Flight-Test Approach for X-57 Mod II Configuration

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The primary objective of the X-57 Mod II test flights is to perform a functional checkout of the research traction battery power and motor systems, perform an airworthiness assessment of the modified vehicle, and to collect baseline performance, stability, and acoustic data for comparisons with later modifications of the X-57 airplane. This paper describes the planned flight operations of the Mod II airplane, the unique considerations and decisions made in operating an electric aircraft, and the development and planning of the research test points necessary to achieve the Mod II flight objectives. Due to the constrained flight time, which resulted from limited capacity of the battery system, careful scripting of flights was required to maximize test time and execute test points efficiently.

I. Nomenclature

ft	=	feet
kW	=	kilowatts
min	=	minute
nm	=	nautical mile
s	=	second
V	=	volt
V_{FE}	=	Maximum full flap extended speed
V_{NE}	=	Never exceed speed
V_{NO}	=	Maximum cruise speed
V_S	=	Stall speed
V_{S0}	=	Stall speed in the landing configuration.

II. Introduction

The X-57 "Maxwell" all-electric airplane is a National Aeronautics and Space Administration (NASA) flight demonstrator concept for distributed electric propulsion (DEP) technologies, where distributed electrically driven propulsors are strategically placed along the wing to yield aero-propulsive benefits. The X-57 Subproject encompasses three major phases of development for the transition from a stock general aviation Tecnam P2006T (Costruzioni Aeronautiche Tecnam srl, Sapua, Italy) twin-engine airplane into the X-57 distributed electronic propulsion (DEP) demonstrator (a.k.a., the X-57 airplane): Modification II (Mod II); Mod III; and Mod IV. The Mod II configuration focuses on the installation and integration of electrical power systems in place of the traditional gas-powered propulsors and fuel systems; Mod III involves the replacement of the stock P2006T wing with one optimized for

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efficiency at cruise flight conditions and the relocation of the cruise motors to the wing tips; and finally, Mod IV integrates the DEP motors along the wing.

The primary purpose of the Mod II flight-test campaign is to perform a functional checkout of the research traction battery power and motor systems, perform an airworthiness assessment of the modified airplane, and to collect baseline performance, stability, and acoustic data for comparisons with future X-57 configurations.

The Mod II configuration presents several novel considerations for the test planning process. The amount of flight time on battery power is drastically reduced when compared to a traditionally fueled aircraft, which requires each flight to be scripted as efficiently as possible to accomplish all desired test points within a reasonable number of flights. Also, a direct replacement for a fuel gage on an electric aircraft that is as linear, trustworthy, and well understood as the gages on combustion-powered vehicles does not exist in this configuration, requiring the development of new methods for monitoring remaining energy capacity, both for flight-test planning purposes and for in-flight monitoring.

This paper discusses the general ground and flight operations of the Mod II airplane as well as the research test points necessary to achieve the airworthiness and performance-related flight objectives of the Mod II flight-test campaign.

III. Airplane Description

A. Tecnam P2006T Airplane

The X-57 Mod II airplane is a modified version of the Tecnam P2006T, a high-winged twin-engine airplane built by Costruzioni Aeronautiche Tecnam. The pilot controls the X-57 airplane using a control yoke, rudder pedals, throttle levers, and propeller pitch levers. These control yoke and rudder pedals are connected to each control surface by pushrods, cables, and pulleys. The control surfaces include a single-unit stabilator, stabilator trim, ailerons, aileron trim, rudder, and rudder trim. The trim settings for the stabilator and rudder can be adjusted in flight via a dial in the cockpit, but the aileron trim tab can only be adjusted on the ground. Deployable slotted flaps are used for takeoff and landing operations and are adjustable via a switch on the instrumentation panel.

B. Overview of Mod II Changes

The modification to the airplane for Mod II, depicted in Fig. 1, are primarily to the internal systems and the engines. The Tecnam stock Rotax (BRP-Rotax GmbH & Co KG, Gunskirchen, Austria) engines have been replaced with Joby (Joby Aviation, Inc., Santa Cruz, California) JM-57, 72 kW, electric cruise motors powered by an experimental battery system located in the aft portion of the cabin. The experimental battery system is referred to as the traction battery system because it provides power to the electric motors.

Fig. 1 X-57 Mod II airplane.

The throttle and propeller pitch levers have been modified to send torque and propeller pitch commands to the electric motors. These modifications are depicted in Fig. 2. The difference between throttle and torque levers is that instead of the throttle levers increasing fuel flow to achieve a thrust output, the torque levers increase current draw to achieve a desired motor torque. Past the full-torque detent is the overdrive mode, which allows for up to a 30-percent increase in torque output for each cruise motor controller (CMC). This mode is meant for emergency situations when one CMC is inoperative, and the pilot requires additional torque to execute an emergency descent and landing procedure. At the bottom of the torque lever, beyond the idle detent, is the regen area, where a negative torque is applied to the cruise motors to extract energy from the airflow and provide battery recharging inflight.

Fig. 2 Torque and propeller pitch levers.

For flight operations, the propeller pitch control is operated in a constant speed mode where the pilot sets an RPM command via the propeller pitch levers that is then sent to a constant speed controller that automatically (auto) adjusts blade pitch to achieve the desired revolutions per minute (RPM). The range of available RPM commands in the auto mode is 1,700 to 2,700 RPM. At the aft stop of the propeller pitch lever is a feather switch that overrides all propeller pitch commands and drives the propeller pitch to the feathered position. Moving the propeller pitch levers forward, off the aft stop, restores the propeller pitch control in the constant speed mode.

