X-57 Maxwell Battery
From cell level to system level design and testing

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Primary Objective
Goal: 5x Lower Energy Use (Compared to Original P2006T @ 175 mph)
  • IC Engine vs Electric Propulsion Efficiency changes from 28% to 92% (~3.3x)
  • Synergistic Integration (~1.5x)

Derivative Objectives
• ~30% Lower Total Operating Cost
• Zero In-flight Carbon Emissions

Secondary Objectives
• 15 dB Lower community noise
• Flight control redundancy and robustness
• Improved ride quality
• Certification basis for DEP technologies
• Advance the Technology Readiness Level for aircraft electric propulsion. Aerospace has weight, safety, and flight environment challenges which complicate adaption of COTS technologies
  • Need high voltage lithium batteries with intrinsic propagation prevention and passive thermal management
  • Establish motor/inverter ground and flight test program
  • Design crew interface and human factors approach to manage workload for complex propulsion systems
• Pathfinder for aircraft electric traction system standards. Lessons learned used to inform FARs and standards
• Reduces risk for Mod III and IV on a proven vehicle configuration
• Develop capability within NASA to design, analyze, test, and fly electric aircraft
Project Approach

Spiral development process
• Build – Fly – Learn

**Mod 1**
Ground validation of DEP high lift system

**Mod 2**
Flight testing of baseline Tecnam P2006T
Ground and flight test validation of electric motors, battery, and instrumentation.

**Mod 3**
DEP wing development and fabrication
Flight test electric motors relocated to wingtips on DEP wing including nacelles (but no DEP motors, controllers, or folding props).

**Mod 4**
Flight test with integrated DEP motors and folding props (cruise motors remain in wing-tips).

**Goals:**
• Establish Baseline Tecnam Performance
• Pilot Familiarity

**Goals:**
• Establish Electric Power System Flight Safety
• Establish Electric Tecnam Retrofit Baseline

**Achieves Primary Objective** of High Speed Cruise Efficiency

**Achieves Secondary Objectives**
• DEP Acoustics Testing
• Low Speed Control Robustness
• Certification Basis of DEP Technologies
X-57 Battery Top Level Requirements

- Provide electrical power to the Traction Battery Bus, with a nominal voltage range within 320 and 538 VDC.

- Provide source current capable of delivering 60kW of continuous power per battery sub-system (120kW total), 74kW for a minimum of 3 minutes per sub-system, and 132kW for a minimum of 45 seconds per sub-system.

- Monitor the state of health and safety conditions for each parallel group of cells including cell temperatures, voltages and current, during charging and discharging.

- Contain a thermal runaway event without propagating to other cells.

- Contain any battery fire to the enclosed battery module case and prevent any damage to adjacent materials or components.
X-57 Flight Batteries (Original Approach)

• Major Lessons Learned for Aviation Battery Development.
• Use of lighter more energetic cells can pose greater safety risks.
• Cooling of cells while minimizing cell-to-cell propagation risks.
• Containment of gases and particulates drive closed designs and increased weight.
• Lighter weight Thermal Management & Containment is possible.
• eVTOL target of 30% Packaging overhead is achievable and to be demonstrated on X57.
X-57 Flight Battery Destructive Testing
NASA Technical Direction

- Battery re-design to address the failures on the first design
  - Include a design that addresses side wall rupture
  - Include an Interstitial Material
  - Conduct cell screening, matching and characterization
  - Conduct stress/structural analysis on the battery module enclosure
  - Re-test for thermal runaway propagation
  - Re-size the vent line for adequate flow to not pressurize the battery enclosure
- Recommendations from GRC and JSC have been made to the X-57 project to assist with the re-design effort
- The vendor is currently working to re-design and re-test the battery to comply with DO-311, DO-160, and JSC-20793 requirements
Design #2 Details and Nomenclature

- Li-ion Cells
  - Samsung INR18650-30Q
    - Cell Chemistry: NCA
    - Capacity = 3.0 Ah
    - Nominal Voltage = 3.60 V
    - Rated = 10 A discharge
  - Battery Operating Voltage = 320-538 V
  - Nominal Voltage = 461 V
  - Energy = 47.0 kWh
  - Battery Overall Mass Allocation = 386 kg (850 lbs)
  - Single Battery Module Mass = 22.7 kg (50 lbs)

<table>
<thead>
<tr>
<th>Battery System</th>
</tr>
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<tbody>
<tr>
<td>2 Parallel Batteries</td>
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<tr>
<td>(2) 20P128S</td>
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<tr>
<td>5120 cells</td>
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<table>
<thead>
<tr>
<th>Single Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 Modules</td>
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<tr>
<td>20P16S</td>
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<tr>
<td>320 cells</td>
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<tr>
<td>Sub-Module</td>
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<tr>
<td>20P8S</td>
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<tr>
<td>160 cells</td>
</tr>
<tr>
<td>20-Cell Brick</td>
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<tr>
<td>20P1S</td>
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<tr>
<td>20 cells</td>
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X-57 Battery Layout
X-57 Flight Batteries (New Approach)

