



# **X-57 Project Update**

## **Electrification, Integration and Vehicle Tests**



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**X-57 Principal Investigator**

# Distributed Electric Propulsion?



- Distributed Electric Propulsion refers to a way that electric propulsion can be integrated onto an airplane to  
(1) enhance the inherent benefits and  
(2) minimize the inherent shortcomings
- Successful adoption of new propulsion technologies requires that the airframe, the propulsion system, and the mission are effectively matched



Aircraft	P-59A	P-63A
Top Speed	413 mph	410 mph
Fuel	290 gal	100 gal
Range	375 mi	450 mi
Ceiling	46,200 ft	43,000 ft

# Meet “Maxwell”



- X-57 is NASA's Flight Demonstrator for Distributed Electric Propulsion (DEP) technology
- Highly modified Tecnam P2006T
- Cruise goal: show 5x less energy consumption than baseline aircraft at high-speed cruise (150 knots true/8,000 ft MSL)
- Low Speed Goal: Make complex DEP airworthy and demonstrate end-to-end airframe-propulsion-mission benefit

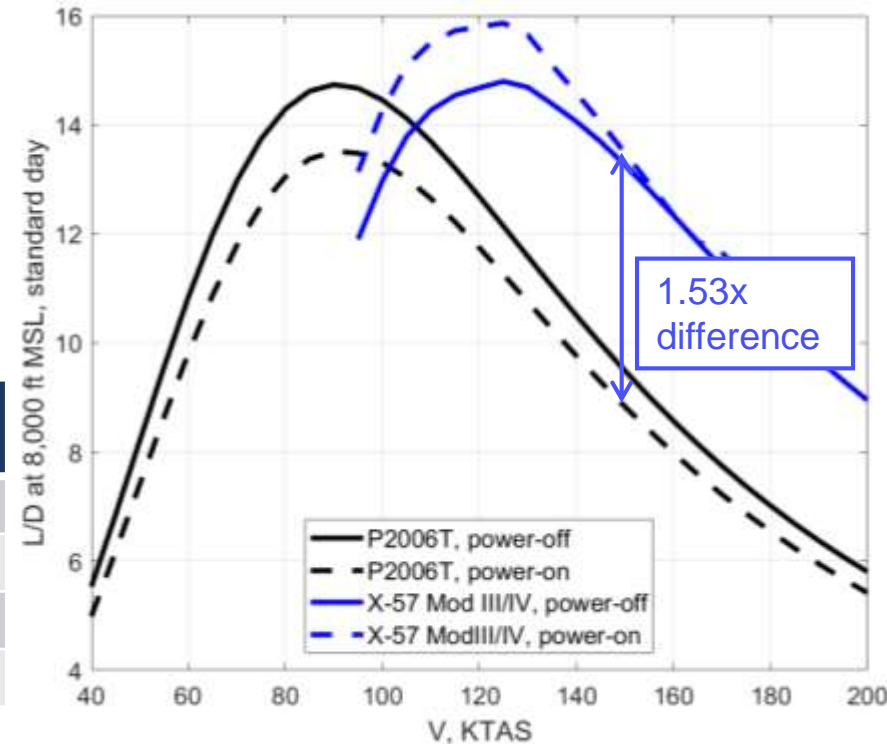


# Anatomy of a "5x" Improvement



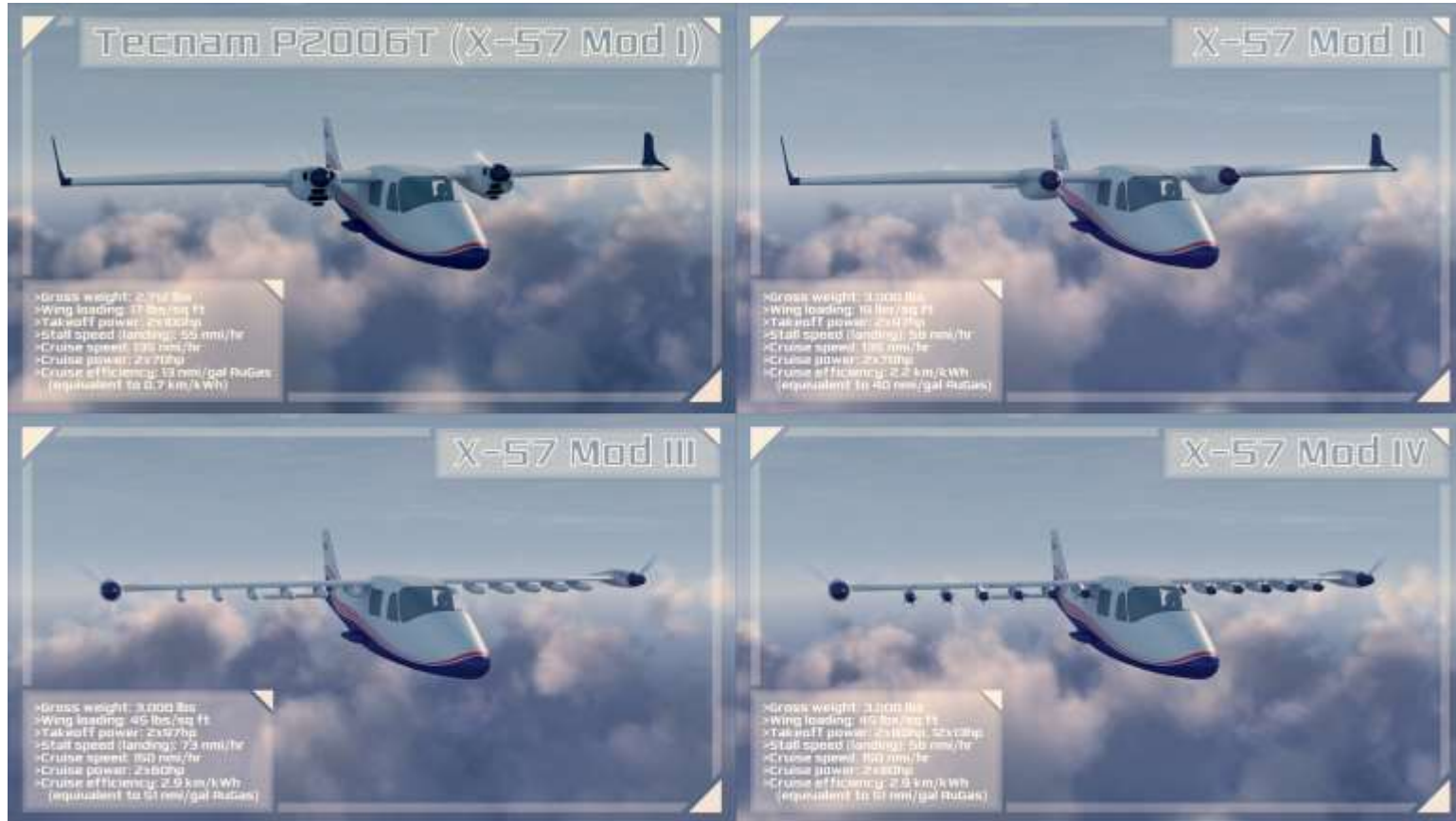
- Most change in efficiency due to electrification (30% to 93% efficient – 3.1x)
- High-speed L/D improvement
  - › Smaller wing shifts max L/D to higher speeds
  - › Wingtip-mounted props turn power-on installation loss into installation gain

Aircraft & Power Setting	L/D (max / 150 KTAS)	Comparison to P2006T (max / 150 KTAS)
P2006T power-off	14.7 / 9.5	--
P2006T power-on	13.5 / 8.8	--
X-57 power-off	14.8 / 13.3	1.00 / 1.40
X-57 power-on	15.9 / 13.5	1.17 / 1.53