Changes to the outer mold line (OML) include the modification of the motor cowling area to accommodate the electric motors, the addition of inlet scoops to provide cruise motor controller cooling, and the addition of a noseboom for collecting research quality air-data measurements. The copilot seat, yoke, and rudder pedals have been removed and replaced with a research instrumentation pallet.

C. Mod II Flight Envelope

Figure 3 depicts the full-flight envelope for the Mod II flights. The maximum altitude is 14,000-ft mean sea level (MSL), but due to energy capacity limitations in the traction battery system, the maximum testing altitude is limited to 8,000-ft MSL. Maximum cruise speed (VNO) is 136 knots-calibrated airspeed (KCAS), never exceed speed (VNE) is 172 KCAS, and stall speed (VS) in the cruise configuration is 68 KCAS. With full deployment of flaps and gear, the stall speed (VS0) is reduced to 58 KCAS. The maximum speed at which flaps can be fully deployed (VFE) is 93 KCAS.

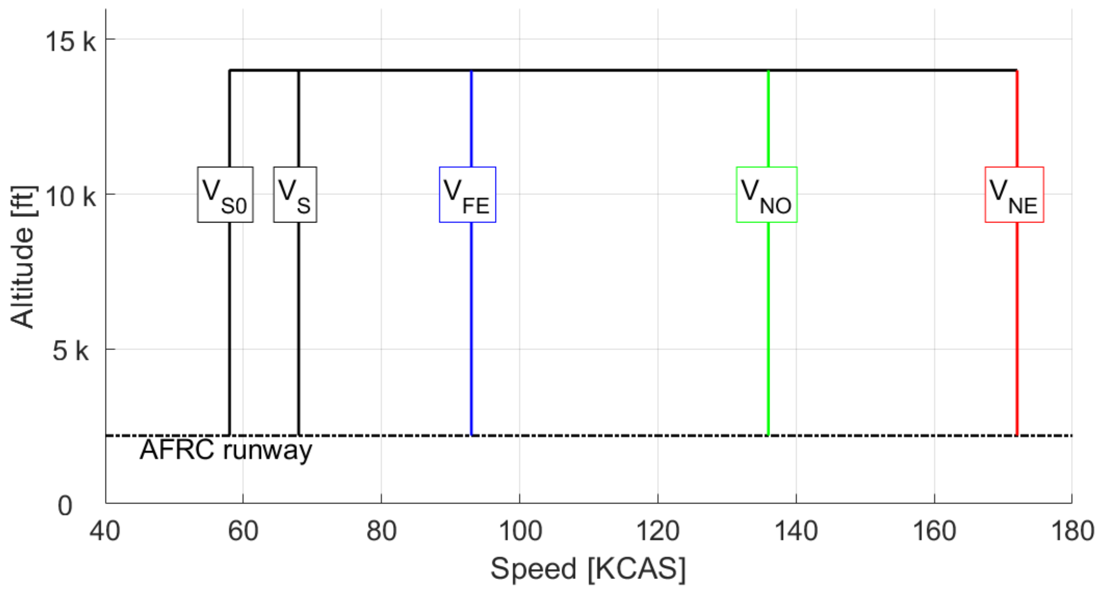

Fig. 3 Mod II flight envelope.

IV. Flight Objectives

The Mod II flight objectives are derived from project goals of retrofitting a general aviation airplane with an electric propulsion system, sharing design and airworthiness processes with regulators and standards organizations as well as lessons learned with industry and academic shareholders. As part of this retrofitting effort, several design drivers were developed to target specific energy reduction thresholds with the implementation of each X-57 modification. These design drivers are listed in listed in Table 1.

Table 1 X-57 design drivers.

Design drivers	Success criteria
Mod II: Retrofit a baseline general aviation airplane with an electric propulsion system.	Optimize the design for cruise power consumption with a target of a 3.3-times reduction in energy from the baseline airplane.
Mod III: Modify the configuration with a cruise-optimized wing and provisions for a distributed electric propulsion system.	Optimize the design for improved cruise power consumption with a target of a 1.5-times reduction in energy from the Mod II configuration.

Table 2 includes the flight objectives for the Mod II flight campaign, which are categorized into airworthiness and performance-based objectives. The airworthiness objectives refer to objectives that verify the safe operation of the airplane, whereas the performance objectives refer to data collection to quantify how well the X-57 design achieves the design drivers. Each flight-test maneuver, described in Section V, traces directly to one of these four flight objectives.

Table 2 Mod II flight objectives.

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.

V. Ground and Flight-Test Concept of Operations

A. Flight Operations Location

The X-57 pre and postflight activities occur outside the X-57 hangar or on one of the local National Aeronautics and Space Administration (NASA) Armstrong Flight Research Center (AFRC) ramps prior to the airplane being towed to the taxiways closest to the Edwards Air Force Base (EAFB) (Edwards, California) main runway. Much of the preflight is done on external power to help preserve battery capacity for the flight tests. The target state of charge (SOC) prior to takeoff is 90 percent after the completion of all preflight checklists and with the airplane positioned at the end of the runway in the idle power setting. Nominal takeoff operations would occur on the EAFB main runway. Takeoff direction is selected based on wind conditions, where the preference is to take off into a headwind to maximize the window for straight-ahead landings on the runway in the event of an emergency during takeoff.

As a key precaution, takeoffs should only occur if there is an option to glide to a usable lakebed or runway if a failure occurs during the takeoff profile. This requirement necessitates flying over usable lakebeds during takeoff or climbing out in a flameout pattern over the main runway in the event that the lakebed is flooded or otherwise unavailable.

