Flight Performance Estimates for the NASA X-57 Distributed Electric Propulsion Flight Demonstrator

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Abstract

The X-57 flight demonstrator concept featured four configurations starting with a conventional combustion-powered multiengine airplane and ending with a fully electric configuration with two forms of distributed propulsion and a highly modified wing. These configurations, called Mods, were designed to gain incremental insight into different aircraft propulsion configuration options and their impact on the aircraft performance. The gasoline-powered Mod I configuration consumed 2.6 to 2.9 times more stored energy in cruise than the electric but otherwise conventionally configured Mod II configuration. The highly loaded wing of Mod III led to an increase of 40% in the power-off lift-to-drag ratio as compared to Mod II at the project high-speed cruise target speed and altitude. The power-on lift-to-drag ratio of Mod III was 53% higher than Mod II due to the beneficial aero-propulsive interaction of the wingtip-mounted cruise propellers in Mod III. The high-lift propeller system of Mod IV recovered the low-speed performance of the conventional configuration in Mod II that was otherwise lost with the introduction of the highly loaded Mod III wing. The battery-electric configurations also benefitted from a lack of power lapse in the electric motors with increasing air density as compared to the combustion-powered baseline aircraft.

Keywords: Distributed Propulsion, Electric Propulsion, Flight Performance

1. Introduction

The X-57 “Maxwell” was a NASA flight demonstrator concept for Distributed Electric Propulsion (DEP) technology. This technology resulted from the confluence of distributed propulsion (the integration of propulsive devices strategically placed about the airframe to yield aero-propulsive benefits) and electric propulsion (the use of electric machines to drive propulsive devices). The X-57 project planned to demonstrate this technology through successive retrofits, called Mods (for modifications). The sequence of these Mods is given in Figure 1, which shows the planned evolution of the aircraft from a general aviation baseline in Mod I to a fully distributed electric propulsion flight demonstrator in Mod IV.

The goals of the project evolved as the X-57 project[1] progressed. The initial project goals focused on the use of DEP to improve cruise efficiency relative to a general aviation baseline aircraft [1]. Later, the project moved its focus to a broader set of objectives including establishing data for nascent regulations and standards associated with electric propulsion and distributed propulsion [2]. The former objective of increased cruise efficiency then became a design driver for the configuration. The use of the different Mods enabled the investigation of differences in flight performance and integration challenges across a steady cadence of configuration changes: the impact of electrified propulsion versus conventional propulsion (Mod II compared to Mod I), the impact of a distributed propulsion wing on cruise performance (Mod III compared to Mod II), and the impact of distributed propulsion on low-speed performance (Mod IV compared to Mod II and Mod III).

[1] The X-57 was also called CEPT (Convergent Electric Propulsion Technology) and SCEPTOR (Scalable Convergent Electric Propulsion Technology Operations Research) prior to the X-57 designation in 2016.

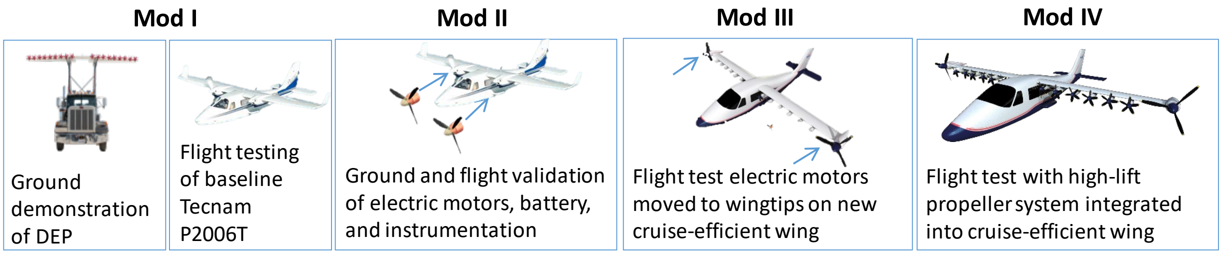

Figure 1 – X-57 development through multiple modifications (Mods).

The X-57 project concluded prior to conducting flight tests for Mods II, III, and IV [2], so the direct comparison of flight performance values cannot be accomplished. However, the X-57 team conducted extensive analysis, simulation, and test campaigns for each configuration. This paper summarizes the flight performance estimates for each of the X-57 configurations and notes the drivers of the different performance values for each Mod.

2. Background

The flight performance comparisons in this paper are built from an extensive collection of simulation and performance models. The subsections below detail the flight configurations, ambient conditions, and performance models used to establish the X-57 flight performance across each configuration.

