NASA's X-57 Maxwell All-Electric Aircraft

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NASA’s X-57 Maxwell
All-Electric Aircraft

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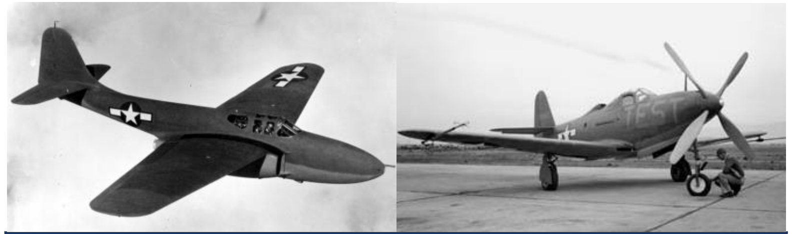
X-57 Principal Investigator

https://nasa.gov/x57/technical

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 the X-57 Maxwell

- The X-57 Maxwell is NASA first all electric experimental aircraft and the agency’s first crewed X- plane in two decades
  - Highly Modified Tecnam P2006T
- Need
  - Advance the Nation's ability to design, test, and determine airworthiness of distributed electric and aero-propulsive coupling technologies, which are a critical enabler of emerging, advanced air mobility markets.
- Goals
  - Goal-1: Share NASA X-57 design & airworthiness process with regulators and standards organizations to further development of distributed electric propulsion (DEP) airworthiness certification approaches and procedures.
  - Goal-2: Establish a reference platform for integrated approaches of distributed electric propulsion technologies, including best practices and lessons learned, to advance the Nation's science and industrial base

Tecnam P2006T

X-57 Maxwell

https://nasa.gov/x57/technical

X-57 Participating Organizations

NASA Langley: Vehicle, Wing, Performance, Controls IPTs

NASA Armstrong: Power, Instrumentation IPTs, Flight Ops

NASA Glenn: Battery Testing, Thermal Analysis, HL Motor Controller Development (Mod IV)

NASA Ames: Aerodynamic analysis

Empirical Sys. Aero.: Prime contractor

Scaled Composites: Mod II Integration (batteries, motors, controllers, cockpit)

Joby Aviation: Mod II Cruise Motor & Controller development

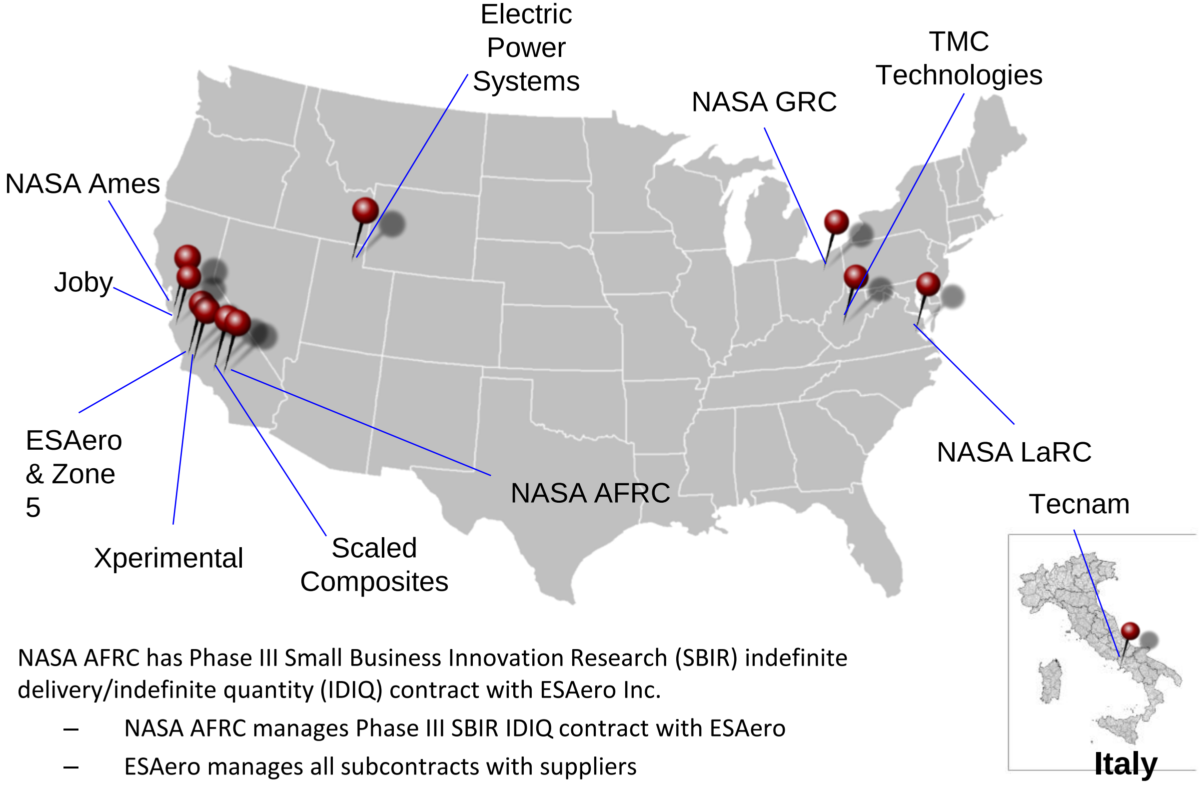
Zone 5: Mod IV HL Motor development

Xperimental: Wing design and manufacturing

Electric Power Sys.: Battery development

TMC Technologies: Software V&V

Tecnam: Baseline COTS airframe

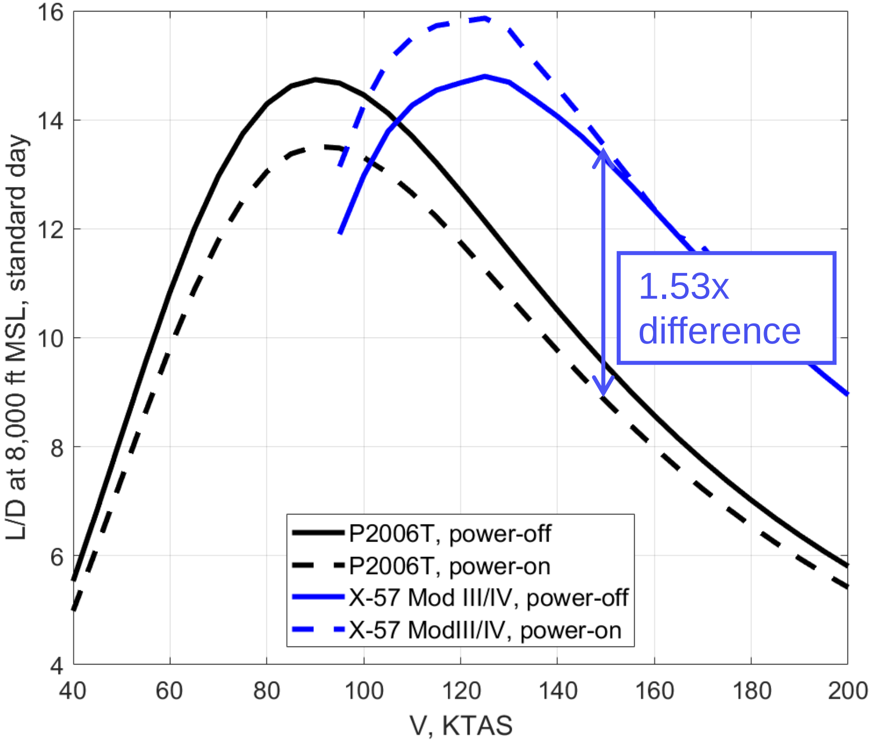


- NASA AFRC has Phase III Small Business Innovation Research (SBIR) indefinite delivery/indefinite quantity (IDIQ) contract with ESAero Inc.
  - NASA AFRC manages Phase III SBIR IDIQ contract with ESAero
  - ESAero manages all subcontracts with suppliers

