National Aeronautics and Space Administration

X-57 Maxwell

NASA's Distributed Electric Propulsion Research Platform

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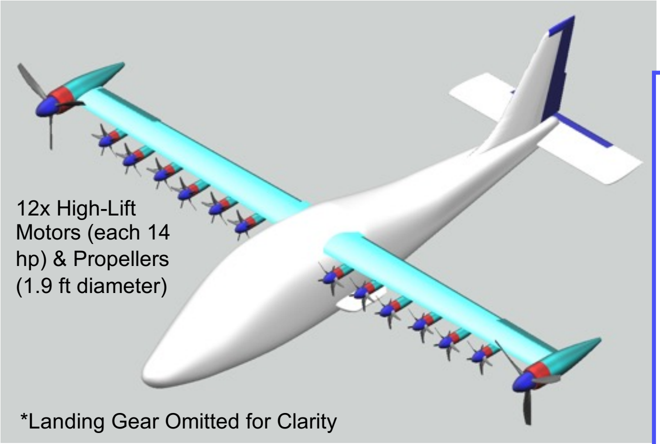
S&T Electrical Systems and Wiring Inter-Agency Meeting

https://nasa.gov/x57/technical

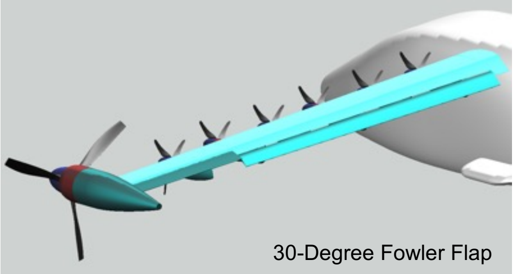
X-57 Walkaround

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)

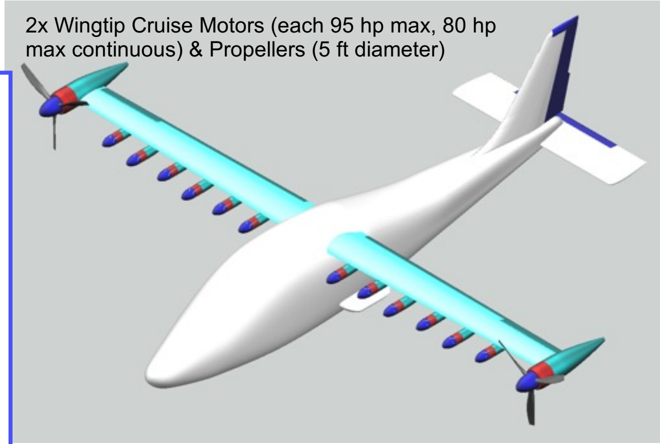
150 KTAS Cruise at
8,000 ft MSL

58 KCAS Stall
(73 KCAS Unblown)

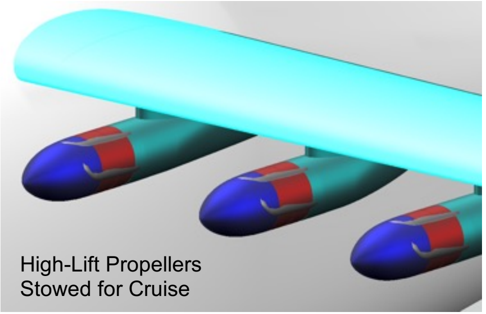
167 KCAS Max Level
Flight Speed

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

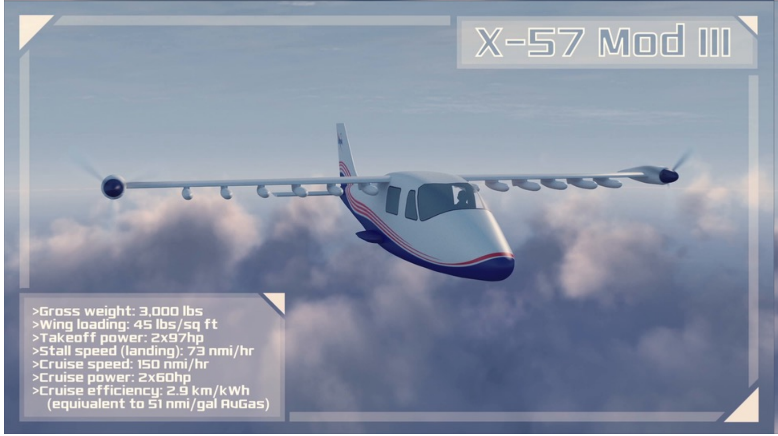
Crawl, Walk, Run

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 AvGas (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 AvGas)



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 AvGas)

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 AvGas)

https://nasa.gov/x57/technical

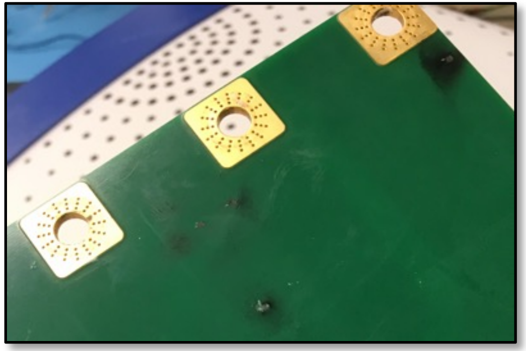
Motivation for X-57 Mod II; Retiring Electric Propulsion Barriers

- 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
- Expand 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)

Inverter/Motor Controller Challenges

- Ground tests (environmental lab, Airvolt static test stand, regenerative dynamometer) showed inverter was thermally marginal for the X-57 mission, FET module selection was inadequate for flight environment, and gate driver margin unacceptable. ntrs.nasa.gov/citations/20205002485
- Required controller inverter subsystem redesign (FETs, drivers, internal power distribution, feedback control sensors). Led by NASA in-house.
- **Manufacturing Challenges**
  - Long component lead-times due to high demand and limited production. Worse in 2020/2021 for specialized parts as alternatives are not practical.
  - Sub-contractors process control short of aircraft fabrication requirements.
  - Dyno build/test iterations essential to establishing margin to reduce failure rates.
- **Testing Challenges**
  - Flight-like environmental testing not practical at high power. Reduced power may require longer dwell time to precipitate latent defects.
  - Lack of insight into the control logic due to the COTS nature of the core controller 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)

Cruise Motor Manufacturing and Testing Challenges

- Flight motor is Rev K of the design; 11th major design iteration. (AIAA 2016-3925)
- Passively air-cooled electric motor presents testing and analysis challenges. (AIAA 2017-3783, 3784)
- Tuning performance map to match motor and inverter (efficiency and torque) difficult due to EMI and high frequencies.
- Motor assembly is a laborious process. Was not expected for a mechanically simple system.
- First order thermal analysis did not show margin; full CFD iteration with nacelle cooling system was needed.

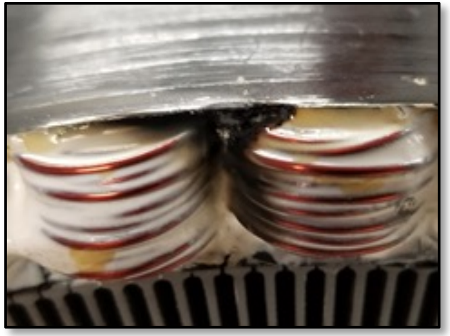
Damage to stator wiring from contact with mounting bolts

Self-induced vibration exposes insulation overstress areas efficiently

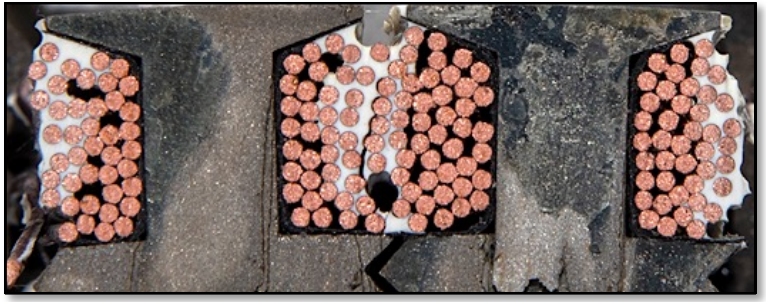
Redesign by integrated NASA and Contractor team to incorporate flight experience and rapid iteration

Cruise Motor (CM) Technical Challenges

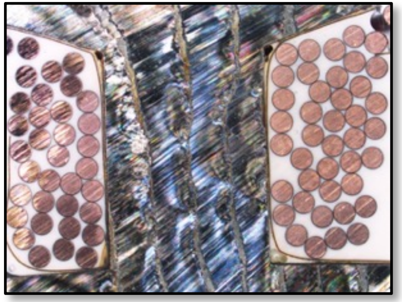
- **Stator insulation flaws (fixed via unplanned fab cycle)**
  - Stator laminate stack up design introduced high-stress at end-turn areas. Phase-to-structure isolation faults after prolonged operation.
  - Potting process control did not ensure sufficient penetration into winding bundle. New fabrication run improved from 20% to 90% penetration, but pockets still exist which reduce thermal margin



Electrical isolation failure during HV vehicle test produced internal arc fault



Original motor winding poor epoxy penetration (typical throughout)



Improved fabrication process (typical for 80% of samples)

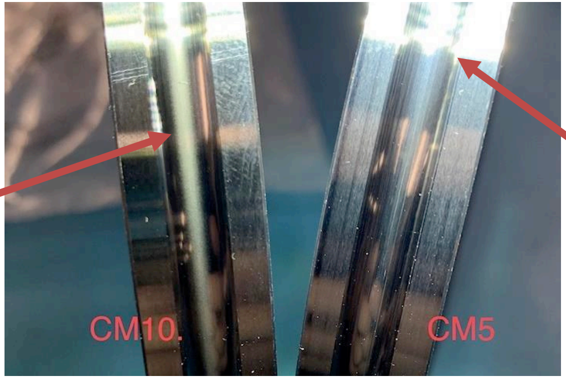
Improved fabrication process still exhibits some voids

Cruise Motor (CM) Technical Challenges

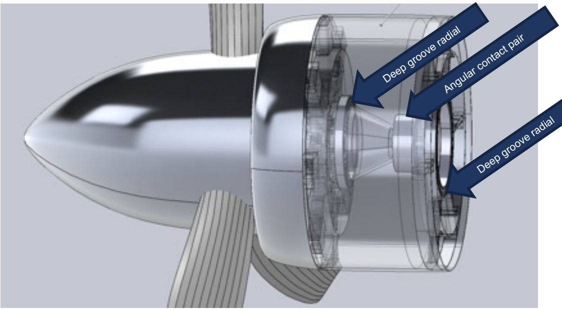
- **Motor bearing design gaps**
  - Forward guide bearing not rated for X-57 motor speed range. Conflicting data between manufacturer and distributors. Replacement part is not sealed and may be less resistant to FOD.
  - Bearings are not preloaded by rotor design. Thrust, inertial, and gravity loads add some bearing load, but not enough to meet spec, and not in bench configuration (e.g., dyno). Expect this to lead to increased wear and early failure (imposes additional monitoring and maintenance overhead).

Cruise Motor endurance testing on NASA Airvolt stand at AFRC

Teardown inspection after an overspeed event shows 'frosting' wear pattern



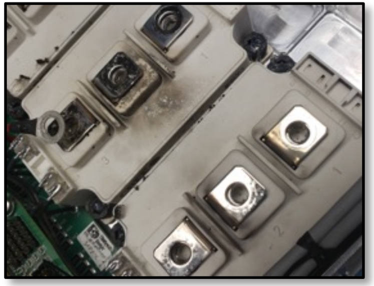
CM5 rotor inspected after fewer hours. Wear shows sliding / wiping pattern due to poor loading contact



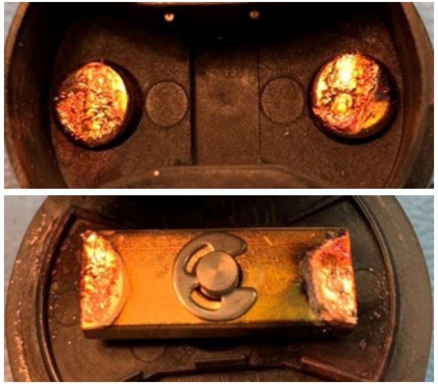
Rotor with Bearings

High Voltage Contactor Failure

- Inverter MOSFET failure caused intermittent faults on DC distribution bus with increasing frequency and persistence before eventual hard fault
- Bus isolation contactor feeding that CMC was exposed to current above it's rating transiently before protection circuitry reacted. Bus could not be isolated from powerplant.