2.1 Flight Configurations

Mod I of the X-57 project included a ground demonstration of a candidate DEP wing as well as a flight test of a general aviation baseline aircraft. In this paper, Mod I refers only to the performance of the unmodified baseline aircraft and not to the ground demonstration of the DEP wing. The Mod I configuration of the X-57 was a Tecnam P2006T [3], a general aviation aircraft with a maximum takeoff mass of 1230 kg that could be flown with a single pilot and carry up to three additional passengers. It had two 73.5 kW gasoline-fueled engines that each powered a two-bladed, 178 cm diameter, hydraulically actuated, constant-speed propeller. Mod I flight tests gathered baseline aircraft energy (fuel) consumption data and validated stability and control models used for the Mod II piloted simulation. Figure 2 shows the aircraft during one of the X-57 Mod I test flights.

Figure 2 – A Tecnam P2006T during one of the Mod I flights to gather baseline aircraft data.

The Mod II configuration of the X-57 was a highly modified Tecnam P2006T. The original gasoline-fueled engines were removed and replaced with 72.1 kW electrified propulsion units driving electrically actuated, three-bladed, 152 cm diameter, variable-pitch propellers that could operate in a manual or constant-speed mode. Other modifications included removal of the rear seats and installation of battery modules and control systems in the aft cabin, installation of a large air data boom in the nose, and removal of the co-pilot seat and installation of instrumentation and data handling components in its place. The X-57 Mod II configuration could operate up to a maximum takeoff mass of 1361 kg. Mod II flight tests were intended to establish the airworthiness of the experimental cruise propulsion and energy system, as well as establish the difference in performance when moving from the normally aspirated gasoline engines of Mod I to the electrified cruise propulsor in Mod II. The X-57 in the Mod II configuration is shown undergoing ground tests in Figure 3.

Figure 3 – X-57 in the Mod II configuration during a ground test.

The Mod III configuration of the X-57 introduced a highly loaded, high-aspect ratio wing. The wing area of this configuration was reduced from the original Mod I/II value of 14.76 m^2 to the Mod III/IV value of 6.19 m^2, and the aspect ratio increased from 8.8 to 15.0. The maximum takeoff mass of the configuration was originally limited to the same as Mod II (1361 kg), but later iterations involved performance calculations up to a maximum takeoff mass of 1452 kg to provide additional mass margin for systems and instrumentation.[2] This reduced wing area and increased takeoff mass lead to a dramatic increase in wing loading, which was intended to improve the high-speed aerodynamic efficiency of the aircraft, though this also significantly increased the stall speed. The cruise propellers were moved to the wingtips to enable a favorable interaction between the propeller swirl and the wingtip vortex, which provided a potential aero-propulsive benefit. Mod III, shown in Figure 4, was intended as a programmatic risk mitigation—when the X-57 project first started, Mod IV had not yet been approved for funding [2]. In this paper, Mod III refers to the cruise configuration of the final, Mod IV configuration since the full project plan had Mods III and IV flying as the same aircraft.[3]

Figure 4 – Rendering of the X-57 in the Mod III configuration in flight.

The Mod IV configuration of the X-57 introduced 12 high-lift propellers (HLPs) distributed along the leading edge of the Mod III wing driven by 12.6 kW electric motors. The HLPs were designed to increase the dynamic pressure over the wing at low speeds to reduce the stall speed of the highly loaded wing to be comparable to that of the Mod II configuration [4]. The cruise efficiency benefits of the Mod III

[2] This paper only includes performance estimates at a Mod III/IV takeoff mass of 1361 kg.
[3] As noted in Ref. [2], the X-57 project plan went through several iterations—initially an expansion of work to include Mod IV, and later de-scoping as the project ran into technical and budgetary challenges.

wing would then be realized by folding the HLPs conformally against their nacelles using a unique fixed-pitch folding propeller design [5]. X-57 Mod IV is shown in the low-speed configuration with the HLPs deployed in Figure 5.

Figure 5 – Rendering of the X-57 in the Mod IV configuration with the high-lift propellers deployed.

Figure 6 shows a comparison of the planforms of Mod I/II to Mod III/IV. The dramatic reduction in wing area (14.76 m^2 to 6.19 m^2), increase in aspect ratio (8.8 to 15.0), and decrease in root chord (1.39 m to 0.76 m) are readily apparent. Even with the addition of the high-lift nacelles, the wetted area Mod III/IV was reduced by 18% compared to Mod I/II (67.8 m^2 to 55.5 m^2). The Mod III/IV configuration had a smaller span than the Mod I/II configuration, despite the larger aspect ratio (11.40 m for Mod I/II compared to 9.94 m for Mod III/IV, not including the wingtip propeller). This reduction in span, in addition to the increase in aircraft mass, increased the span loading. This led to higher induced drag for Mod III and IV (despite the higher aspect ratio of the Mod III/IV wing) and increased the importance of the aero-propulsive benefit of the wingtip-mounted propellers.