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

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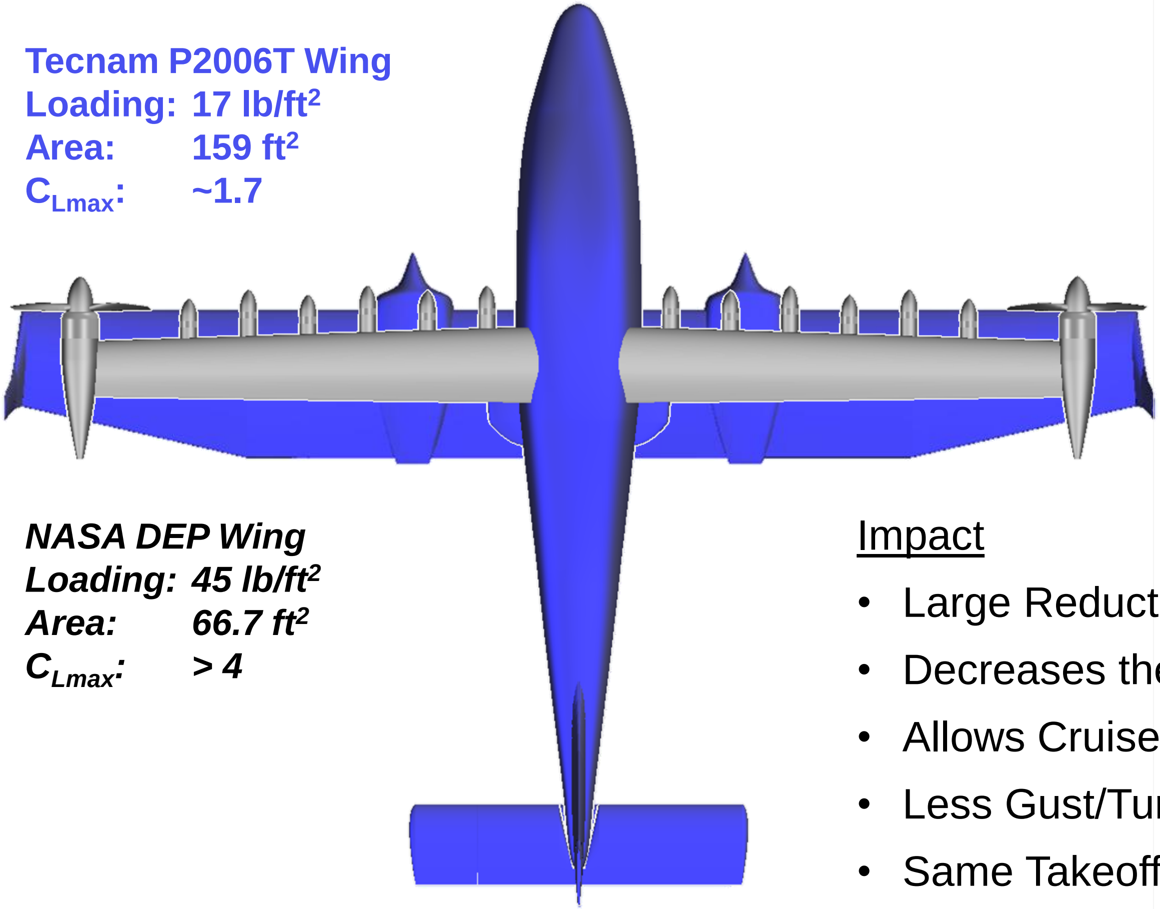
P2006T → X-57



Tecnam P2006T Wing

Loading:	**17 lb/ft^2**
Area:	**159 ft^2**
C_{Lmax}:	**~1.7**

NASA DEP Wing

Loading:	***45 lb/ft^2***
Area:	***66.7 ft^2***
C_{Lmax}:	***> 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

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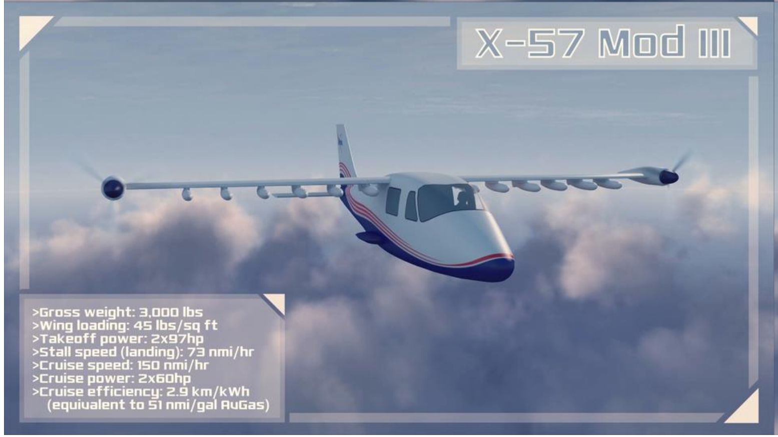
Crawl, Walk, Run

Tecnam P2006T (X-57 Mod I)

- >Gross weight: 2,712 lbs
- >Wing loading: 17 lbs/sq ft
- >Takeoff power: 2x100hp
- >Stall speed (landing): 55 nmi/hr
- >Cruise speed: 135 nmi/hr
- >Cruise power: 2x70hp
- >Cruise efficiency: 13 nmi/gal AuGas (equivalent to 0.7 km/kWh)

X-57 Mod II

- >Gross weight: 3,000 lbs
- >Wing loading: 19 lbs/sq ft
- >Takeoff power: 2x97hp
- >Stall speed (landing): 58 nmi/hr
- >Cruise speed: 135 nmi/hr
- >Cruise power: 2x70hp
- >Cruise efficiency: 2.2 km/kWh (equivalent to 40 nmi/gal AuGas)



X-57 Mod III

- >Gross weight: 3,000 lbs
- >Wing loading: 45 lbs/sq ft
- >Takeoff power: 2x97hp
- >Stall speed (landing): 73 nmi/hr
- >Cruise speed: 150 nmi/hr
- >Cruise power: 2x60hp
- >Cruise efficiency: 2.9 km/kWh (equivalent to 51 nmi/gal AuGas)

X-57 Mod IV

- >Gross weight: 3,000 lbs
- >Wing loading: 45 lbs/sq ft
- >Takeoff power: 2x80hp, 12x13hp
- >Stall speed (landing): 58 nmi/hr
- >Cruise speed: 150 nmi/hr
- >Cruise power: 2x60hp
- >Cruise efficiency: 2.9 km/kWh (equivalent to 51 nmi/gal AuGas)

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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)

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 Manufacturing and Testing Challenges

- Flight motor is Rev K of the design; 11th 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 overstress areas efficiently

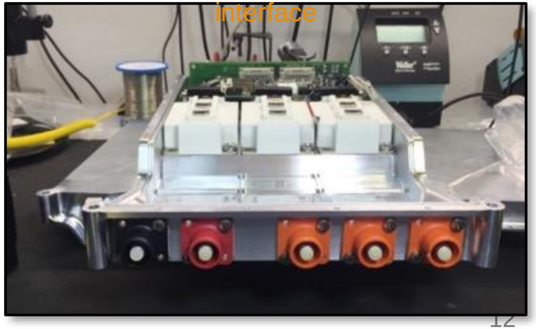
Redesign by integrated NASA and Contractor team to incorporate flight experience and rapid iteration

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



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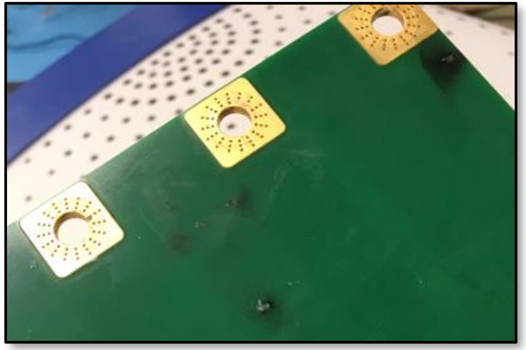
CMC Manufacturing and Testing Challenges

- **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.

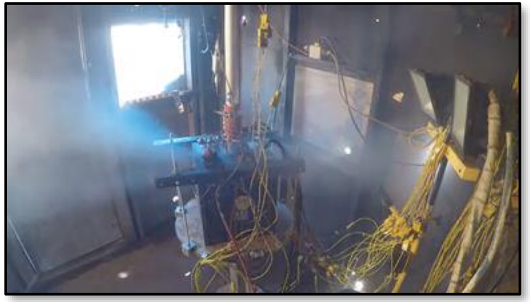


PCB shows evidence of arcing after lab and field testing

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)

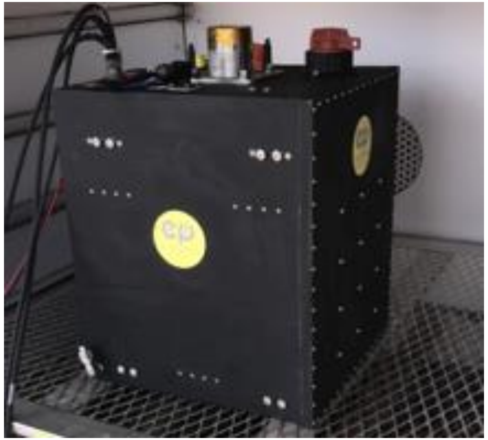


Original battery failed containment propagation test in Dec 2016

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.