Cruise Motor endurance testing on NASA Airvolt stand at AFRC



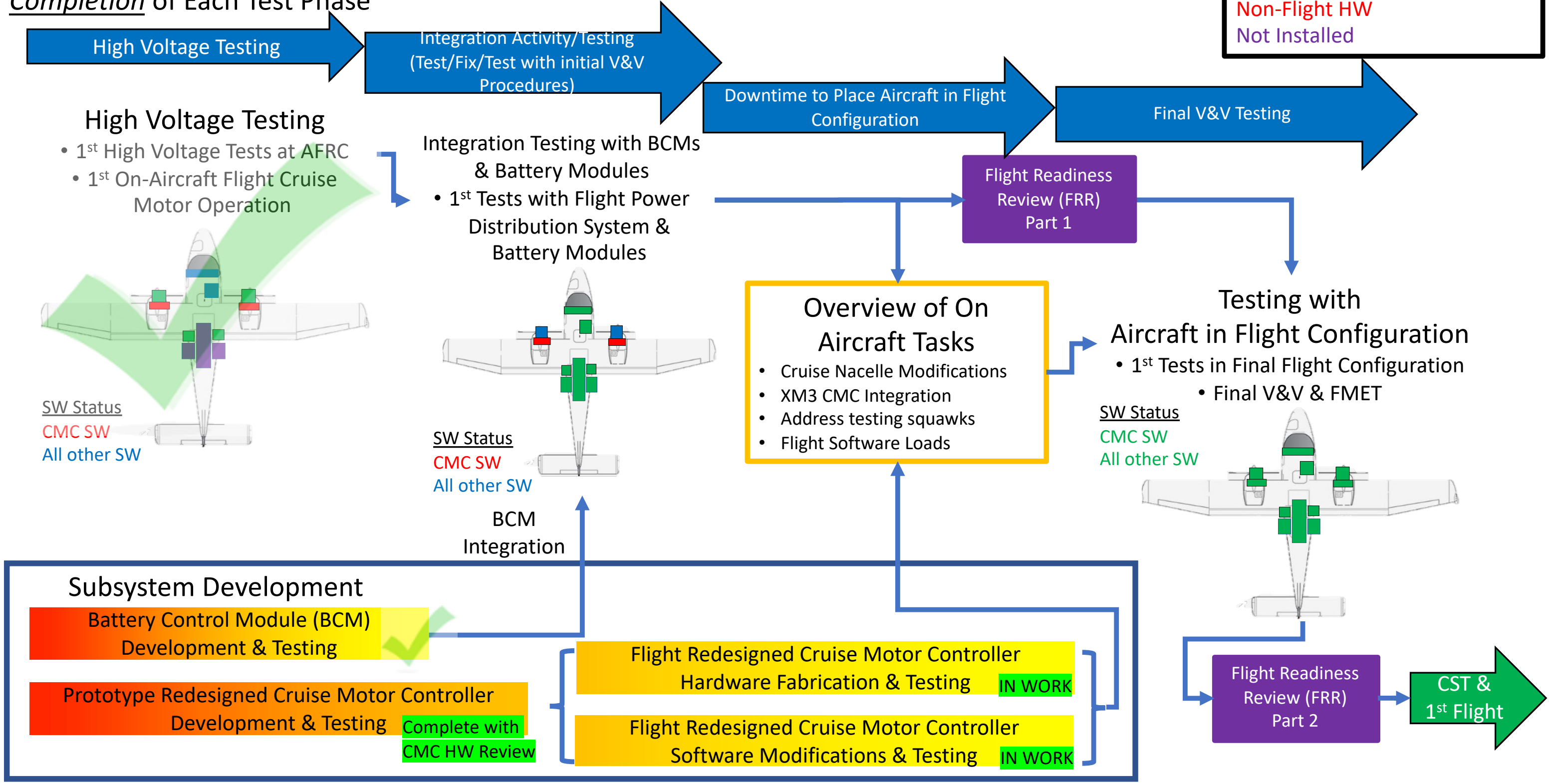
Failed contactor (brazed closed)

Operational contactor

Integration Status and Preparation for Flight

X-57 System Test Approach & Configurations to Flight & Summary of Hardware & Software Status at *Completion* of Each Test Phase

Subsystem Maturity Key
Flight Configuration
Requires Minor Mod for Flight
Non-Flight HW
Not Installed



High Voltage Testing → Integration Activity/Testing (Test/Fix/Test with initial V&V Procedures) → Downtime to Place Aircraft in Flight Configuration → Final V&V Testing

High Voltage Testing

- 1st High Voltage Tests at AFRC
- 1st On-Aircraft Flight Cruise Motor Operation

SW Status
CMC SW
All other SW

Integration Testing with BCMs & Battery Modules

- 1st Tests with Flight Power Distribution System & Battery Modules

SW Status
CMC SW
All other SW

BCM Integration

Flight Readiness Review (FRR) Part 1

Overview of On Aircraft Tasks

- Cruise Nacelle Modifications
- XM3 CMC Integration
- Address testing squawks
- Flight Software Loads

Testing with Aircraft in Flight Configuration

- 1st Tests in Final Flight Configuration
- Final V&V & FMET

SW Status
CMC SW
All other SW

Subsystem Development

Battery Control Module (BCM) Development & Testing

Prototype Redesigned Cruise Motor Controller Development & Testing — Complete with CMC HW Review

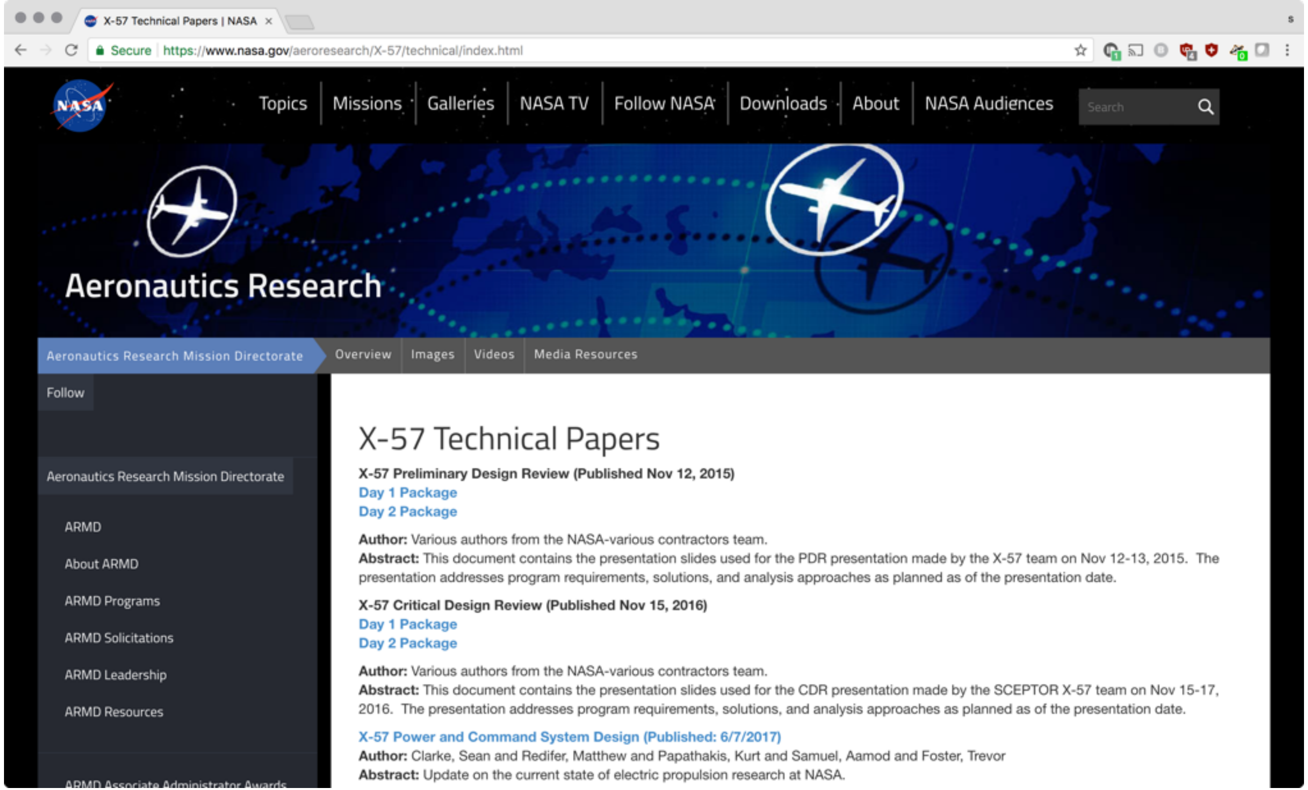
Flight Redesigned Cruise Motor Controller Hardware Fabrication & Testing — IN WORK

Flight Redesigned Cruise Motor Controller Software Modifications & Testing — IN WORK

Flight Readiness Review (FRR) Part 2 → CST & 1st Flight

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

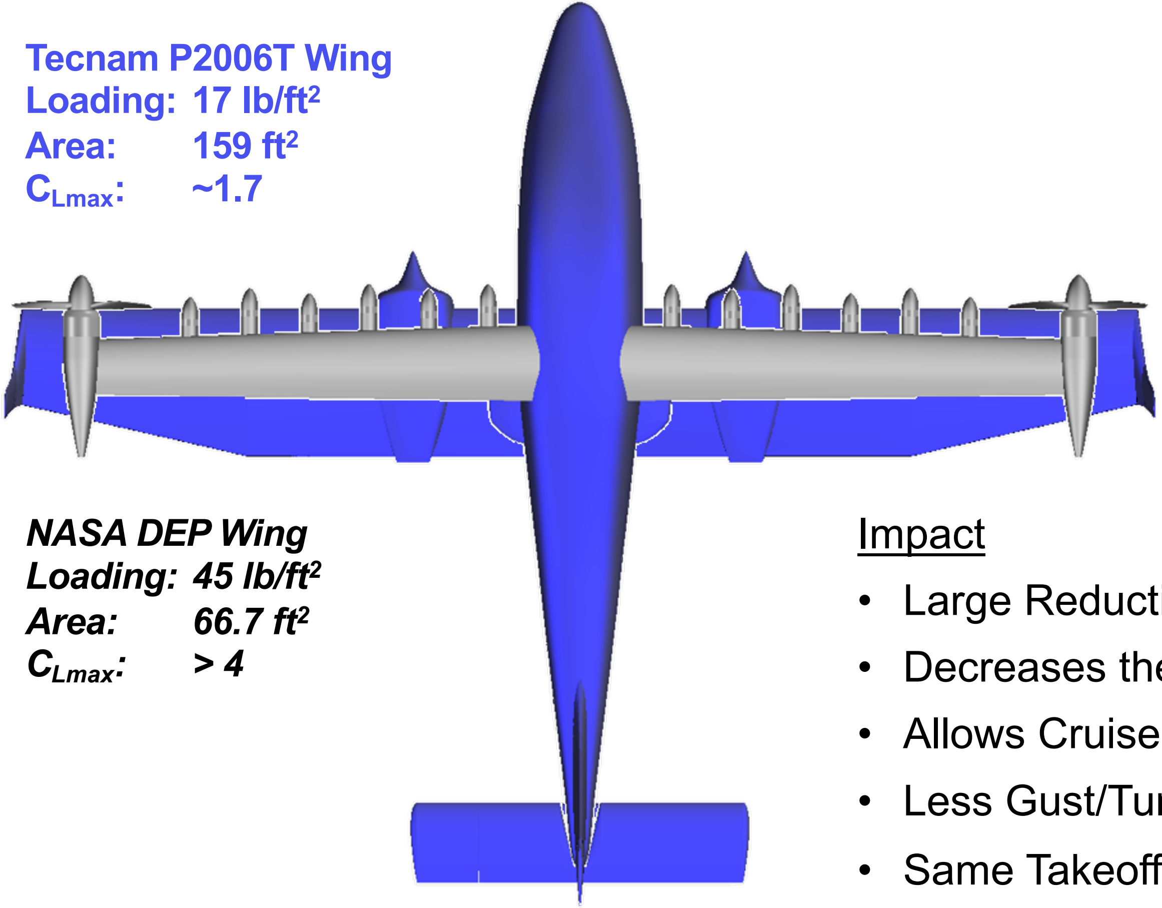
Author: Various authors from the NASA-various contractors team.
Abstract: This document contains the presentation slides used for the PDR presentation made by the X-57 team on Nov 12-13, 2015. The presentation addresses program requirements, solutions, and analysis approaches as planned as of the presentation 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.