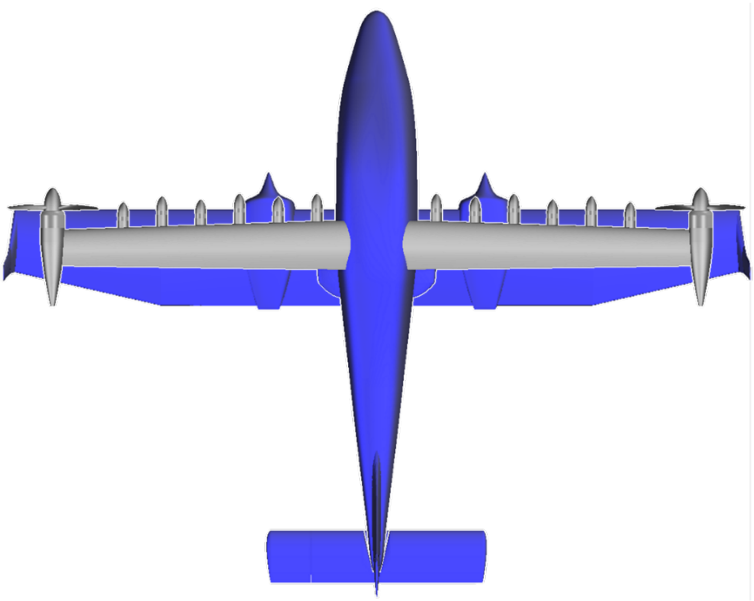

Figure 6 – Planform comparison of Mod I/II (blue wing) to Mod III/IV (gray wing).

2.2 Project Reference Atmospheres

The X-57 was only to be operated within the Dryden Aeronautical Test Range at NASA's Armstrong Flight Research Center. As such, typical reference atmospheres, particularly those used for performance extremes (e.g., hot and cold days), would not be as applicable to X-57 flight operations. The X-57 team developed a series of reference atmospheres based on the Dryden Aeronautical Test Range to guide system development and testing [6]. These four reference atmospheres included a standard day reference atmosphere that was identical to the 1976 U. S. Standard Atmosphere, a mean operational day atmosphere based on the mean test range condition, and hot and cold day atmospheres based on typical yearly temperature variations at the test range. The temperature versus pressure altitude profiles are shown in Figure 7 for these four reference atmospheres.

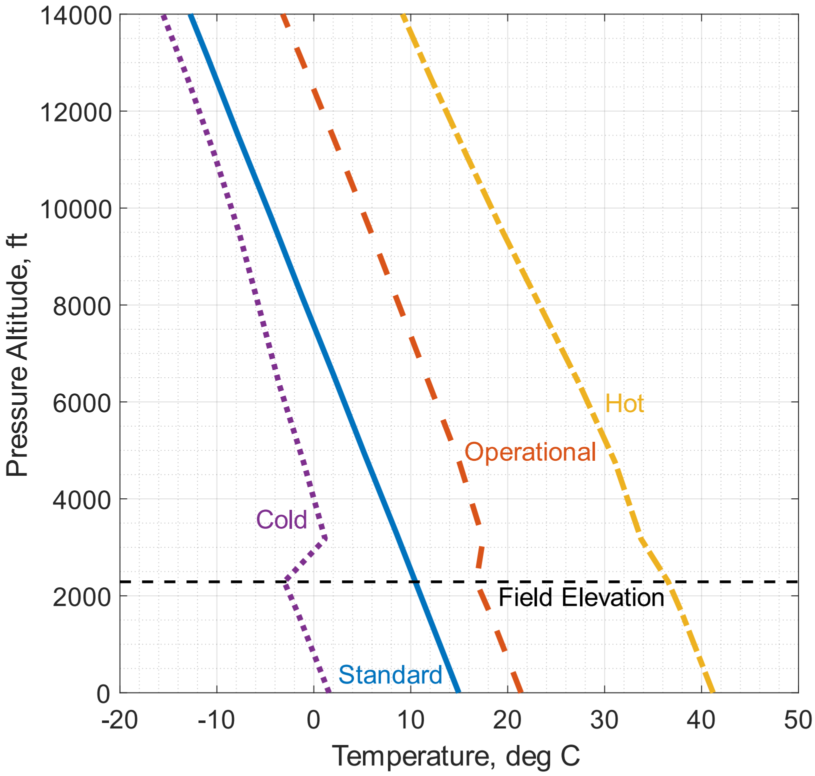

Figure 7 – Temperature profiles of X-57 Project Reference Atmospheres.

