Electric Aircraft Battery Technology

EAGLEPICHER
TECHNOLOGIES

Rechargeable, High-Energy and Rate Capable Cell

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Electric Flight Platform Opportunities

Aviation Platforms:

- Electric vertical take-off and landing (eVTOL)
  - Urban air mobility (UAM), regional air mobility (RAM), air taxi
- Future vertical lift (FVL)
  - Next-generation Department of Defense rotorcraft
- Hybrid propulsion
  - Mixed propulsion to improve efficiency
  - Electric motor supplements base fuel engine load

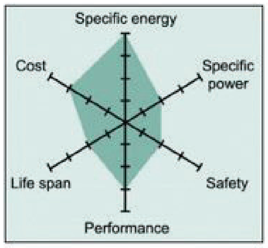
Application Requirements:

- High power for lift-off and descent
  - Must include the gross vehicle weight including the craft, passengers and cargo
- High energy for extended range
  - Optimal balance of power and energy: 4 to 8C discharge
- High-cycle life to decrease operating cost
- Safety certifications: UN38.3, FAA DO-311A

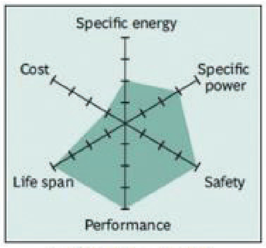
Required Battery-Level Capabilities:

- High-specific energy: > 300 Wh/kg
- High-discharge rate capability/specific power (kW/kg)
- Fast-recharge capability: ≥ 4C
- High-cycle life: > 1,000 at 80-100% depth-of-discharge (DoD)

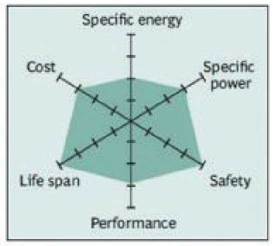
Lithium-Ion Electrochemistry Capabilities and Trades



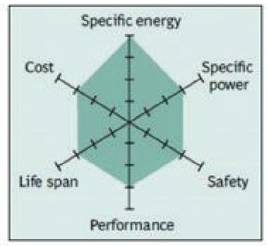
$LiCoO_2$ (LCO)



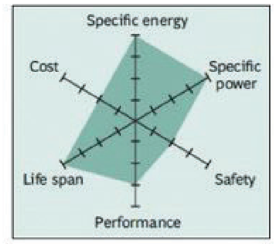
$Li_4Ti_5O_{12}$ (LTO)



$LiFePO_4$ (LFP)



$LiNiMnCoO_2$ (NMC)

