Flight-Test Approach for X-57 Mod II Configuration

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X-57 Overview

X-57 is NASA's Flight Demonstrator for *Distributed Electric Propulsion Technology (DEP)*

- **Project Goals**: generate data and procedures and share these with academia, industry, standards organizations, and regulators to enable design and certification of DEP concepts
- **Project Approach**: spiral development through multiple design "Mods"

Mod I: Flight Testing of the baseline Tecnam P2006T	**Mod II:** Retrofit a baseline General Aviation aircraft with an electric propulsion system.	**Mod III:** Modify the configuration with a cruise-optimized wing and distributed electric propulsion system.	**Mod IV:** Design for adequate low speed takeoff and landing characteristics with an integrated DEP system.
<ins>Mod I provides baseline data</ins> 	<ins>Mod II reduces risk for Mods III and IV</ins>: 	<ins>Mod III provides cruise speed data for DEP designs, technologies and systems</ins>: 	<ins>Mod IV provides low speed data for DEP designs, technologies and systems</ins>: 

Mod II Flight Test Plan – Flight Objectives

- Mod II Flight Test Objectives developed to meet the Subproject Objectives
- Flight Test Objectives then flowed down to individual maneuvers

Identifier	Mod II flight objectives	Description
A. II	Limited evaluation of the system performance within the Mod II flight envelope in order to support research objectives.	Evaluate the performance of the traction system (batteries, cruise motors), the airplane systems, and the effect of airplane modifications within the Mod II flight envelope. Assess airplane airworthiness and ability to support research objectives.
A. III	Acquire data to support Mod III airworthiness.	Acquire data and demonstrate system capability to support the Mod III airworthiness assessment.
P. II	Acquire data to assess Mod II design drivers.	Acquire data to assess the success criteria for each of the Mod II design drivers.
P. III	Acquire data to assess Mod III design drivers.	Acquire data to enable the assessment of the Mod III design drivers during the Mod III flights.

X-57 Subproject Objectives

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Mod II Flight Objectives

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Flight-Test Maneuvers

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Flight-Test Maneuvers Detailed Description

X-57 Mod II Flight Test Plan Buildup Approach

- The X-57 Mod II flight-test philosophy was to conduct a limited evaluation of airworthiness related test points in order to clear the flight envelope to acquire the required performance test data

- The Mod II flight campaign was planned to consist of four phases:
  - Ramp and Taxiway Taxi Tests
  - High-speed Taxi Tests
  - Basic Airworthiness and System Functionality (BASF) Flights
  - Data Collection (DC) Flights

- Each of these four phases has discrete test points, which build on the successful completion of the previous phases

Basic Airworthiness & System Functionality Flights

- Equivalent to the first flight of a new airframe
- Flight control build-up
  - 1/3, 2/3, full control deflection – yaw, pitch, roll
  - Evaluate controllability, predictability, friction, breakout, free-play
- Configuration build-up
  - Takeoff configuration, landing configuration, clean
    - Gear remains down for entirety of first flight
- Speed build-up
  - Test points initially done at 90 KIAS and 4,500 ft MSL, with a strict restriction on minimum state of charge
    - Near best glide speed, safe for gear and flap deflections, margin above stall speeds
    - >100% margin on Mod II flutter prediction assuming no structural damping
  - 90 KIAS, 1.2 Vs, 1.1 Vs, 115 KCAS, 135 KCAS
    - Slow first for controllability then speed up for loads/dynamics
- Evaluation of research traction system
  - Checkout of torque and propeller response
  - Inflight electrical shutdown and restart capabilities
- 4 BASF flights total to accomplish functional checkout of the system

