National Aeronautics and Space Administration

X-57 Maxwell Aircraft

Certification Pathfinder

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X-57 Project Manager

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X-57 Project 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.

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

The Mod II flight test program is a pathfinder for the experimental propulsion system performance and reliability to reduce the risk in the X-57 configuration.

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X-57 Project Technical Challenge and Goals

Tech Challenge	Demonstrate the performance of a complex, integrated electric propulsion system through manned flight test and collaborate with standards and certification agencies to develop a certification basis for electric aircraft.	
Goals	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.	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.

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

- Raises the TRL of EP components and improves the airworthiness assessment capability in order to independently inform certification authorities
  - Mature high voltage lithium batteries with intrinsic propagation prevention and passive thermal management
  - Establish motor/inverter ground and flight test program
  - Design a crew interface and human factors approach to manage workload for complex propulsion systems
- Provides a pathfinder for aircraft electric traction system standards; lessons learned used to inform FARs and standards
- Reduces electrified system development risk for a Mod III and IV configuration through early testing on a proven vehicle configuration
- Develops 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 (AAM)

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Mod II Design Driver

The X-57 project derived a design driver for Mod II from the project objectives. The design driver is used to guide the design and operations of the Mod II aircraft and is meant to advance the state of the art in the design of a distributed electric propulsion aircraft.

Design Driver	Performance Target
Mod II: Retrofit a baseline General Aviation aircraft with an electric propulsion system.	Optimize the design for cruise power consumption with a target of 3.3x reduction in energy from the baseline aircraft.

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X-57 Mod II Team

Contractor Team

Prime Contractor
ESAero Inc.

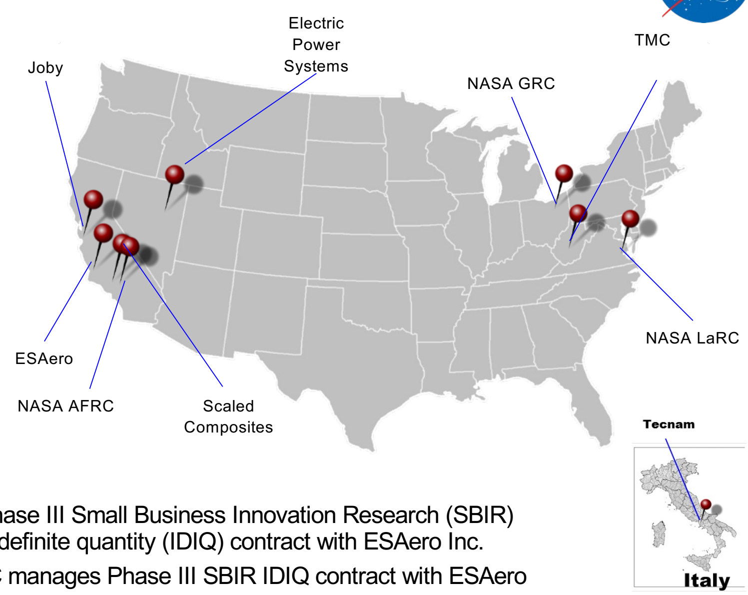
Motors/Controllers
Joby Aviation

Battery Design & Fabrication
Electric Power Systems (EPS)

Mod II Initial Integration
Scaled Composites

Airframe
Tecnam

Software V&V
TMC



- 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

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NASA Multi-Center Team

Armstrong Flight Research Center

- Oversight and project management
- Airworthiness/design reviews
- Mission management
- Piloted simulation
- Ground and flight testing
- Power system design specification

Langley Research Center

- Wing design requirements
- Wing structural analysis
- Vehicle design /analysis
- Flight dynamics simulation
- Wind tunnel testing
- Propulsor sizing

Glenn Research Center

- Thermal Management analysis
- Battery Expertise
- Electrical Systems Expertise
- Cruise Motor Controller Redesign Lead

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X-57 Project Aircraft Configurations – Mod II Flights

Current X-57 Project Scope

Mod II

Validates Cruise Motors & Subsystems

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

Mod III

Electric motors relocated to wingtips on newly developed and fabricated DEP wing.

Mod IV

DEP motors and folding props (cruise motors remain in wing-tips).

- Value of Mod II
  - Drives testing and analysis rigor that leads to more discovery
  - Spurs thought on how systems need to operate as an integrated whole in flight
  - Real human interfaces: integration, maintenance, operation
  - Integrated thought about failure modes and related flight risks
  - Pushes beyond things that might be acceptable in ground test but not in flight
  - Demonstrate passive cooling performance of motor, inverter, and batteries.