**(3.1x electric) x (1.53x powered L/D at cruise) ~ 4.7x reduction**

# Crawl, Walk, Run



# P2006T → X-57

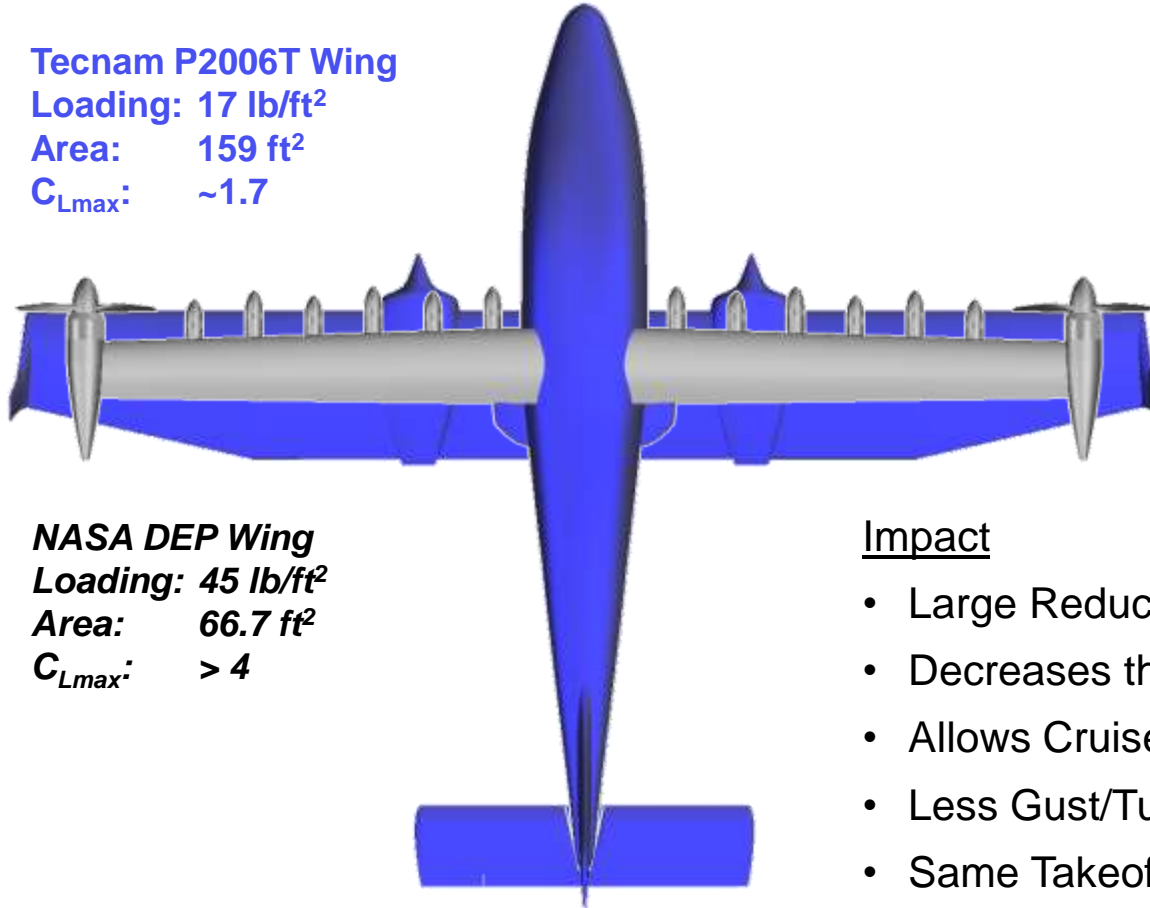


## **Tecnam P2006T Wing**

**Loading:** 17 lb/ft<sup>2</sup>

**Area:** 159 ft<sup>2</sup>

**C<sub>Lmax</sub>:** ~1.7



## **NASA DEP Wing**

**Loading:** 45 lb/ft<sup>2</sup>

**Area:** 66.7 ft<sup>2</sup>

**C<sub>Lmax</sub>:** > 4

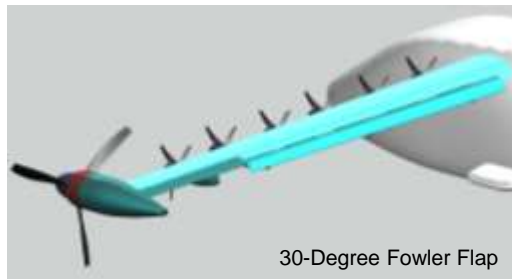
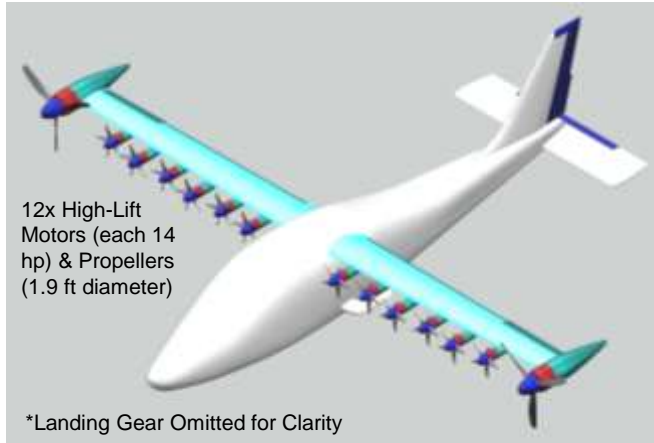
## Impact

- Large Reduction in Wing Area
- Decreases the Friction Drag
- Allows Cruise at High Lift Coefficient
- Less Gust/Turbulence Sensitivity
- Same Takeoff/Landing Speed

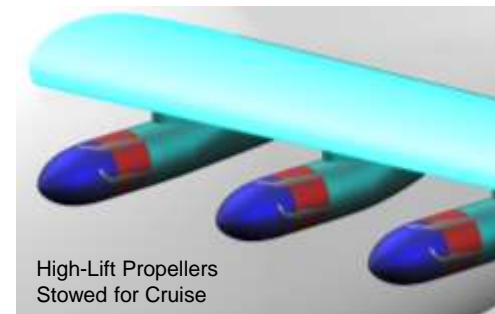
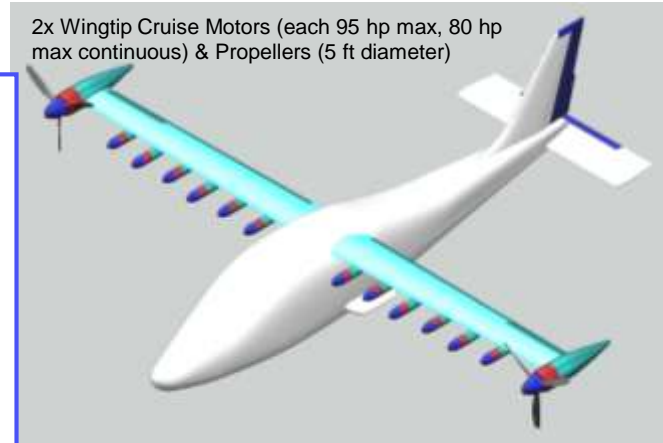
# X-57 Walkaround



Landing Configuration\*



Cruise Configuration



Tecnam P2006T  
Fuselage & Tail

3,000 lb Gross Weight

32.8 ft Span  
(36.6 ft w/ Props)