- 461 V, 47 kWh effective capacity
- 860 lbs. (16 Modules, 51 lbs. each)
- Two packs supports redundant X-57 traction system.
- Initial battery destructive testing conducted Dec 2016.
- Battery modules redesigned based on new NASA design guidelines and retested Nov 2017.
Thermal Runaway Testing Overview

- The cells are Samsung model INR18650-30Q types, 3Ah capacity cells.
- Each cell has a maximum voltage of 4.2V, a nominal voltage of 3.6V making the battery module a 67.2V maximum, 57.6V nominal, 60Ah capacity battery.
- Cells were wrapped with MICA sheet material, with a disc of gap pad material at the base of the cell. This isolates each cell from the aluminum honeycomb structure.
X-57 Flight Profile Load

- Discharge via the baseline flight profile including zero power operations

<table>
<thead>
<tr>
<th>Operation</th>
<th>Time (sec)</th>
<th>Cell Power Watts</th>
<th>Cell Watt-sec</th>
<th>Battery Power Watts</th>
<th>Battery Energy Wh</th>
<th>Battery Energy Wh (cum)</th>
<th>Battery % SoC Used</th>
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<tr>
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<td>2.15</td>
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<td>688</td>
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<td>0</td>
<td>0</td>
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<td>2576</td>
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<td>412</td>
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<td>6182</td>
<td>515</td>
<td>2164</td>
<td>65</td>
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<td>0</td>
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<td>80</td>
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<tr>
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<td>86</td>
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<td>6182</td>
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<tr>
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<td>0</td>
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<td>3057</td>
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<td>1290</td>
<td>688</td>
<td>115</td>
<td>3172</td>
<td>95</td>
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</table>

Currently predicts 46.2 kWhr required for the aircraft
Peak Power of ~145 kW
Capacity test of 30Q cells under X-57 mission profile

Under X-57 power profile, the 30Q cells end-of discharge temperature reach higher than 60deg C
Thermal Normal Discharge

Starting Maximum Temperature: 17° C
Maximum Temperature During Discharge: 60° C
Discharge: 43° C
Temperature Rise: 60.3 Ah
Total Capacity Discharged: 2.93 kWhr
Total Energy Discharged: kWhr
Minimum Voltage (V): 38.9 V
Maximum Current (tester limited): 160 A

The delta between cells within the battery module is of <10deg C.
Thermal Propagation Test Sub-Module

- One 160 block of cells was comprised of 4 M36 ISC trigger cells in the four corners, and 156 standard 30Q cells
- The M36 cells were wired independently of each other and electrically isolated from the rest of the battery sub-module
- High rate cycling of the ISC trigger cells using a DC power supply and a DC load bank was performed to drive each trigger cell individually into thermal runaway
- The testing sequence was TC #1, #4, #2, then #3.

Reference: Internal Short Circuit Device is a NASA and NREL Invention recently licensed to Wind Power Engineering
Single Cell Short Circuit/Thermal Runaway Without Propagation

X-57 Thermal Propagation Test Module
(316 flight-like cells, 4 “Trigger Cells” with internal shorting devices)

http://go.nasa.gov/2iZ51Yi
Single Cell Short Circuit/Thermal Runaway Without Propagation

X-57 Thermal Propagation Test Module (316 flight-like cells, 4 “Trigger Cells” with internal shorting devices)

http://go.nasa.gov/2iZ51Yi
Thermal Runaway with Trigger Cells

Maximum Temperature at Key Points

<table>
<thead>
<tr>
<th></th>
<th>Trigger Cell #1</th>
<th>Trigger Cell #2</th>
<th>Trigger Cell #3</th>
<th>Trigger Cell #4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger Cell</td>
<td>197°C</td>
<td>87°C</td>
<td>320°C</td>
<td>262°C</td>
</tr>
<tr>
<td>Nearest Neighbor</td>
<td>100°C</td>
<td>52°C</td>
<td>112°C</td>
<td>113°C</td>
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<tr>
<td>Nearest Neighbor</td>
<td>93°C</td>
<td>51°C</td>
<td>111°C</td>
<td>111°C</td>
</tr>
<tr>
<td>Near Vent Port on Module</td>
<td>198°C</td>
<td>19°C</td>
<td>20°C</td>
<td>22°C</td>
</tr>
<tr>
<td>End Vent Port in Exhaust Fan</td>
<td>19°C</td>
<td>13°C</td>
<td>13°C</td>
<td>28°C</td>
</tr>
</tbody>
</table>

- Trigger Cell #2 failed to achieve a normal thermal runaway event
- Opposing Cell and Opposing Neighbors exhibited no discernable related increase in temperature
Conclusions

- The revised X-57 Battery Module design successfully passed the Thermal Normal test under the mission profile regime and exhibited a maximum cell temperature of 60°C with a maximum cell-to-cell temperature gradient of 7°C across 320 Samsung INR18650-30Q cells.

- Thermal Runaway testing was victorious with 3 out of 4 trigger cells functioned properly and no cell-to-cell thermal runaway events were observed. Maximum measured cell temperatures of adjacent cells were in the 93°C to 113°C range.

- The battery subsystem is on schedule for the X-57 Mod II demonstration flights commencing in the summer 2018 at the NASA Armstrong Flight Research Center.
Credits

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