The EAFB main runway is a 15,000-ft runway with 9,000 feet of lakebed overrun, which allows for takeoff emergencies that occur below 700-ft above ground level (AGL) to be mitigated by removing power from the system and landing straight ahead on the runway. The X-57 test pilots adopted the approach of being stop oriented for all emergency scenarios during takeoff. As soon as any failure or unexpected behavior occurs, the pilot will immediately attempt to land the airplane. This approach is taken primarily because both Mod II cruise motors are experimental systems under test, and the pilots must operate under the assumption that if one motor fails, there is an increased likelihood the second motor will fail soon after.

B. Airspace Use

All X-57 Mod II flight operations take place within gliding distance of a usable lakebed or runway, primarily due to the nature of testing experimental cruise motors. Most test points take place at 6,000- or 8,000-ft MSL and are to be executed along an 18-nm elongated orbit within the EAFB airspace. This elongated orbit provides 6 to 8 minutes of continuous test time per leg to maximize the amount of test time at testing altitudes. This orbit along with glide ranges at 4,500- and 6,000-ft altitudes are depicted in Fig. 4.

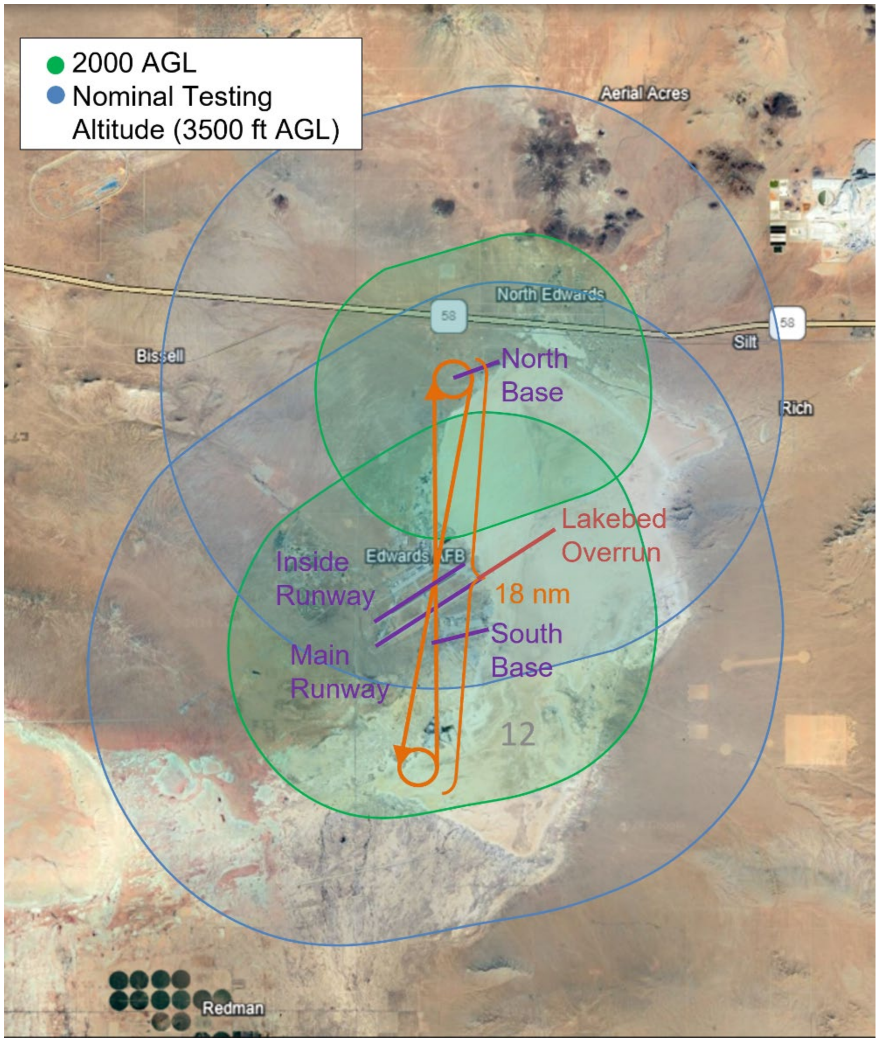

Fig. 4 Planned airspace use and glide range.

The EAFB main runway is the primary landing location, with the EAFB North- and South-base runways serving as backups. The lakebeds were identified as additional backup depending on their usability status. At EAFB, the airfield management performs inspections of the lakebed to determine the usability of runways for all aircraft that fly in the airspace. Because the X-57 Mod II airplane is relatively lightweight and lands at lower airspeeds, the tire footprint of the airplane is significantly lower than that of a jet or cargo aircraft that routinely use the EAFB range, resulting in more potential landing locations. To assess the usability of the lakebed runways, the test pilots perform independent inspections on the day of flight.

C. Flight Operations

This section summarizes the preflight, day of flight, in-flight, and postflight tasks to be executed as part of the flight-test campaign. The flight operations are streamlined to allow sufficient time for battery charging and to maximize the amount of flight time dedicated to performing research test points.

Preflight

Airplane preflight operations occur inside the hanger or on the local AFRC ramps and occur the day before a scheduled flight. Major preflight tasks consist of battery charging, completion of airplane preflight checklists and instrumentation preflight checklists, and the T-1 crew brief. The goal for battery charging operations is a charge of up to 95 percent of the SOC threshold with at least a 90-percent SOC when the airplane is sitting on the runway ready for takeoff (after the completion of day-of-flight checklists).