X-57 Flight Battery Destructive Testing

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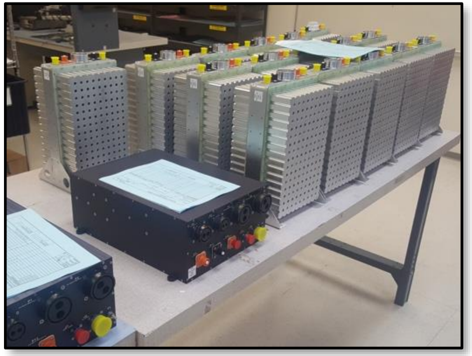
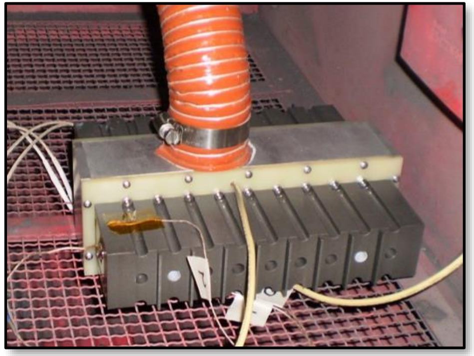
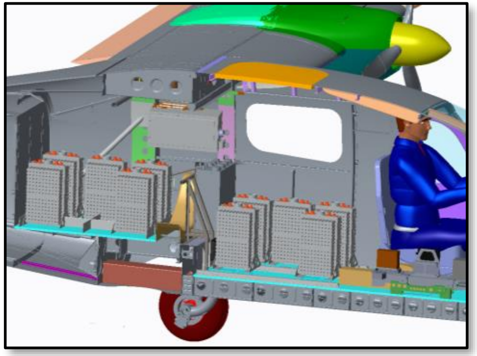
X-57 Flight Batteries (New Approach)

- 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

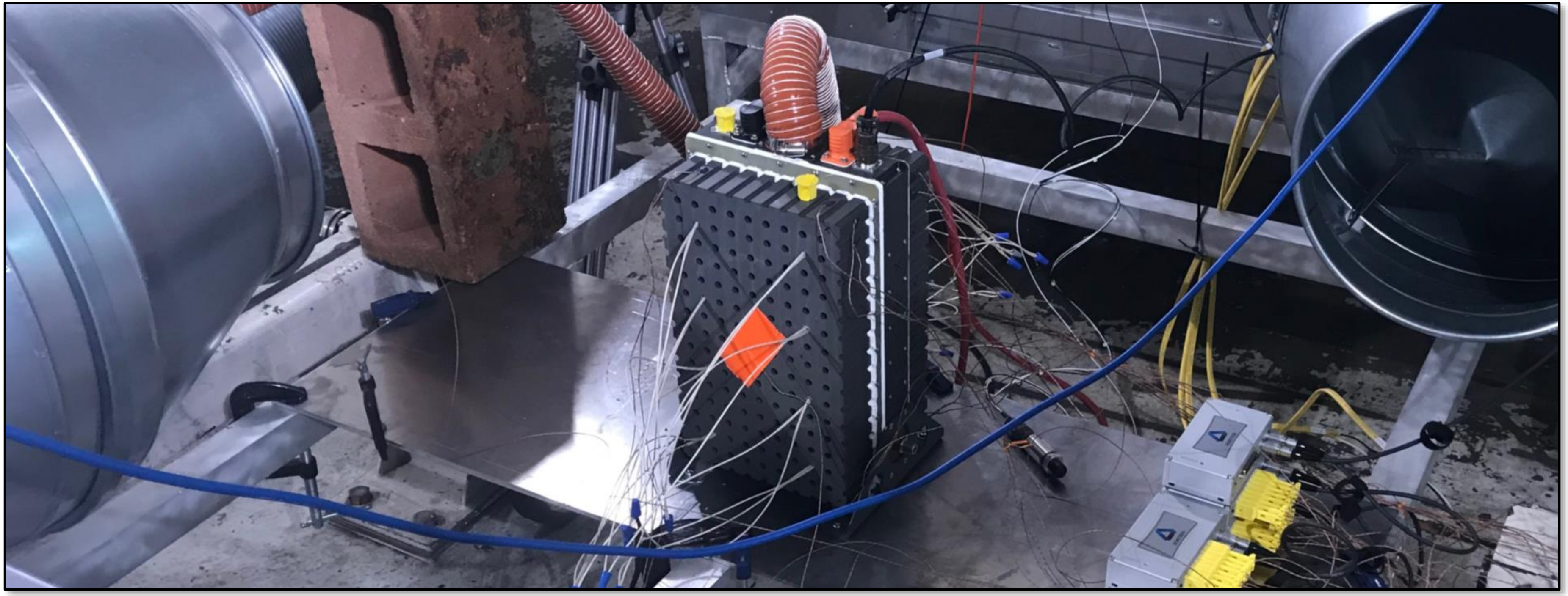

NASA JSC Test Unit With Interstitial Barrier and Heat Spreader (Design Template)


X-57 Battery System Mockups


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


Cutaway showing Battery Installation (10 of the 16 modules)

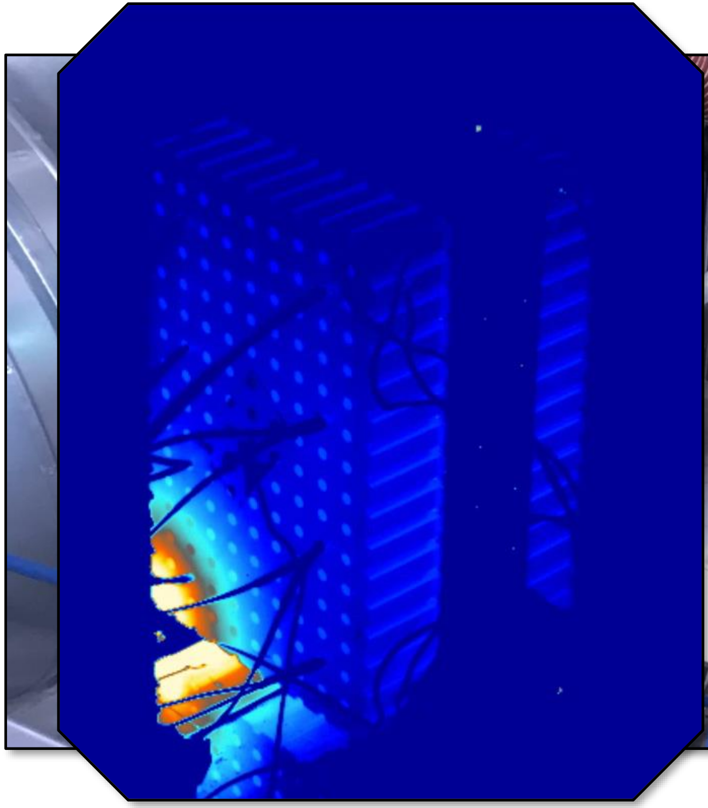
Single Cell Short Circuit/Thermal Runaway Without Propagation



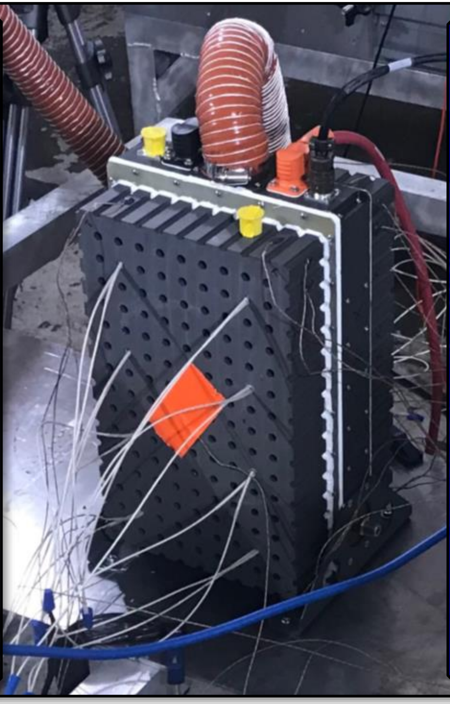
X-57 Thermal Propagation Test Module
(316 flight-like cells, 4 “Trigger Cells”
with internal shorting devices)