P2006T → X-57



Tecnam P2006T Wing
Loading: 17 lb/ft^2
Area: 159 ft^2
C_{Lmax}: ~1.7

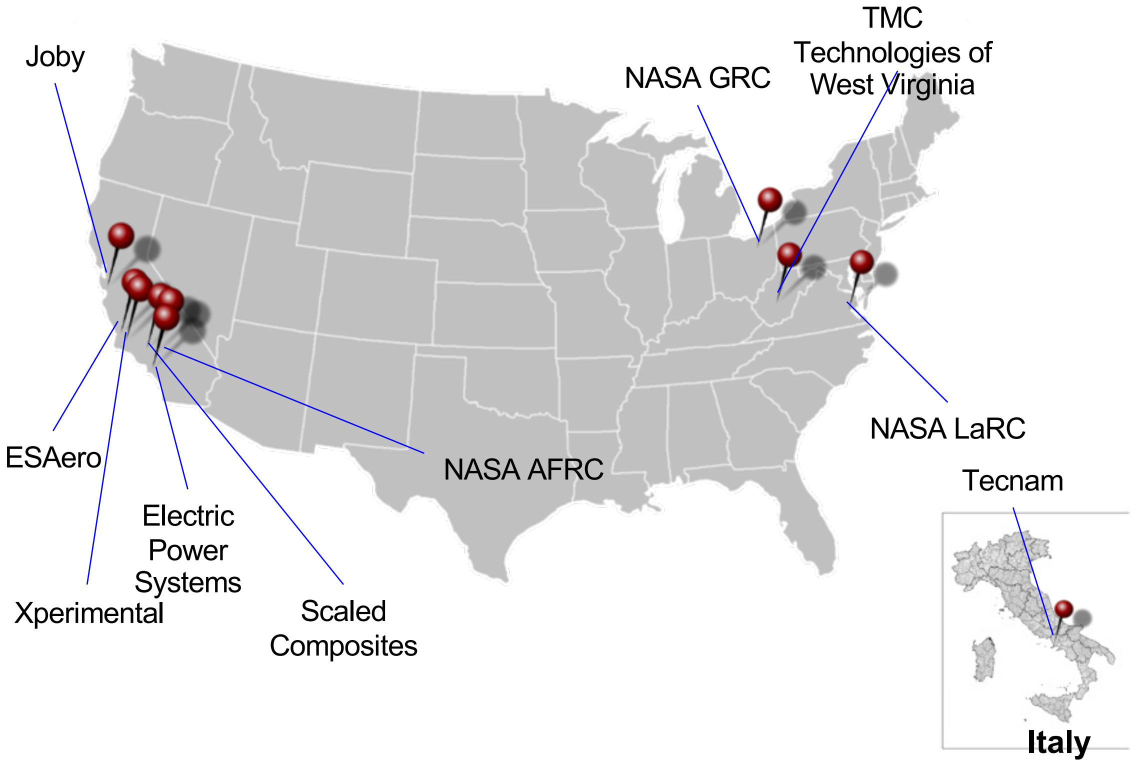
NASA DEP Wing
Loading: 45 lb/ft^2
Area: 66.7 ft^2
C_{Lmax}: > 4

Impact

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

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



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

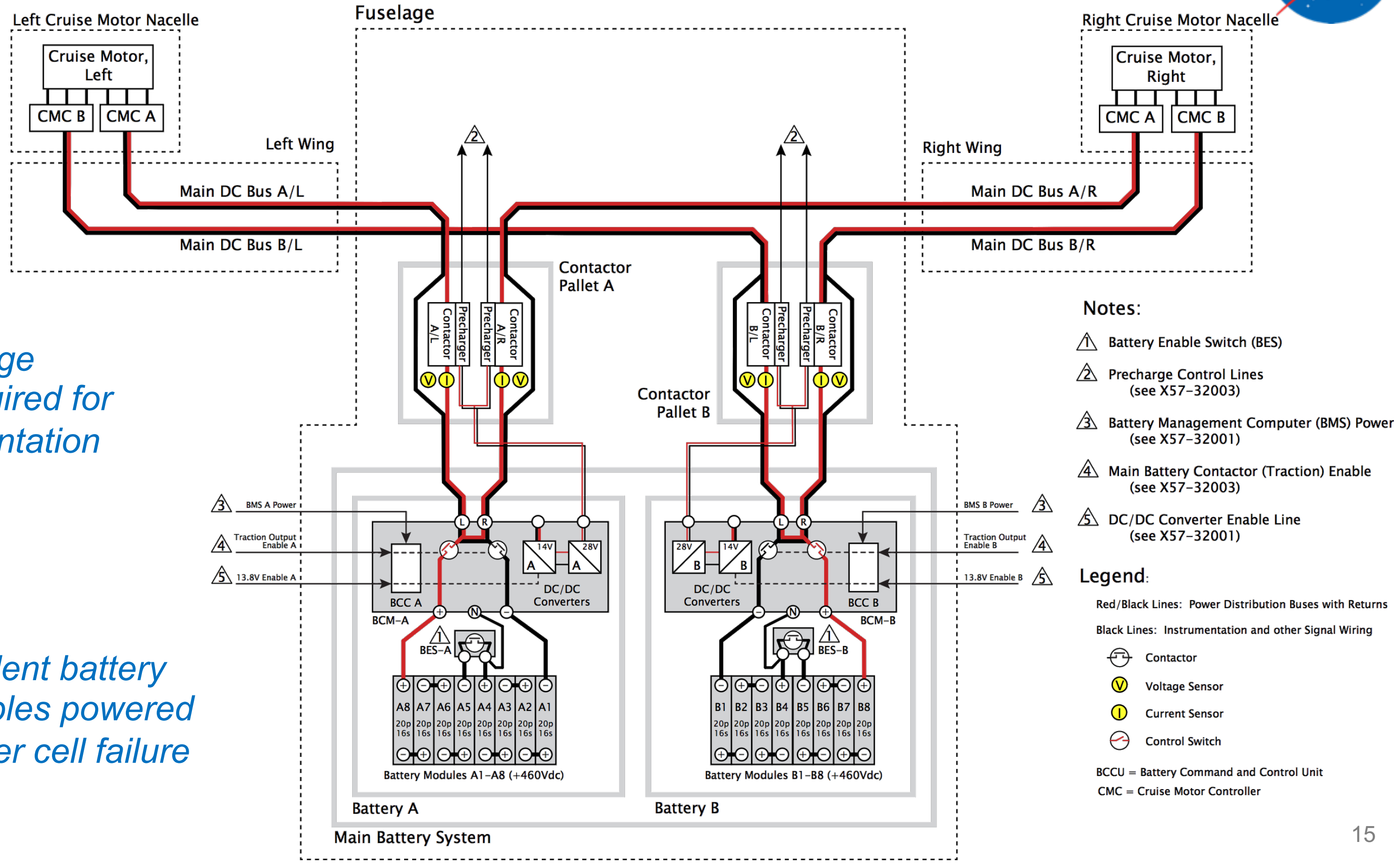
https://nasa.gov/x57/technical

Mod 2 Traction Power System

Dual inverter reduces failure severity

High voltage contactors required for hazard segmentation

Independent battery packs enables powered landing after cell failure



Notes:

- △1 Battery Enable Switch (BES)
- △2 Precharge Control Lines (see X57-32003)
- △3 Battery Management Computer (BMS) Power (see X57-32001)
- △4 Main Battery Contactor (Traction) Enable (see X57-32003)
- △5 DC/DC Converter Enable Line (see X57-32001)

Legend:

Red/Black Lines: Power Distribution Buses with Returns

Black Lines: Instrumentation and other Signal Wiring

Contactor

Ⓥ Voltage Sensor

Ⓘ Current Sensor

Control Switch

BCCU = Battery Command and Control Unit

CMC = Cruise Motor Controller

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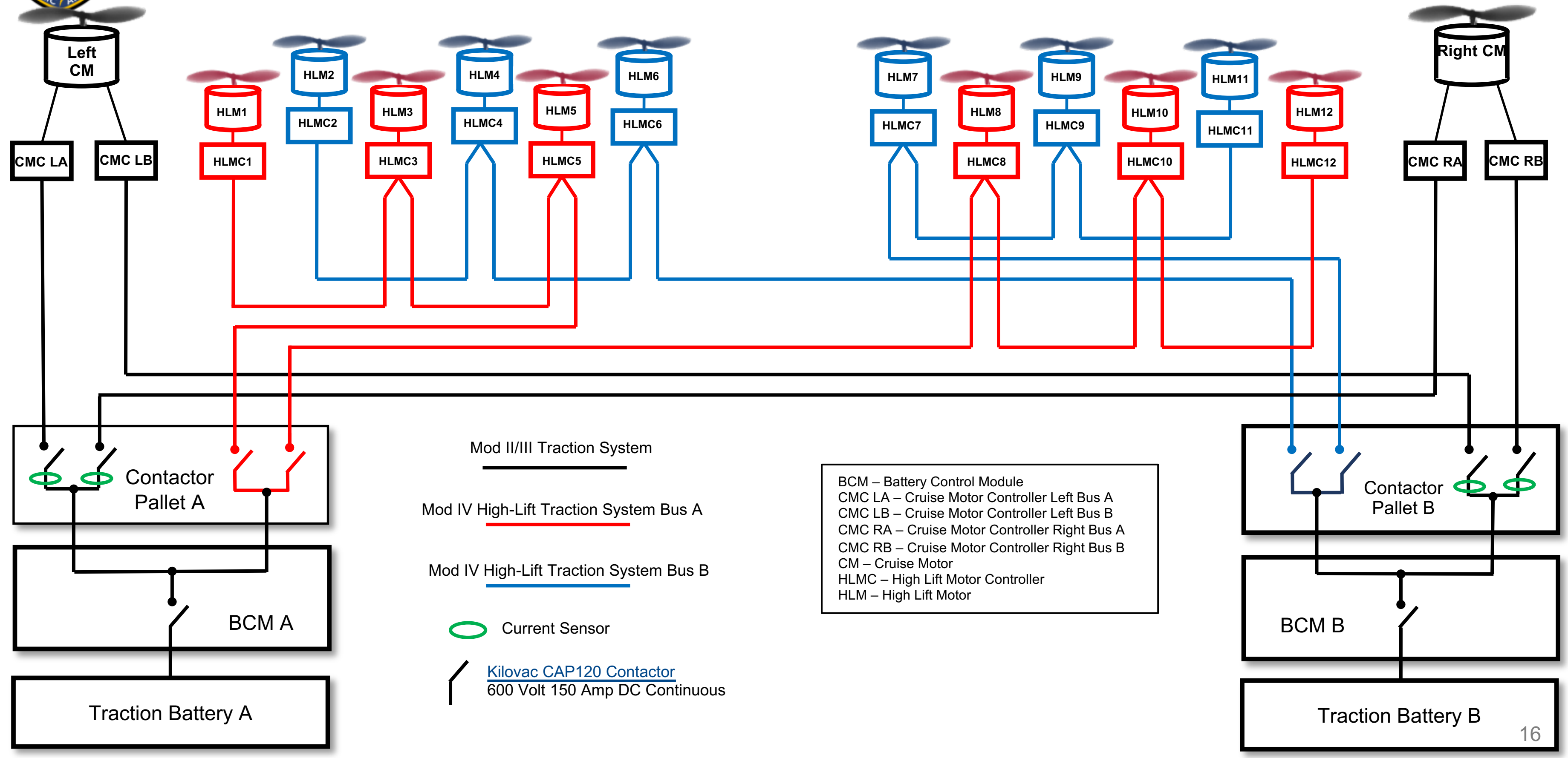
Mod 4 Traction Power System



