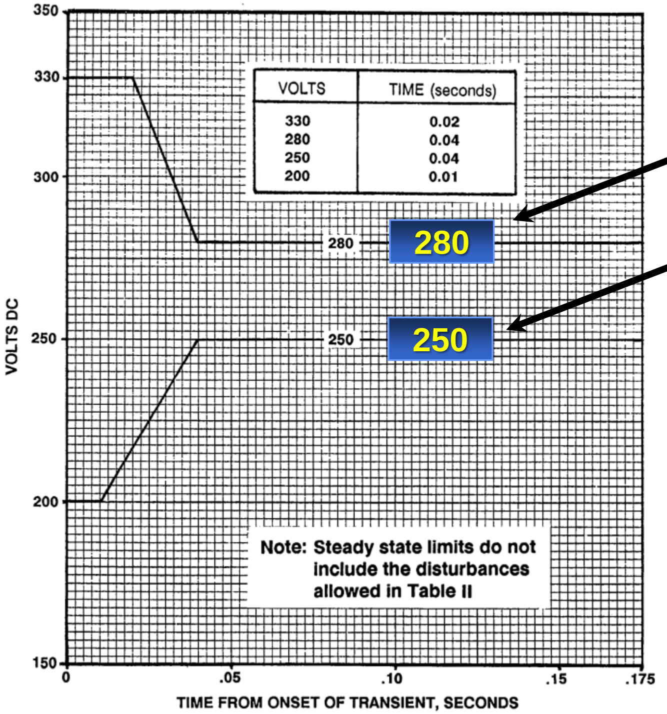
Battery Management Systems: Electronics Create Bottlenecks

- **The need to regulate the output voltage of batteries to the power system creates added Size, Weight & even potential needs for cooling**
  - More needs to power regulate drive more needs for high efficiency BMS Power Electronics Subsets
  - Capacitors, Inductors need to be smaller for a low SWaP BMS
  - Role of Silicon Carbide in BMS?



- A Battery float charged can only receive charge up to 280V
- A Battery discharge below 250V to a bus is unusable

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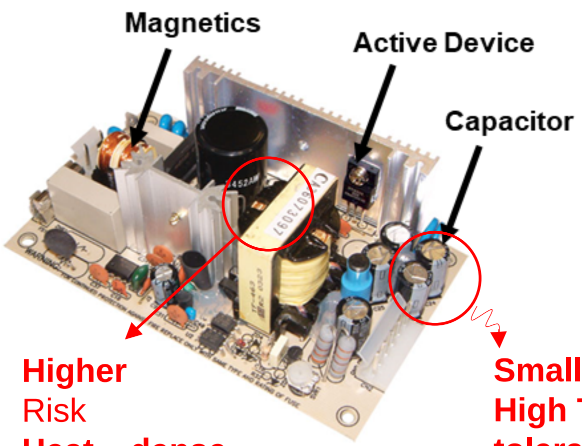
Passive Components and Package Layout: BMS Constraints

Capacitor Technologies	(Typical) Upper Operating Temp Limit (˚C)	Temperature Limiting Factors/Comments
Traditional Ceramic	125	Non uniform heating for large geometries, insulation resistance drops above the Currie point of the dielectric
Aluminum Electrolytic	125	Electrolyte, voltage derating implications vs. temp.
High Temp Tantalum	230	Traditional tantalums limited by electrolyte and packaging
Traditional Film (polyethylene, polyphenylene)	150	Limitations in the film material (as plastic transition temperature is approached insulation properties lost)
Ultracapacitor Module (Electric Double Layer)	65	Electrolyte boiling point (80 deg. C), life of technology both temp. and voltage dependent

Typical Power Supply



Higher Risk **Heat – dense** packaging

Smaller High Temperature tolerance

Other Components:

Diodes: 200 deg. C feasible (170 deg. C easy)
Magnetics: Capable up to 250 deg. C
Control circuitry (high density): "Sweating" at 70 deg. C and "dying" at 90 deg. C

Power Components in Aircraft: BMS Constraints

- **Beyond Wide Bandgap Semiconductors, there are influences that impact component performance:**
  - **Packaging**
    - Moisture intrusion in poorly sealed boxes
    - Environmental inducted (vibration, high thermal fatigue, high temperature)
  - **Proper selection of components for the application (& considering system dynamics)**
    - MOSFETs vs. IGBTs?
      - What conditions in the system drive temperature shifts in devices, SOA, etc.?

Battery Power Management Electronic Devices may be challenged in the future

Battery Packaging: Areas for Consideration

- **Rigid cylindrical cells packaged are a volume hindrance in certain applications (e.g. dead space)**
  - Are flexible (or formable) batteries an option for Aerospace?
    - Failure modes to be examined for flexible batteries
- **Pouch cells are trending due to certain performance advantages**
  - Ability to scale (add layers of electrode/active content)
  - Added power density
    - ➢ Are there failure modes the Aerospace industry needs to understand more fully? (e.g. installations in unpressurized bay and rapid ascent/descent exposure to package?)
- **Ensuring robust cell-lead design for vibe, shock**
  - Glass type sealing might be a weak area

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Conclusions

- **Next Generation Applications (MEA, etc.) will continue to need higher power density (& at cold temperatures to minimize required pre-heat time)**
  - "Ultracapacitor (Electric Double Layer Technology) like" energy density with 5-10x power density
  - Drive improved electrolyte innovation throughout industry
- **Integration of batteries to aircraft loads, packaging can make the best performing and high energy dense cells perform poorly**
  - High ripple content injected back into cells, etc.
    - More battery cooling required?
  - The need to voltage regulate lithium-ion solution outputs
    - Unusable energy if voltage drops below MIL-STD-704 range

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