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X-57 Highlights Leading up to Mod II Flight Test

- Completed High Voltage Testing Fall 2021
  - Tested functionality of integrated systems under full power (auxiliary power supply)

  - Uncovered Electromechanical Interference (EMI) challenges that have been addressed

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X-57 Highlights Leading up to Mod II Flight Test

- Final system integration and test

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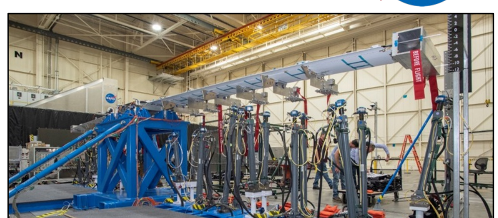
X-57 Highlights Leading up to Mod II Flight Test

- Final Verification and Validation (V&V) testing on aircraft this spring
- Mod II to complete Airworthiness and Flight Readiness Review process this spring and early summer
  - Flight Readiness Review (FRR)
  - Airworthiness and Flight Safety Review Board (AFSRB)
  - Flight Tech Brief (approval of flight request)
- Mod II flights this summer
  - Basic airworthiness and system functionality flights and data collection test maneuvers to support research objectives
- X-57 team is prioritizing knowledge transfer following Mod II flights

Progress Made on Mod III and Mod IV Configurations

- Mod III
  - Design/fabrication/structural testing of high-aspect ratio wing accommodates design with cruise motors at wing-tips and distributed high lift motors
  - Design of wing-tip cruise nacelles to house cruise motors/controllers
    - Fabrication of nacelle components complete; install in progress
  - Wire integration complete; includes avionics/traction power for cruise and high lift motors, instrumentation, and communication signals
- Mod IV
  - Design in progress; fabrication of high lift components in progress
    - Design/fabrication of high lift pylons complete (installed on wing)
    - Design of high lift motors/controllers complete; fabrication in progress
    - Design of high lift propellers complete; fabrication in progress
  - High lift motor controller software near complete; testing in February



Loads applied using 30 hydraulic actuators

Mod III wing wire integration

Informing the path forward for electrification

- NASA is furthering innovation challenge
  - Open and able to inform entire industry
- Lessons learned provided to the FAA to inform standards and regulations
- Generating the technical basis for new standards and thresholds
- NASA subject matter experts participating in working groups and standards bodies
- Lessons learned fed into EPFD

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Further Reading

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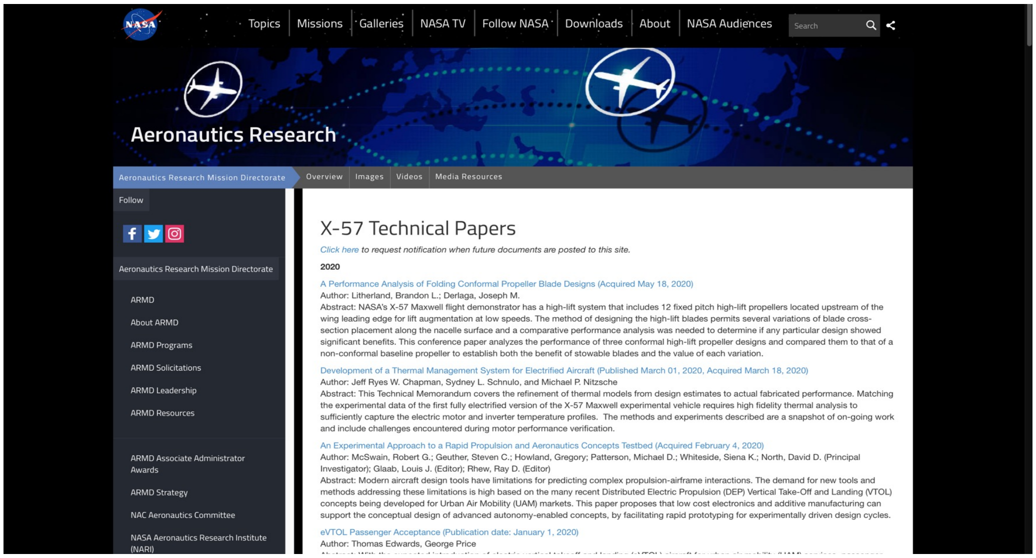

