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

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What is X-57 Trying to Do?

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

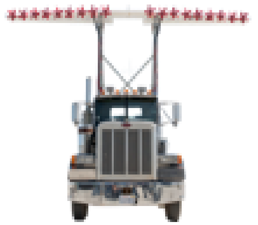
Motivation for Mod II; Retiring Electric Propulsion Barriers

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

Flight testing of baseline Tecnam P2006T

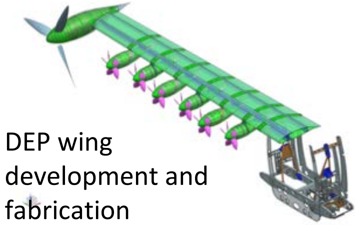
Goals:
- Establish Baseline Tecnam Performance
- Pilot Familiarity

Mod 2

Ground and flight test validation of electric motors, battery, and instrumentation.

Goals:
- Establish Electric Power System Flight Safety
- Establish Electric Tecnam Retrofit Baseline

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).

Achieves Primary Objective of High Speed Cruise Efficiency

Mod 4

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

Achieves Secondary Objectives
- DEP Acoustics Testing
- Low Speed Control Robustness
- Certification Basis of DEP Technologies

Mod 1

Mod 2

Mod 3

Mod 4

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

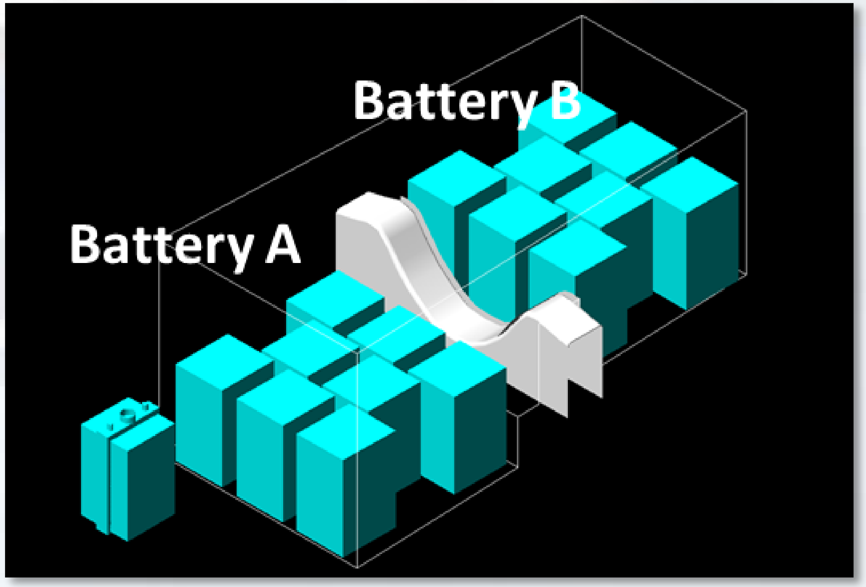
Design #2 Details and Nomenclature

- Li-ion Cells
  - o 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)

Battery System		
2 Parallel Batteries	(2) 20P128S	5120 cells

Single Battery		2560 cells
8 Modules	20P16S	320 cells
Sub-Module	20P8S	160 cells
20-Cell Brick	20P1S	20 cells

X-57 Battery Layout

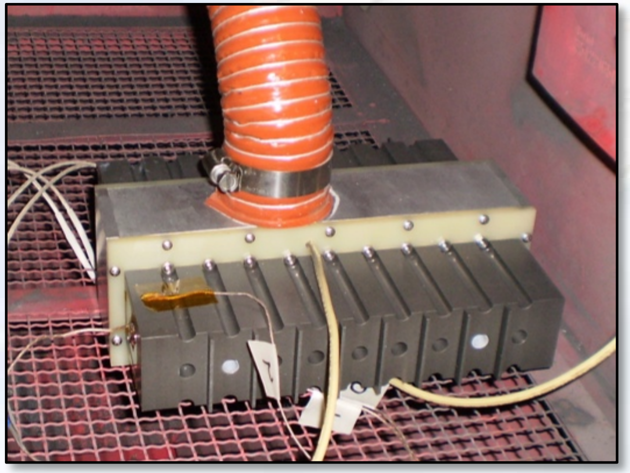


X-57 Flight Batteries (New Approach)