150 KTAS Cruise at  
8,000 ft MSL

58 KCAS Stall  
(73 KCAS Unblown)

167 KCAS Max Level  
Flight Speed

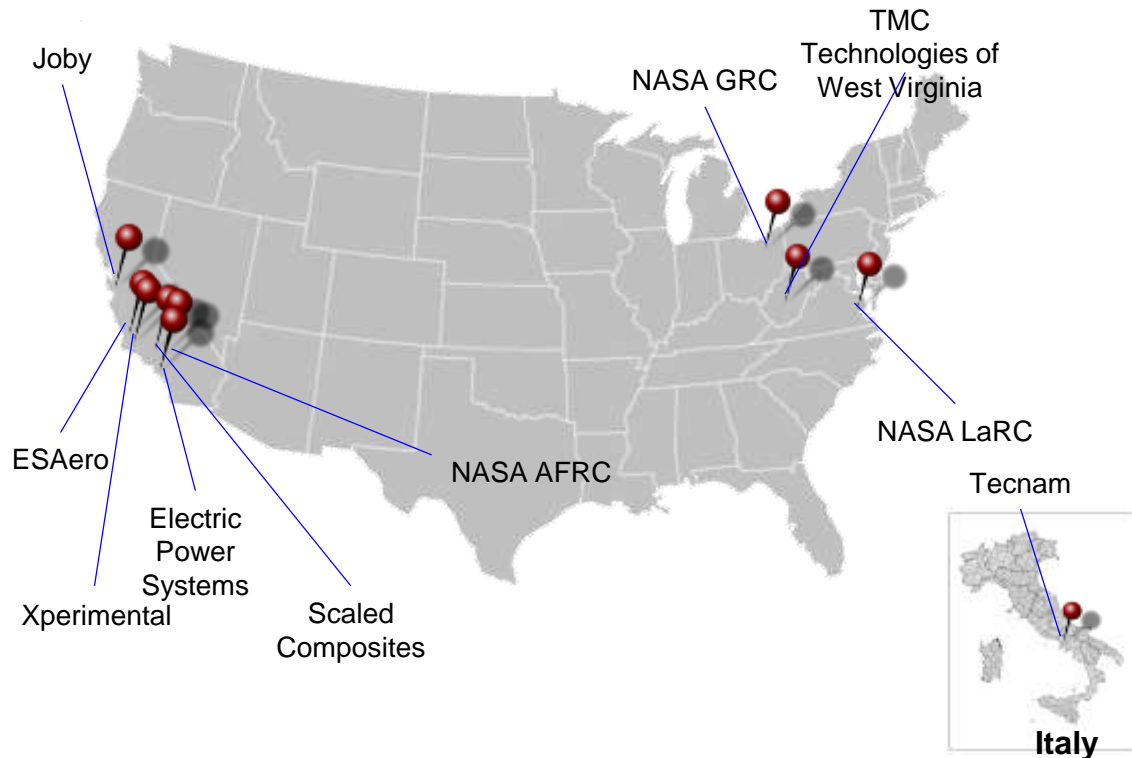
15,000 ft Ceiling



# X-57 Participating Organizations



- NASA Langley:** Vehicle, Wing, Performance, Controls IPTs
- NASA Armstrong:** Power, Instrumentation IPTs, Flight Ops
- NASA Glenn:** Battery Testing, Thermal Analysis
- Empirical Sys. Aero.:** Prime contractor
- Scaled Composites:** Mod 2 Integration (batteries, motors, controllers, cockpit)
- Joby Aviation:** Motor & Controller and folding prop development
- Xperimental:** Wing design and manufacturing
- Electric Power Sys.:** Battery development
- TMC Technologies:** Software certification
- Tecnam:** Baseline COTS airframe without engines





# Motivation for X-57 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
  - › X-57 needs 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 electrified system development risk for Mod III and IV through early testing on a proven vehicle configuration
- Develop capability within NASA to design, analyze, test, and fly electric aircraft

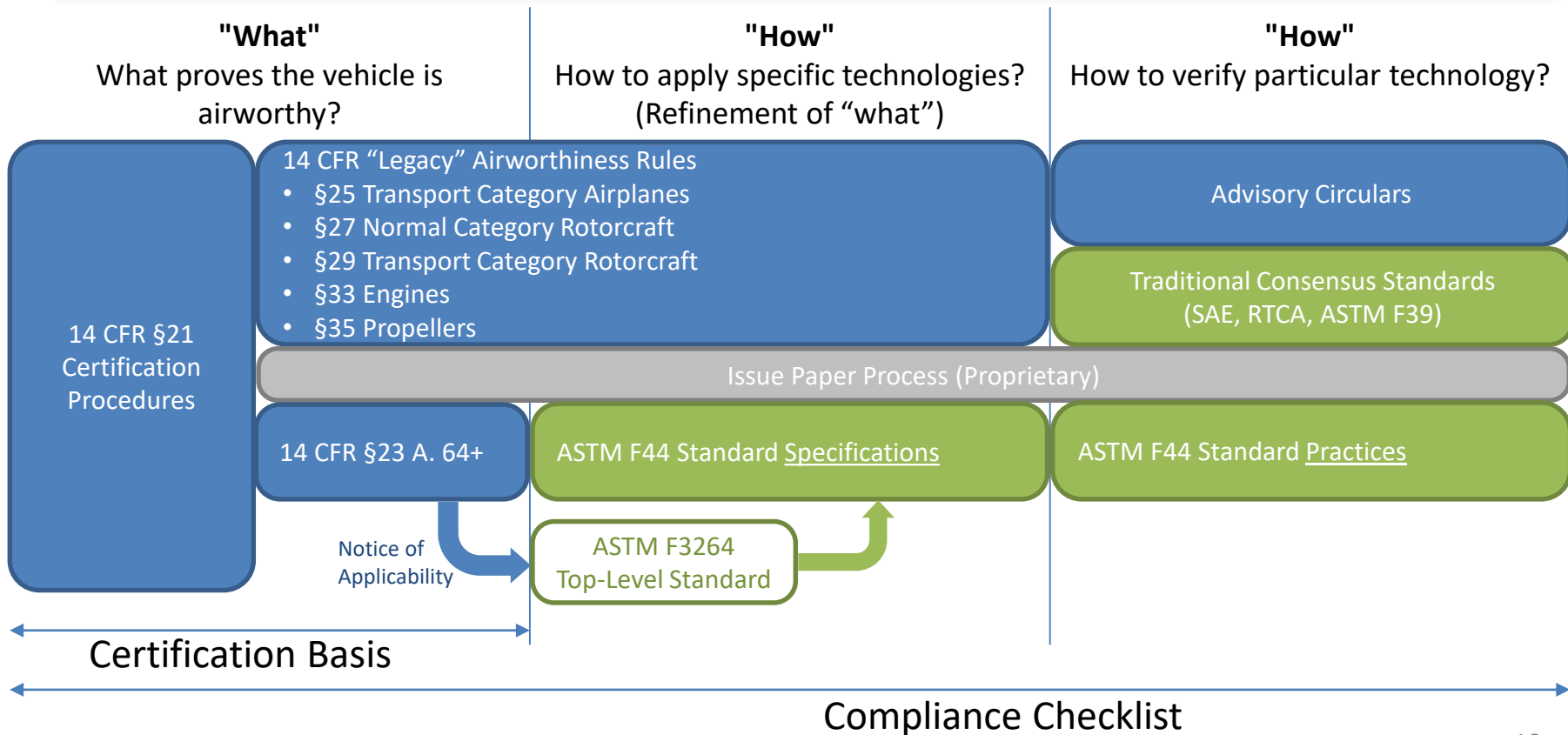


The value of X-57 lies in advancing the Nation's ability to design, test, and certify electric aircraft, which will enable entirely new markets (UAM)



# Performance-Based Airworthiness Approach

In Response to Small Airplane Revitalization Act of 2013



Legend:

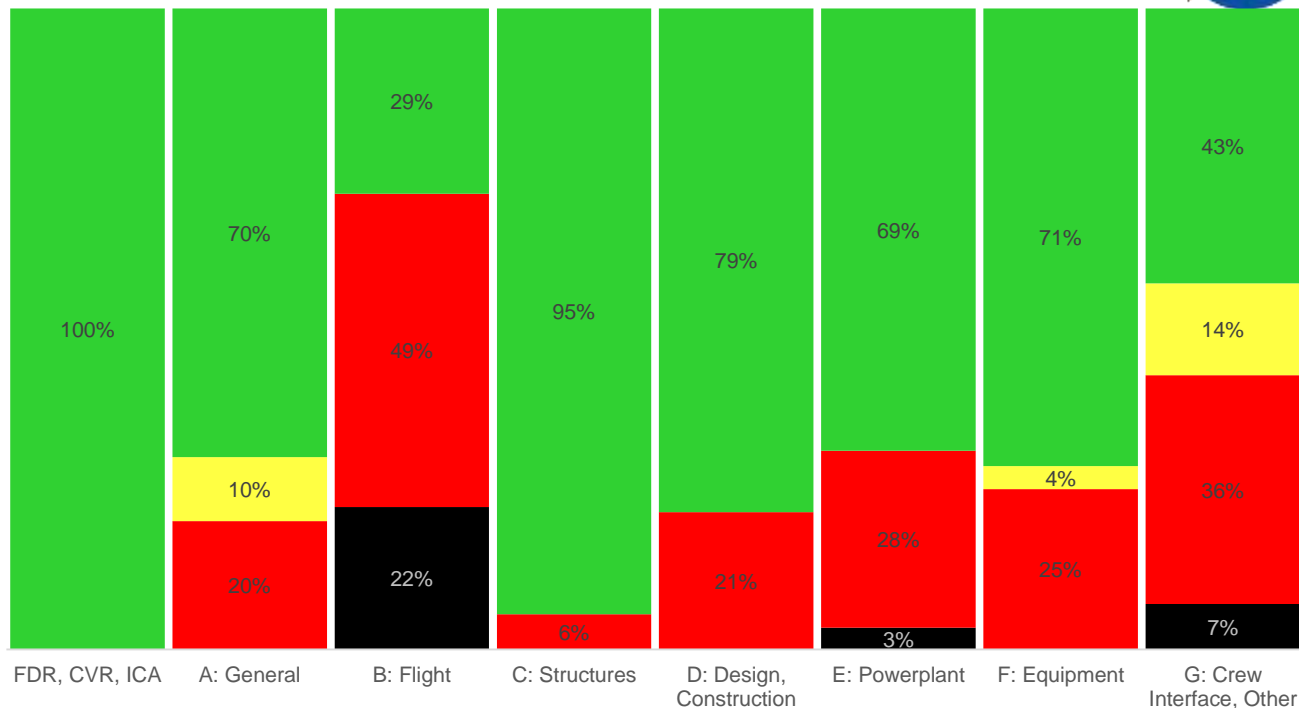
FAA

Industry / Consensus

# Examination of FAR 23: Normal Category Aircraft



- Many needs identified by FAA Future Aircraft Safety Team (FAST) related to high-lift vehicle concepts (whether Distributed Propulsion or eVTOL)



## Legend

Changes needed for Electrified Aircraft

None

Minor tailoring

Major Revision

Remove (N/A)

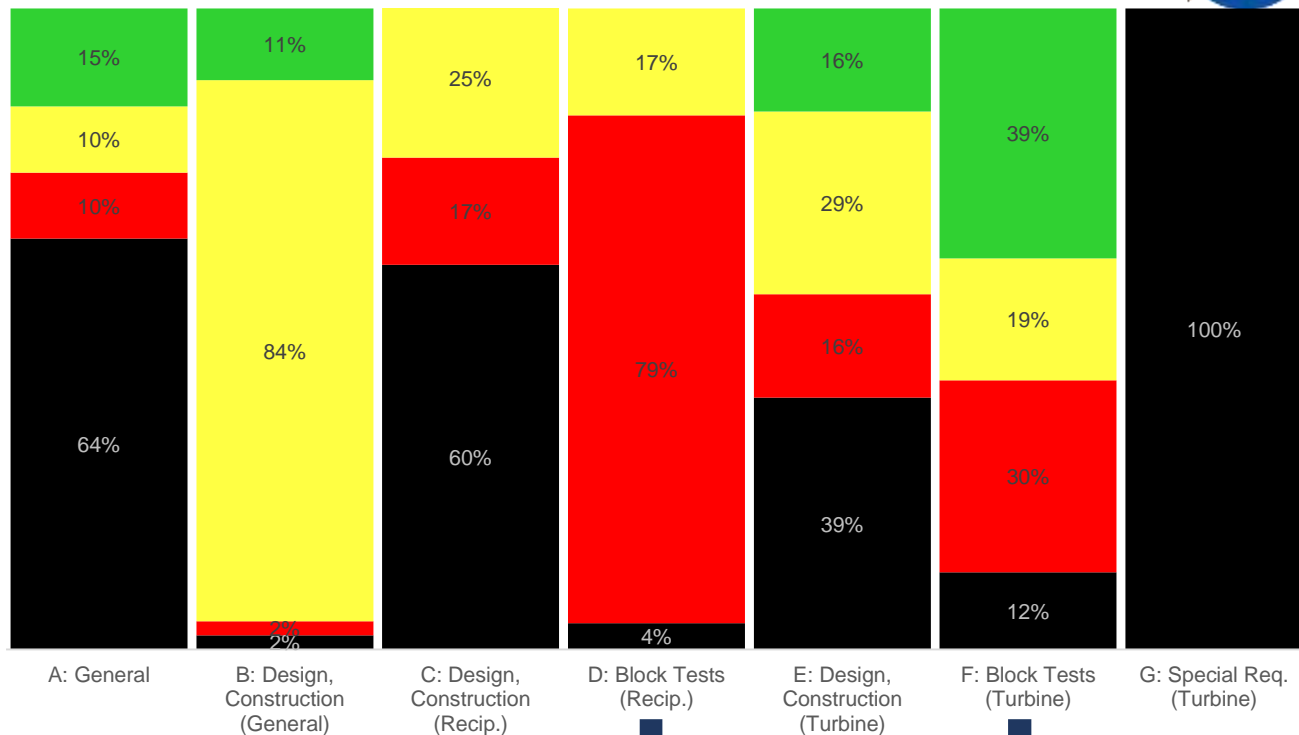
X-57 impact opportunity

FAR 23 Highest Need is Subpart B, Flight

# Examination of FAR 33: Aircraft Engines



- Much of the open need in the ASTM F44.40 and F39.05 subcommittees is on Electric Propulsion Unit (EPU) Block Testing



## Legend

Changes needed for Electrified Aircraft

None

Minor tailoring

Major Revision

Remove (N/A)

X-57 impact opportunity

FAR 33 Highest Need is Block Tests

# Lessons Learned and Tech Transfer Opportunities



Stakeholder/ Technology Area	FAA	ASTM, SAE	Vertical Lift Technologies (eVTOL)	On Demand Mobility (UAM)	Electric Transport Aircraft
Certification Basis	Part 23, 33	Top-Level Standard	Part 23 Lessons for Part 27 & Part 33	Part 23/33 for 21.17(b)	Part 23/33 Lessons for Part 25
Batteries	MOC	Standards	Lessons Learned	Lessons Learned	Lessons Learned
Motors	MOC	Standards	Lessons Learned	Lessons Learned	Lessons Learned
Motor Controllers	MOC	Standards	Lessons Learned	Lessons Learned	Lessons Learned
Aero Perf.	MOC	Standards	Wing-Borne Transition	Wing-Borne Transition	Lessons Learned
Human/Aircraft Integration	MOC	Standards	Elec. Health Display/Control	Elec. Health Display/Control	Lessons Learned
Distributed Propulsion	MOC	Standards	Power Distribution/Control	Power Distribution/Control	Lessons Learned