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Sean Clarke, P.E.
X-57 Principal Investigator

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X-57 Knowledge Transfer: Make More Documents Available

- Internal document library includes over 640 documents and counting
  - Wide ranging and includes overall vehicle and project architecture information, insight into how design and airworthiness is assured for flight
    - Descriptions of the vehicle systems and how engineering and operations crew interface with the system in design, maintenance, and flight modes
  - Includes Project Plans, Requirements, Operational Plans, Verification/Validation Matrices, Specifications, Procedures, Interface Control Documents, Analyses, Safety Reports, System Test Plans, CAD
  - Flight Readiness Review, Tech Briefs, and Airworthiness Flight Safety Board documents will be produced as we get closer to Mod II flights

- Request to stakeholders: What do you want to see? What are the gaps? What types of documentation would be helpful for us to prioritize?

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Visit us at AIAA/IEEE Aviation/EATS 2023 (and beyond…)

- X-57 Cruise Motor Controller Design and Testing
- X-57 Cockpit Display System Development and Features
- X-57 High Lift Motor Controller Design and Testing
- X-57 Electromagnetic Interference Design, Integration, and Test Considerations
- Thermal Environments and Margin Guidelines for NASA's X-57 "Maxwell" Flight Demonstrator
- Cruise Propulsion System Thermal Analysis for NASA's X-57 "Maxwell" Mod II Configuration
- X-57 Systems Engineering Lessons Learned
- Testing of X-57 Maxwell's 80kW Electric Propulsion System and Challenges in Certification for Airworthiness
- Performance Evaluation of an 80kW Electric Propulsion Motor and Inverter System for NASA's X-57 Maxwell Flight Demonstrator
- Tuning of Cruise Motors and Cruise Motor Controllers Utilizing Frankinverter Architecture
- Utilizing Code Generation from Models for Electric Aircraft Motor Controller Flight Software
- Development of the Mod II X-57 Pilot Simulator
- Computational Analysis on the Effects of High-lift Propellers and Wing-tip Cruise Propellers on X-57

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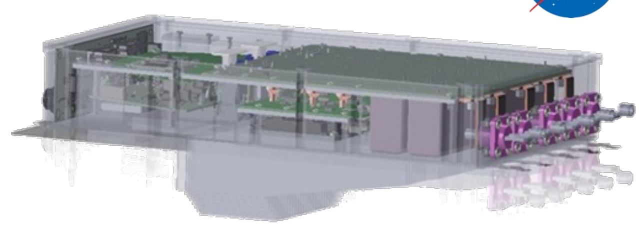
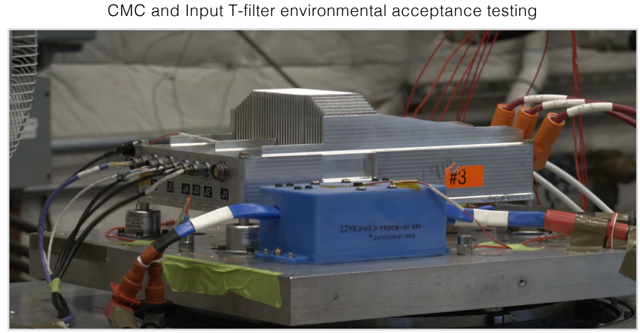
X-57 Cruise Motor Controller Design and Testing

- X-57 power inverters (CMCs) maintain efficiency of 98% at peak loading conditions to enable passive air cooling
- Each CMC must reliably control up to 39 kW nominally and 55 kW in contingency modes.
- SiC MOSFET modules, driver controller, and power distribution are qualification and acceptance tested via high power environmental tests and dynamic system tests.
- Environmental testing identified defective electronic components that had not be screened during manufacturing and thermal dissipation material that did not meet documented electrical specs.
- PCB development requires unit-level and integrated tests, but some defects were not effectively screened leading to lessons learned for future test programs.
- Assembly was complicated and required iteration with the flight electronics fabrication team to meet the demanding requirements of the X-57 application.