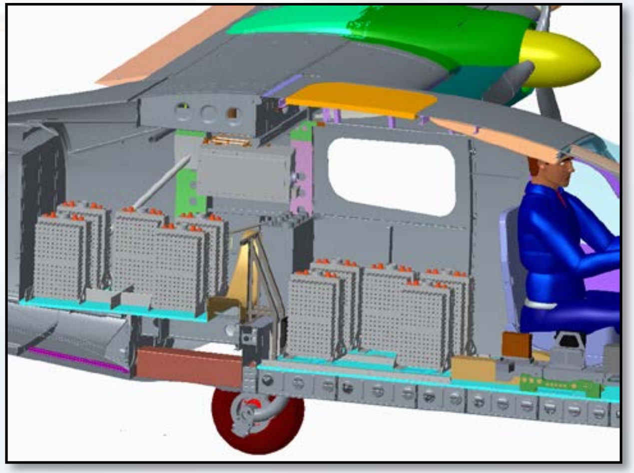
- 461 V, 47 kWh effective capacity
- 860 lbs. (16 Modules, 51 lbs. each)
- Two packs supports redundant X-57 traction system.
- Initial battery destructive testing conducted Dec 2016.
- Battery modules redesigned based on new NASA design guidelines and retested Nov 2017.

NASA JSC Test Unit With Interstitial Barrier and Heat Spreader (Design Template)

X-57 Battery System Mockups



X-57 Thermal Propagation test Unit (2 parallel blocks; ⅛ Module)

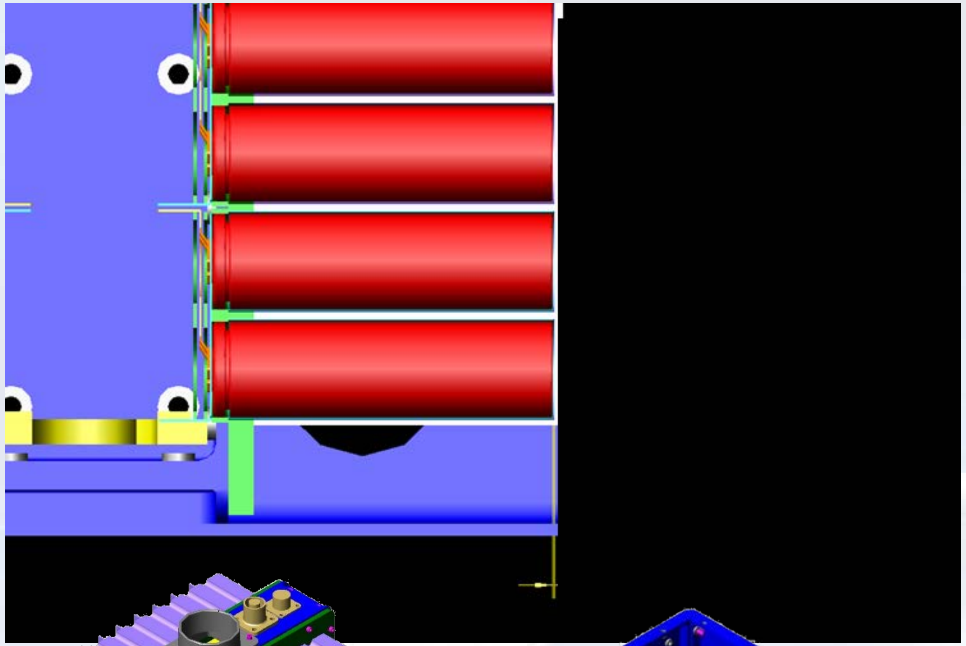


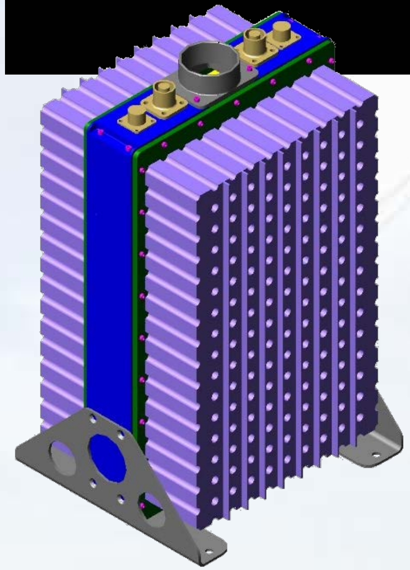
Cutaway showing Battery Installation (10 of the 16 modules)