Mod II/III Traction System

Mod IV High-Lift Traction System Bus A

Mod IV High-Lift Traction System Bus B

Current Sensor

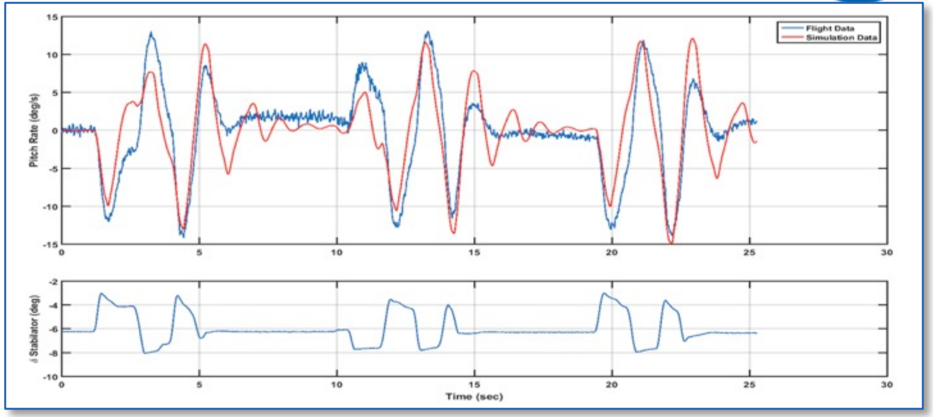
Kilovac CAP120 Contactor
600 Volt 150 Amp DC Continuous

BCM – Battery Control Module
CMC LA – Cruise Motor Controller Left Bus A
CMC LB – Cruise Motor Controller Left Bus B
CMC RA – Cruise Motor Controller Right Bus A
CMC RB – Cruise Motor Controller Right Bus B
CM – Cruise Motor
HLMC – High Lift Motor Controller
HLM – High Lift Motor

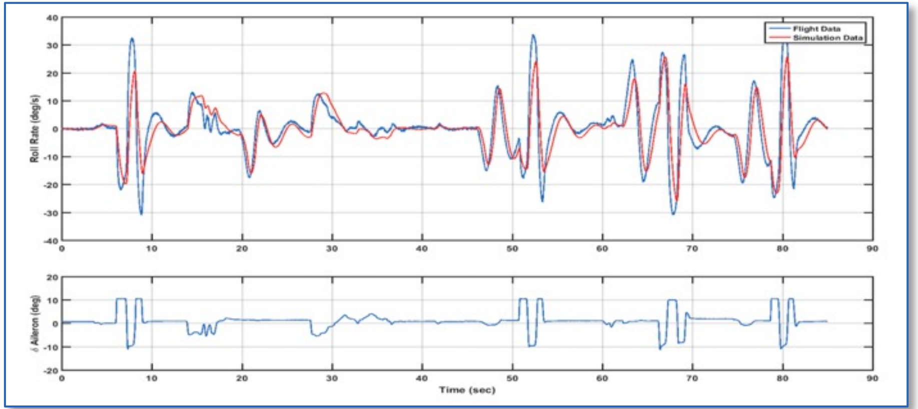
Mod I: Flight Test at NASA

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



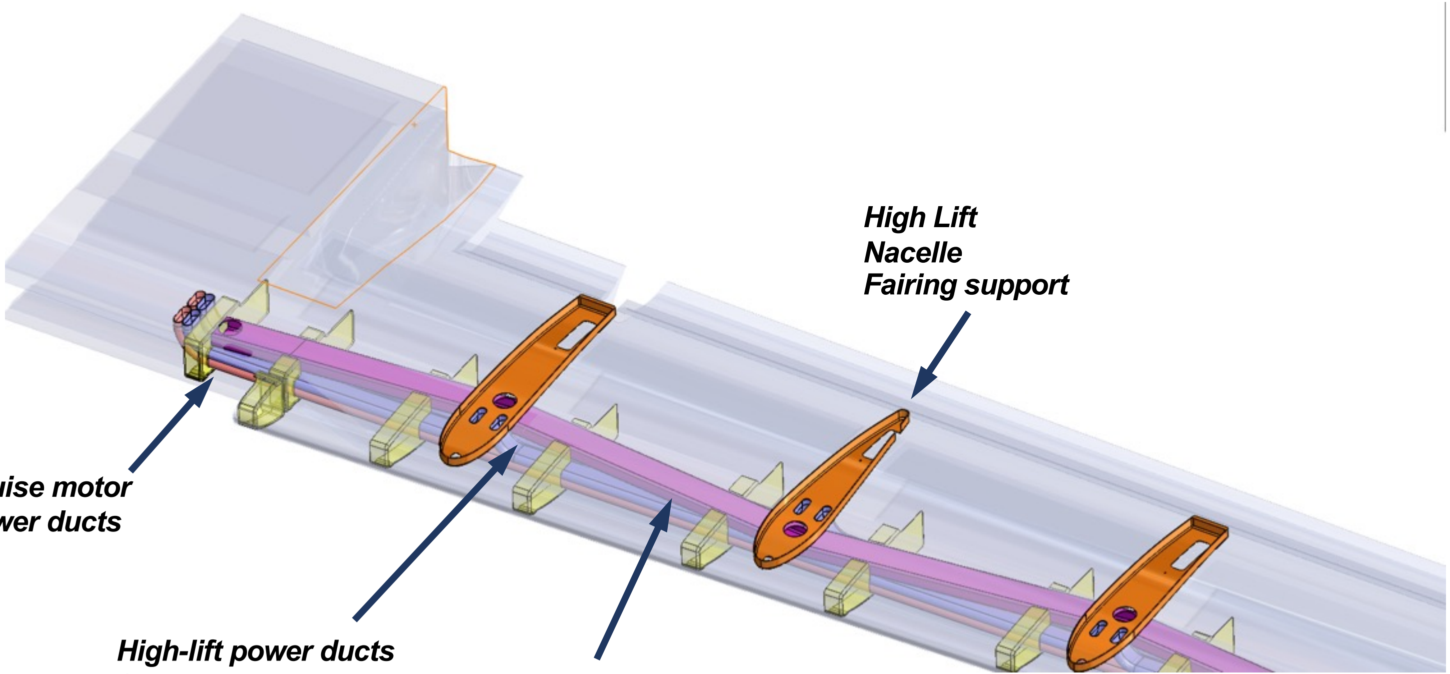
Simulation vs Flight Response, roll rate

https://nasa.gov/x57/technical

Mod I: DEP Validation Experiment

https://nasa.gov/x57/technical

Internal Ducts for Power and Instrumentation Wiring (Lower Surface View)



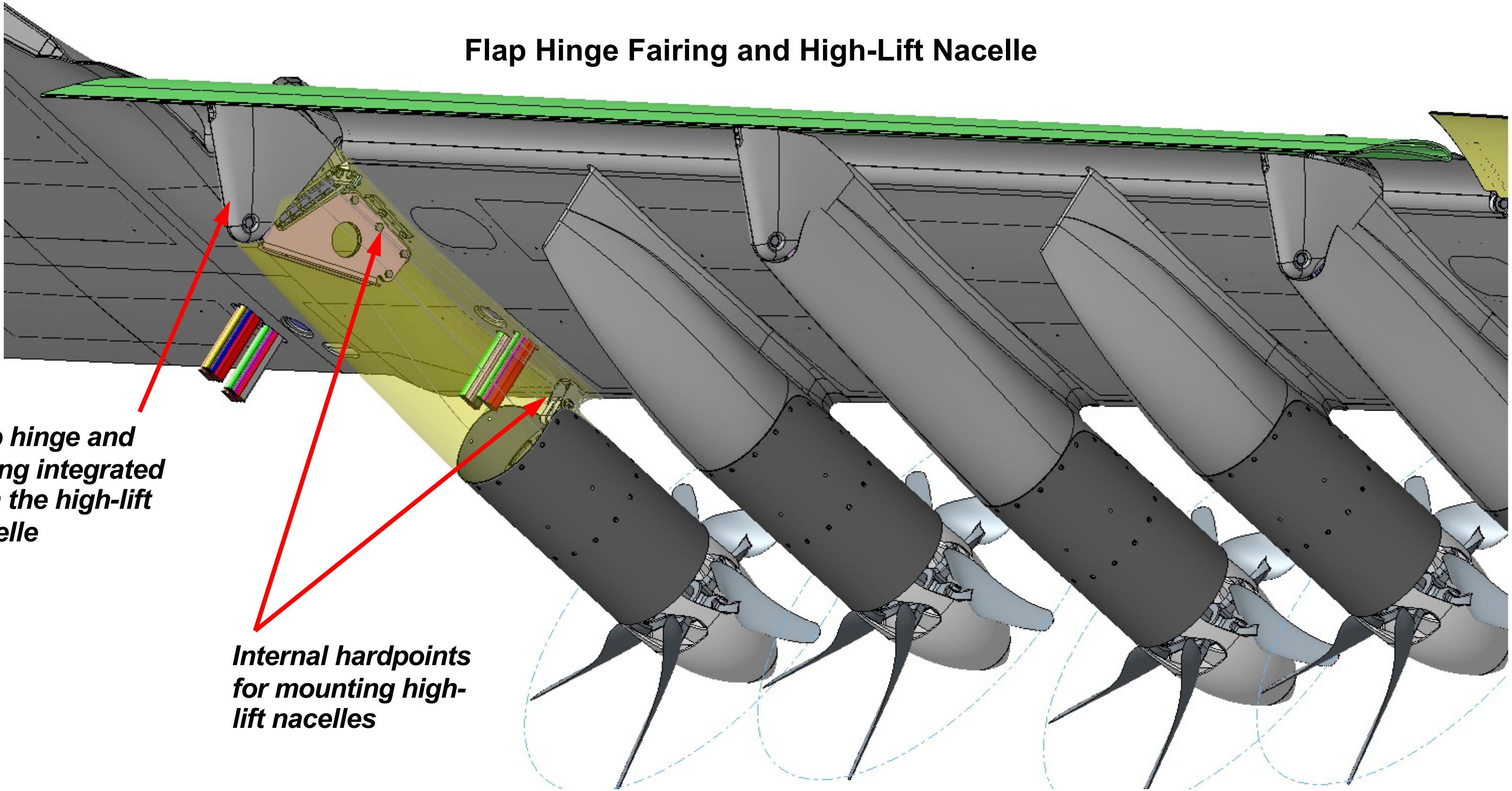
High Lift Nacelle Fairing support

Cruise motor power ducts

High-lift power ducts
(access alternate HL nacelles)

Instrumentation duct
(access every HL nacelle)