CMC featuring upgraded MOSFET modules and new driver and power boards

CMC and Input T-filter environmental acceptance testing



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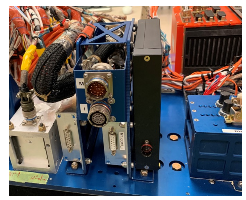
X-57 Cockpit Display System Development and Features

- COTS Hardware for display, computer, and external DAQs
- Displays critical data from the traction systems and air temperatures in multiple locations in the cruise nacelles
- Temperatures of the low voltage and high voltage sections of the CMCs and CMs are displayed and generate visual alerts
- Battery voltage and state of charge are displayed
- All metrics are communicated via CAN bus
- CDS not required for safety of flight but is used for mission support

Multifunction Display

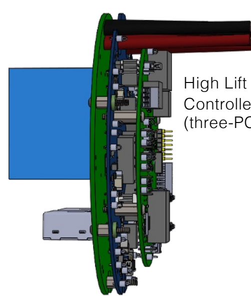


Display Controller

Data Acquisition System

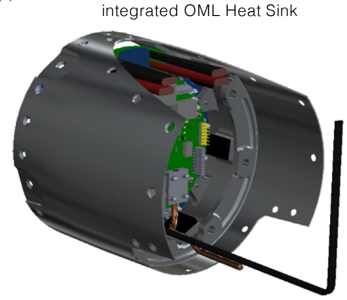
X-57 High Lift Motor Controller Design and Testing

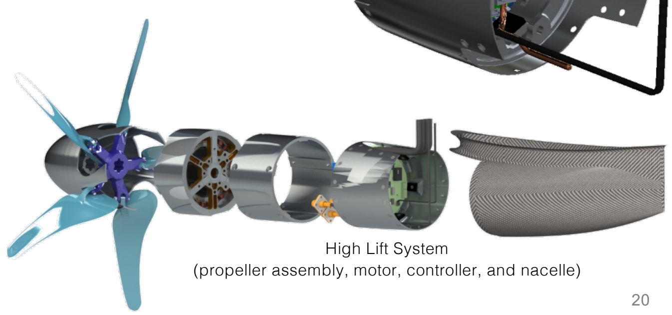
- The X-57 Mod IV wing relies on a Distributed Electric Propulsion (DEP) system to provide expanded low speed flight capability.
  - This High-lift system uses twelve independent motors and controller/inverters to dynamically augment aircraft lift and thrust
  - Does not degrade aircraft performance as a result of credible failure modes
  - Does not increase pilot workload substantially more than traditional, passive high-lift devices
- The High Lift Motor Controller (HLMC) is an integrated 11kW, lightweight, 97% efficient SiC MOSFET based motor drive and features:
  - Passive thermal (outer mold line) cooling
  - 40kHz switching frequency to reduce motor current ripple
  - Optical communication capability (Ethernet) for EMI immunity
  - Advanced motor controller that utilizes rapid software and hardware prototyping and development



High Lift Motor Controller subassembly (three-PCB stack up)

High Lift Motor Controller with SiC MOSFETS and integrated OML Heat Sink

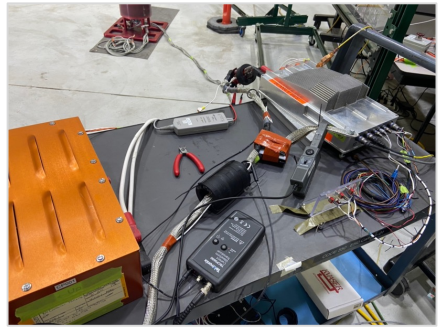




High Lift System (propeller assembly, motor, controller, and nacelle)

X-57 EMI Design, Integration, and Test Considerations

- The X-57 requires SiC MOSFETs to achieve power conversion performance needed for a passively ram-air cooled propulsion system. Results in high EMI from power switching transients
- A flight-like iron-bird testbed is preferred to identify interference interfaces and treatments ahead of aircraft integration but was out of project scope.
- EMI was identified during aircraft integration and testing, primarily as an incompatibility with traction battery cell monitoring system.
- Iteration through various isolation, grounding, and filtering architectures resulted in fabrication of a compact, lightweight, low-pass T-filter that would allow the battery monitoring circuits to operate without internal modifications to the motor controller hardware or software.
- Other mission critical EMI on adjacent circuits on the aircraft required methodical testing of adjacent circuits, electrically isolating the motor and controller chassis, and the addition of toroidal chokes on several cable harnesses in the cruise nacelle.