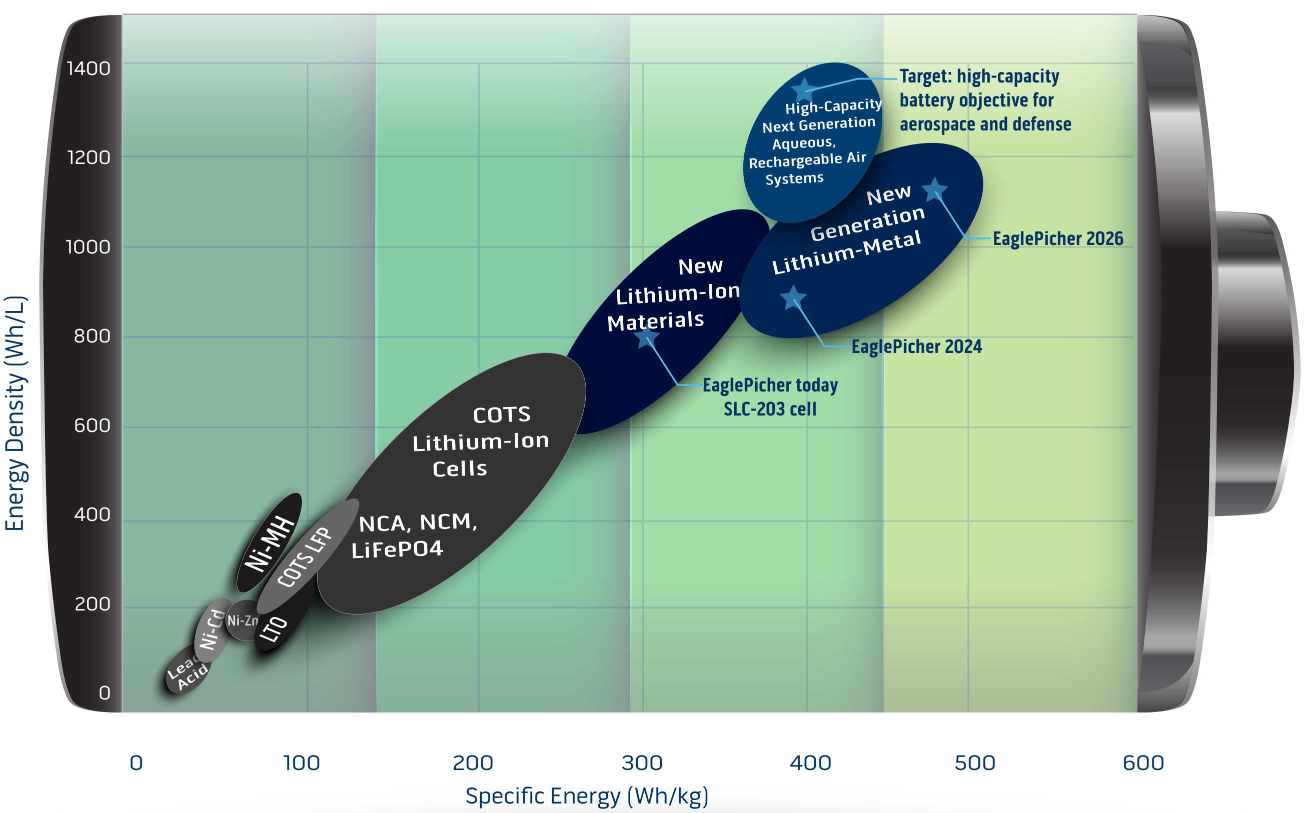


$LiNiCoAlO_2$ (NCA)

Charts courtesy of Cadex Electronics/Battery University: www.slideshare.net/AndrewGelston/types-of-lithiumion

- Flight requirements must extend cell capabilities beyond the present state-of-the-art cathode and anode materials, electrolytes and interfaces, e.g. solid-state
- Theoretical capabilities of any electrochemical couple are limited by practical means necessary to harness the energy potential
- ALL cells have varying degrees of required volume and mass overhead
  - Can, cover, pouch, current collectors, tabs, electrolyte, separator
- Optimization of these supporting elements to increase active material content will further improve the cell's energy and power densities...***potential impacts to safety?***

Cell Technology Landscape



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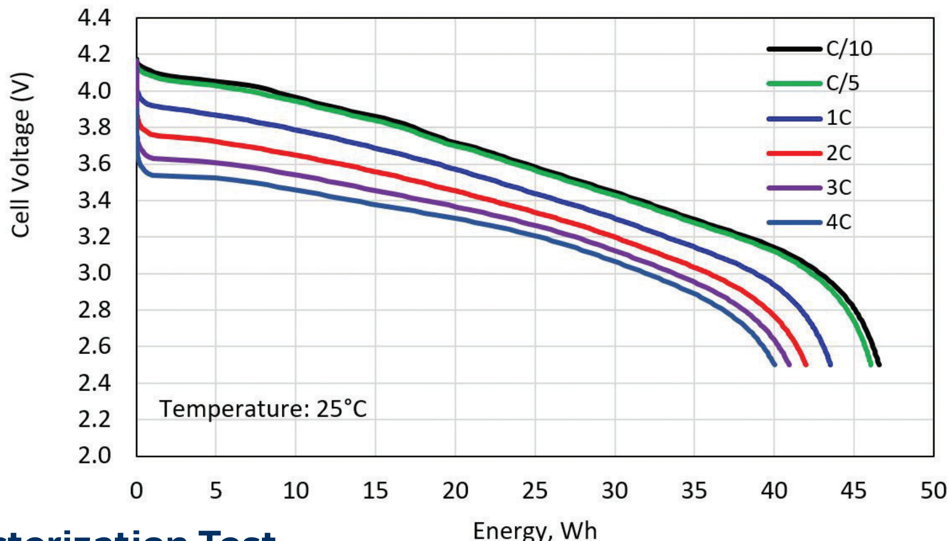
Aviation Cell Performance