Mod IV Components in Mod III Wing Structure



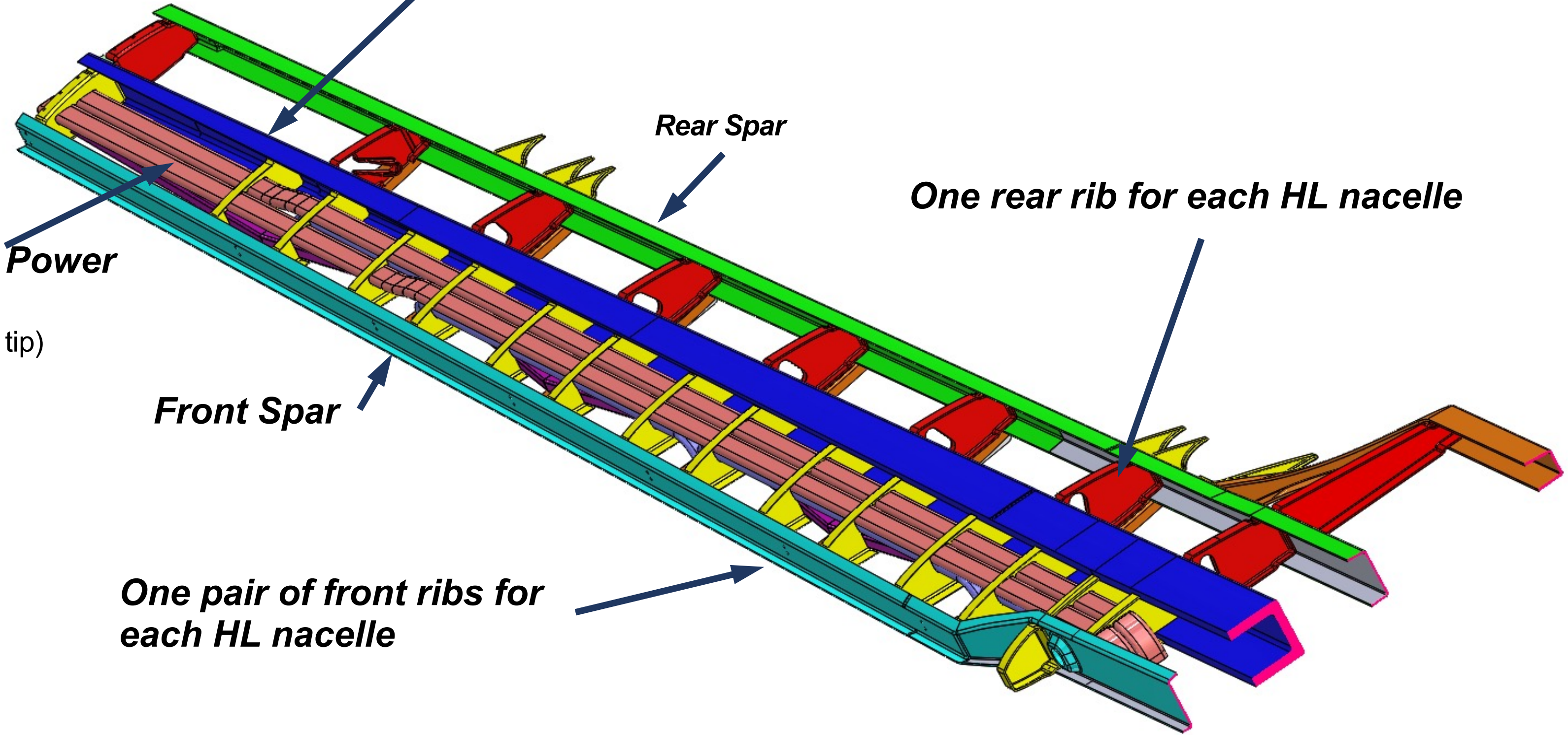
Flap Hinge Fairing and High-Lift Nacelle

Flap hinge and fairing integrated with the high-lift nacelle

Internal hardpoints for mounting high-lift nacelles

https://nasa.gov/x57/technical

Wing Internal Structural Features



Main Spar

Rear Spar

One rear rib for each HL nacelle

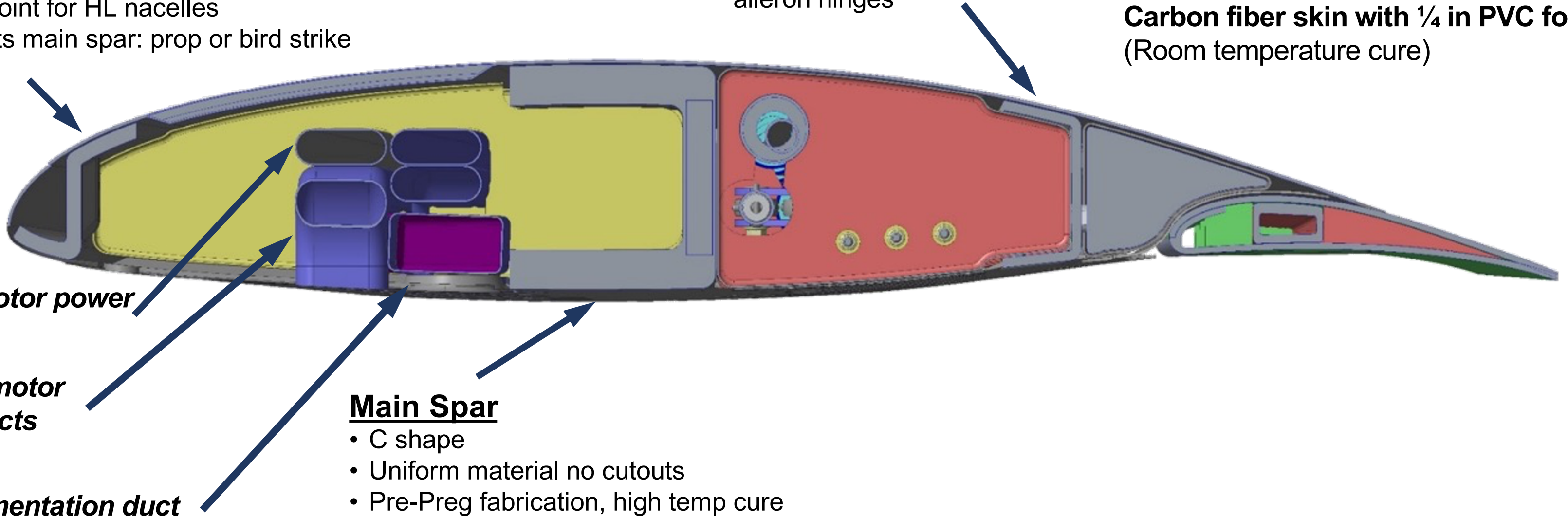
Cruise Motor Power Ducts
(continuous root to tip)

Front Spar

One pair of front ribs for each HL nacelle

Mod IV Components in Mod III Wing Structure

X-57 Wing Construction Features



Front Spar
- Z shape
- Hard point for HL nacelles
- Protects main spar: prop or bird strike

Rear Spar
- C shape
- Hard point for bell cranks and aileron hinges

Carbon fiber skin with ¼ in PVC foam
(Room temperature cure)

Cruise motor power ducts

High-lift motor power ducts

Instrumentation duct

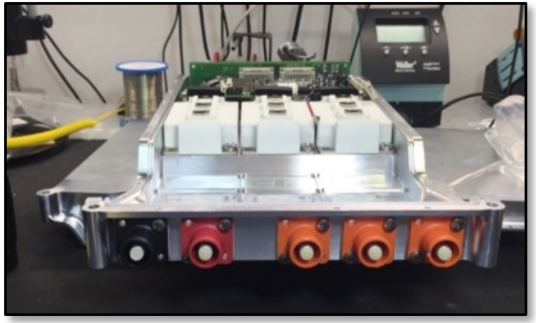
Main Spar
- C shape
- Uniform material no cutouts
- Pre-Preg fabrication, high temp cure

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.
  - 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.

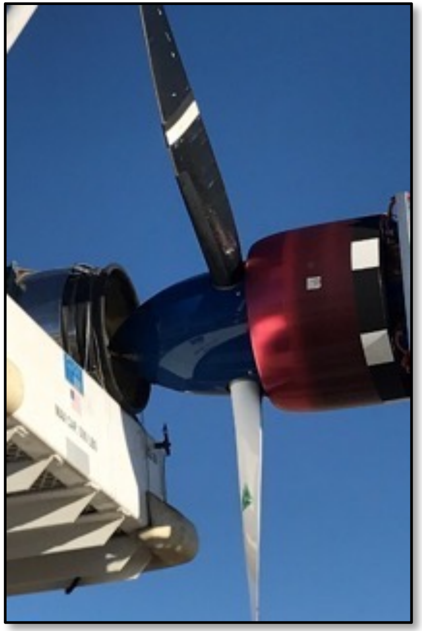
Flight CMC prototype

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



Cruise Motor (CM) Technical Challenges

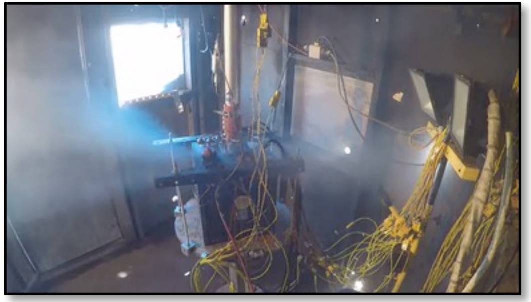
- **Design standards for electric propulsion motor not established.**
  - No suitable USA sourced COTS electric motor design existed during X-57 design phase
  - Adapted industry design approaches for aerospace applications.
  - Cruise motor development is helping to write the design standards.
  - Dual 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

X-57 Flight Batteries Technical and Testing Challenges

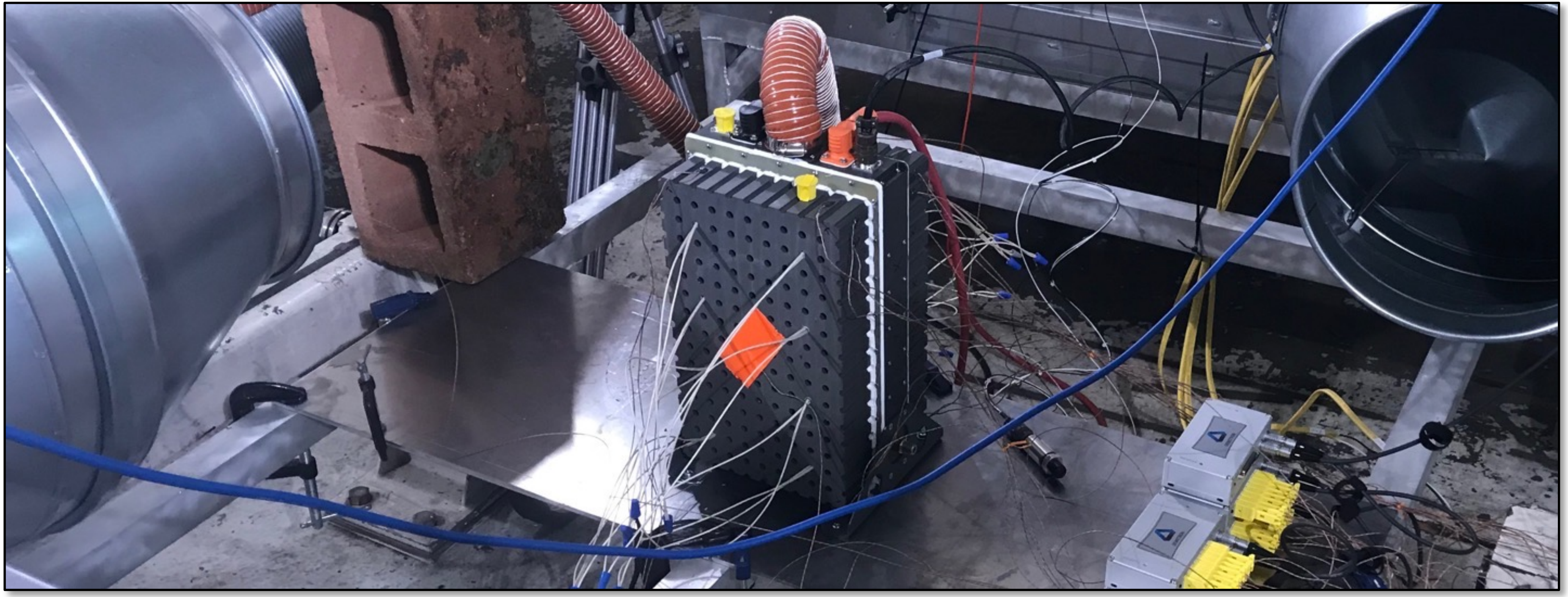
- **No commercial solutions existed for battery systems with sufficient energy and power to provide meaningful aircraft flight duration.**
  - High power requirements within a "flight-weight" limitation- 461 V, 47 kWh effective capacity, 859 lbs. (16 Modules, 51 lbs. each).
    - Aircraft propulsion 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)