The performance values provided in this paper are at project standard day conditions unless otherwise noted. Not surprisingly, the hot day conditions tended to be critical for takeoff as well as thermal system performance [7], and the spread between the hot and cold day performance impacted the high-lift propeller systems [8].

2.3 Performance Models

The aerodynamic performance of the X-57 was estimated using the same models that drove the X-57 Mod II [9] and Mod III/IV piloted simulators [10]. These were full six degree of freedom simulation models that included the effects of control surface and flap positions, as well as the power-on effects from the cruise and high-lift propulsion systems, as appropriate to the Mod. The Mod I/II aerodynamic data described in this paper is largely derived from the Tecnam P2006 flight manual [3] with corrections and modifications based on the results of the Mod I flight tests. The flight performance model was derived from this data and included power-on effects from the manufacturer. This data is not publicly available due to the inclusion of protected data from the manufacturer, though U.S. Government users may request this model [11]. The aerodynamics database for the Mod III/IV configuration was developed from thousands of data points analyzed from computational fluid dynamics modeling, including variations in flight conditions, control surface position, and power settings. Though unpublished as of the writing of this manuscript, NASA intends to release a Technical Memorandum describing the Mod III/IV aerodynamics database, and the database itself is available for public release upon request.

The cruise propellers for Mods II, III, and IV were type-certified units manufactured by MT-Propeller, specifically the MTV-7-A-152/64 model. The manufacturer provided tables of uninstalled propeller efficiencies indexed to propeller power coefficients and advance ratios. These values were used to develop a calibrated blade element momentum theory model that was implemented during generation of the aerodynamics databases for the power-on conditions. Given that this data is protected by the manufacturer, this calibration is not publicly available, though U.S. Government users can request the calibration report and model [12]. The installed performance of the Mod II cruise propellers was developed from the Mod I installed thrust estimates and was corrected for the different characteristics of the Mod II propellers (two blades and 178 cm diameter for Mod I; three blades and 152 cm diameter for Mod II, III, and IV) by matching installed performance loss to propeller advance ratio.

3. Flight Performance

The flight performance of the four X-57 Mods in each of the four project reference atmospheres was established from the performance models. A summary of some of the salient performance characteristics is provided below, including the minimum steady flight speed, cruise performance in the cruise configuration, and climb performance in cruise configuration.

3.1 Minimum Steady Flight Speed (Stall Speed)

The minimum steady flight speed, V_S, is one of the key parameters for low-speed aircraft handling characteristics. This is often referred to as the "stall speed" and is determined via flight test in a decelerating flight maneuver for a particular configuration and worst-case weight and balance. "Minimum steady flight speed" is a more fitting name than stall speed since although the flight maneuver used to determine V_S may result in an aerodynamic stall of the wing or tail, V_S may also occur when the aircraft saturates control authority (e.g., for conventional airplanes, when the aircraft can no longer command nose-up pitch due to saturation of elevator authority). For this paper, stall speed is considered synonymous with minimum steady flight speed.

In the United States, the requirements associated with minimum steady flight speed include Part 23 of Title 14 of the Code of Federal Regulations (14 CFR §23) for civil aircraft fitting X-57's characteristics [13]. The rules for 14 CFR §23.2110 state that "the stall speed or minimum steady flight speed must account for the most adverse conditions for each flight configuration with power set at (a) idle or zero thrust for propulsion systems that are used primary for thrust; and (b) a nominal thrust for propulsion systems that are used for thrust, flight control, and/or high-lift systems." All X-57 Mods used cruise propellers that were "primarily for thrust" and therefore subject to §23.2110(a)—that is, determination of V_S considered the power setting with the cruise propellers at idle or zero thrust in all Mods. X-57 Mod IV was the only configuration that included high-lift propulsion systems, so determination of V_S for Mod IV included the high-lift propulsion system configured for a power setting used during nominal operations per §23.2110(b). In addition, the X-57 V_S determinations considered different flap configurations for each Mod, generally, cruise (also known as clean, with the flaps stowed), takeoff (with the flaps in the takeoff position), and landing (with the flaps in the landing condition). The minimum steady flight speeds in these configurations were referred to as V_S, V_{S_1}, and V_{S_0}, respectively. Only the takeoff and landing flap configurations of Mod IV were used with the HLPs. The minimum steady flight speeds with the high-lift propeller system activated were referred to as $V_{S_{1hl}}$ and $V_{S_{0hl}}$ for the takeoff and landing configurations, respectively. The V_{S_1} and V_{S_0} values for Mod IV referred to the minimum steady flight speed with the high-lift propeller system inactive.