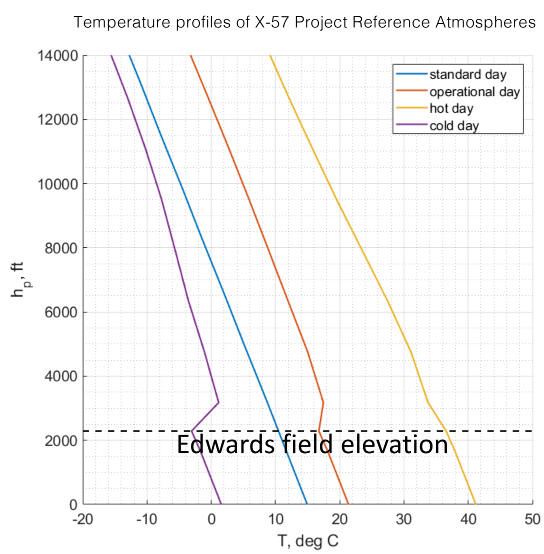


Minimal test configuration with single battery, controller, motor and iterated filter architectures

Final filter design is lightweight, compact. Qualified for flight via environmental and system testing.

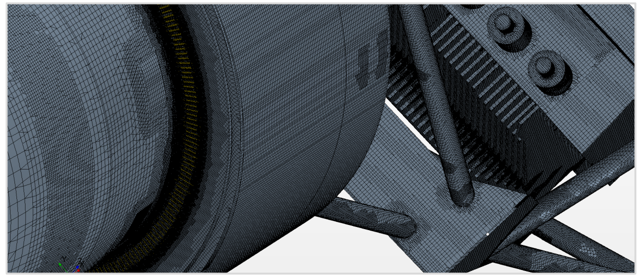
Thermal Environments and Margin Guidelines for X-57

- X-57 operates without active thermal management, so forecasting of operational conditions and environmental stress screening of custom equipment is critical.
- The X-57 is operated only at the Dryden Aeronautical Test Range, so specific reference atmospheres are used:
  - Standard Day atmosphere (1976 U. S. Standard Atmosphere),
  - Mean Operational Day atmosphere (based on the mean 2019 Edwards Range Reference Atmosphere),
  - Hot and Cold Day atmospheres (based on the ±2σ yearly temperature variations in the Edwards Range Reference Atmosphere).
- Thermal Cycle Testing of X-57 systems use temperature limits established from these reference atmospheres
- Thermal testing program was developed based on SMC-S-016 and DO-160G. Thermal margin management is also based on SMC-S-016.
- Establishes requirements for the development of new electrified propulsion system components.



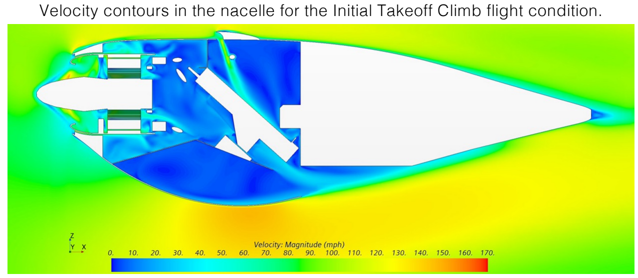
Cruise Propulsion System Thermal Analysis for X-57 Mod II

- The X-57 Mod II configuration features one electric cruise motor mounted in an integral nacelle on each wing.
- The electric motors and associated control equipment are air-cooled and require adequate airflow to comply with temperature limits across flight envelope and expected range of ambient conditions.
- Computational flow analysis estimates the internal flow properties of the nacelles in three critical flight conditions.
- These flow properties determine the boundary conditions for individual component thermal models, which estimate individual component operating temperatures.
- Unsurprisingly, low-speed, low-altitude initial takeoff climb during hot day conditions is the cooling sizing case.
- The predicted nacelle cooling flow paths provide adequate cooling to each component with the appropriate thermal margin, except for two of the low-voltage control boards in the motor controller, which violate thermal margins by less than two degrees Celsius.



Surface mesh details on major components inside the Mod II cruise nacelle

Velocity contours in the nacelle for the Initial Takeoff Climb flight condition.



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Development of the Mod II X-57 Pilot Simulator

- Piloted sim developed for X-57 Mod II including predicted flight dynamics.
- Initially based on data published by Tecnam, then improved via Parameter Identification of flight data modeling modeling tools (e.g., CFD).
- Realistic cockpit aids pilot training; pilots have advanced experience with aircraft behavior throughout the flight envelope per FAR and MIL standards.
- Simulation results show that the aircraft will be statically and dynamically stable and achieve Level 1 flying qualities.