Balance of Energy and Power

EaglePicher's SLC-203 Key Characteristics:

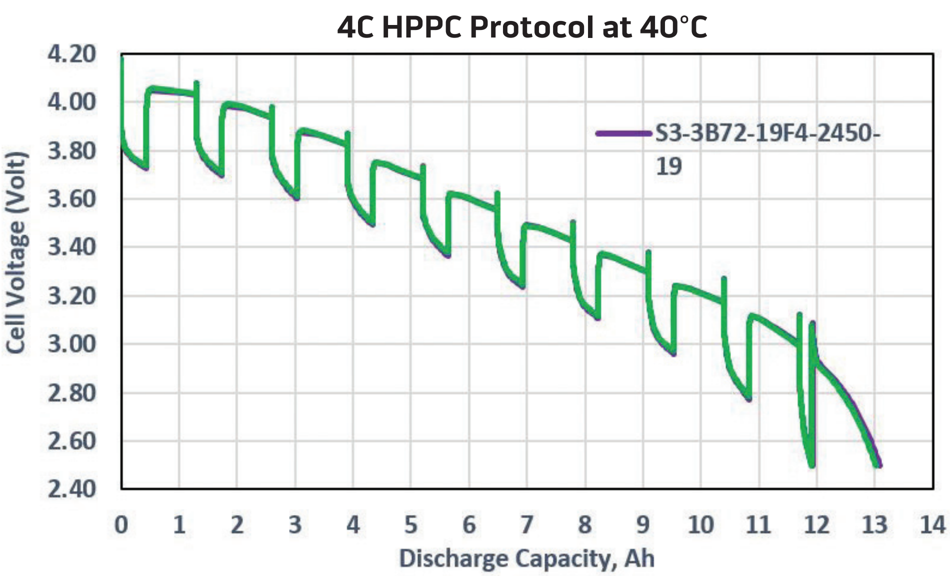
- Next-generation silicon-carbon anode material
- High-specific energy: 13 Ah cell with >300 Wh/kg
- Good rate capability: 4C continuous and 8C+ pulse rate capability
- >500 1C/1C cycles at 80% retention
- Wide operational temperature: -30 to 50°C (-22 to 122°F)



Hybrid Pulse Power Characterization Test

The main purpose of the hybrid pulse power characterization (HPPC) test is to characterize the dynamic power capability of a battery used in electric vehicle market

- Test of discharging and feedback (charging) pulses within the range of current and voltage available to the battery
- Particularly important for aircraft to quantify power reserves at lower state-of-charge operational conditions



4C HPPC Test Protocol

- Test temperature : 40°C (104°F)
- Pulse: 4C for 30sec based on nominal capacity
- 4C pulse carried out every 10% state-of-charge (100% to 10%)
- C/3 discharge to reach specific SOC
- 1-hour rest time prior to pulse test
- 1 cycle at C/3 (charge and discharge)