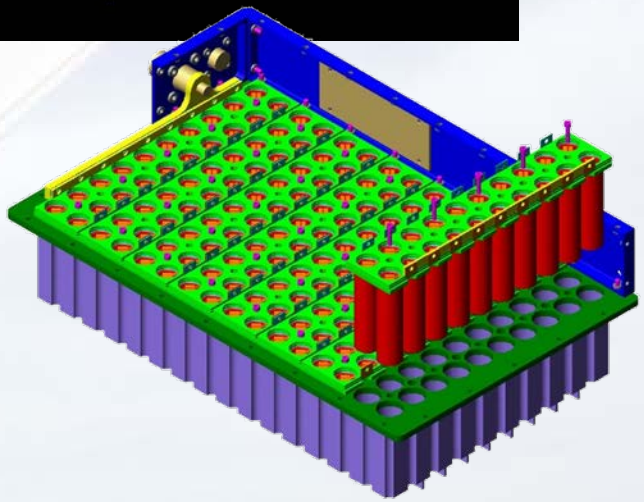
Thermal Runaway Testing Overview

- 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.

Side view of sub-module section







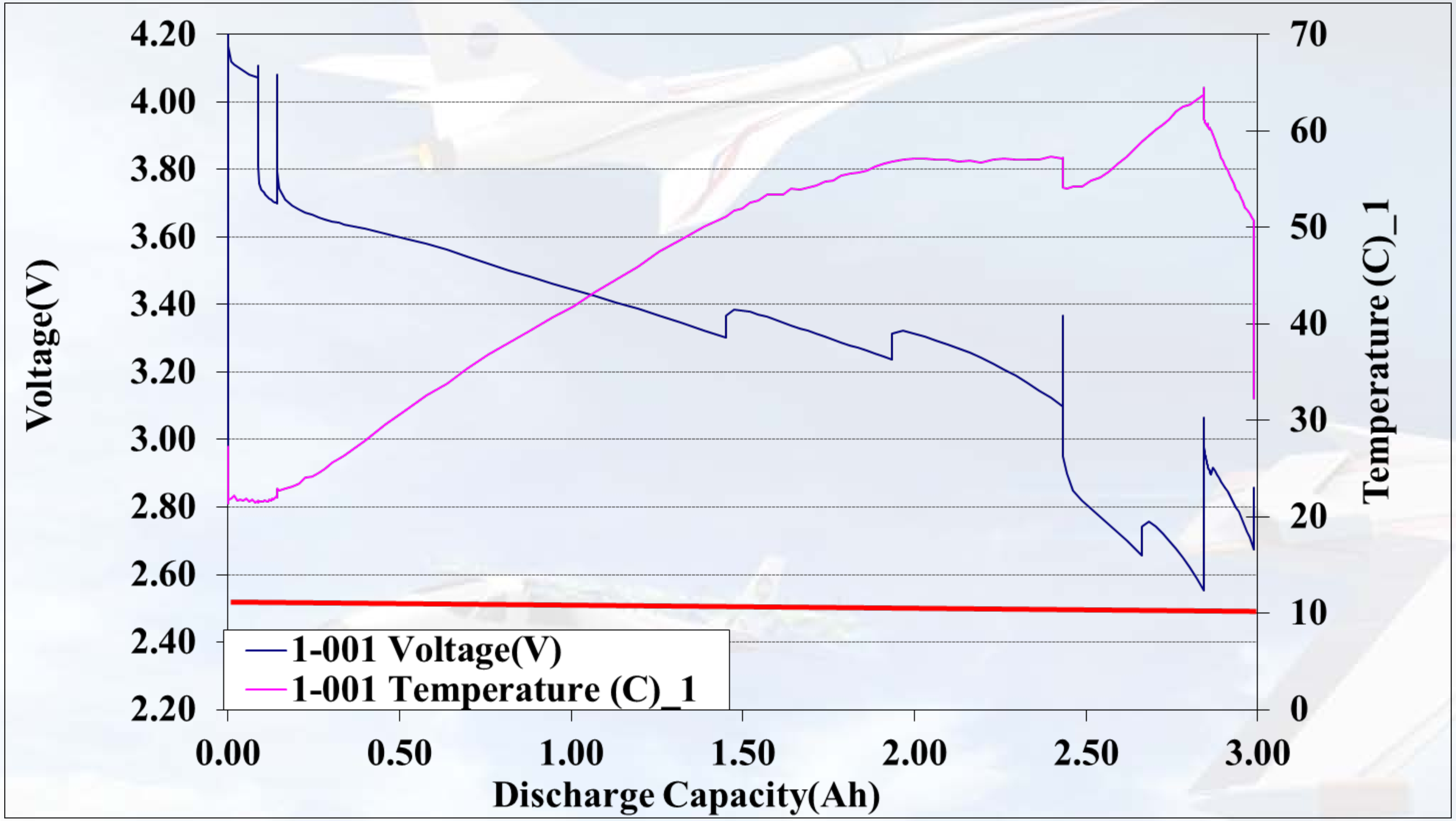
X-57 Flight Profile Load

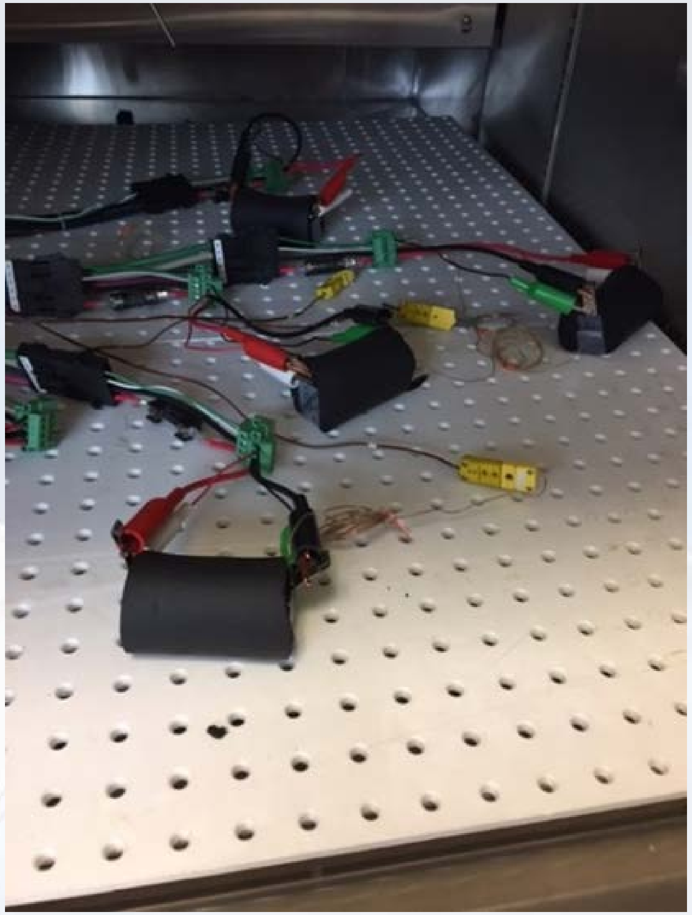
- Discharge via the baseline flight profile including zero power operations