Given that Mod I was a certified civil aircraft, the rules in 14 CFR §23.2110(a) or their equivalent[4] would apply to the published stall speeds used in the aircraft flight manual and type certificate data sheet. For flight performance planning, the published stall speeds from the Tecnam P2006T were scaled for Mod II by adjusting for the difference in maximum takeoff mass. This mass scaling adjustment assumed that the maximum lift coefficient, control surfaces, and critical center of gravity conditions were identical for

[4] The Tecnam P2006T was originally certified under the European Aviation Safety Agency's Certification Specification 23, amendment 3, though the rules were functionally similar to 14 CFR §23.2110(a).

the P2006T and the X-57 Mod II configuration. In reality, the most forward center of gravity for X-57 Mod II was lower and further aft than for the P2006T/Mod I, but this impact was considered small for flight planning purposes. With this assumption, the mass-adjusted stall speeds of Mod II were calculated from Equation (1),

$$V_{s,Mod\,2} = V_{s,Mod\,1}\left(\sqrt{MTOM_{Mod\,2}/MTOM_{Mod\,1}}\right) \tag{1}$$

where $MTOM$ is the maximum takeoff mass and the subscripts refer to the Mod I (published in the airplane flight manual) or Mod II configuration. The Mod III and Mod IV power-off stall speeds were estimated from the speed at which the aircraft reached its maximum lift coefficient in the particular configuration in unaccelerated flight (one times the force of gravity or *1g*). Therefore, this estimate did not account for the maneuvers or secondary effects necessary to meet 14 CFR §23.2110(a); the extensive aerodynamic investigation referenced in Section 2.3 provided insight into the estimated maximum lift coefficient. The Mod IV minimum steady flight speeds with the high-lift propeller system active were based on the program goal to recover the stall speed of the Mod II aircraft. More detailed investigations indicated that the high-lift propeller system may have been able to provide an even higher maximum lift coefficient [14], so the minimum steady flight speed observed in flight would likely have been lower. The project minimum steady flight speeds for flight planning purposes, given the caveats established above, are provided in Table 1 in knots calibrated airspeed (KCAS).

Table 1 – Estimated X-57 minimum steady flight speeds for all configurations and Mods.

Configuration	Symbol	Mod I	Mod II	Mod III	Mod IV
Clean	V_S	65 KCAS	68 KCAS	88 KCAS	88 KCAS
Takeoff	V_{S_1}	57 KCAS	60 KCAS	80 KCAS	80 KCAS
Landing	V_{S_0}	55 KCAS	58 KCAS	73 KCAS	73 KCAS
Takeoff with HLPs	$V_{S_{1hl}}$	N/A	N/A	N/A	70 KCAS
Landing with HLPs	$V_{S_{0hl}}$	N/A	N/A	N/A	58 KCAS

3.2 Cruise Performance Estimates

Aircraft generally spend most of their time and energy in the cruise segment of flight, so increased cruise efficiency can lead to increased range, endurance, and/or reduced operating costs. The DEP configuration of X-57 Mod IV was intended to improve cruise efficiency through two primary effects: (a) improved aerodynamic efficiency at high-speed cruise by taking advantage of two forms of distributed propulsion (distributed high-lift propellers and wingtip-mounted cruise propellers) and (b) improved powertrain efficiency through electrified propulsion. The highlights of each are given below; more detailed information can be found in Ref. [14] for the aerodynamics and Ref. [15] for the electric propulsion system.

3.2.1 Aerodynamic Effects of Distributed Propulsion

A key motivation of the X-57 project was to tackle the tradeoff between more efficient cruise performance at higher speeds and the ability to maintain flight at low speeds. This trade is challenging for smaller airplanes since they tend to require lower-speed flight to get into and out of smaller airfields. Smaller aircraft tend to have less wing volume available for sophisticated high-lift mechanisms (e.g., multi-element flaps and slats) that are used to increase the wing maximum lift coefficient, which is an important factor in determining safe speeds for low-speed maneuvering (e.g., takeoff and landing). As such, smaller airplanes tend to have lower wing loading values than larger airplanes. A lower wing loading lowers the speed at which the airplane will cruise most efficiently [1]. The goal of the high-lift propeller system for X-57 Mod IV was to retain the minimum steady flight speed of the Mod II configuration with its conventional wing while being more efficient at higher speeds by using a more highly loaded wing. Better efficiency at higher speeds can result in a more productive aircraft.