EaglePicher's SLC-203 delivered full 4C pulse capability down to <20% SOC

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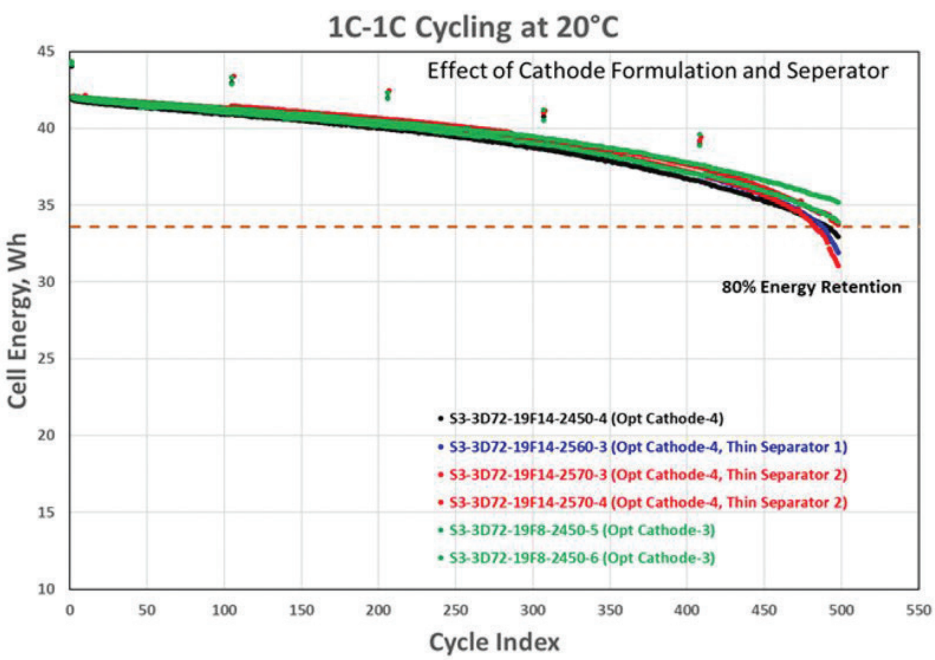
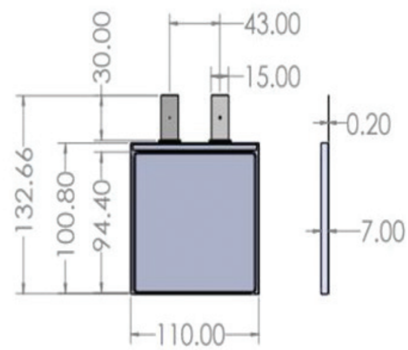
Silicon-Based Cell Capabilities

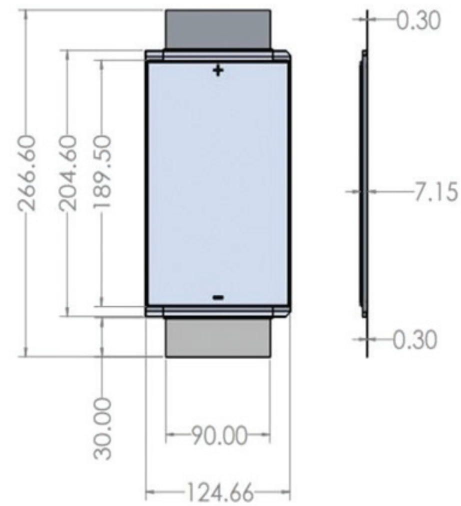
High-Energy, Rate-Capable, Lithium-ion Cell Family

- Three cell form-factors (sizes)
- Same electrochemistry
  - Cathode: nickel-rich, NMC 811
  - Anode: pre-lithiated silicon-oxide
  - Separator: ceramic tri-layer
  - Electrolyte: proprietary high-temperature