Operation	Time (sec)	Cell Power Watts	Cell Watt-sec	Battery Power Watts	Battery Energy Wh	Battery Energy Wh (cum)	Battery % SoC Used
Taxi from NASA	600	2.15	1288	688	115	115	3
TO Checklist	120	0	0	0	0	115	3
Cruise Runup	30	25.76	773	8243	69	183	5
HLP/GO/No-go	60	0	0	0	0	183	5
Ground/climb	100	25.76	2576	8243	229	412	12
Cruise Climb	540	25.76	13908	8243	1236	1649	49
Cruise	300	19.32	5796	6182	515	2164	65
Descent to 1500'	450	12.88	5796	4122	515	2679	80
Final approach	180	0	0	0	0	2679	80
Go Around to 1500'	90	25.76	2318	8243	206	2885	86
Approach pattern	90	19.32	1739	6182	155	3040	91
Final approach	180	0	0	0	0	3040	91
Rollout and turnoff	60	3.22	193	1030	17	3057	92
Taxi to NASA	600	2.15	1290	688	115	3172	95

Currently predicts 46.2 kWhr required for the aircraft
Peak Power of ~145 kW

Capacity test of 30Q cells under X-57 mission profile

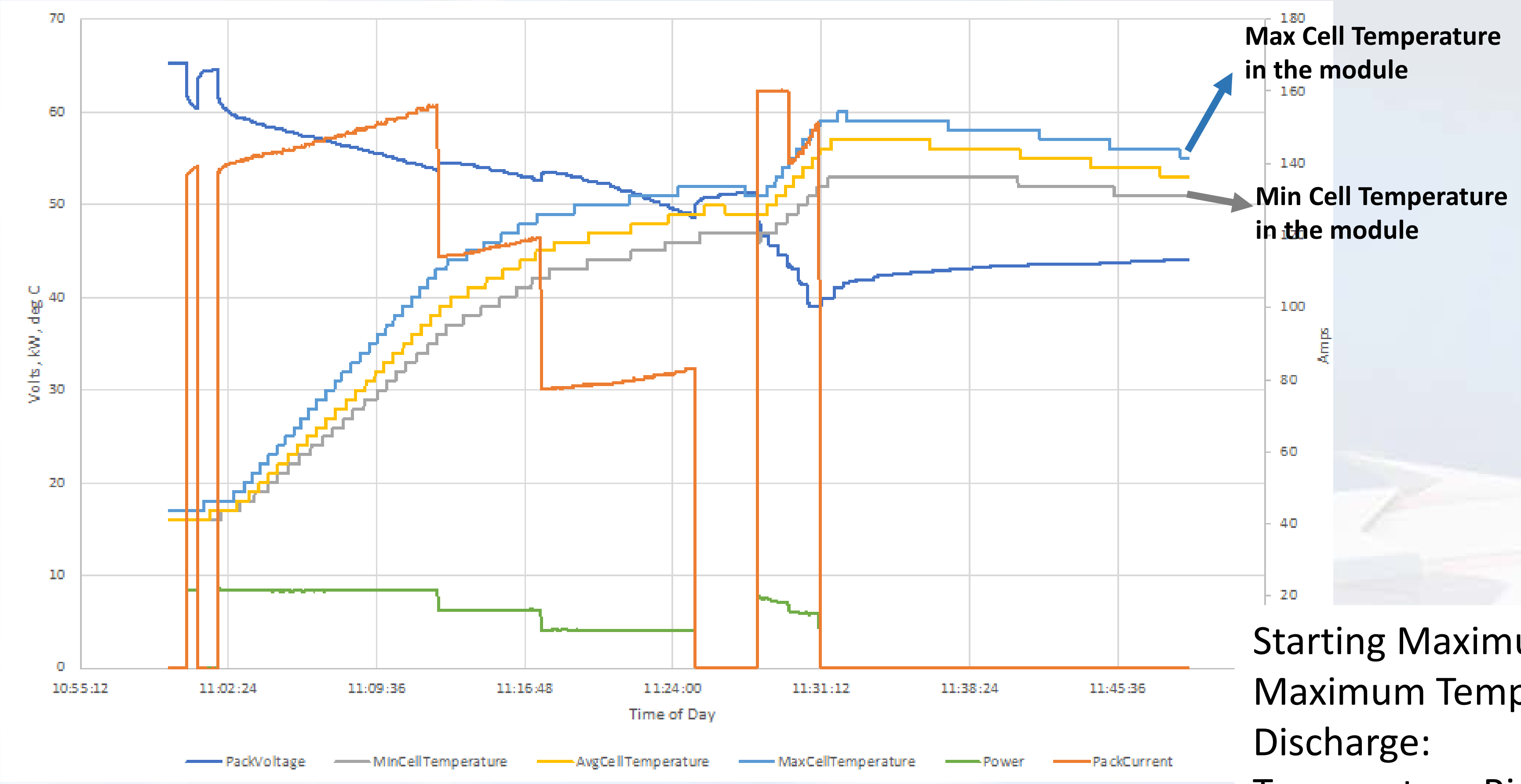




30Q cells tested under flight simulated environment

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

Thermal Normal Discharge

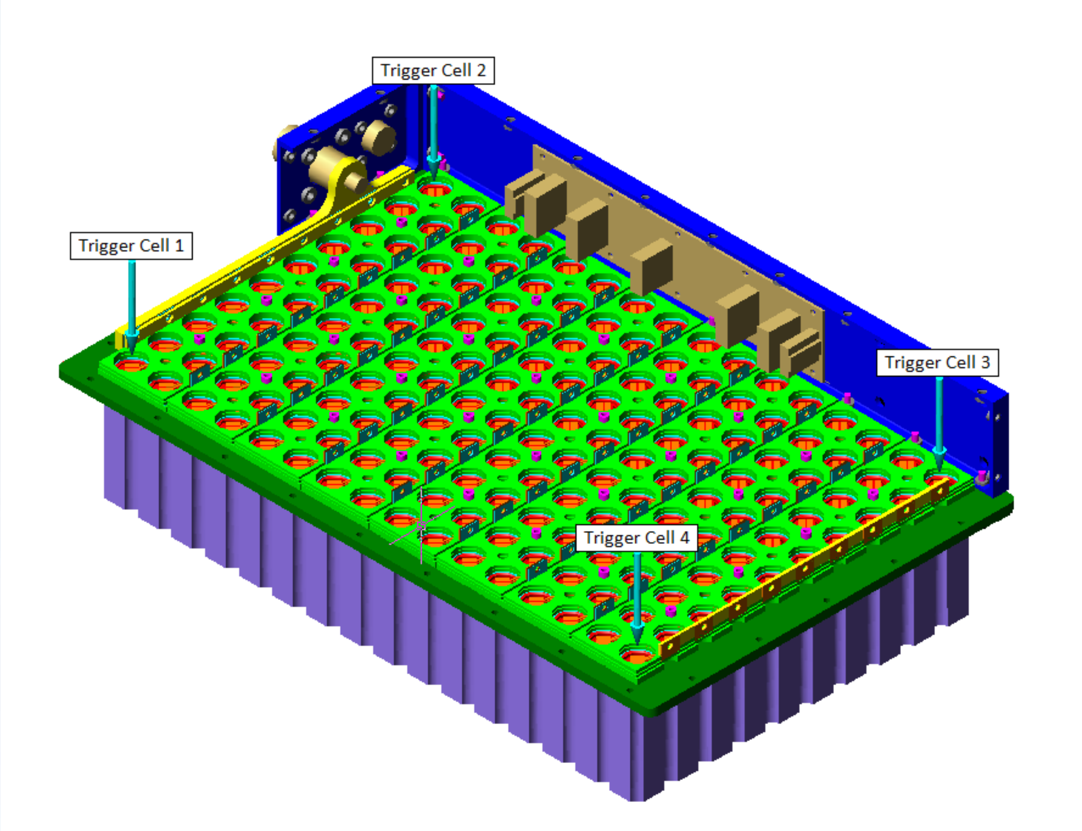


The delta between cells within the battery module is of <10deg C.