Day of Flight

On the day of flight, the airplane is towed to the launch site near the end of the runway, primarily to conserve SOC during taxi. Concurrently, the T-0 flight crew brief occurs between the pilots, chase crew, Mission Controller, and Test Director. At this time the pilot would discuss weather conditions, details of the chase plan, and any last-minute coordination. The pilot then travels to the launch site, the Mission Control Room begins staffing, and day-of-flight checklists are performed to work through the final airplane and instrumentation checks.

Flights are scheduled to begin within an hour of sunrise when outside ambient temperature and wind velocities are generally at the lowest values for the day. This schedule is meant to minimize the impact of the ambient temperature on the thermal characteristics of the research electrical systems and to avoid exceeding crosswind landing restrictions.

Flight

Prior to takeoff, the test pilot establishes communication with the test director in the Mission Control Room and proceeds through the pilot's checklists, which includes arming and verifying the successful operation of the electrical systems, performing a motor runup, and taxiing to the end of the runway. Once the test director confirms that the Control Room is ready, the pilot takes off from the EAFB main runway and begins a climb out to the testing altitude. Many of the parameters related to the experimental cruise motor and battery systems telemetered from the airplane are considered safety critical and required to be operational for ground- and flight-testing. These parameters are discussed further in Section V, F. The telemetry transmission and clear communications between the pilot and the Control Room are an essential part of the flight operations of the X-57 airplane due to the need to monitor and communicate the status of these safety critical parameters.

At the testing altitude, the pilot works through all of the planned flight cards until each one was completed, or a bingo or joker SOC is reached, and a return to base (RTB) is called. Joker SOC refers to the battery charge state when the pilot completes the current test point before returning to base. Bingo SOC refers to the battery charge state that elicits an increased level of urgency, requiring the pilot to immediately cease flight-testing operations and RTB.

Postflight

Postflight operations begin with a full shutdown of the airplane and instrumentation systems while the Control Room continues to monitor the airplane and electrical systems until the shutdown of the instrumentation pallet. An initial airplane postflight inspection assesses if there is any damage or maintenance required. The pilot returns to AFRC to conduct the debrief with the Flight-Test Team soon after landing. The airplane is towed to the hangar where a detailed postflight inspection occurs. The Instrumentation Team collects the onboard flight data from the recorder and begins the transfer of the flight data from the airplane.

As part of the postflight activities, engineers are required to review the data to clear airworthiness test points and ensure that the required performance data is captured. This postflight data analysis is discussed in further detail in Section VI, I.

D. Bingo and Joker SOC Determinations

Due to the X-57 Mod II airplane being a fully electric airplane, traction battery SOC was identified as an alternative to using fuel remaining indicators in order to make bingo and joker determinations midflight.

To set the bingo thresholds, the Performance Engineering Team used the X-57 Mission Planning tool [1] to determine the minimum SOC at the testing altitude in order to land above 340 V with a descent profile derived from the standard energy profile [2]. This SOC was determined to be at 18 percent when descending from 6,000-ft MSL and 22 percent when descending from 8,000-ft MSL.

Included in the standard energy profile descent is a 2-min pattern orbit. Because of the strict battery limitations, it is not possible for the pilot to perform a go-around and retain the desired flight time at the testing altitudes. Instead, the pilot uses the two minutes dedicated to the pattern orbit to find a suitable landing area. This time frame allows the pilot to accommodate elements of the EAFB airfield such as air traffic, ground vehicles, and other emergency considerations that impact the immediate availability of the primary runway. The joker SOC levels are increased to allow for a 5-min pattern orbit, resulting in a joker SOC of 28 percent at 6,000-ft MSL and 32 percent at 8,000-ft MSL.

One additional complexity of the bingo and joker determinations is that the real-time SOC calculation used in the traction battery system was determined to be an unreliable calculation of the actual SOC levels of the batteries, primarily due to inaccuracies in the current sensor driving the SOC calculation. These inaccuracies vary with current draw, resulting in a SOC error that varies based on the flight profile.

The SOC characteristics were the primary factor in the decision to not rely solely on the SOC estimate for monitoring battery charge status during flight, and instead, voltage readings on cockpit energy meters, driven by the battery management system, were chosen to be the truth source for the energy state. The voltage readings do not decrease linearly at a constant power setting and further fluctuate with changes to the power setting, requiring a more intricate process to determine the energy state of the battery system. To account for this behavior in flight, the pilot sets the power setting of the motors to a pre-established power state, such as idle or full power, and compares the voltage readings from the cockpit meters to voltage predictions derived from the X-57 battery model [3] at a target minimum SOC to determine whether the batteries are below the bingo and joker charge levels. This solution allowed the pilot to use the most accurate battery information provided in the cockpit, and still allowed the Test Planning Team to plan flights around the linear SOC predictions.

E. Flight Scripting

Due to the limited battery capacity, the flight time for each Mod II flight is severely limited. As depicted in Table 3, the amount of useful time on condition is between 5 and 20 minutes at the target altitude and airspeeds. This restrictive test time drove the need to heavily script each flight to maximize the test efficiency and minimize the number of required flights to accomplish the flight-test objectives.

Table 3 Estimated time on condition.

	Estimated time on condition, min						
	Airspeed, KCAS						
Altitude, ft MSL	**80**	**90**	**100**	**110**	**120**	**130**	**136**
4,000	26.8	24.3	20.9	17.9	15.1	12.4	10.9
5,000	22.9	21.1	18.0	15.4	13.0	10.7	9.2
6,000	19.7	18.1	15.7	13.3	11.2	9.2	7.9
7,000	16.3	14.8	13.1	11.0	9.2	7.6	6.7
8,000	13.0	11.7	10.3	8.8	7.4	5.9	5.2
9,000	9.5	8.7	7.6	6.6	5.5	4.4	3.9
10,000	6.3	5.9	5.2	4.4	3.6	3.0	2.6

To facilitate the scripting process, the Performance Team developed tables that estimated SOC usage per minute based on airspeed, altitude, and power setting. These tables also included SOC usage for climbs and descents. The performance tables were then used as look-up tables to estimate the SOC usage for climb and descent to the testing altitude and to estimate the SOC used during a test maneuver. The climbs, descents, and maneuver estimates were then combined into draft missions where the bingo and joker SOC were used as the cut off points. The draft missions were then cross-checked with the pilots in the AFRC simulator [4] to verify the feasibility of executing the mission within the flight time limitations.