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
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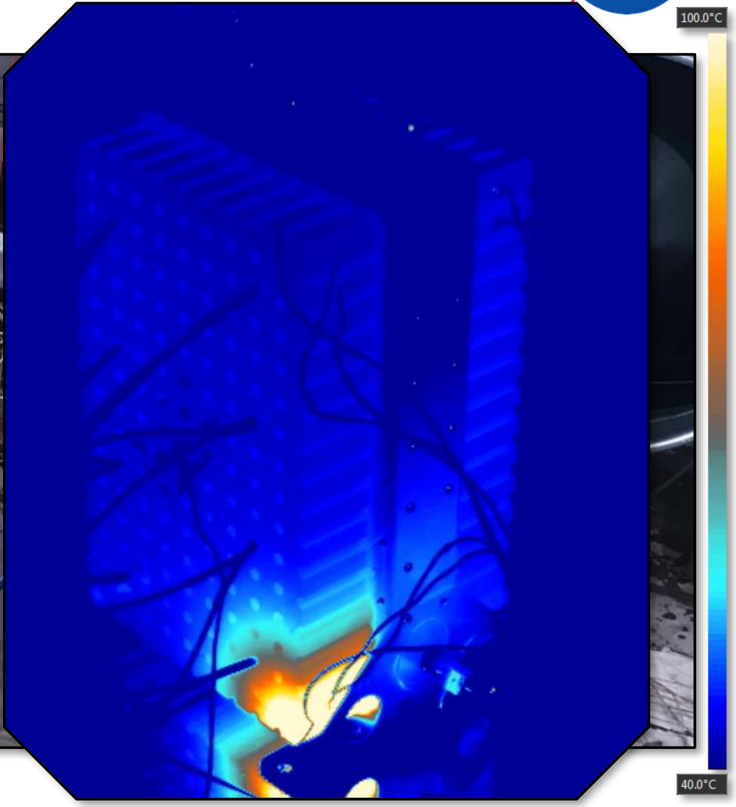
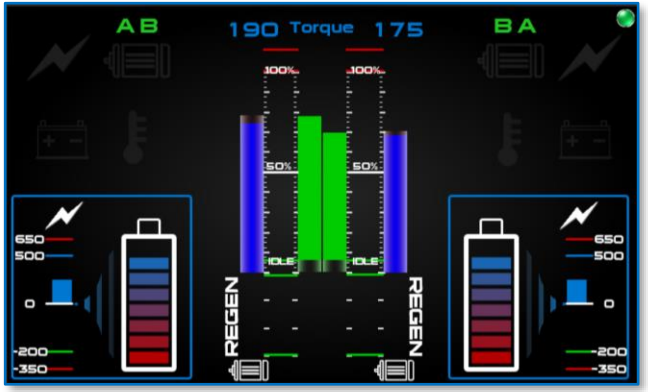


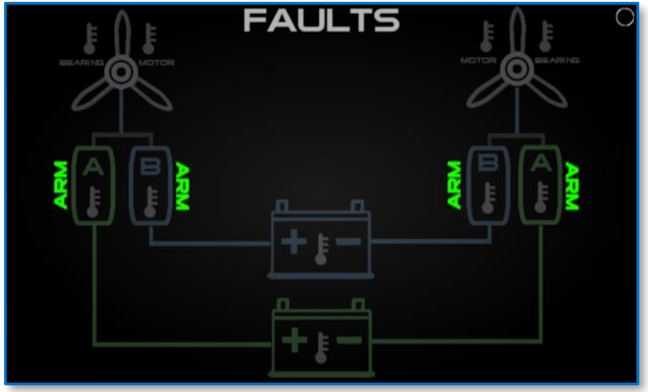
FLIR Video of Trigger Cell #3 Event (8x speed)

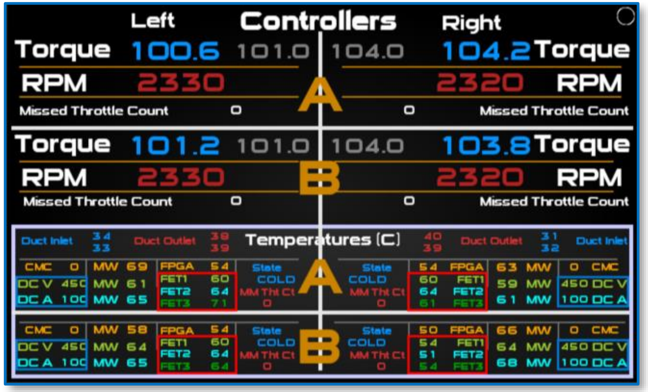
http://go.nasa.gov/2iZ5lYi

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

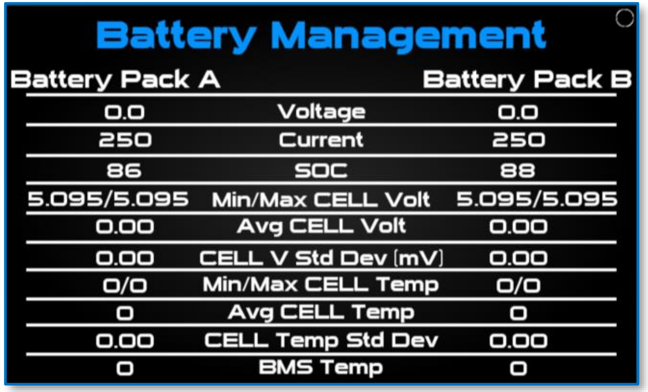





Left		Controllers		Right	
Torque	100.6	101.0	104.0	104.2	Torque
RPM	2330	A		2320	RPM
Missed Throttle Count	0			0	Missed Throttle Count
Torque	101.2	101.0	104.0	103.8	Torque
RPM	2330	B		2320	RPM
Missed Throttle Count	0			0	Missed Throttle Count

Temperatures (C)

Duct Inlet	34 33	Duct Outlet	39 39			40 39	Duct Outlet	31 32	Duct Inlet
CMC 0 DC V 450 DC A 100		MW 69 MW 61 MW 65	FPGA 54 FET1 60 FET2 64 FET3 71	State COLD MM Thl Ct 0	A	State COLD MM Thl Ct 0	54 FPGA 60 FET1 64 FET2 61 FET3	63 MW 59 MW 61 MW	0 CMC 450 DC V 100 DC A
CMC 0 DC V 450 DC A 100		MW 58 MW 64 MW 65	FPGA 54 FET1 60 FET2 64 FET3 64	State COLD MM Thl Ct 0	B	State COLD MM Thl Ct 0	50 FPGA 54 FET1 51 FET2 54 FET3	66 MW 64 MW 68 MW	0 CMC 450 DC V 100 DC A


Battery Management

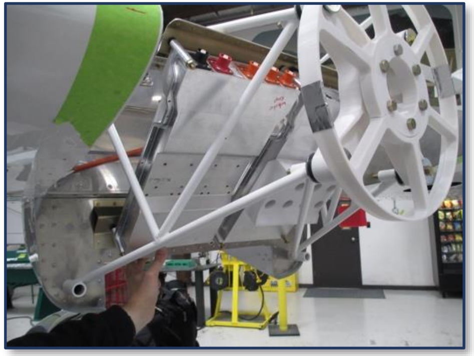
Battery Pack A		Battery Pack B
0.0	Voltage	0.0
250	Current	250
86	SOC	88
5.095/5.095	Min/Max CELL Volt	5.095/5.095
0.00	Avg CELL Volt	0.00
0.00	CELL V Std Dev (mV)	0.00
0/0	Min/Max CELL Temp	0/0
0	Avg CELL Temp	0
0.00	CELL Temp Std Dev	0.00
0	BMS Temp	0

https://nasa.gov/x57/technical

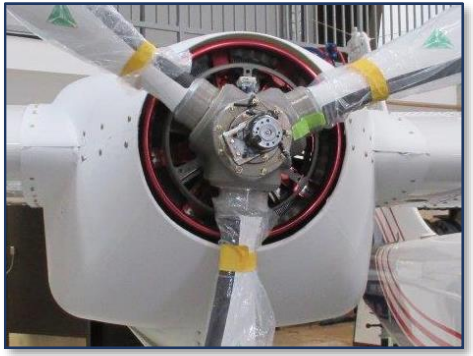
Mod II Vehicle Integration

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

Cruise Motor Mount and Torque Controllers (Inverters)