**MOC: Means of Compliance**

- Table shows technical transfer product **outreach paths** to electric aviation industry
- X-57 Deputy Project Manager joined ASTM F44 Executive Committee
- NASA SMEs participating on subcommittees for General Aviation and Powerplants
- Coordinating with other ARMD Projects, FAA, and Standards bodies share relevant X-57 research and technology

***X-57 technologies and experience are good candidates for tech transfer to broad swath of electric aviation industry***

# Motivation for X-57 Mod III/IV; Leveraging Distributed Electric Propulsion



- Matures Distributed Electric Propulsion system architectures
  - › NASA will tackle technical challenges operating multiple motors in configurations relevant to industry (UAM, Thin Haul)
  - › Validates higher power electric propulsion system operation (120 kW in Mod II → 250 kW in Mod IV)
  - › Pathfinder for certification of complex DEP systems
- Exploration of novel, optimized configuration enabled by DEP (Thin Haul and larger scale)
  - › Exploration of wingtip propulsion/vortex interaction
  - › Cruise-optimized wing enabled by blown high-lift system
  - › High performance, high aspect ratio wing requires new wing material structure system
- Optimized DEP configuration enables significant improvement to aircraft performance not currently explored in the marketplace
  - › Goal is 500% improvement in energy consumption at cruise
  - › Zero In-flight Carbon Emissions
  - › Opportunity for significant noise reduction



Mod III/IV will explore the benefits of Distributed Electric Propulsion which will revolutionize aircraft architecture and performance





# Further Reading



<https://nasa.gov/x57/technical>

The screenshot shows a web browser displaying the NASA X-57 Technical Papers page. The browser's address bar shows the URL <https://www.nasa.gov/aeronautics/X-57/technical/index.html>. The page features a dark blue header with the NASA logo and navigation links: Topics, Missions, Galleries, NASA TV, Follow NASA, Downloads, About, and NASA Audiences. Below the header is a large banner with the text "Aeronautics Research" and two white airplane icons. The main content area is titled "X-57 Technical Papers" and lists three documents: "X-57 Preliminary Design Review (Published Nov 12, 2015)", "X-57 Critical Design Review (Published Nov 15, 2016)", and "X-57 Power and Command System Design (Published: 6/7/2017)". Each document entry includes a link to "Day 1 Package" and "Day 2 Package", an "Author" field, and an "Abstract" field. A left sidebar contains a "Follow" section and a list of links related to the Aeronautics Research Mission Directorate, including ARMD, About ARMD, ARMD Programs, ARMD Solicitations, ARMD Leadership, and ARMD Resources.

**X-57 Technical Papers**

**X-57 Preliminary Design Review (Published Nov 12, 2015)**  
[Day 1 Package](#)  
[Day 2 Package](#)  
**Author:** Various authors from the NASA-various contractors team.  
**Abstract:** This document contains the presentation slides used for the PDR presentation made by the X-57 team on Nov 12-13, 2016. The presentation addresses program requirements, solutions, and analysis approaches as planned as of the presentation date.

**X-57 Critical Design Review (Published Nov 15, 2016)**  
[Day 1 Package](#)  
[Day 2 Package](#)  
**Author:** Various authors from the NASA-various contractors team.  
**Abstract:** This document contains the presentation slides used for the CDR presentation made by the SCEPTOR X-57 team on Nov 15-17, 2016. The presentation addresses program requirements, solutions, and analysis approaches as planned as of the presentation date.

**X-57 Power and Command System Design (Published: 6/7/2017)**  
**Author:** Clarke, Sean and Redfer, Matthew and Papathakis, Kurt and Samuel, Aamod and Foster, Trevor  
**Abstract:** Update on the current state of electric propulsion research at NASA.

# Mod I: Flight Test at NASA

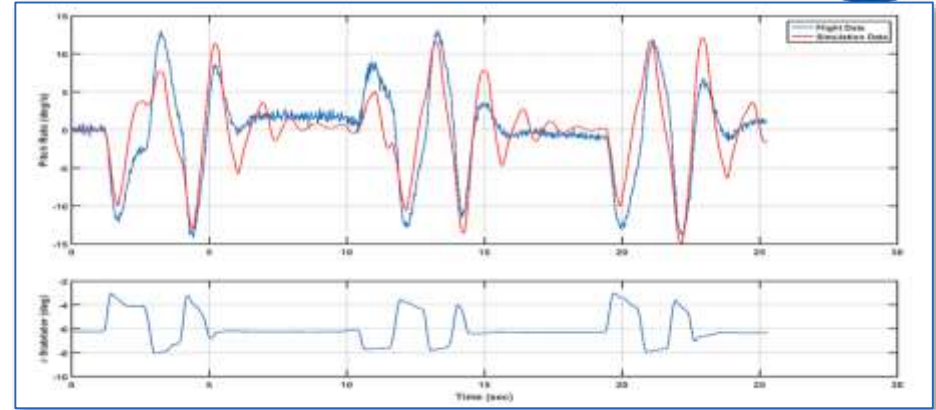


Test flights conducted on a commercial Tecnam P2006T

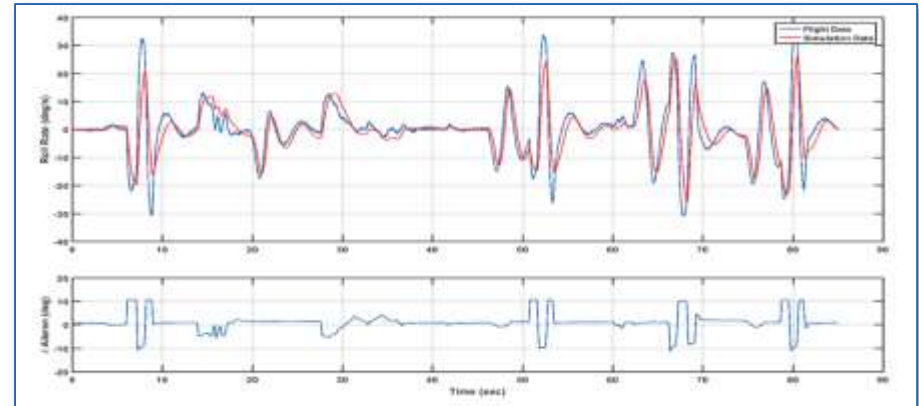
Flights supported both pilot familiarization, and a validation data-source for the Mod-II piloted simulation.