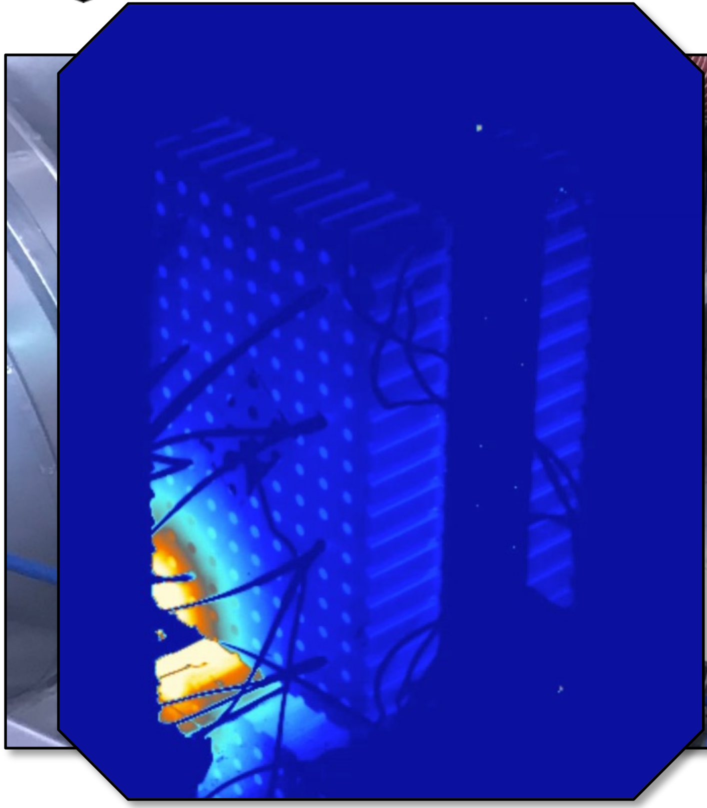
Single Cell Short Circuit/Thermal Runaway Without Propagation



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

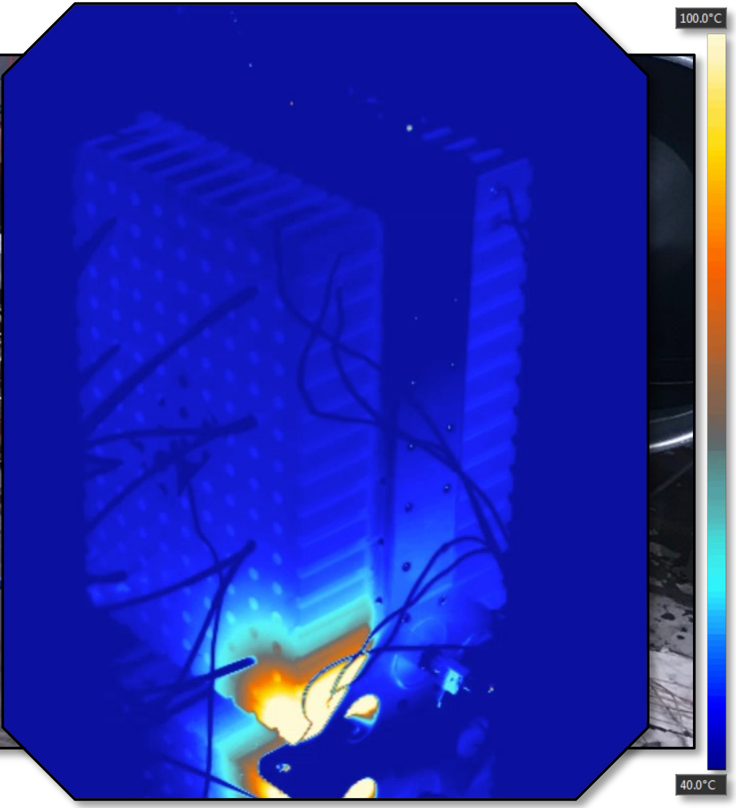
http://go.nasa.gov/2iZ5lYi

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)



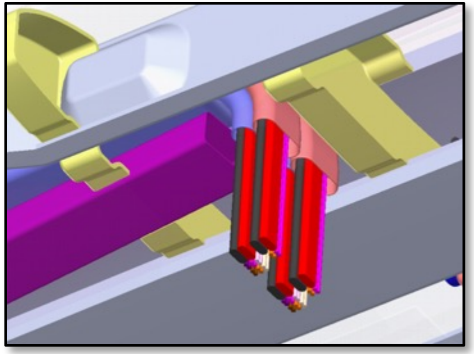
FLIR Video of Trigger Cell #3 Event (8x speed)

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

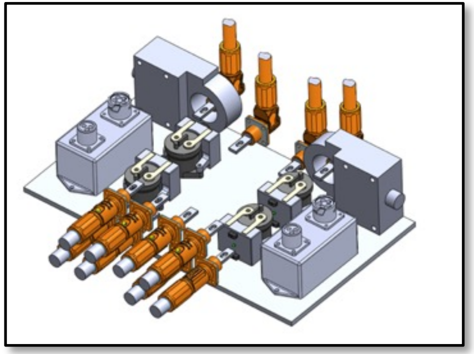
Traction Power Distribution

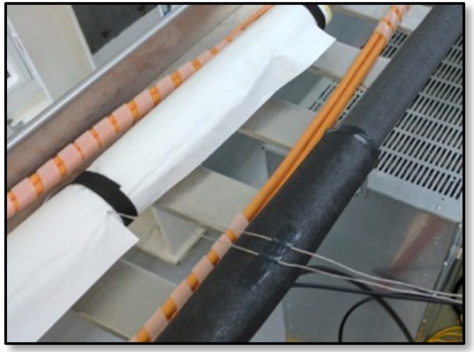
- Redundant bus design supports Mod IV (branches to each high lift motor)
- Thermal model for traction bus validates wire sizing and duct venting
- Custom "flat cable" for lower inductance and Electromagnetic Interference (EMI)
- EMI radiated emittance tests and thermal dissipation tests performed at the NEAT facility (Plum Brook Station)

Isolated Ducts Protect Redundant Power and Command for Cruise and DEP Systems



Contactor Pallet Includes Smart Prechargers and "Primary Objective" Power Measurement



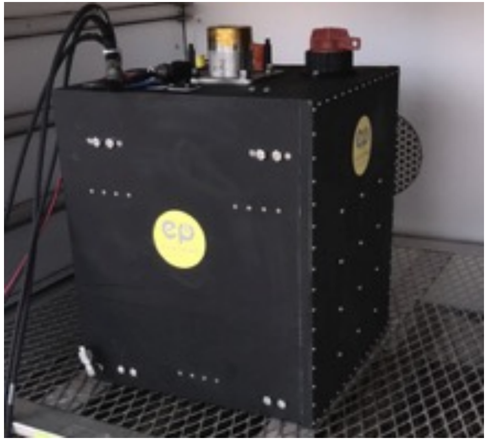


X-57 EMI Testing At
Plum Brook Station/NEAT

Flat Cable Custom X-57 Design for
Electric Propulsion Systems

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.



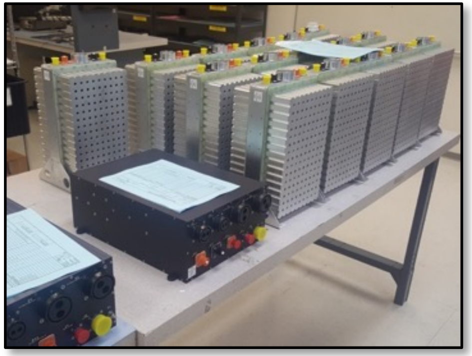
https://nasa.gov/x57/technical

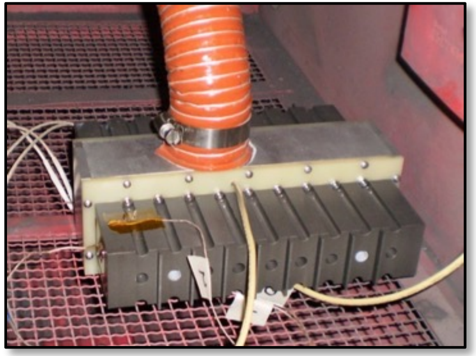
X-57 Flight Batteries (New Approach)

- 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

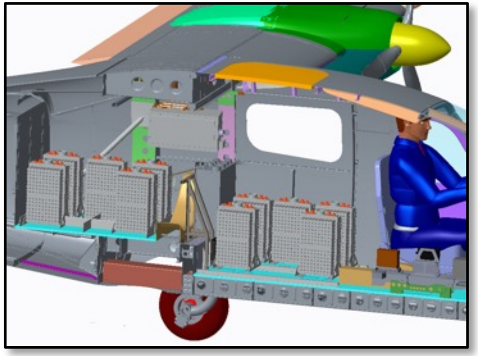
NASA JSC Test Unit With Interstitial Barrier and Heat Spreader (Design Template)

X-57 Battery System Mockups





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



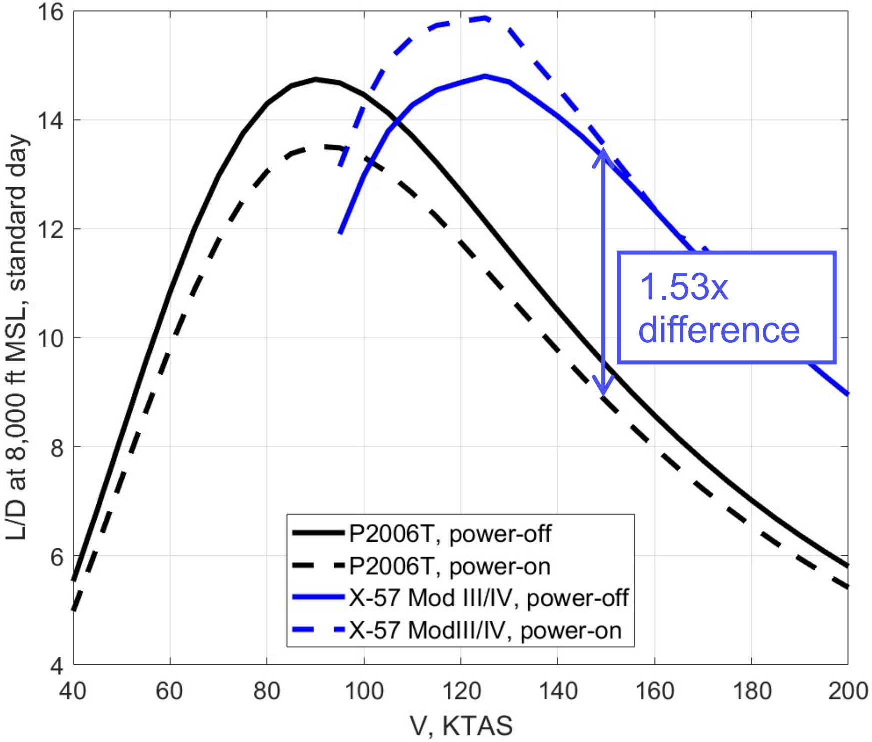
Cutaway showing Battery Installation (10 of the 16 modules)