The solid lines in Figure 8 show the estimated lift-to-drag ratio (L/D)—an important measure of aerodynamic efficiency—for the Mod II configuration (conventional wing) and the Mod III configuration[5] (highly loaded wing) in unaccelerated *1g* flight at identical masses without the influence of cruise propeller thrust. The peak L/D for both configurations was nearly identical (14.7 for Mod II, 14.8 for Mod III), indicating that, in the absence of thrust, both were capable of the same aerodynamic efficiency. The key difference was that the peak L/D occurred approximately 40 knots true airspeed (KTAS) faster in the Mod III configuration as compared to Mod II. The X-57 target cruise speed requirement was 150 KTAS at 8,000 ft mean sea level (MSL) on a standard day, and the power-off performance was a key performance parameter for the X-57 project [16]. The Mod III power-off L/D of 13.3 was 40% higher than that of Mod II (L/D of 9.5) at the project cruise speed and altitude target.

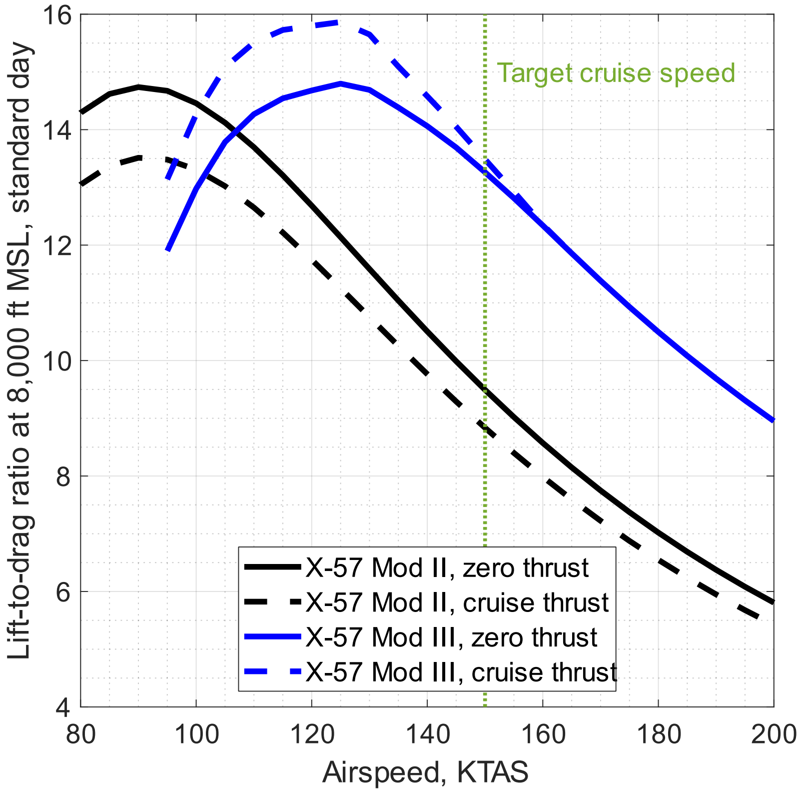

Figure 8 – Lift-to-drag ratios in unaccelerated *1g* flight for Mod II and Mod III at zero thrust and cruise thrust (i.e., thrust suitable for level flight) with aircraft mass of 1361 kg.

The cruise propeller placement of the X-57 Mod III configuration enabled further efficiency increases though beneficial aero-propulsive coupling. For Mods I and II, the cruise propeller thrust introduced aerodynamic losses via increased slipstream velocity over a portion of the wing and nacelle (known as scrubbing drag) as well as changes in the lift distribution due to the rotational component (swirl) of the propeller slipstream, which increased the induced drag. For Mod III, the scrubbing drag component was reduced due to less wetted area in the slipstream, and the lift-induced drag was reduced by the propeller swirl component countering the wingtip vortex shed by the lifting wing. The dashed lines in Figure 8 capture the combined effects of the wing loading and thrust for level flight. The thrust effects on L/D were larger at lower airspeeds. This was because the lift-induced portion of the thrust impact was larger

[5] Mod I and II are aerodynamically similar in cruise, as are Mod III and IV.

at the higher lift coefficients necessitated by lower airspeeds in *1g* flight. In addition, the induced propeller axial velocity component was greater at lower airspeeds, which led to higher scrubbing losses. Power-on performance was also a key performance parameter for the X-57 project from peak L/D to the target cruise speed [17]. Peak power-on L/D was estimated to be 13.5 for Mod II and 15.9 for Mod III; this dropped to 8.8 for Mod II and 13.5 for Mod III at 150 KTAS and 8,000 ft MSL. Table 2 summarizes the aerodynamic efficiency values (L/D) at the peak and cruise point for Mods II and III.

Table 2 – Summary of lift-to-drag ratios for X-57 Mod II and Mod III configurations.