Cruise Motor Nacelle & Cowling



Mod II Wing installation

NASA Administrator Bridenstine Inspecting X-57 Maxwell

Digital Throttle Quadrant

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

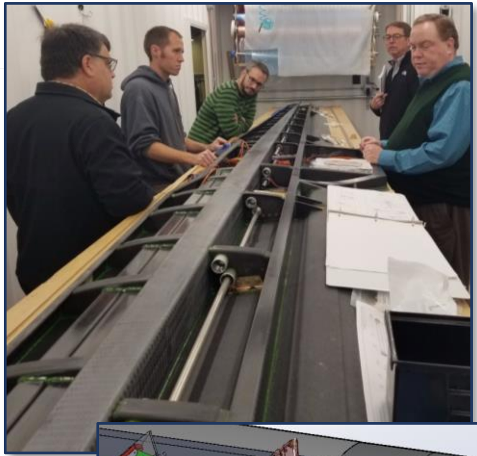
- Matures Distributed Electric Propulsion system architectures
  - NASA will tackle technical challenges operating multiple motors in configurations relevant to industry (UAM, Thin Haul)
  - Validates higher power electric propulsion system operation (120 kW in Mod II → 250 kW in Mod IV)
  - Pathfinder 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

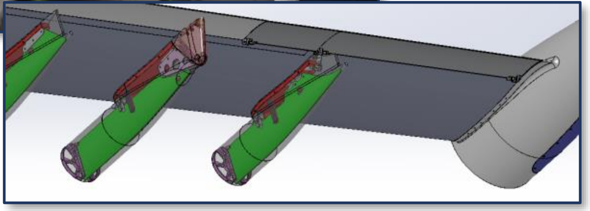
https://nasa.gov/x57/technical

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

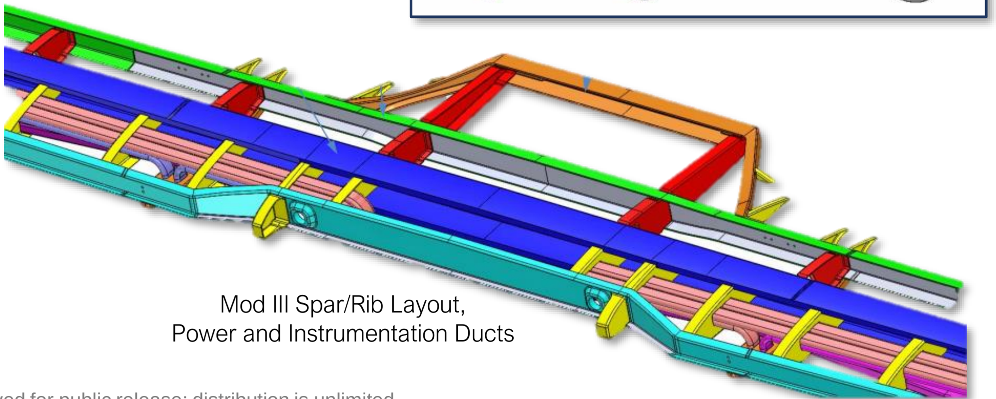


Mod III wing: Bottom Skin, Rear Spar



Aileron, Flap, High Lift Nacelle Interface

Wing Delivery and Prep for GVT and Loads Tests



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)

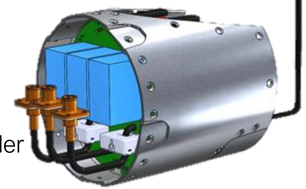
Unpowered Stability and Control Dynamics Test in the 12' Tunnel at LaRC

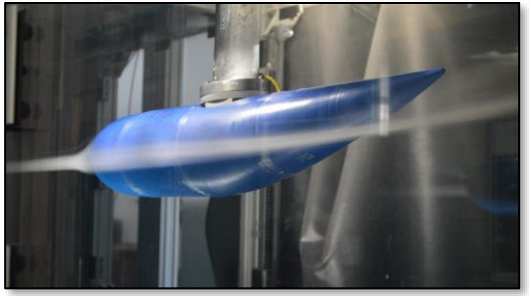
Piloted Simulator at AFRC Includes Flight Like Instrument Panels, Switches, MFD

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


Mod IV High Lift Nacelle


High Lift Motor Controller

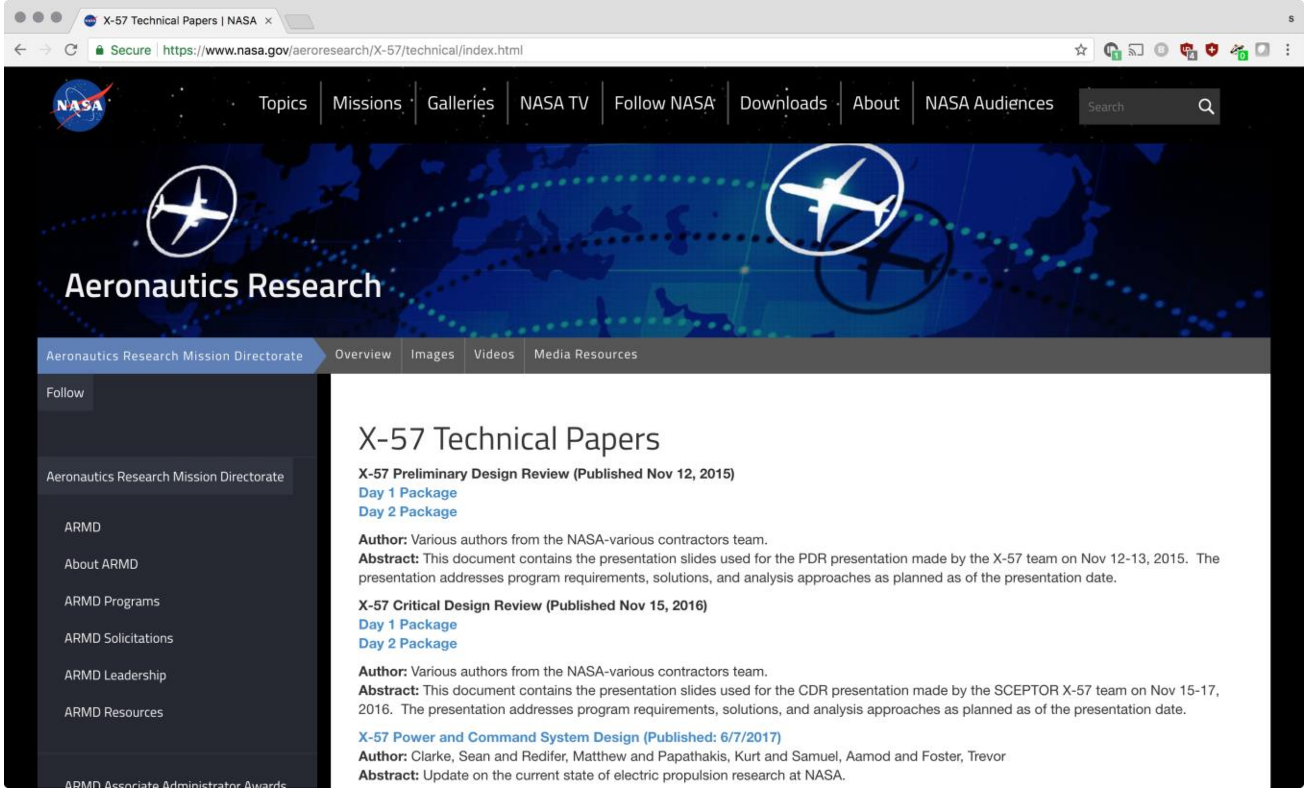

CFD Model For Initial High Lift Folding Propeller Blade Performance

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

https://nasa.gov/x57/technical

Further Reading

https://nasa.gov/x57/technical



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, 2015. 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 Redifer, Matthew and Papathakis, Kurt and Samuel, Aamod and Foster, Trevor
Abstract: Update on the current state of electric propulsion research at NASA.

National Aeronautics and Space Administration

NASA's X-57 Maxwell
All-Electric Aircraft

Sean Clarke, P.E.
X-57 Principal Investigator

https://nasa.gov/x57/technical

NASA's X-57 Maxwell All-Electric Aircraft

PRESENTED BY:

Sean Clarke, P.E.