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

Thermal Propagation Test Sub-Module

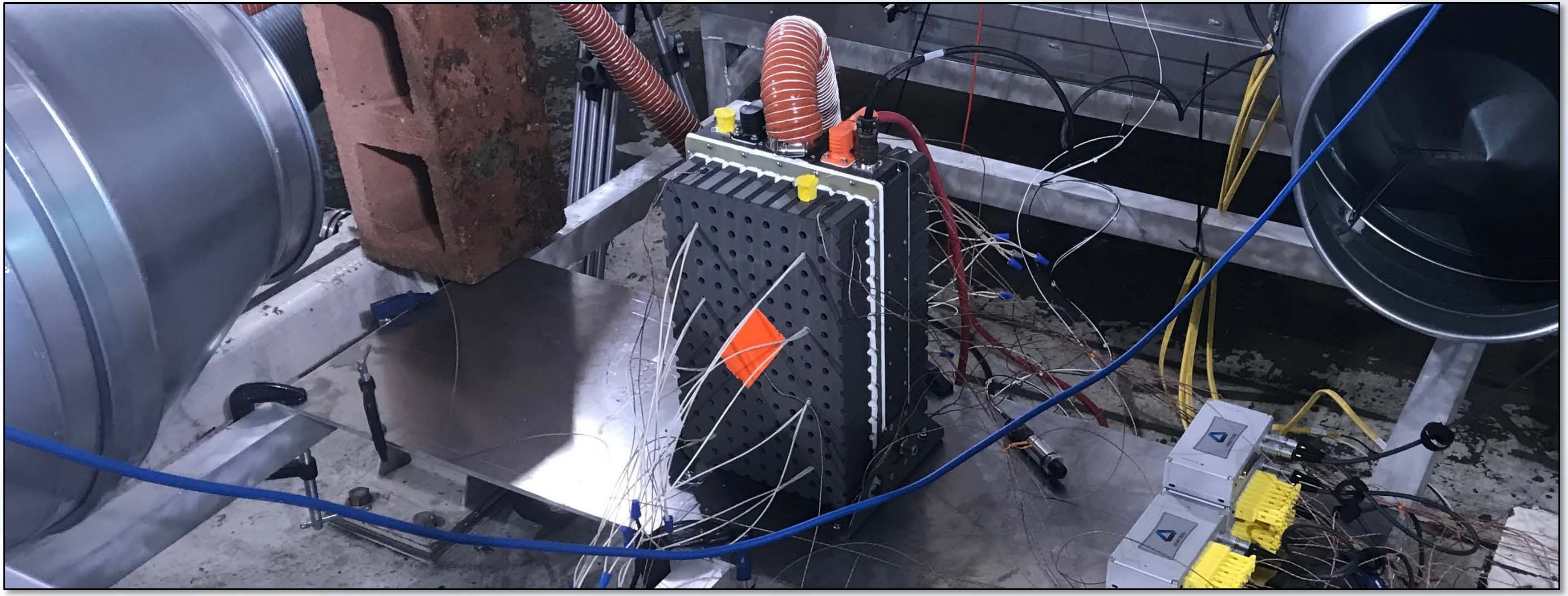
- One 160 block of cells was comprised of 4 M36 ISC trigger cells in the four corners, and 156 standard 30Q cells
- The M36 cells were wired independently of each other and electrically isolated from the rest of the battery sub-module
- High rate cycling of the ISC trigger cells using a DC power supply 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.