https://nasa.gov/x57/technical

Anatomy of a "5x" Improvement

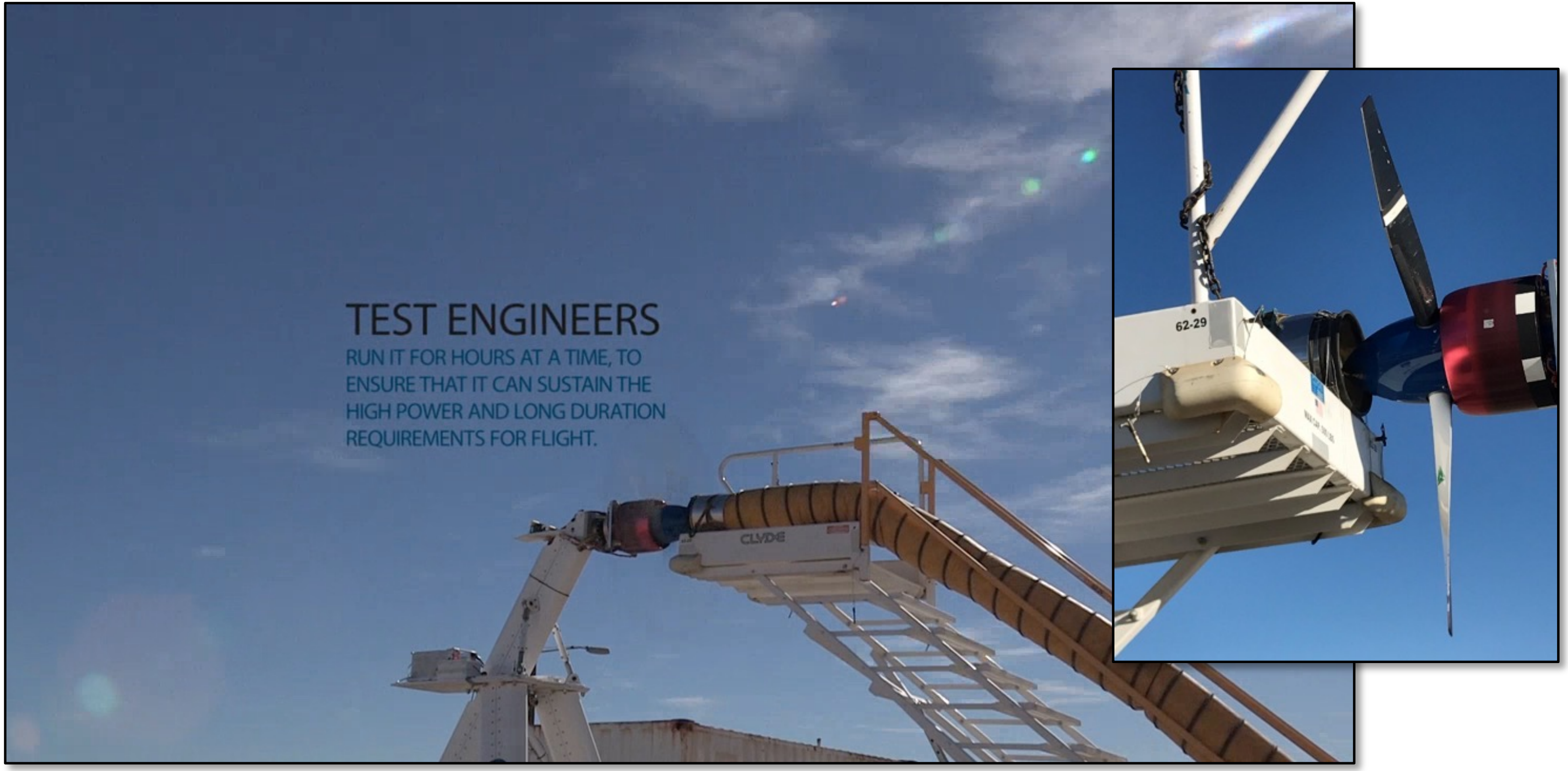
- Most change in efficiency due to electrification (30% to 93% efficient – 3.1x)
- High-speed L/D improvement
  - Smaller wing shifts max L/D to higher speeds
  - Wingtip-mounted props turn power-on installation loss into installation gain