Senior Research Systems Development Engineer, NASA

MODERATED BY:

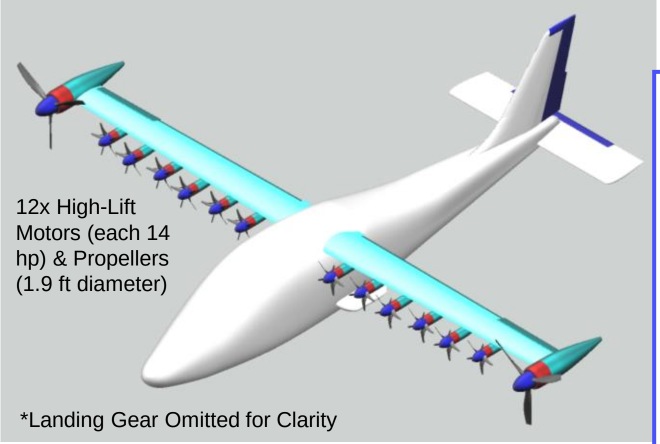
Steve Redifer

2020-04-21

Homeland Defense & Security
Information Analysis Center

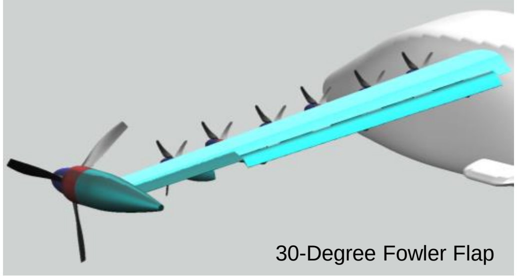
X-57 Walkaround

Landing Configuration*



12x High-Lift Motors (each 14 hp) & Propellers (1.9 ft diameter)

*Landing Gear Omitted for Clarity



30-Degree Fowler Flap

Tecnam P2006T Fuselage & Tail

3,000 lb Gross Weight

32.8 ft Span
(36.6 ft w/ Props)

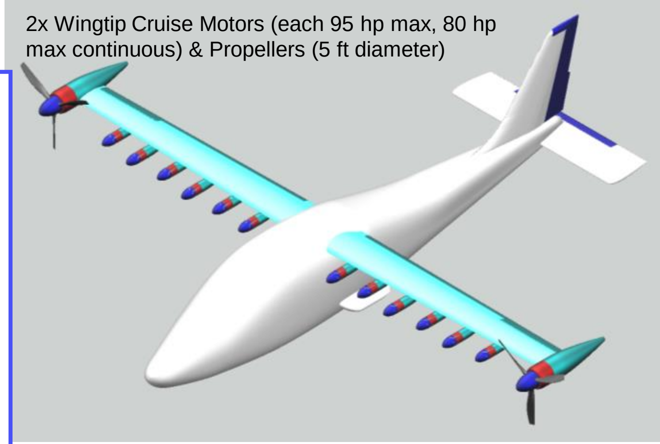
150 KTAS Cruise at 8,000 ft MSL

58 KCAS Stall
(73 KCAS Unblown)

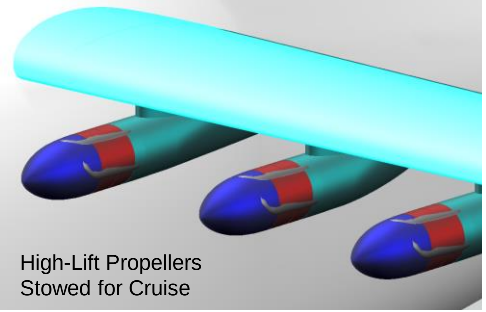
167 KCAS Max Level Flight Speed

15,000 ft Ceiling

Cruise Configuration



2x Wingtip Cruise Motors (each 95 hp max, 80 hp max continuous) & Propellers (5 ft diameter)



