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

What is X-57 Trying to Do?
Motivation for Mod II; Retiring Electric Propulsion Barriers

• Advance the Technology Readiness Level for aircraft electric propulsion. Aerospace has weight, safety, and flight environment challenges which complicate adaptation 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

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

Spiral development process
- Build – Fly – Learn
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>
<th>2 Parallel Batteries</th>
<th>(2) 20P128S</th>
<th>5120 cells</th>
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<tr>
<td>Single Battery</td>
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<tr>
<td>8 Modules</td>
<td>20P16S</td>
<td>320 cells</td>
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<td>20-Cell Brick</td>
<td>20P1S</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.
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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<td>115</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
Temperature Rise: 43° C
Total Capacity Discharged: 60.3 Ah
Total Energy Discharged: 2.93 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)

FLIR Video of Trigger Cell #3 Event (8x speed)

http://go.nasa.gov/2iZ5lYi
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>
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<td>113°C</td>
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<tr>
<td>Nearest Neighbor</td>
<td>93°C</td>
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<td>111°C</td>
<td>111°C</td>
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<tr>
<td>Near Vent Port on Module</td>
<td>198°C</td>
<td>19°C</td>
<td>20°C</td>
<td>22°C</td>
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<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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