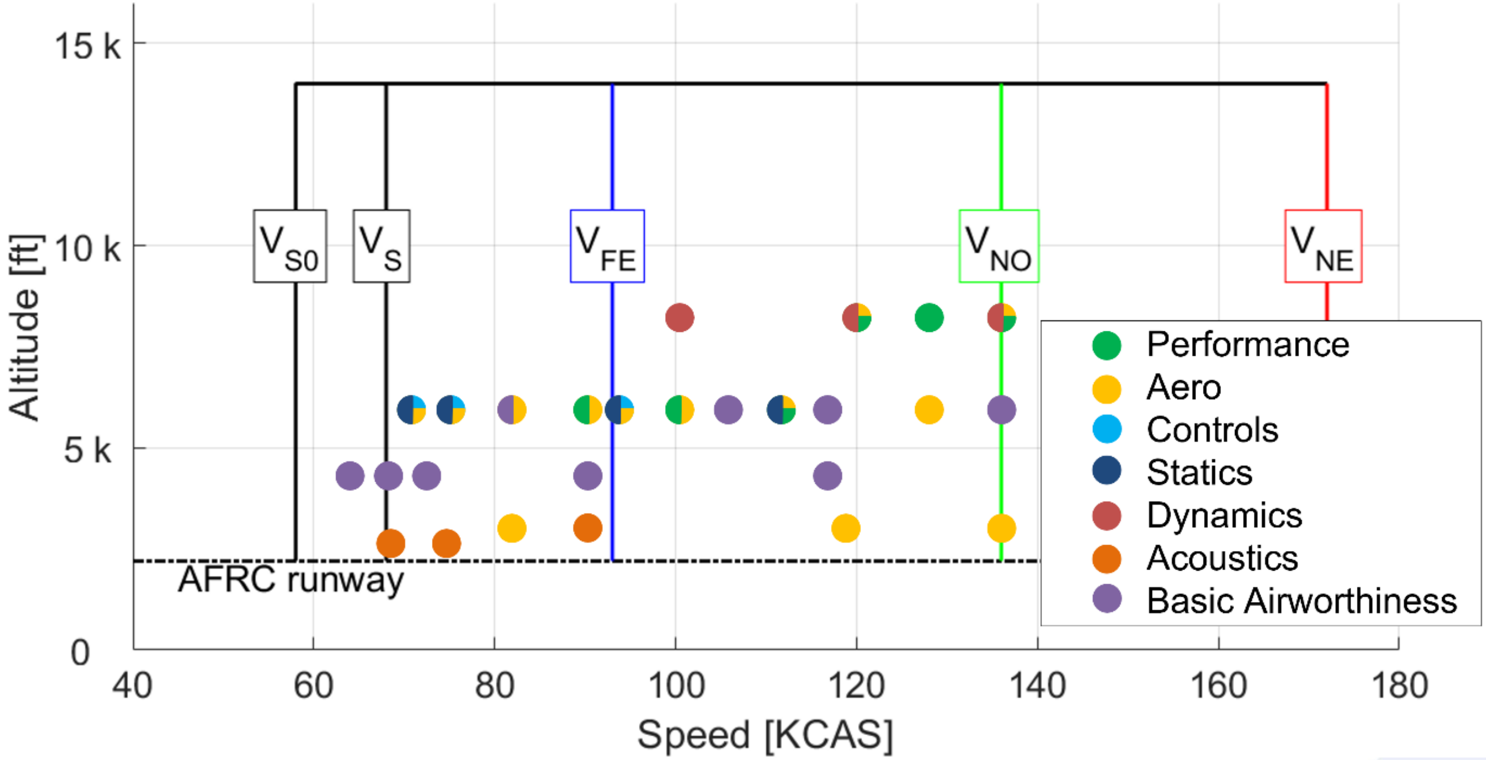
Data Collection Flight Test Maneuvers

Title	Purpose	A.II	A.III	P.II	P.III
Phasing Maneuver	Verify instrumentation is working as expected	X			
Bank-to-Bank Turn	Characterize the roll performance	X	X		
Wings Level Sideslip	Evaluate the rudder and aileron/flight spoiler flight dynamic interconnections and characterize the flight dynamic limits Calibrate the nose boom angle of sideslip measurement Assess vertical tail loads as part of defining the strength envelope for the Mod III/IV flights	X	X		
Steady Heading Sideslip	Evaluate the rudder and aileron/flight spoiler flight dynamic interconnections and characterize the flight dynamic limits Assess vertical tail loads as part of defining the strength envelope for the Mod III/IV flights	X	X		
Speed Stability	Characterize the static longitudinal stability	X	X		
Tower Fly-by	Calibrate the nose boom pitot-static system and the total air temperature sensor Estimate the drag of the landing gear			X	X
Accel/Decel	Calibrate the nose boom pitot-static system and the total air temperature sensor			X	X
2-1-1s	Perform spot checks of the aerodynamic model Assess vertical tail loads as part of defining the strength envelope for the Mod III/IV flights	X	X		