<https://nasa.gov/x57/technical>



Simulation vs Flight Response, pitch rate



Simulation vs Flight Response, roll rate

# Mod I: DEP Validation Experiment



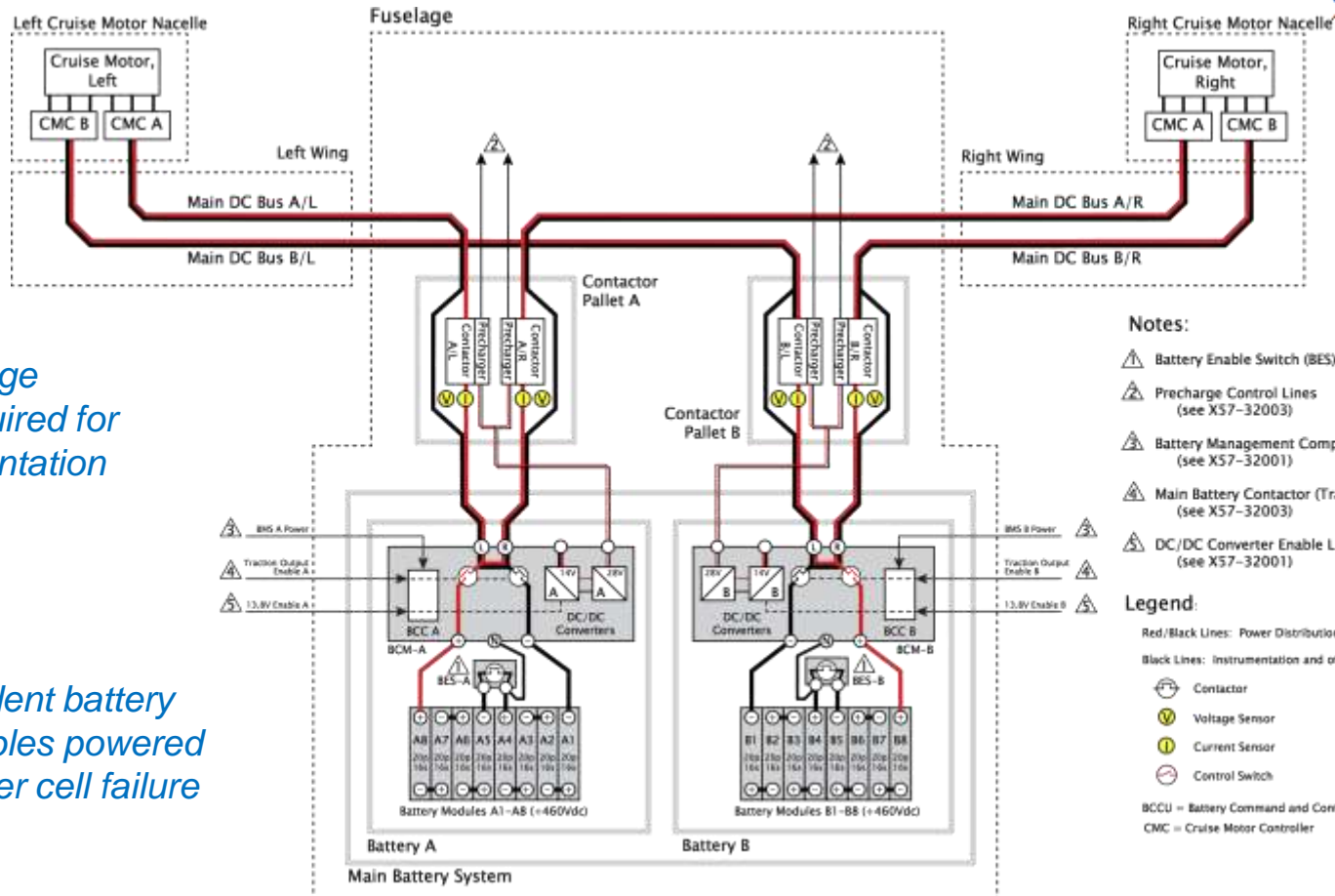
# Electrified Architecture with Redundancy



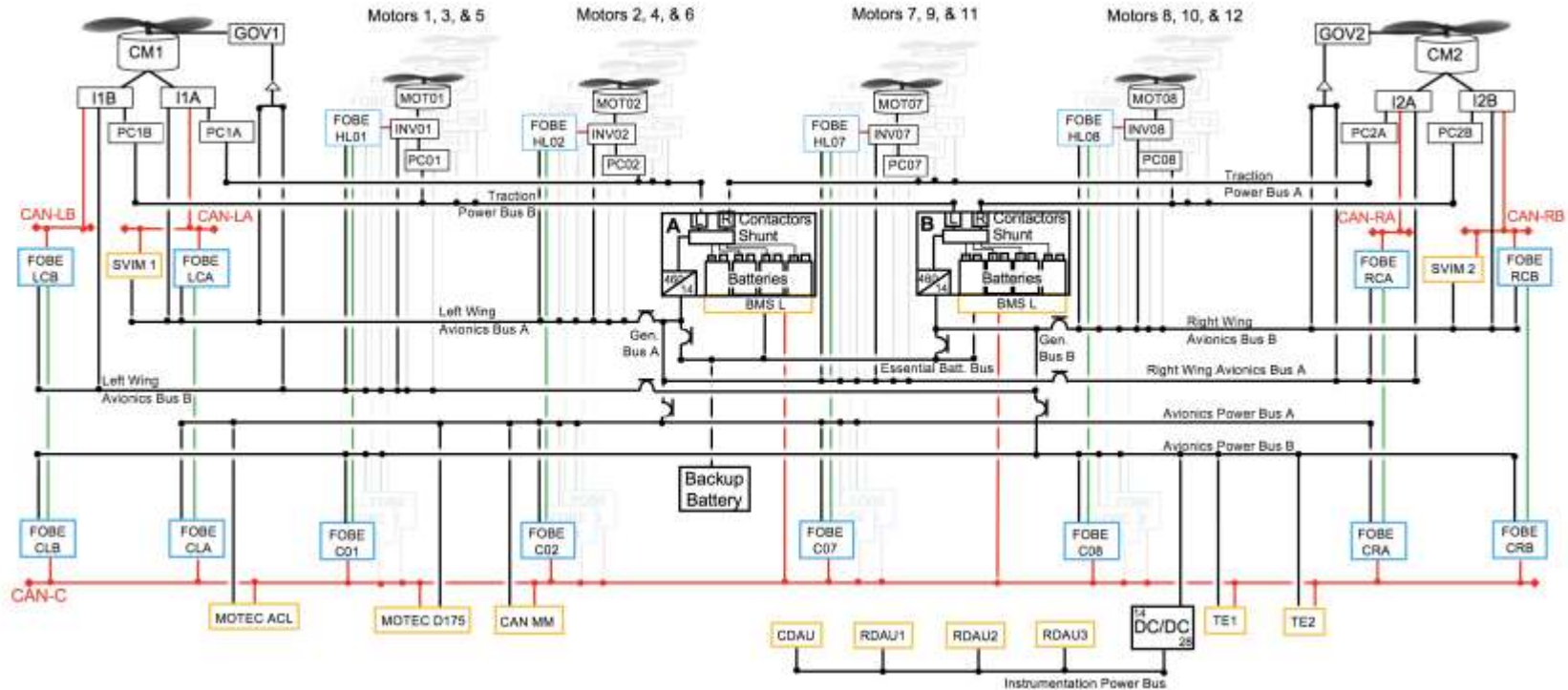
*Dual inverter  
reduces failure  
severity*

*High voltage  
contactors required for  
hazard segmentation*

*Independent battery  
packs enables powered  
landing after cell failure*



# Power and Command Interconnection Diagram



*Large number of interfaces  
even for "simple" vehicle  
architectures*

*Failure Analyses and Tests  
validate redundancy and  
segmentation approach*

# Cruise Motor (CM) Technical Challenges



- **Design standards for electric propulsion motor not established.**
  - › No suitable USA sourced COTS electric motor design existed
  - › Adapted industry design approaches for aerospace applications.
  - › Cruise motor development is helping to write the design standards.
  - › Dual winding motor architecture for aerospace applications mitigates effects of component failures, but requires validation.
- **Testing standards for electric propulsion motor not established.**
  - › X-57 developed an electric motor testing approach.
  - › X-57 motor testing providing lessons and data in support of testing standards ([ASTM F39.05 WK47374](#)).
- **Maintenance standards for electric propulsion motor not established.**
  - › X-57 is tailoring a maintenance approach from other industries.
  - › X-57 maintenance plans are a prototype for industry.



Cruise Motor endurance testing on NASA Airvolt stand at AFRC



# Cruise Motor Development – Flight Qualification



## TEST ENGINEERS

RUN IT FOR HOURS AT A TIME, TO ENSURE THAT IT CAN SUSTAIN THE HIGH POWER AND LONG DURATION REQUIREMENTS FOR FLIGHT.