Using this method, the estimated number of flights consisted of 4 basic airworthiness and system functionality (BASF) flights and 12 to 14 data collection flights to accomplish all test points required to meet the Mod II flight objectives.

F. Mission Control Room

The Mission Control Room is staffed as part of the research test flights and provides real-time data monitoring of safety and mission critical parameters for the pilot. The control room staff consists of a Mission Controller (who has direct communication with the pilot and the Test Director); a Test Director (who maintains communication with the Mission Controller and the Engineering Leads); and engineering discipline teams (who communicate among their respective team members and provide status updates to the test director). [5]

The engineering discipline teams consist of structural dynamics and statics, aerodynamics, flight controls, instrumentations, flight systems, and software teams, each charged with monitoring critical parameters [6] telemetered to their discipline-specific control room displays.

The safety of flight parameters primarily consisted of battery cell temperatures, faults, and voltages, cruise motor temperatures, and cruise motor controller temperatures and faults. For many of these parameters, the only indications the pilot receives in the cockpit are visual fault alerts or aural alerts, however, the pilot is not able to track which specific parameter has triggered the alert. These indications were designed intentionally to avoid overloading the pilot displays with excessive information and, instead, rely on the Control Room to provide additional information and guidance if an alert is triggered.

The Control Room also monitors the time histories of these safety critical parameters, especially the temperature parameters. The Control Room will notice and alert the pilot if a specific parameter was trending towards a safety limit prior to the exceedance of that limit.

G. Safety Chase

A safety chase aircraft is required for all Mod II flights and provides safety observations and air data call outs as necessary during flights. The Beechcraft (Raytheon Aircraft Company, Arlington, Virginia) T-34C Mentor airplane was identified as the preferred safety chase airplane due to similarities in performance to the X-57 Mod II airplane, with the Beechcraft (Raytheon Aircraft Company, Arlington, Virginia) King Air B200 aircraft serving as a backup option if the T-34C was not available. The safety chase aircraft also provides photo and video documentation of the flights.

H. Training Requirements

All project pilots and Mission Controllers are required to complete two phases of piloted simulation training prior to being declared ready for flight operations. The first phase requires the pilot to fly each planned test maneuver at the specified flight conditions and execute a simulation of all emergency procedures. The pilots also simulate takeoff emergency scenarios to determine safe landing zones based on the airplane altitude at the time of the failure. This training is required to occur within 180 days of the first flight.

The second phase of piloted simulation training requires the pilots to do full mission rehearsals of an upcoming flight within a 48-hr window prior to a planned flight. Critical emergency procedure scenarios are simulated as a refresher of the previous emergency procedure training.

VI. Flight-Test Approach

The overarching approach of the X-57 Mod II Flight-Test Program is to steadily build up from low-speed handling and taxi testing to first flight and functional test flights, then to the research data collection flights. All test points within each phase of testing have defined evaluation criteria and success criteria that must be met before the test point is considered cleared.

There are four major phases of the flight-test program: 1) ramp and taxiway taxi tests; 2) high-speed taxi tests; 3) BASF flights; and 4) data collection flights.

A. Ramp and Taxiway Taxi Tests

The purpose of the ramp and taxiway taxi testing is to execute ground handling tests of the Mod II airplane under power of the traction battery system. The ground handling speed is defined as below 25 knots indicated airspeed (KIAS). The pilot performs qualitative evaluations of yoke freeplay, nosewheel steering, and the ability to maintain the runway centerline. The pilot also applies moderate braking to assess brake performance, then evaluates if there are any asymmetric braking concerns. These low-speed tests serve as a final ground check of the experimental electrical systems prior to moving towards higher power settings.

B. High-Speed Taxi Tests

The high-speed taxi tests are split into two different speed categories: 40 KIAS taxi maneuvers and 60 KIAS taxi maneuvers. At 40 KIAS, the pilot performs a buildup of airplane power, starting with 36 kW, ramping up to 60 kW, and finally, to a 72-kW setting per cruise motor. These taxi tests are performed on the main runway. The pilot evaluates nosewheel steering, differential thrust, and brake performance. This test series will be the first time the pilot operates the airplane at higher power settings representative of the takeoff profile.

For the 60 KIAS taxi testing, the pilot executes four different abort procedures at the target airspeed to evaluate abort effectiveness and airplane response. The four abort procedures include: 1) setting the torque levers to idle; 2) setting the torque levers to idle and the propeller levers to feathered; 3) setting the torque levers to full regen; and 4) setting the torque levers to idle and applying heavy braking. Throughout each of these abort tests, the pilot evaluates nosewheel tracking, yoke freeplay, and surface positioning with zero trim settings. During the heavy braking abort, the pilot evaluates skidding and distance to complete a full stop.

C. Basic Airworthiness and System Functionality Flights

The BASF flights encompass the first several flights of the test program and are similar to a functional check flight on a production airplane. The primary goal of the BASF flights is to fully test the control surface operation, landing gear operation, and motor performance over the full range of power settings prior to the data collection research flights.