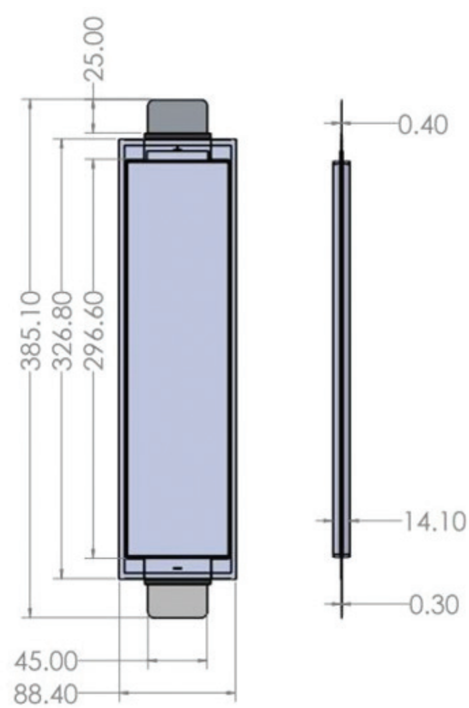


SLC-203: ***13 Ah***



SLC-205: ***31 Ah***

Part No.	SLC-203	SLC-205	SLC-206
C/3 Capacity (Ah)	13	31	68
Specific Energy (Wh/kg)	296	306	310
Energy Density (Wh/L)	702	696	752
Weight (g)	155	417	776
Dimensions (mm)	95 x 102 x 7	204 x 125 x 2	295 x 77 x 14
Continuous Discharge Rate	4C	6C	4C
Peak/Pulse Discharge Rate	8C	12C	8C
Cycle Life (1C/1C, 100% DoD)	500	500	500



SLC-206: ***68 Ah***

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Lithium-Ion Electrochemistry Capabilities

- Simply packaging and managing a cell requires "overhead" (added weight and volume)
  - Structural constraints for intended operational performance
  - Electrical interconnections – intercell tabbing, wiring, connectors

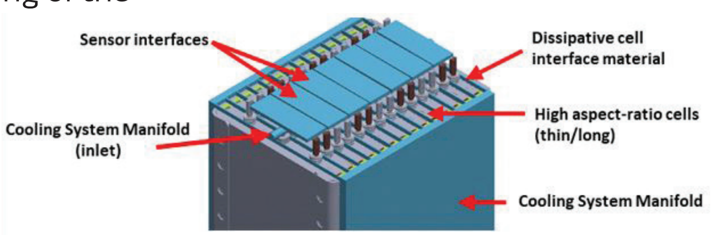
These elements can add 10-30% overhead that de-rate the base cell capabilities

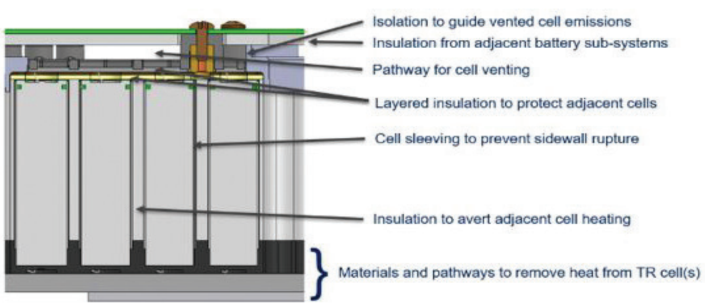
- Need to consider the other needs of a full-up battery assembly
  - Battery management system (BMS): protections, monitoring, control, redundancy, power conversion, relays, communications, other electronic subsystems
  - Thermal management: cell heaters, exothermic dissipation
  - Failure mitigations: propagation avoidance and containment

Total impact of all add-ons can degrade the base cell capabilities by 25-65%

The Battery as a System

- Reliability and safety require a clear understanding of the selected electrochemistry
  - Characterize per relevant context, defined within application CONOPS
    - RTCA DO-311A, NASA JSC-20793, NAVSEA S9310-AQ-SAF-010/ SG270-BV-SAF-010, MIL-STD-32383, UN 38.3, etc.
- Battery design considerations should include
  - Competent BMS to oversee proper "care and feeding" of cells
  - Cell thermal management for both safety and extended operating cycle-life
  - Effluent channeling for failed cell emissions handling to avoid ignition and propagation
- These subsystems detract from the cell capabilities with added weight and volume