Configuration & Thrust	Lift-to-Drag Ratio		Ratio of Mod III to Mod II	
	Maximum	*Cruise Point*	*Maximum*	*Cruise Point*
Mod II zero thrust	14.7	9.5	-	-
Mod II cruise thrust	13.5	8.8	-	-
Mod III zero thrust	14.8	13.3	1.01	1.40
Mod III cruise thrust	15.9	13.5	1.18	1.53

3.2.2 Energy Consumption

The engines of combustion-powered aircraft of the scale typical of those certified under 14 CFR §23 struggle to attain the thermal efficiencies of the engines used in larger aircraft [18]. The use of a battery-electric propulsion system for X-57 Mod II and beyond introduced a substantial improvement in energy efficiency.[6] The comparison of Mod I to Mod II provides the most direct comparison of stored energy consumption rate since both aircraft used the same wing planform. However, Mod II was a slightly heavier aircraft, and its three-bladed cruise propellers were slightly less efficient than the two-bladed propellers of Mod I. The ratio of energy used by Mod I versus Mod II at the same flight condition is shown in Figure 9. The fuel consumption of Mod I was translated into energy consumption by using an estimated fuel lower heating value of 43.5 MJ/kg.

The contours in Figure 9 are overlaid with the stall speed and maximum level flight speed at maximum power (V_H) to bound the space. The V_H contour for Mod I declines sharply with altitude; the normally aspirated gasoline-fueled engines experienced power lapse as air density decreased with higher altitude. The battery-electric motors of Mod II acted as turbonormalized engines and did not experience power lapse with air density. As such, there are several areas of the flight envelope where Mod II would have been able to fly but Mod I could not. The energy requirements of Mod I were extrapolated in the portions of the flight envelope where Mod II could fly but Mod I could not to enable comparison to the higher-speed, higher-altitude cruise points. The irregularity of the contours in Figure 9 is due to the sampling resolution for the Mod I and II energy consumption. Overall, Figure 9 shows that Mod I would consume about 2.6 to 2.9 times the energy of Mod II for a given flight condition. This follows the ratio of engine efficiencies; the gasoline-powered engines of Mod I were approximately 30% efficient at converting fuel energy into shaft work whereas the electric motors of Mod II were approximately 90% efficient at converting battery energy into shaft work. This implies a ratio of about 3:1, though Mod II was a heavier aircraft with less efficient cruise propellers, which contributed to the lower ratios seen in Figure 9.

[6] These and other comparisons do not account for the vast difference in specific energy and associated capabilities (e.g., range) between the two stored energy types.