Sub-Module

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

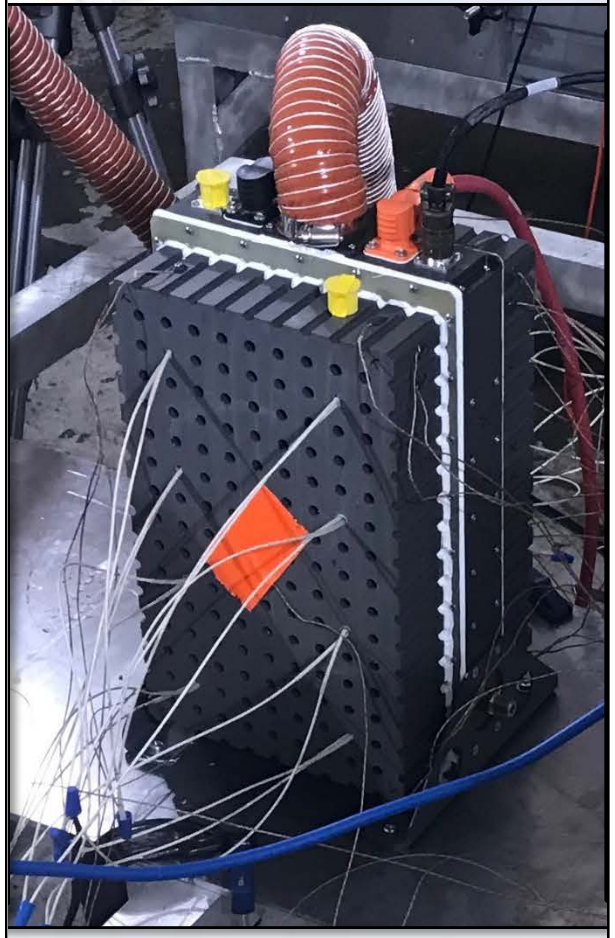


X-57 Thermal Propagation Test Module
(316 flight-like cells, 4 “Trigger Cells”
with internal shorting devices)

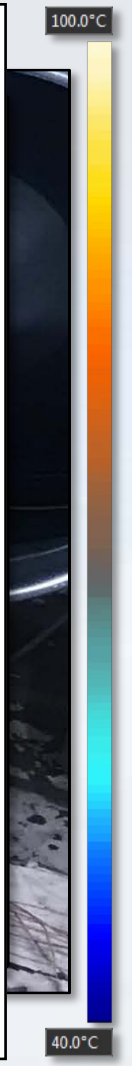
http://go.nasa.gov/2iZ5lYi

Single Cell Short Circuit/Thermal Runaway Without Propagation

FLIR Video of Trigger Cell #4 Event (8x speed)



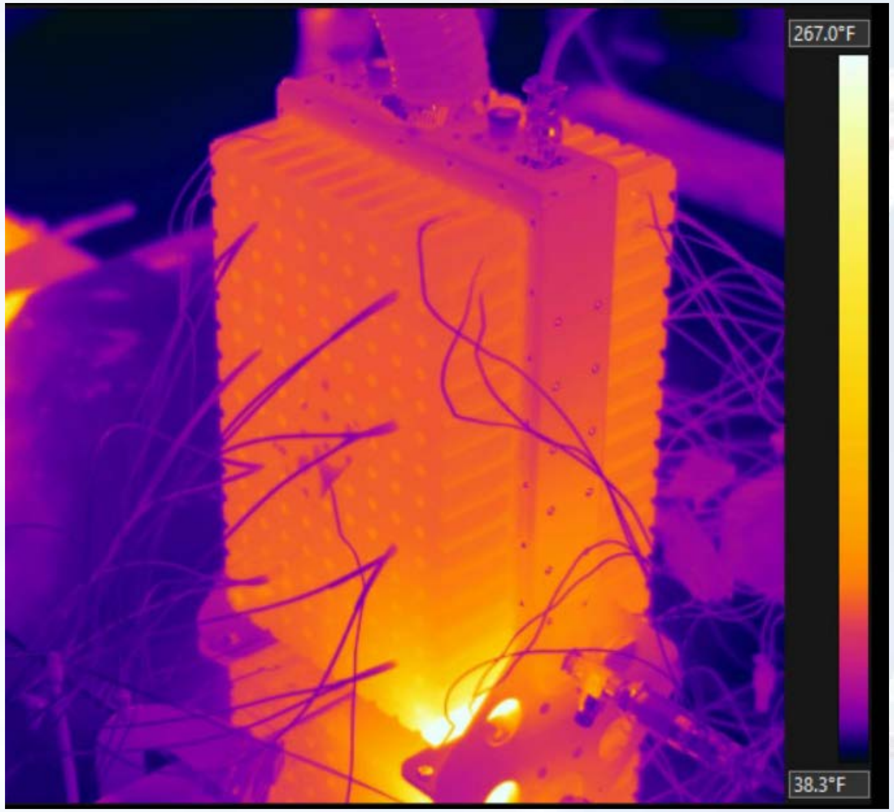
X-57 Thermal Propagation Test Module (316 flight-like cells, 4 “Trigger Cells” with internal shorting devices)



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

http://go.nasa.gov/2iZ5lYi

Thermal Runaway with Trigger Cells



Maximum Temperature at Key Points

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

- 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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