For the first flight, heavy restrictions on the flight envelope and minimum SOC levels are placed on the airplane. The landing gear is to remain in the down position for the duration of the flight, and the minimum SOC is increased by 10 percent to provide additional margin above the minimum battery voltages. As a result of the additional drag due to airplane climbing with the landing gear down, the testing altitude has been lowered to 4,500-ft MSL to increase the amount of time at the testing altitude. The planned flight path has a more restrictive orbit over the main runway to stay within glide distance at the lower testing altitude. While leaving the gear down is common in the first flight of many aircraft, it is especially critical for the X-57 configuration due to flight time limitations and should any gear extension emergency scenarios develop during the first flight of these experimental electrical systems, additional time may be needed to solve these problems.

The first flight consists mainly of control and trim surface checks, pitot-static checks, and airplane avionics checks. For the control surface checks, the pilot evaluates controllability, friction, breakout, binding, and freeplay. For the trim checks, the pilot verifies the ability to trim at speeds throughout the flight envelope. For pitot-static checks, the pilot coordinates with the chase airplane to verify altitude, vertical speed, and airspeed.

After the first flight, the airplane is thoroughly inspected for any maintenance items, and the aileron trim is adjusted per pilot recommendations after the first flight.

The second flight focuses primarily on the gear and flap operations and is the first time the airplane is in the clean cruise configuration. The pilot performs additional controllability checks before and after gear operation and makes note of any lateral or pitch changes after the gear has been raised.

The third flight includes test points for the torque and propeller lever responses. The pilot verifies that the torque and propellor responses are stable and linear throughout the full range of both the torque and propeller levers.

The fourth BASF flight includes a motor feather, electrical shutdown, and inflight restart. This test point is meant to characterize the in-flight restart capabilities of the experimental propulsion system prior to performing an in-flight restart during the power-off glide test points, which are planned during the data collection flights.

These initial flights are conducted in a sanitized airspace, where the X-57 airplane is the only airplane flying in the EAFB airspace.

D. Data Collection Flights

The data collection flights consist of test points focused on collecting research data for airframe airworthiness assessments and performance data. There are three major categories of research data collected during the DC flights: 1) aerodynamic data needed to calibrate the air data system; 2) flight controls and structures data to perform an airworthiness assessment on the Mod II configuration; and 3) vehicle performance data necessary to characterize the Mod II vehicle and serve as a baseline data set for future airplane configurations. Figure 5 depicts each of the test points separated by discipline within the Mod II flight envelope.

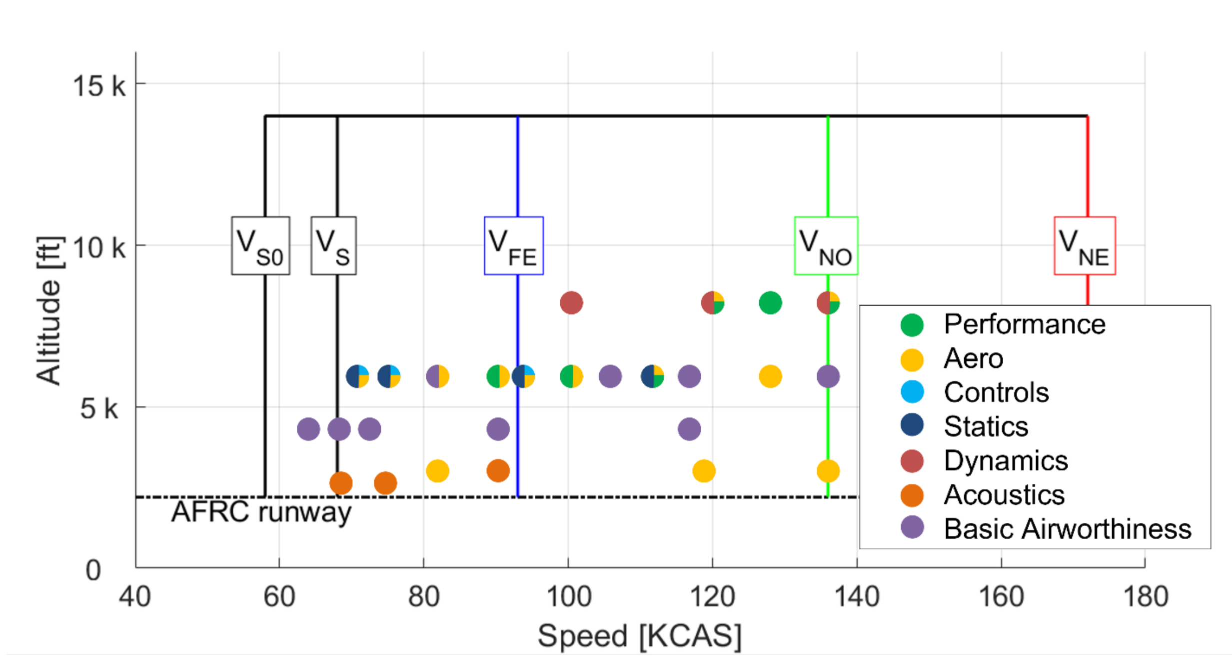

Fig. 5 Flight-test points by primary discipline.

Aerodynamics

The aerodynamic test points are primarily meant to calibrate the research air data system for use in airspeed and altitude-sensitive calibrations used by other disciplines. To calibrate the pitot-static system and total air temperature sensor, the Aerodynamics Team uses acceleration and deceleration data collected at the testing altitude and during a weather tower flyby. For alpha and beta calibrations, wings level side slips, wind-up turns (WUT), and pull-up-push over (PUPO) maneuvers are used. Data collected from the 180-degree wind turns are used to account for wind effects in the alpha and beta calibrations.