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

Cruise Motor Development – Flight Qualification

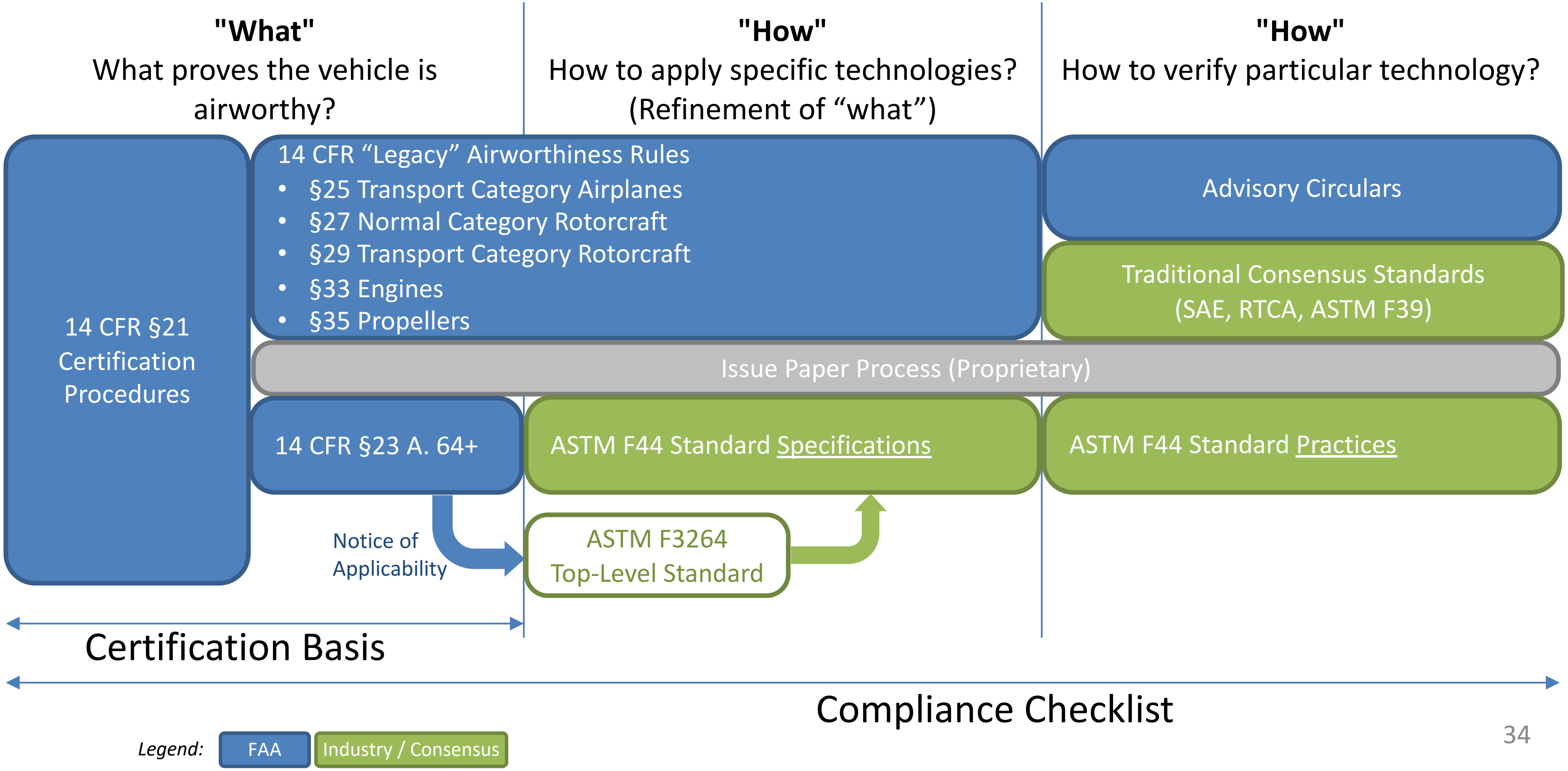


TEST ENGINEERS

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

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

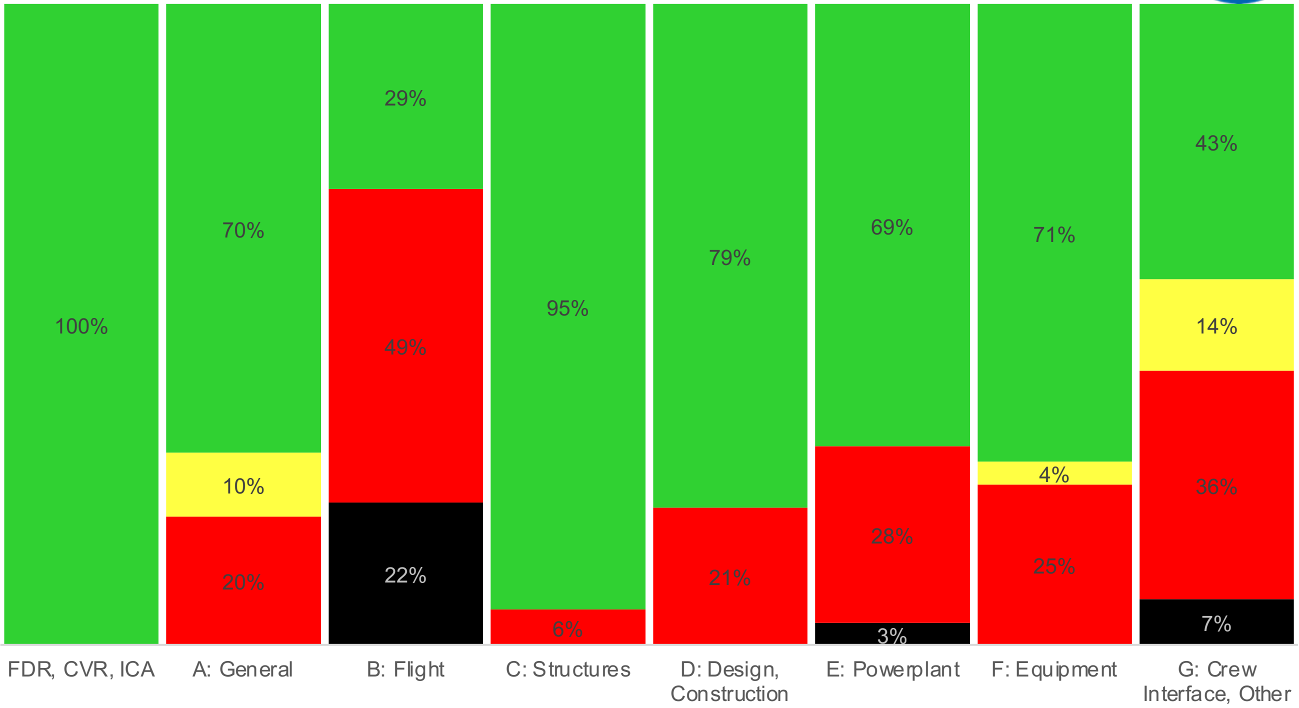
Certification Basis

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

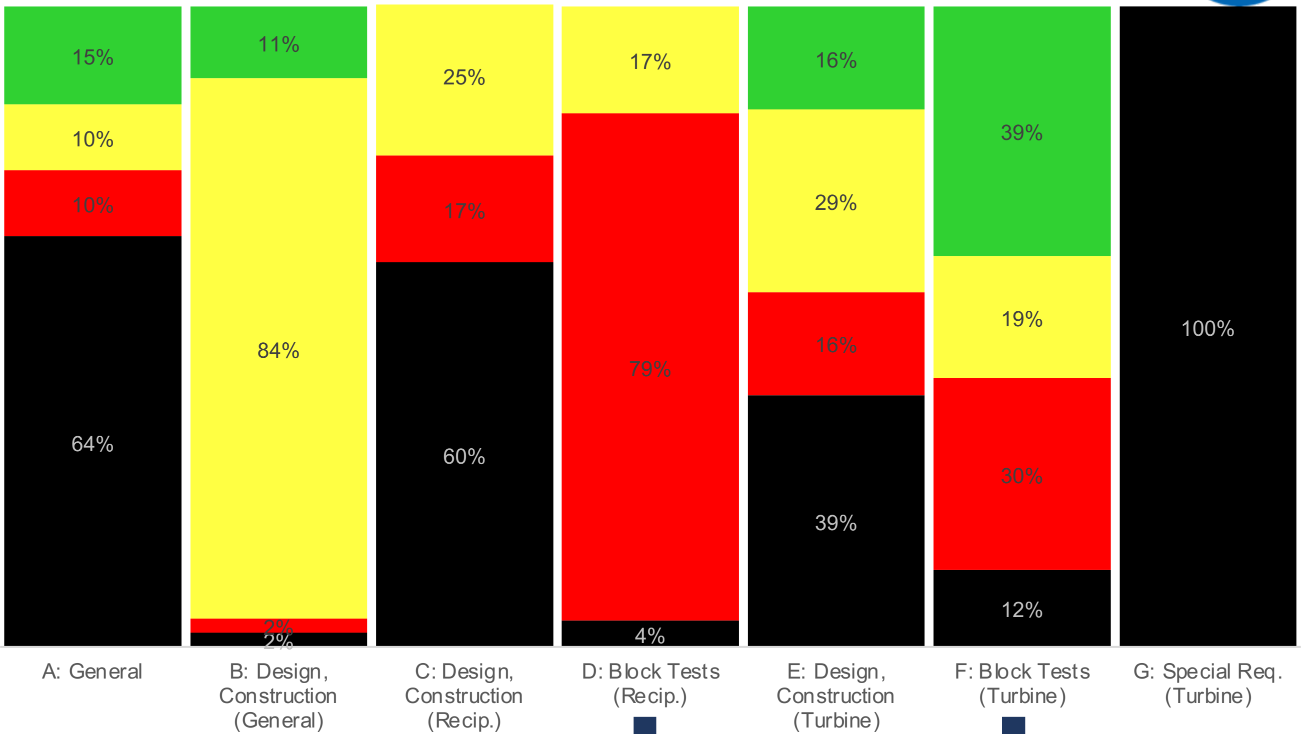
⬛ Remove (N/A)

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

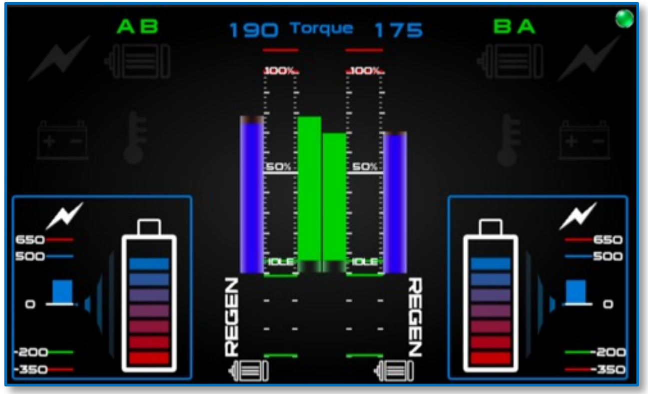
Changes needed for Electrified Aircraft
🟩 None
🟨 Minor tailoring
🟥 Major Revision
⬛ Remove (N/A)

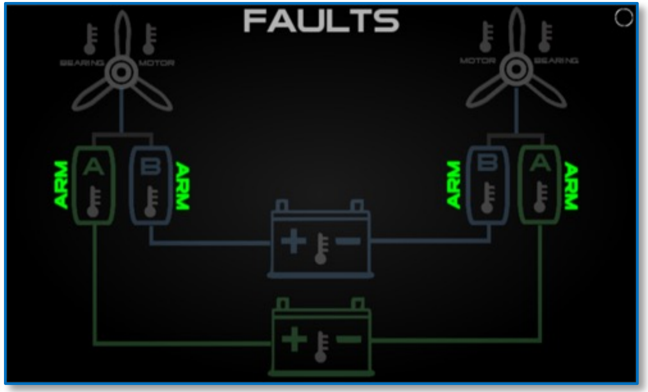
X-57 impact opportunity

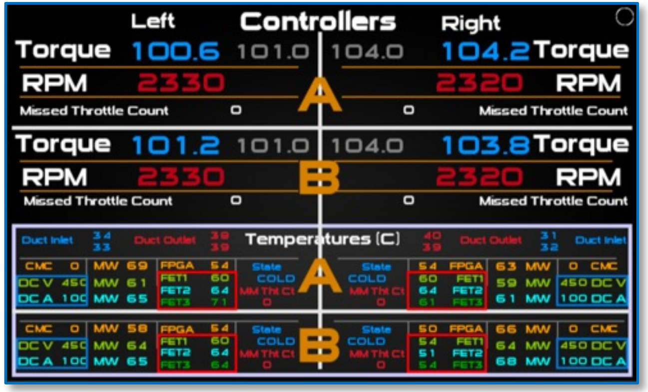
FAR 33 Highest Need is Block Tests

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






Controllers

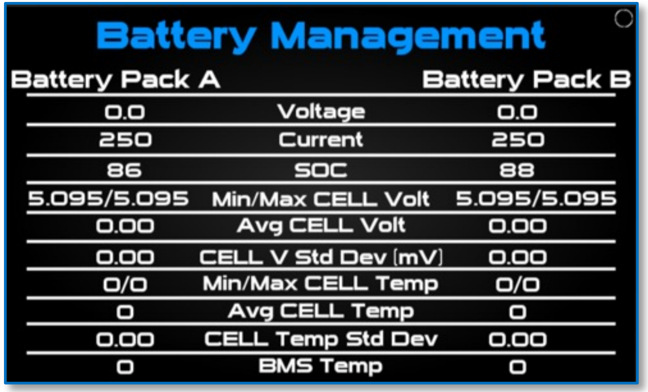
	Left			Right	
Torque	100.6	101.0	104.0	104.2	Torque
RPM	2330	A		2320	RPM
Missed Throttle Count	0			0	Missed Throttle Count
Torque	101.2	101.0	104.0	103.8	Torque
RPM	2330	B		2320	RPM
Missed Throttle Count	0			0	Missed Throttle Count

Temperatures (C)

Duct Inlet 34 33 Duct Outlet 39 39 | 40 39 Duct Outlet 31 32 Duct Inlet

A: 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 Thr Ct 0 | State COLD, MM Thr Ct 0, 54 FPGA, 60 FET1, 64 FET2, 61 FET3, 63 MW, 59 MW, 61 MW, 0 CMC, 450 DC V, 100 DC A

B: 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 Thr Ct 0 | State COLD, MM Thr 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

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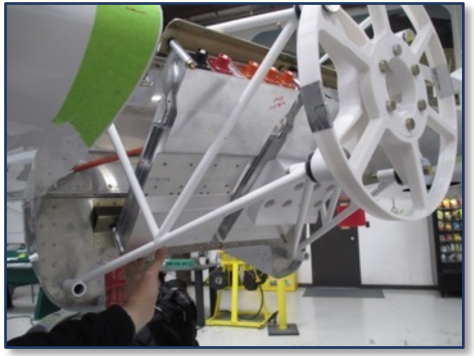
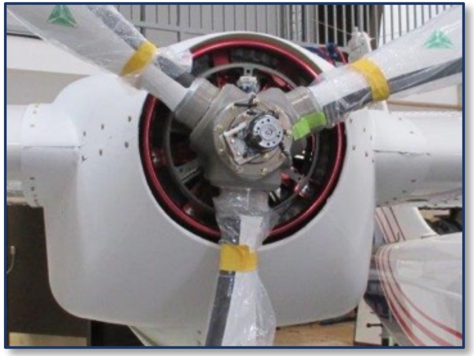
Mod II Vehicle Integration

- 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



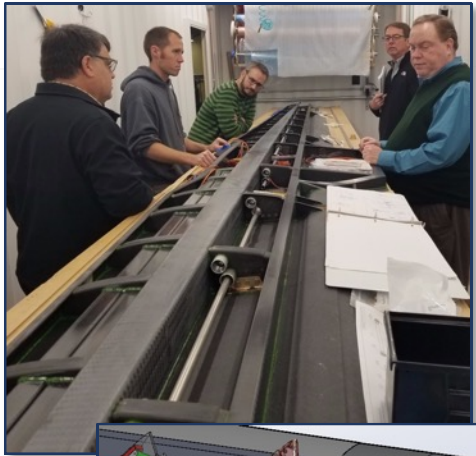
Mod II Wing installation

NASA Administrator Bridenstine Inspecting X-57 Maxwell

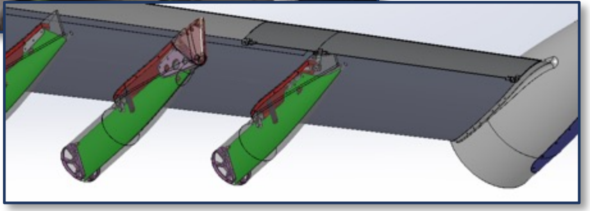
Digital Throttle Quadrant

Mod III Wing Design

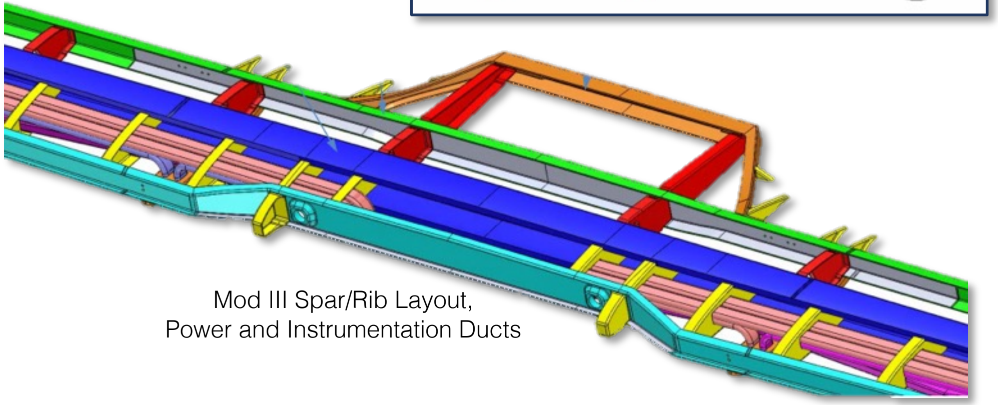
- Composite wing fabricated at Xperimental/California
- Single, continuous main spar carries normal and axial loads (shear and bending)
- Working skin–buckling free–carries torsional loads
- Front and rear spars receive external loads (nacelles and controls)
- Isostatic attachment to the fuselage. No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



Mod III wing: Bottom Skin, Rear Spar



Aileron, Flap, High Lift Nacelle Interface



Mod III Spar/Rib Layout, Power and Instrumentation Ducts

Remote Control Quick Look Stability & Control Model

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)

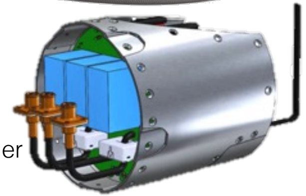
Unpowered Stability and Control
Dynamics Test in the 12' Tunnel at LaRC

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

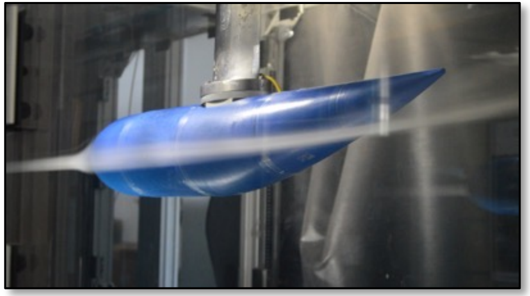
High Lift/Distributed Electric Propulsion System

- 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

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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