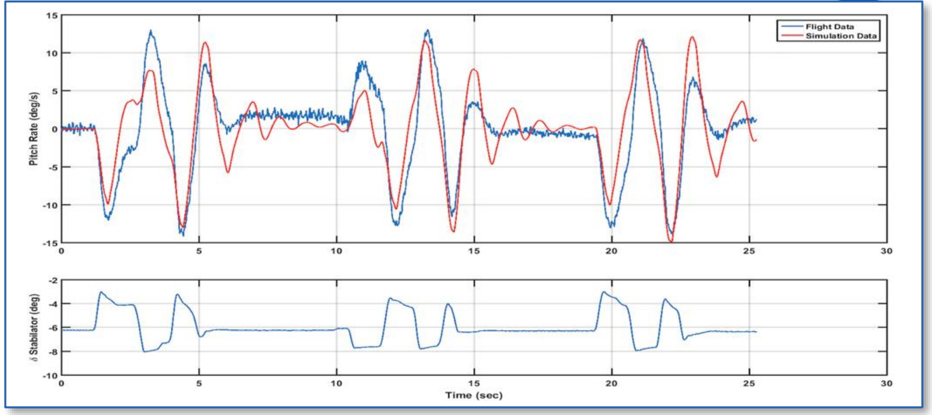
High-Lift Propellers Stowed for Cruise

https://nasa.gov/x57/technical

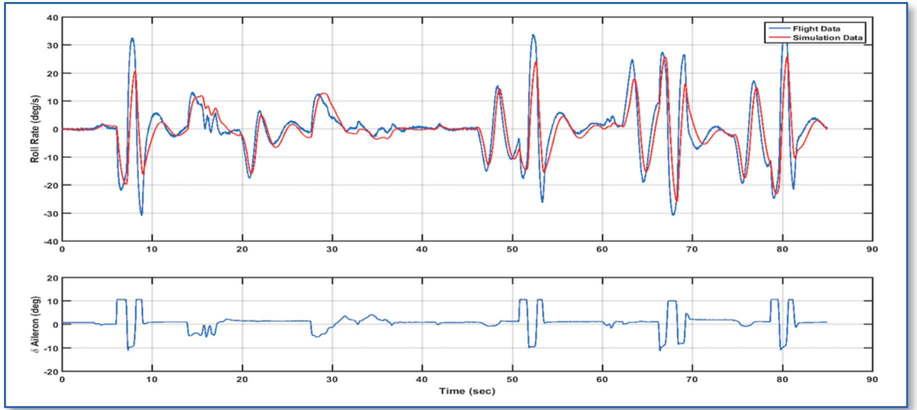
Mod I: Flight Test at NASA

Test flights conducted on a commercial Tecnam P2006T

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



Simulation vs Flight Response, pitch rate



Simulation vs Flight Response, roll rate

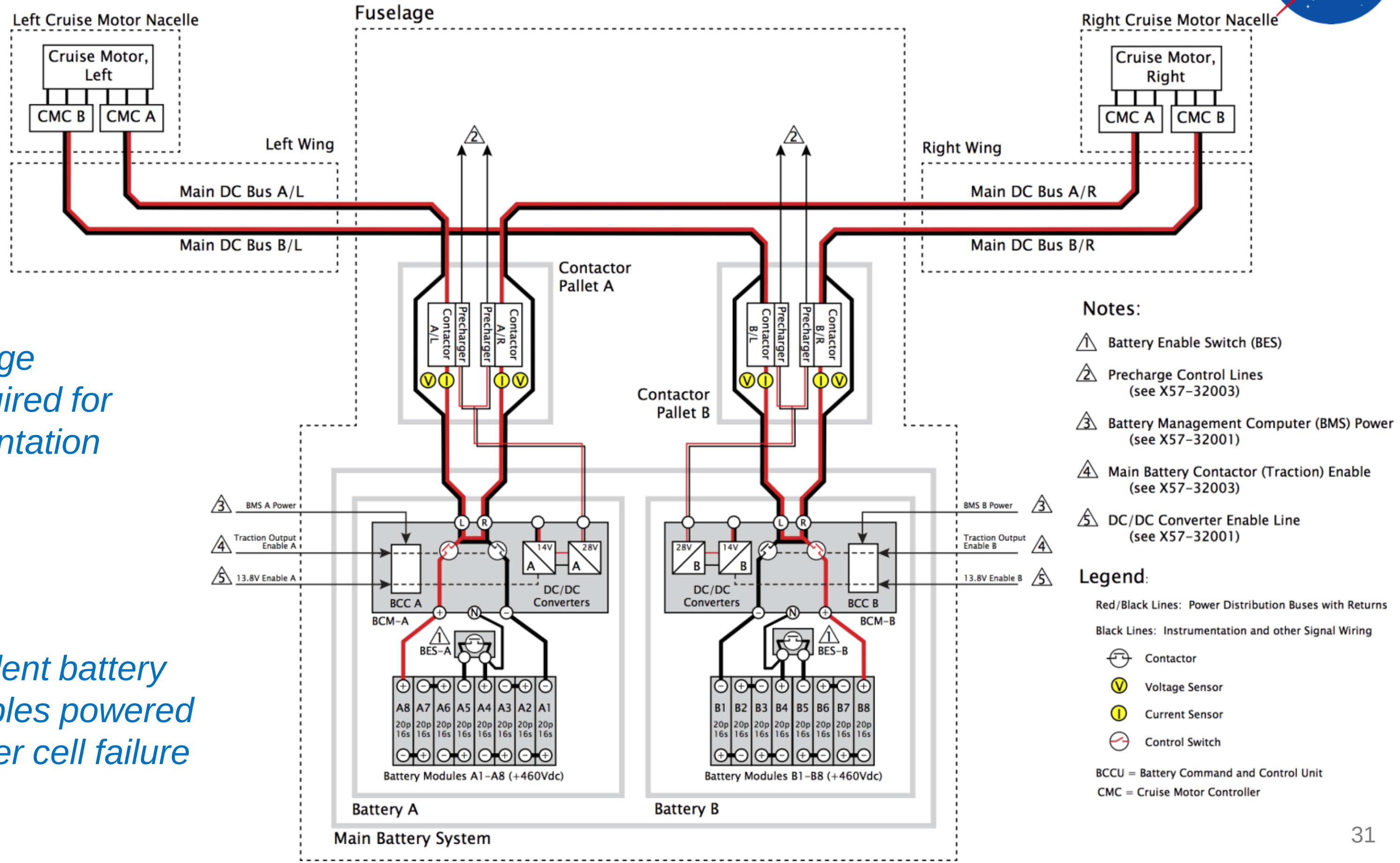
https://nasa.gov/x57/technical

Electrified Architecture with Redundancy

Dual inverter reduces failure severity

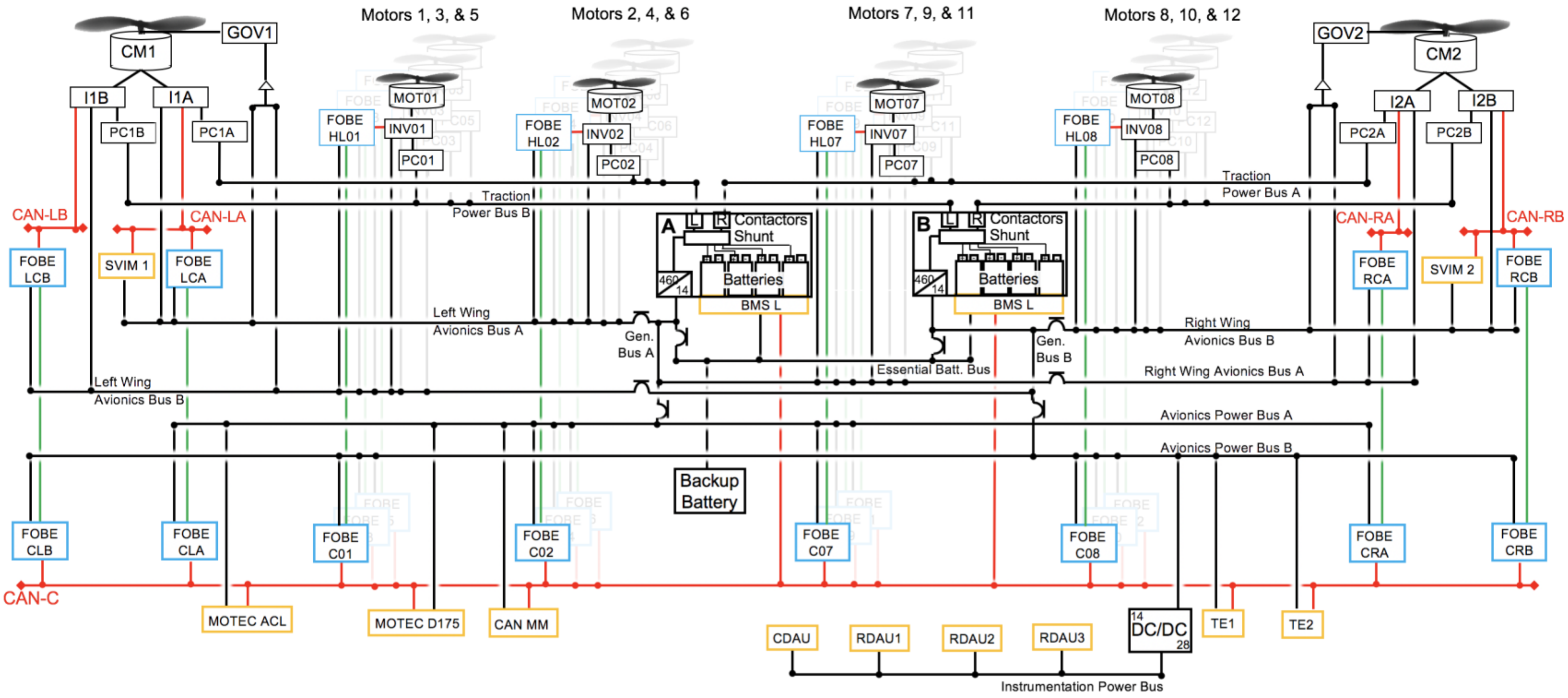
High voltage contactors required for hazard segmentation