Data Collection Flight Test Maneuvers

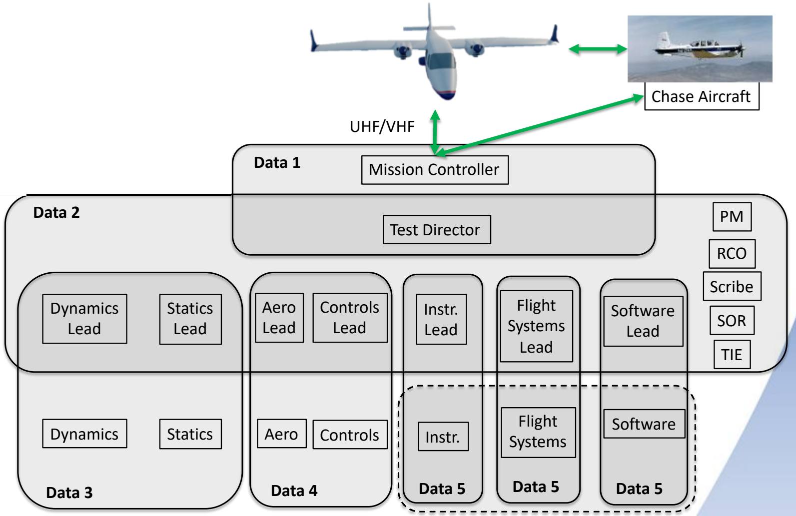
Title	Purpose	A.II	A.III	P.II	P.III
Pull-up Push-over (PUPO)	Calibrate the nose boom angle of attack measurement Provides stick force per g and empennage loads data	X	X		
Wind-up Turns (WUT)	Obtain vehicle load data under an increased g load factor while maintaining a constant airspeed Obtain higher lift coefficient drag data than can be achieved in 1-g level flight and stick force per g data		X	X	
Wind Turn	Estimate winds at specific altitude for angle of attack and angle of sideslip reconstruction.		X	X	
Power-Off Glide	Determine the power-off aerodynamic characteristics of the aircraft: primarily the relationships between drag and lift			X	X
Power-On Climb	Determine power-on (installed) aerodynamic characteristics of the aircraft: primarily to calibrate the thrust model as compared to the drag model developed during power-off glides			X	X
Power-On Cruise	Model check/error points for power-on (installed) aerodynamic characteristics of the aircraft: primarily to develop error estimates for the thrust and drag models			X	X
Gear Drag Determination	Characterize the increase in drag due to the deployment of the landing gear			X	X
Maximum Speed Determination	Anchor point for determination of power-on installed aerodynamic characteristics	X		X	X
Resonance Assessment Profile (RAPs)	Excite aircraft normal resonance modes and measure how they respond or interact in flight			X	X
Acoustics	Capture acoustic data during takeoffs, landings, and tower fly-bys			X	X

DC & BASF Test Points in the Mod II Envelope by Discipline



Mission Control Room and Test Point Clearance Philosophy

- Provides real-time data monitoring of safety and mission critical parameters
  - Safety critical parameters include battery temperature and voltages, cruise motor temperatures, system faults
  - Pilot relies on safety critical monitoring due to limited information available in the cockpit
- Test Point Clearance:
  - Each test point has defined evaluation criteria, data requirements and success criteria that must be met for test point to be considered cleared
  - Between flights, disciplines examine flight data and use defined evaluation and success criteria to ensure data requirements are met