Piloted Sim Cockpit. Pilot seat, Controls, Out-the-Window View, Instrumentation

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Computational Analysis of X-57 High-lift & Wing-tip Propellers

Motivation and Goal

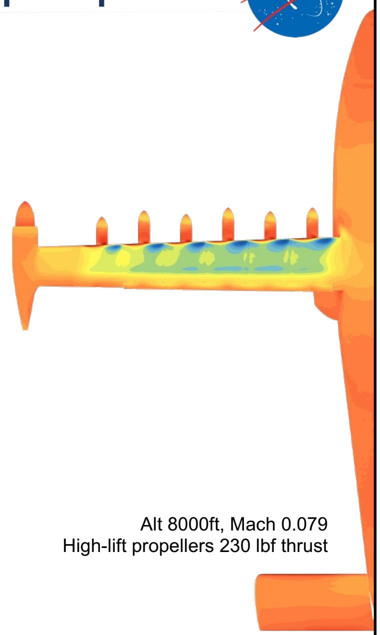
- The aerodynamics of X-57 MOD-3 and MOD-4 are very complex due to its innovative distributed propeller system
- Goal of this study is to understand the individual effects of high-lift propeller wing-tip cruise propeller system on the aircraft forces and moments as well as its influence on flow physics over the wing of the aircraft

Method

- Analyze the flow physics using computational fluid dynamics (CFD) simulations
- 3 separate NASA centers (AFRC, ARC, LARC) participating with different solvers and grids to increase confidence in solution

Results

- Wing-tip Cruise propellers
  - Reduces drag while increasing lift
- High-lift propellers
  - Increases lift, lift-curve slope, drag, and pitching moment
  - Have effects similar to having a flap but with additional phenomena of increasing the lift-curve slope



Alt 8000ft, Mach 0.079
High-lift propellers 230 lbf thrust

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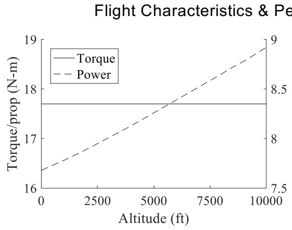
X-57: Impact on Regulations & Standards

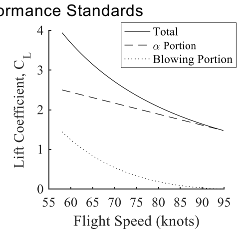
- The X-57 project continues to be involved with the FAA and consensus standards committees regarding airworthiness

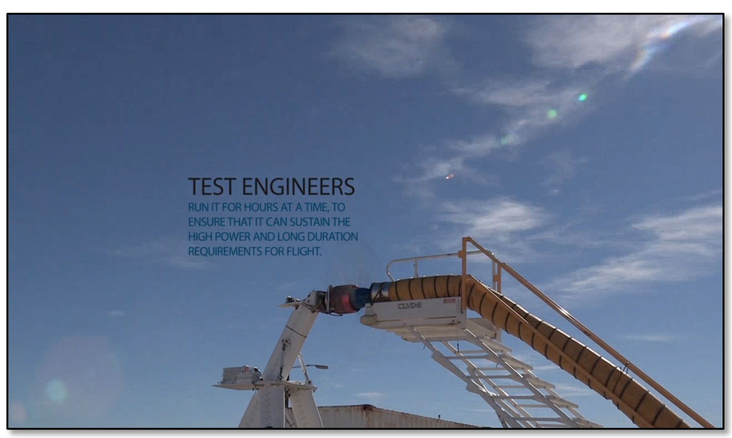
Airworthiness Regulations

14 CFR §23.2110 (Amdt 64): Stall speed.
The applicant must determine the airplane stall speed … with power set at—
(a) Idle or zero thrust for propulsion systems that are used primarily for thrust; and
(b) A nominal thrust for propulsion systems that are used for thrust, flight control, and/or high-lift systems.

Flight Characteristics & Performance Standards







Motor Test/Endurance Standards

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Standards Development

- X-57 SME's Mapping areas where NASA technology development and methods can fill gaps
- NASA participating directly in the writing of distributed electric propulsion standards via ASTM & SAE standards subcommittees
  - Voting members on ASTM F44 (General Aviation Aircraft) and F39 (Aircraft Systems)
  - General Aviation Manufac. Assn. Electric Propulsion Integration Committee & ASTM AC433 "Means of Compliance for eVTOL Aircraft"
  - EPFD Formulation process incorporated aspects of X-57 standards development approach and Lessons Learned

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Thank You

Questions?

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