Independent battery packs enables powered landing after cell failure



https://nasa.gov/x57/technical

Power and Command Interconnection Diagram

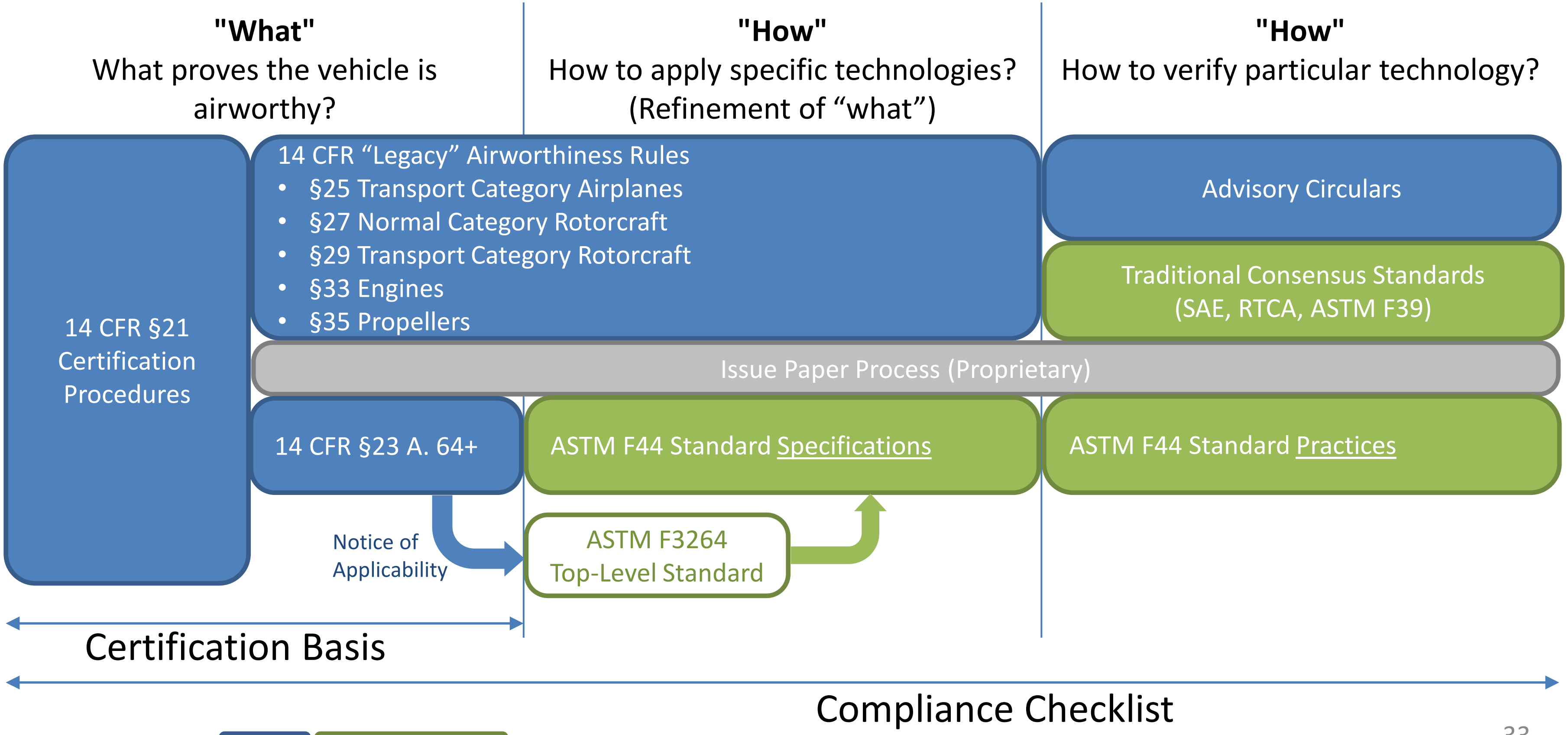


Large number of interfaces even for "simple" vehicle architectures

Failure Analyses and Tests validate redundancy and segmentation approach

Performance-Based Airworthiness Approach

In Response to Small Airplane Revitalization Act of 2013



"What"
What proves the vehicle is airworthy?

"How"
How to apply specific technologies?
(Refinement of “what”)

"How"
How to verify particular technology?

14 CFR §21 Certification Procedures

14 CFR “Legacy” Airworthiness Rules
- §25 Transport Category Airplanes
- §27 Normal Category Rotorcraft
- §29 Transport Category Rotorcraft
- §33 Engines
- §35 Propellers

Advisory Circulars

Traditional Consensus Standards (SAE, RTCA, ASTM F39)

Issue Paper Process (Proprietary)

14 CFR §23 A. 64+

ASTM F44 Standard Specifications

ASTM F44 Standard Practices

Notice of Applicability

ASTM F3264 Top-Level Standard

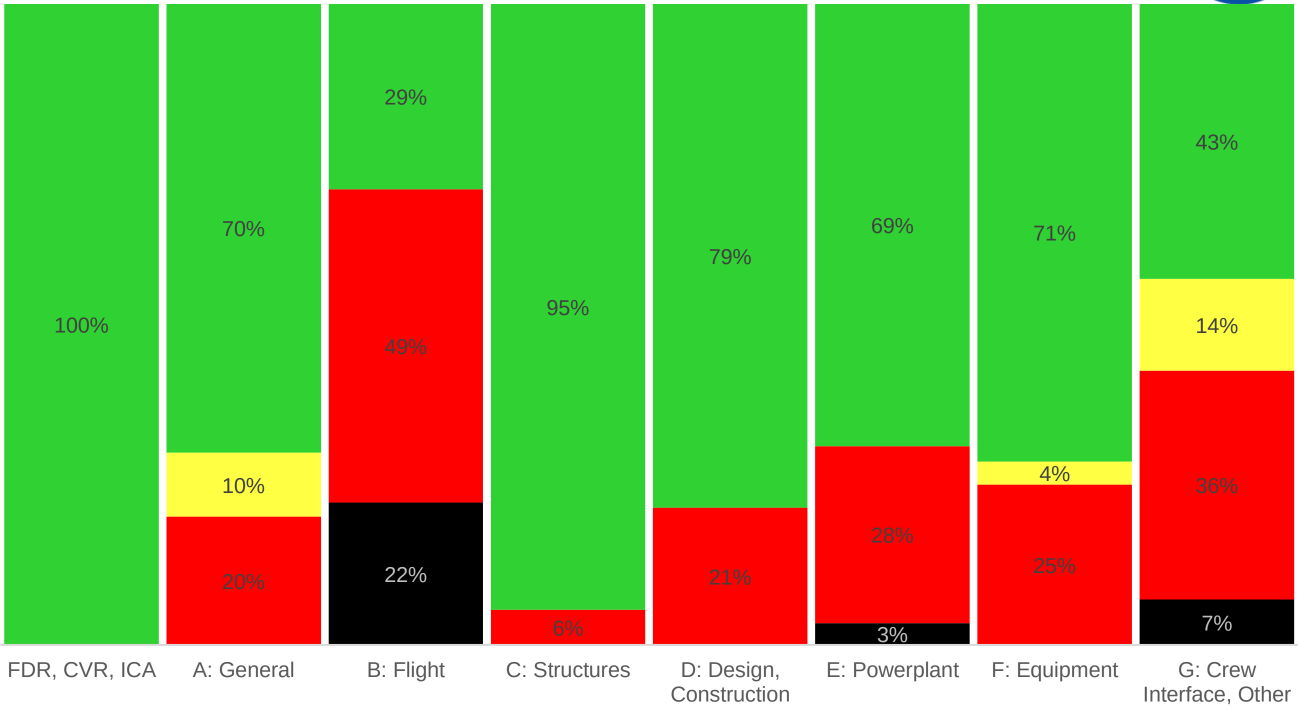
Certification Basis

Compliance Checklist

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

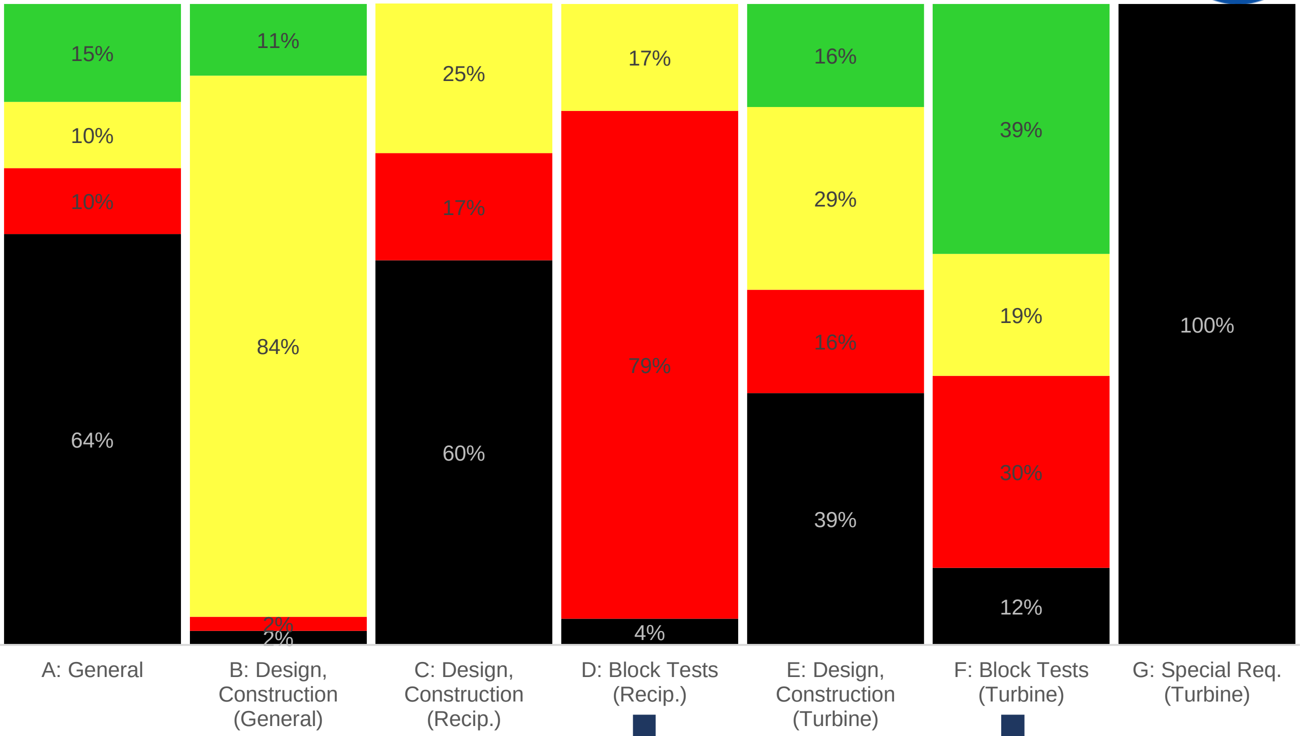
Changes needed for Electrified Aircraft
🟩 None
🟨 Minor tailoring
🟥 Major Revision
⬛ Remove (N/A)

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