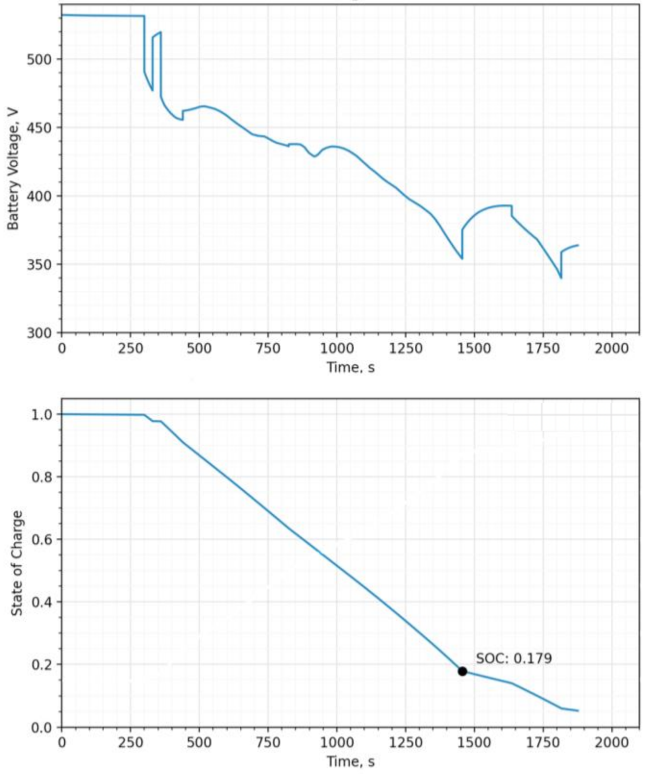
Data Analysis Requirements

Parameter Type	Required Post-flight analysis (SF, ST)	Test Point	Data Quality (MC)
IMU - Accels, rates, angles, altitude, velocities			Aero
Angle of Attack and Angle of Sideslip	Aero	Required for 211s	
Total Air Temperature			Aero
Total Pressure & Static Pressure	Aero	Required for 211s	Aero
KCAS - Calculated	Aero	Required for 211s	
QBAR - Calculated	Aero	Required for 211s	
Control Surface Deflections (except for rudder)			Flight Controls
Gear Position			Flight Controls
Stabilator Deflection/forces			Flight Controls
Accelerometers - Gear		Required for Taxi Test	Dynamics
Accelerometers - motor Mount Y & Z Axis	Static Structures	Entire Flight	Dynamics
Accelerometers – Wing, Stabilator, Rudder, Vertical Tail, Fuselage			Dynamics
Avionics Bus Current	Flight Systems	Entire Flight	
BCM - Cell Average & Maximum Temperatures	Flight Systems	Entire Flight	
BCM - Cell Average & Standard Deviation Temperatures			Flight Systems
BCM Cell maximum & Minimum voltages	Flight Systems	Entire Flight	
BCM - Cell Minimum & Standard Deviation Temperatures			Flight Systems
BCM Failure Indications (Isolation and master Fault)	Flight Systems	Entire Flight	
BCM - Internal Temperatures			Flight Systems
BCM - Pack Voltage	Flight Systems	Entire Flight	
BCM - SOC and Pack Current			Flight Systems
Cruise motor - Bearing Temperatures	Flight Systems	Entire Flight	
Cruise Motor - Winding Temperatures	Flight Systems	Entire Flight	
Cruise motor Controller - Failure Indications	Flight Systems	Entire Flight	
Cruise Motor Controller - Internal Temperatures	Flight Systems	Entire Flight	
Traction Bus Volage & Current	Flight Systems	Entire Flight	
Advanced Nav - Z Accel	Static Structures	Entire Flight	
Rudder Deflection	Static Structures	Required for 211s	Flight Controls
Strain Gages - Vertical Tail			Static Structures
Vertical Tail Calculated Load	Static Structures	Required for 211s	
Prop RPM			Static Structures

Battery State of Charge

- Battery State of Charge (SOC) is analogous to fuel remaining on a traditional aircraft
  - SOC decreases in a predictable trend that remains linear for a constant power setting
  - The on-aircraft calculation of SOC was found to be unreliable due to inaccurate current inputs resulting from the current sensor installation
- For flight test planning, SOC is used as the primary metric for battery charge remaining
- For inflight energy management, the pilot sets cruise motor power to full or idle positions, and compares battery voltages to battery model predictions at joker and bingo limits
  - Joker: Complete current test point and return to base
  - Bingo: Immediately end testing and return to base
- Bingo SOC was selected to be 18%, equivalent to 425 V at idle or 365 V at full power, to allow for landing above the minimum system voltage
  - Allowance for 2 minutes of holding at pattern altitude to find a landing area
    - After 2 minutes, the pilot declares an emergency and lands immediately
  - Joker SOC provides an additional 3 minutes of time in the holding pattern
- For the first flight, bingo/joker SOC increased by 10% to provide additional margin above the minimum battery voltage