Several test points are used to perform a limited model validation of the Mod II aerodynamic model, which include a 2-1-1 maneuver. This maneuver is an extended doublet where the pilot holds a directional step input with the yoke or rudder for two counts, then reverses the direction of the input for one count, then reverses back to the original direction for one more count before releasing the input. This maneuver is done in the pitch, roll, and yaw directions, and allows the Aerodynamics Team to perform a parameter identification analysis on the resulting response. Because the X-57 airplane has reversible flight controls, these are stick-free parameters that require proper trim settings to provide useful data.

The Aerodynamics Team has also developed a gear-drag-determination test point where the gear is deployed from a trim state, and the pilot is tasked with maintaining airspeed and altitude as the gear deploys. The change in power settings required to maintain this flight condition is used to determine the gear drag. Table 4 lists each of the aerodynamic maneuvers, the purpose of each maneuver, and how the maneuvers map to the Mod II flight objectives.

Table 4 Aerodynamic test points.

Maneuver	Purpose	Flight objectives
Acceleration and deceleration	Calibrate the noseboom pitot-static system and total air temperature sensor.	P. II, P. III
Tower flyby	Calibrate the noseboom pitot-static system and total air temperature sensor correlated with weather tower data.	P. II, P. III
2-1-1s	Obtain aerodynamic data in a wide frequency band for aerodynamic modeling.	A. II, A. III
Pull-up-Push-over	Calibrate the nose-boom angle-of-attack measurement. Also, provides empennage loads data for structures discipline.	A. II, A. III
Wind-up turn	Obtain higher lift-coefficient drag data than is possible in a 1-g level flight. Also, used to obtain vehicle load data under an increased g-load factor.	A. III, P. II
Gear drag determination	Characterize the increase in drag due to the deployment of the landing gear.	P. II, P. III
Wind turn	Estimate winds at a specific altitude for angle of attack and side-slip reconstruction.	A. III, P. II

Flight Controls

The specific test points of the flight controls primarily involve performing maneuvers described in AC-23-8C [7] for part 23-type aircraft to assess the airworthiness of the X-57 airplane. These maneuvers include 30-degree bank-to-bank turns, wings level and steady heading side slips, and speed stability test points at specific low-speed settings.

For the 30-degree bank-to-bank turns, a build-up approach is used on the yoke inputs prior to using full inputs to capture the roll rate characteristics of the airplane. Table 5 contains a complete list of the test points where flight controls is the primary discipline monitoring the collection of data.

Table 5 Flight control test points.

Maneuver	Purpose	Flight objectives
Bank-to-bank turn	Characterize the roll performance of the Mod II configuration.	A. II, A. III
Wings level side slip	Characterize the roll and yaw coupling and the lateral stability of the airplane. Maneuver also provides beta sweep information for nose-boom calibration, and vertical tail loads for defining the strength envelope of the Mod III airplane.	A. II, A. III
Steady heading side slip	Characterize the roll and yaw coupling and the crosswind performance. Additionally provides vertical tail loads for defining the strength envelope of the Mod III airplane.	A. II, A. III
Speed stability	Characterize the longitudinal stability of the Mod II configuration and the stick force profile in an off-trim condition.	A. II, A. III

Performance

The performance test points include three categories: 1) power-on cruise; 2) power-on climb, and 3) power-off glide test points. The power-on cruise test points require the pilot to trim at a specified power setting and reduce the rate of climb to less than 100 ft/min. The pilot is then tasked to hold this trim state for 40 seconds while maintaining altitude within 25 feet and airspeed within 2 knots of the original airspeed. These test points are used to develop error estimates for the performance thrust and drag models [8].

The power-on climb test points require the pilot to maintain a near constant airspeed climb for 40 seconds at a specified power setting. This data is used to calibrate the thrust model and compare it to the drag model developed during the power-off glides.

The power-off glide maneuver includes an in-flight shut-down of the cruise motors prior to the start of the glides, then a restart of the cruise motors after the maneuver is complete. This test point begins with the feathering of the propellers and the disengaging of both cruise motors at a high-speed flight condition. The pilot then performs a glide at three specified speeds (85, 120, and 135 KIAS) for 40-s durations. The motors are then re-engaged as the pilot prepares the landing procedure. Prior to performing the maneuver, the pilot aligns the airplane with the main runway, such that the airplane can glide directly into landing should the cruise motors fail to restart after the maneuver is complete. Table 6 contains a complete list of the test points where performance is the primary discipline monitoring the collection of data.

Table 6 Performance test points.

Maneuver	Purpose	Flight objectives
Power-on climb	Determine the installed aerodynamic characteristics of the airplane and to calibrate the thrust model.	P. II, P. III
Power-on cruise	Model checking of the installed aerodynamic characteristics of the airplane, primarily to develop error estimates for the thrust and drag models.	P. II, P. III
Power-off glide	Determine the power-off aerodynamic characteristics of the airplane, primarily the relationship between drag and lift.	P. II, P. III

Statics and Dynamics

The primary dynamics test points are resonance assessment profiles (RAPs), which are done at various airspeeds to excite the normal resonance modes on the aircraft at a variety of dynamic pressures and measure how these modes respond and interact in a flight environment. The RAP technique is to quickly input a moderately sized input, then release the stick to excite the modes.

The Statics Team uses the previously described side slips, wind-up turns, and 2-1-1 maneuvers to characterize vertical tail loads to define the strength envelope for future flight tests. Table 7 documents how the RAPs map to the Mod II flight objectives.

Table 7 Dynamics test points.