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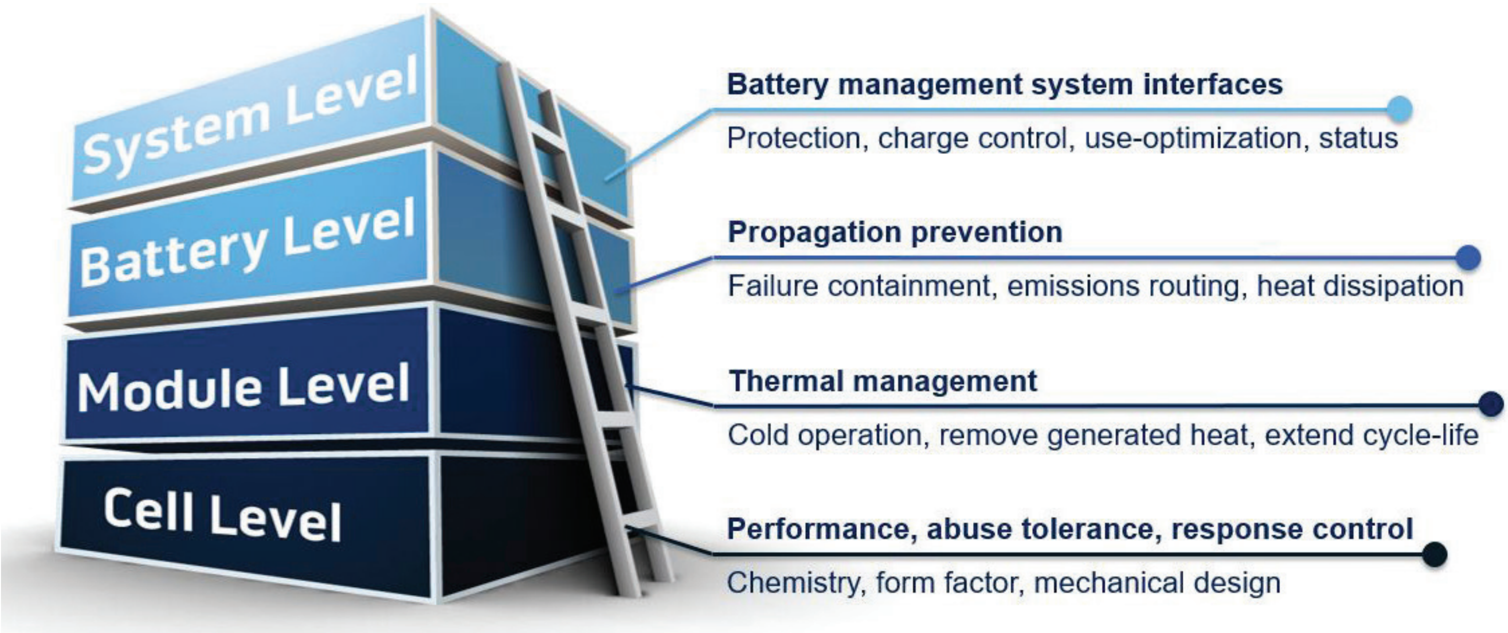
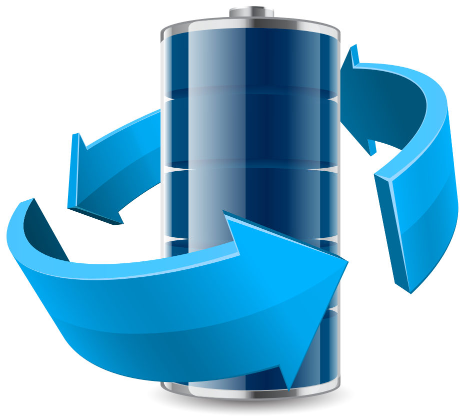
Consequences of Poor Battery Design Integration

- Overly-constrained designs, insufficient baseline characterizations, and inadequate mitigations can lead to a catastrophic outcome during design qualification
  - Initial test outcome to NAVSEA S9310-AQ-SAF-010, Section 11-3.8 (comparable to RTCA DO-311A Section 2.2.2.3 / 2.4.5.4)
  - Results of commercial (COTS) 18650 cells, compliant to UL1642, and UN Manual of Tests and Criteria Part 3, subsection 38.3

Holistic Approach to Performance and Safety



The Value of a Safe Battery Design



- Compliant battery solutions require a layered set of complementary mitigations:
  - Thermal management
  - Emissions control
- Evaluations must consider not only cell-to-cell, but module-to-module propagation
  - Test methods and approach may generate different results from one-another depending upon the method of excitation and the specific cell under test
  - Start small … cell ▶ virtual-cell module ▶ battery ▶ energy storage system
  - Model effects from generated data – predict outcome before engaging resources
- Focus upon the battery material selections, their individual contributions, and the design integration to optimize the realized net energy and power

EaglePicher Overview