Estimated Voltage & SOC for a representative mission



Flight Scripting

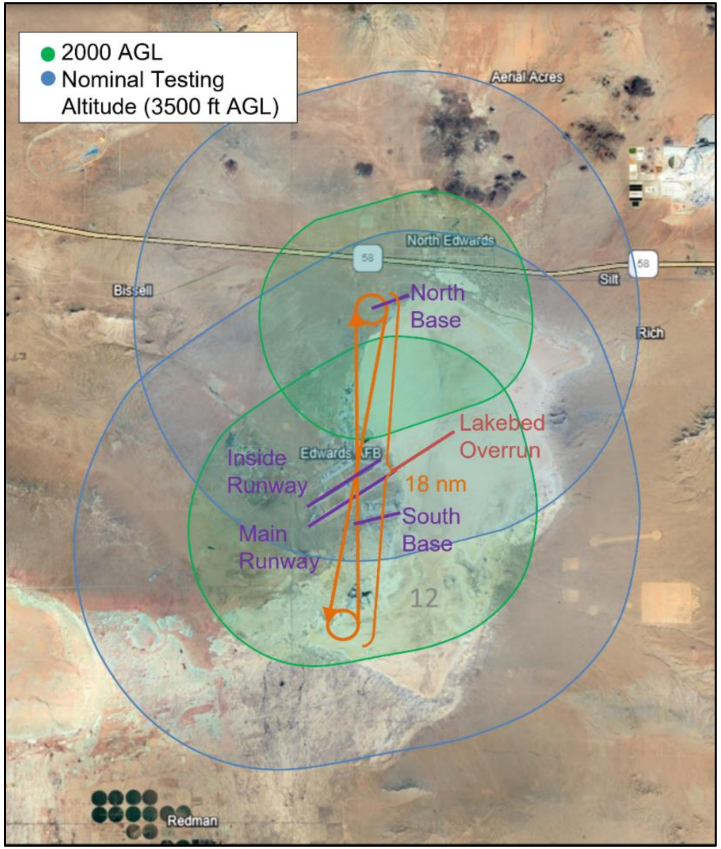
- Due to X-57's limited flight each flight is highly scripted
  - Each flight lasts between 20-25 minutes
  - Scripting necessary to maximize test efficiency and minimize number of flights
    - 14 planned flights with 2 backup flights to clean up any missed points or repeats
  - Test points with similar aircraft configurations and flight conditions are grouped together to reduce setup time
- Initial scripting uses performance lookup tables that estimate state of charge usage throughout the flight envelope
- Pilots and mission controllers walk through each scripted flight in the piloted sim prior to flight test

Flight 6: High Altitude Performance + Raps

Maneuver	Test Point #	Altitude	Airspeed	Flaps	Duration (min)	1.1*Maneuver Duration	SOC Used per Phase	SOC Total	Elapsed Duration
Pre-T/O Time					0.00		0.000	0.90	0
Takeoff + Power-On Climb (CL1, CL2, CL3)	1, 2, 3	8,000			11.98		0.404	0.50	12
Raps	4	8,000	100	0	1.00	1.10	0.031	0.47	13
Power-On Cruise (VC7)	5	8,000	120	0	2.00	2.20	0.086	0.38	15
Raps	6	8,000	120	0	1.00	1.10	0.043	0.34	16
Feather Props + Power-Off Glide (G1, G2, G3)	7, 8, 9	8,000	136	0	3.60	3.96	0.015	0.33	20
Descent/Landing		4,500			2.3		0.007	0.32	22

Flight Operations

X-57 Mod-II Glide Range



- X-57 flight operations are planned to be within glide distance of a usable lakebed or runway
  - If lakebed runways were unavailable, the pilot would climb in a flameout pattern over the main runway
- Pilots adopted a stop-oriented approach for takeoff emergency scenarios
  - Edwards Air Force Base main runway is 15,000 ft runway with 9,000 ft of lakebed overrun.
    - All failures below 700 ft AGL were handled by the pilots immediately removing power and landing the aircraft straight ahead on the main runway

Piloted Sim Evaluations and Training

- Sim evaluations examine off nominal conditions
  - Single motor failures, propeller failures, electric system failures
  - Atmospheric variations such as crosswinds or hot days
- Pilot Checklist and Emergency Procedure (EP) developed with simulation inputs
  - Determined takeoff procedures for maximum altitude for straight-ahead landing
- Provided simulation data to structures, dynamics, and performance teams
  - Help set limits and confirm predictions for flight test planning
- Pilot Simulation Training
  - Practice all planned test maneuvers, takeoff procedures, and EP within six months of first flight to maintain pilot proficiency
  - Perform full mission rehearsals and EP refresher training 1-2 days before flight mission

X-57 Mod II Unique Flight Approach Challenges

- Detailed flight planning and ConOps development began later than is desirable
  - Earlier focus on flight planning and ConOps would have helped to better inform requirements
- Limited battery capacity made flight planning a challenge
  - Highly detailed flight planning/scripting in order to maximize in-flight test efficiency in order to reduce total number of flights
  - Required development of Joker/Bingo equivalent approach
- Flight planning required continuous ability to land on a hard surface/runway, e.g., “plan for the worst, hope for the best”
  - Concern with unknown unknown with traction system that would preclude returning to the runway
  - Ensure ability to immediately land in the event of a battery system or vehicle fire (considered highly improbable, but still needed to be accounted for)
- In general, flight-test approach is similar to any other AFRC project