Maneuver	Purpose	Flight objectives
RAPs	Excite aircraft normal resonance modes for flutter envelope clearance.	A. II, A. III

Acoustics

The acoustics test points are test points added on to the takeoff, landing, and tower flyby profiles. The Acoustics Team has a microphone array that is set up on the EAFB main runway at specific locations to capture the desired acoustics data. For takeoffs, the microphones are set up 8,200 feet from the initial location of the airplane at the runway centerline. For landings, the microphones are located at the end of the runway. For the tower flybys, the microphones are located at the weather tower, and requires the pilot to hold a constant speed over the designated location. An advantage of the EAFB main runway is that it is a wide runway that allows the pilot to easily avoid the microphone arrays if an emergency occurred during the acoustic testing. Table 8 describes how each of these acoustic test points map to project flight objectives.

Table 8 Acoustics test points.

Maneuver	Purpose	Flight objectives
Acoustics takeoff	Compare noise metrics for Mod II configuration against certified airplane.	P. II, P. III
Acoustics flyover	Compare flyover noise measurements to acoustics data taken from a stock P2006T to isolate the impact of the Mod II configuration	P.II, P.III
Acoustics landing	Compare landing noise measurements to acoustics data taken from a stock P2006T to isolate the impact of the Mod II configuration	P.II, P.III

E. Flight Envelope Restrictions

There are two envelope restrictions in place that required the successful completion of specific test points. The first restriction is the completion of the BASF test points prior to beginning data collection test points because the functionality of the airplane and the experimental systems must be tested prior to moving on to more research-oriented testing.

The second envelope restriction is on data collection test points that would stress the vertical tail prior to the calibration of the research air data system (e.g., 2-1-1s or RAPs). The vertical tail parameter is a safety-of-test parameter that uses air data parameters as part of the calculation. As a result, there is a priority in the mission planning to complete the air data calibration test points within the first three data collection flights, thereby removing the restrictions to the test point envelope as early as possible in the flight-test campaign.

F. Postflight Data Analysis

As mentioned previously, each flight-test point has predetermined evaluation and success criteria that are to be quickly processed after each flight to ensure a rapid turnaround for the next flight. Between the completion of a flight and the next crew brief, discipline engineers are to process the flight data and determine if the Test Team is ready to move on to the next flight using predefined criteria and good engineering judgment where applicable. Table 9 defines the analyses and data quality assessments that each discipline was required to perform and lists which analyses and assessments were required to clear the flight envelope for future test points. As part of the data analysis efforts, the Engineering Team is tasked to hold a data review where disciplines confirm all safety-of-flight and safety-of-test parameters are working as intended, preflight predictions match the flight results, and any anomalous results or parameters are reported.

The flight systems discipline is tasked with evaluating battery and cruise motor performance throughout the flight profile. While there are no test points designed specifically by the flight systems discipline, the combination of takeoffs, landings, and other discipline test points provide the data required for performance evaluations of the research system.

Table 9 Postflight data analysis requirements.

Parameter type	Required Postflight analysis	Test point	Data quality
Advanced Nav-X and Y accelerations, rates, angles, altitude, velocities	Static structures		Aerodynamics
Angle of attack and angle of side slip	Aerodynamics	Required for 2-1-1s and RAPs	
Total air temperature			Aerodynamics
Total pressure & static pressure	Aerodynamics	Required for 2-1-1s	Aerodynamics
KCAS (calculated)	Aerodynamics	Required for 2-1-1s	
QBAR (calculated)	Aerodynamics	Required for 2-1-1s and RAPs	
Control surface deflections (except for rudder)			Flight controls
Gear position			Flight controls
Stabilator forces			Flight controls
Accelerometers (gear)		Required for taxi test	Dynamics
Accelerometers (motor mount Y and Z axes)	Static structures	Entire flight	Dynamics
Accelerometers (wing, stabilator, rudder, vertical tail, fuselage)			Dynamics
Avionics bus current	Flight systems	Entire flight	
BCM (cell average and maximum temperatures)	Flight systems	Entire flight	
BCM (cell average and standard deviation temperatures)			Flight systems
BCM (cell maximum and minimum voltages)	Flight systems	Entire flight	
BCM (cell minimum and 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 voltage and current	Flight systems	Entire flight	
Advanced Nav - Z accelerations	Static structures	Entire flight	
Rudder deflection	Static structures	Required for 2-1-1s and RAPs	Flight controls
Strain gages (vertical tail)			Static structures
Vertical tail calculated load	Static structures	Required for 2-1-1s and RAPs	
Propeller RPM			Static structures

VII. Conclusion

This paper describes the flight-test approach for the X-57 modification II (Mod II) configuration to accomplish the flight-test objectives of assessing airworthiness of the modified airplane and to collect flight data for development of the Mod II drag and thrust models to assess energy consumption and serve as baseline data for comparisons with future planned modifications.

The switch from a traditional combustion engine airplane to an all-electric powered airplane results in significant impacts on available flight time and how to best monitor the remaining capacity of the power system. These constraints required scripting of flights (down to the minute) to maximize the amount of time at the testing altitudes and the efficiency of the testing done.

Due to the unreliability of the state of charge (SOC) parameter in the X-57 configuration, the primary indicator of energy states was voltage outputs, which were read directly from the battery system. These outputs required a more complex process of setting torque and RPM commands to predetermined values and comparing the resultant voltage measurements to simulator model predictions to estimate the remaining battery energy.

A robust plan was created that accounted for the unique capabilities and limitations of the platform, established sufficient buildup for the experimental technologies, planned for contingencies, and collected a comprehensive research dataset.

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