# Cruise Motor Manufacturing and Testing Challenges



- Flight motor is Rev K of the design; 11<sup>th</sup> major design iteration. ([AIAA 2016-3925](#))
- Passively cooled electric motor presents testing and analysis challenges. ([AIAA 2017-3783](#), [3784](#))
- Determining motor performance (efficiency and torque) difficult due to EMI and high frequencies.
- Motor assembly is a laborious process.
  - › Was not expected for a mechanically simple system.
- Test program has successfully identified some assembly workmanship/design weaknesses; redesign/rebuild plan in place.

Damage to stator wiring from contact with mounting bolts



Self-induced vibration exposes insulation over stress areas efficiently



Redesign by integrated NASA and Contractor team to incorporate flight experience and rapid iteration



# Cruise Motor Controller (CMC) Technical Challenges

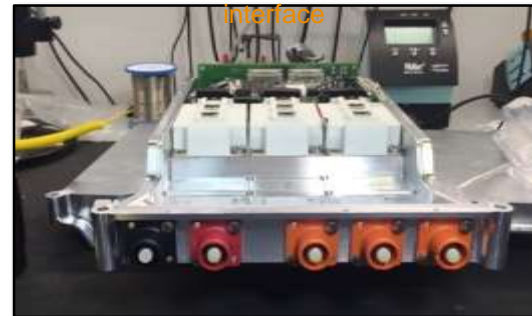


- **Electric aircraft operation requires high-efficiency power conversion from the battery to the motor, which is pushing the state of the art.**
  - › This conversion is handled by the cruise motor controller (CMC).
- **Technical Challenges**
  - › *Si-C MOSFET (Silicon Carbide Switch) is a TRL 3 technology, required to achieve high switching frequencies necessary for aerospace efficiency requirements.*
    - A vendor has indicated this technology is not yet ready for aircraft applications.
    - X-57 is working with our vendor to develop the technology.
  - › Si-C MOSFET technology is sensitive to non-optimized power distribution, which causes challenges with testing and system architecture.
  - › Level 1 Safety Critical software required, new for this type of application.
    - Redundant architecture (required to manage wingtip asymmetric thrust case) introduces complex dual-controller software startup race condition handling
  - › Air cooled heatsink efficiency is critical to efficient operation, and the design required multiple design iterations.



Flight CMC prototype

DC Power is filtered with large capacitor circuit before high-speed SiC module interface



# CMC Manufacturing and Testing Challenges

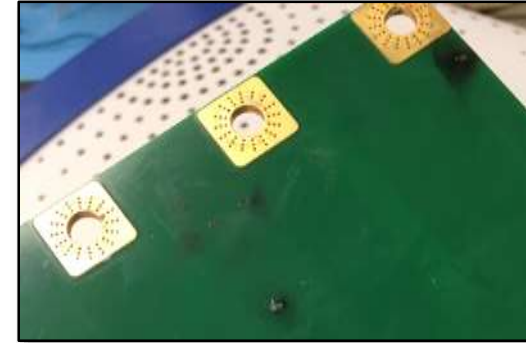


## ■ Manufacturing Challenges

- › Long component lead-times due to high demand and limited production.
- › Sub-contractors process changes were needed to meet aircraft fabrication requirements.
  - NASA engineers and aircraft electronics techs worked with contractor to iterate through several design revisions before flight unit fabrication
- › Build/test iterations improving manufacturing process and design with the flight CMCs.

## ■ Testing Challenges

- › CMC prototypes subjected to early risk reduction testing; prompted some re-design.
- › Flight-like testing difficult to achieve due to high power requirements.
  - Lab testing done at lower power settings.
- › Lab and ground testing (Airvolt test stand) has identified design defects.
  - Root cause analysis in work at NASA, contractor, and vendor forensics lab.
- › Lack of insight into the software due to the COTS nature of the core controller has complicated testing and trouble-shooting.



PCB shows evidence of arcing after lab and field testing



MOSFET body catastrophically failed due to excess current/heat or voltage/vibration (analysis in work)

# X-57 Flight Batteries Technical and Testing Challenges



- **No commercial solutions existed for battery systems with sufficient energy and power to provide meaningful aircraft flight duration.**
  - › High power requirements within a "flight-weight" limitation- 461 V, 47 kWh effective capacity, 859 lbs. (16 Modules, 51 lbs. each).
    - Aircraft propulsion requirements drive design solutions to a higher voltage and current than comparable automotive or auxiliary aircraft operations.
    - Advancing the system-level state of the art for an aircraft battery from TRL 4 to 6.
  - › Industry target of 30% packaging overhead aligns with X-57 mass budget.
  - › Thermal management is a critical design driver and key X-57 design trade-off.
    - X-57 battery system is passively cooled to minimize complexity.
    - Production battery systems require active cooling.
  - › Battery management software and control system had to be developed
    - Not accounted for in most battery weight and performance specs.
  - › No large, high density COTS battery packs prevent thermal runaway propagation.
    - Original X-57 battery design failed to contain a failure propagation test (December, 2016)
    - Battery System re-designed to contain single-cell failures, prevent cascade failures.
    - Thermal runaway gas and ejecta containment drives sealed designs and increased weight.
  - › Battery module/system test approach informing standards ([ASTM F39.05 WK56255](https://nasa.gov/x57/technical))



Original battery failed containment propagation test in Dec 2016

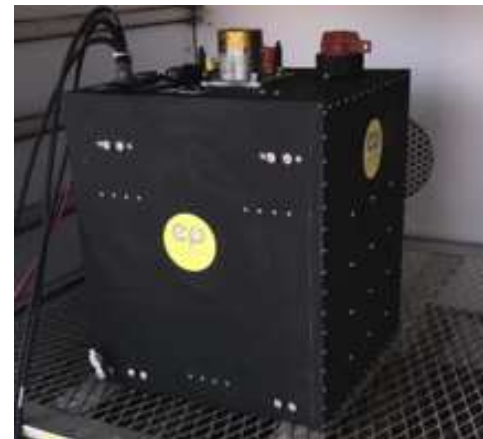
Battery System Ship Set (16 modules)



# 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.

<https://nasa.gov/x57/technical>



# X-57 Flight Battery Destructive Testing





# X-57 Flight Batteries (New Approach)

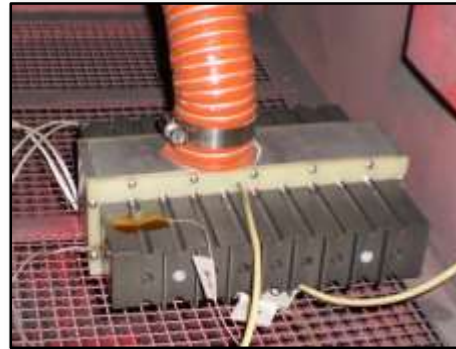


- 461 V, 47 kWh effective capacity
- 860 lbs. (16 Modules, 51 lbs. each)
- Two packs supports redundant X-57 traction system.
- Initial battery destructive testing conducted Dec 2016.
- Battery modules redesigned based on new NASA design guidelines and retested Nov 2017.
- Ship set #2 (spare) qualification and acceptance testing March 2019

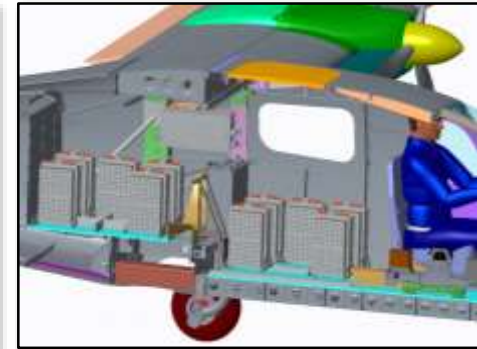
NASA JSC Test Unit With Interstitial Barrier and Heat Spreader (Design Template)



X-57 Battery System Mockups



X-57 Thermal Propagation test Unit  
(2 parallel blocks; 1/8 Module)



Cutaway showing Battery  
Installation  
(10 of the 16 modules)



# 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)

# Single Cell Short Circuit/Thermal Runaway Without Propagation



FLIR Video of Trigger Cell #4 Event (8x speed)  
<https://nasa.gov/x57/technical>

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

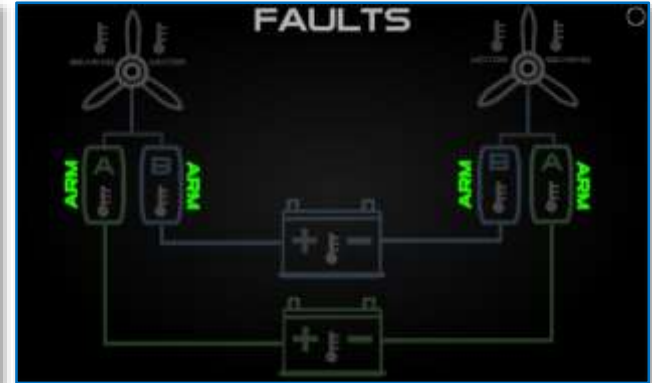
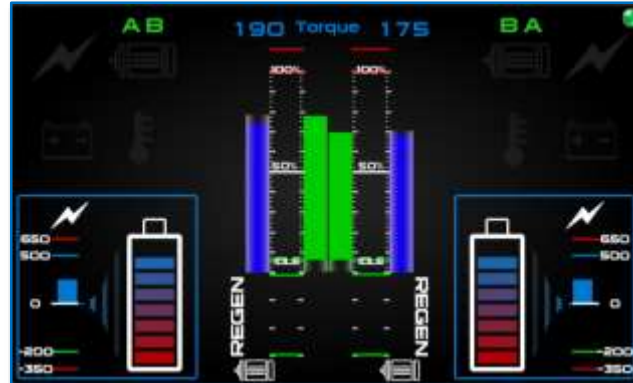
<http://go.nasa.gov/2iz5lYi>

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

# Electric Propulsion Display



- CAN Bus collects data from Motor Controllers, Battery Management System, Throttle Encoders
- Multifunction display provides non-safety critical situational awareness for pilot, detailed debug info for integration and test team.
- Opportunity for industry to come together and establish standard symbology and indication



Battery Management		
Battery Pack A		Battery Pack B
0.0	Voltage	0.0
250	Current	250
86	SOC	88
5.095/5.095	Min/Max CELL Volt	5.095/5.095
0.00	Avg CELL Volt	0.00
0.00	CELL V Std Dev [mV]	0.00
0/0	Min/Max CELL Temp	0/0
0	Avg CELL Temp	0
0.00	CELL Temp Std Dev	0.00
0	BMS Temp	0



# Mod II Vehicle Integration



- Sensors installation: strain gauges, accelerometers, air data probe
- Cockpit modifications: digital display, throttles
- Motor integration: mounts installed, cowling and ducting fabricated



Mod II Wing installation

Cruise Motor Mount and Torque Controllers (Inverters)



Cruise Motor Nacelle & Cowling



NASA Administrator Bridenstine Inspecting X-57 Maxwell



Digital Throttle Quadrant

# Mod III Wing Design

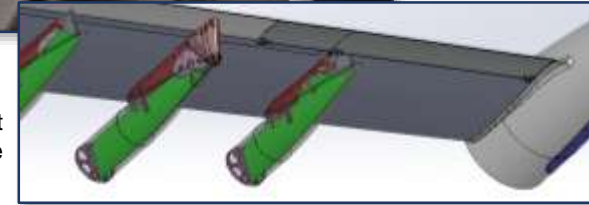
- Composite wing fabricated at Xperimental/California
- Single, continuous main spar carries normal and axial loads (shear and bending)
- Working skin—buckling free—carries torsional loads
- Front and rear spars receive external loads (nacelles and controls)
- Isostatic attachment to the fuselage. No moment transferred with wing bending



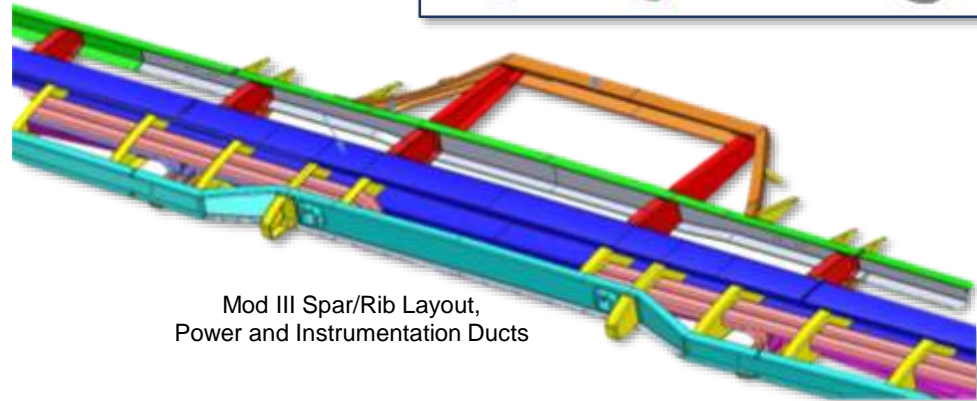
Remote Control Quick Look Stability & Control Model



Mod III wing:  
Bottom Skin,  
Rear Spar



Aileron, Flap, High Lift  
Nacelle Interface



Mod III Spar/Rib Layout,  
Power and Instrumentation Ducts

# Flight Controls and Simulation



- Models electric prop system dynamics in addition to vehicle stability and control
- Aero model validation plan is in work (CFD cases to validate wind tunnel data and to build up uncertainty model)
- Includes failure scenario modeling (e.g. engine out)



Unpowered Stability and Control  
Dynamics Test in the 12' Tunnel at LaRC

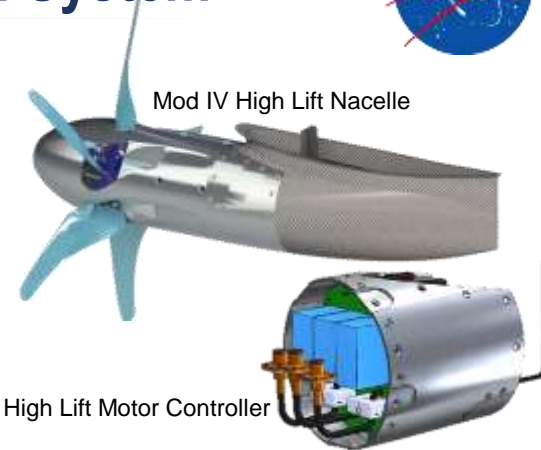


Piloted Simulator at AFRC Includes Flight  
Like Instrument Panels, Switches, MFD

# High Lift/Distributed Electric Propulsion System



- High-lift propeller designed very differently from traditional propellers
  - › Uniform velocity profile vs. most efficient thrust velocity profile
  - › Fold to minimum drag position when not in use
  - › Low-noise features (blade count, tip speed)
- Operation while landing a driver for number, diameter of propellers
  - › More tends to be better
- CFD indicates wing and propeller design will meet or exceed requirements for stall speed
- Critical design and prototype phase underway



CFD Model For Initial  
High Lift Folding  
Propeller Blade  
Performance

Rapid Prototype 3-d  
Printed Model of the Initial  
High Lift Folding Propeller