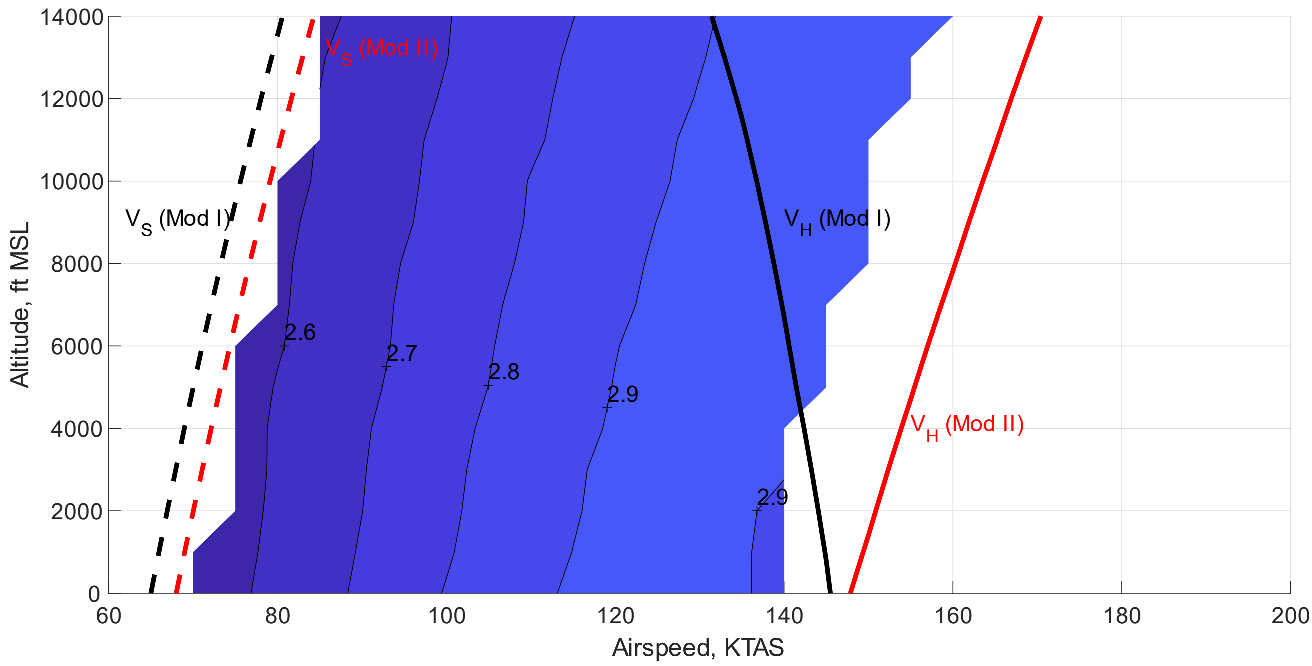

Figure 9 – Ratio of energy consumed for Mod I versus Mod II in cruise flight, standard day.

The Mod III configuration showed greater energy savings compared to Mod I, as shown in Figure 10. This additional energy savings was due to the improvements in high-speed cruise efficiency for the highly loaded wing as seen earlier in Figure 8. This highly loaded wing would not have been possible without the high-lift propeller system to recover the minimum steady flight speed of Mod II.

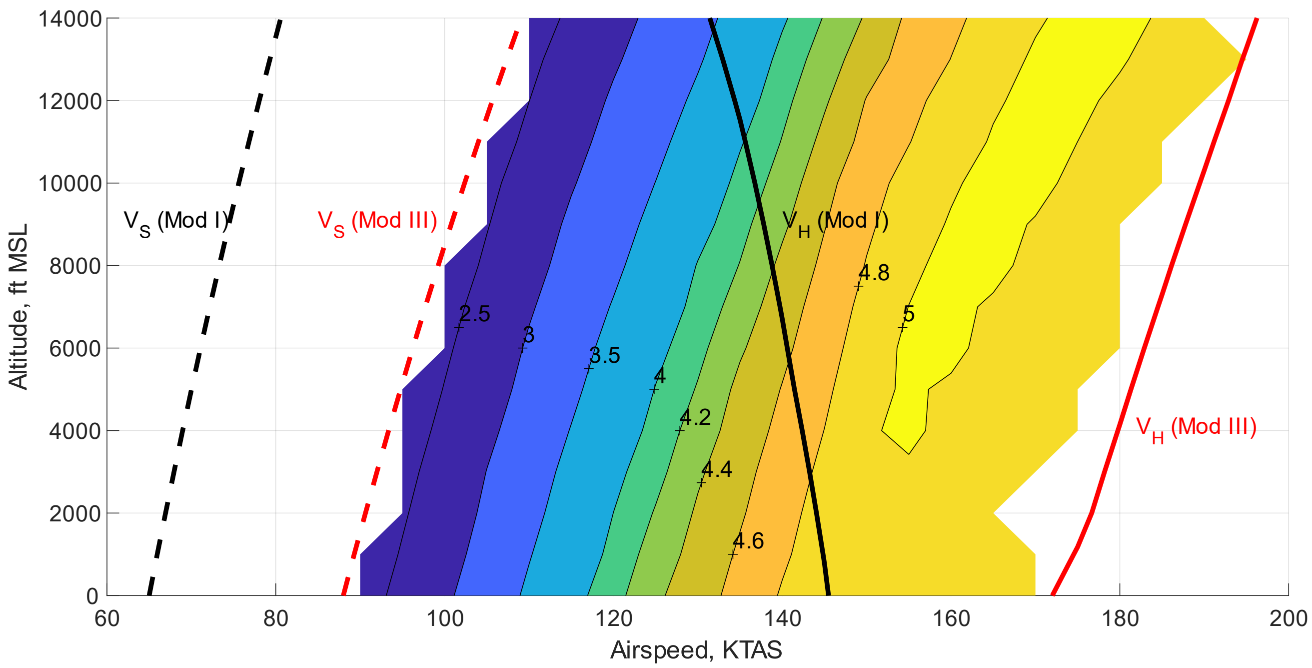

Figure 10 – Ratio of energy consumed for Mod I versus Mod III in cruise flight, standard day.

3.3 Climb Performance Estimates

The climb performance of the X-57 was different for each Mod. The X-57 climbed at maximum continuous power (MCP), which was a lower power setting than used for conditions such as takeoff. Mod I had an MCP of 69 kW, though this was only attainable at sea level standard conditions due to power lapse with altitude. Mods II through IV had an MCP of 60 kW. The impact of the differences in weight, MCP, and power lapse are seen by comparing Figure 11, which shows the rate of climb of Mod I at 1230 kg with its normally aspirated gasoline engines, and Figure 12, which shows the rate of climb of Mod II at 1361 kg with its battery-electric propulsion system.

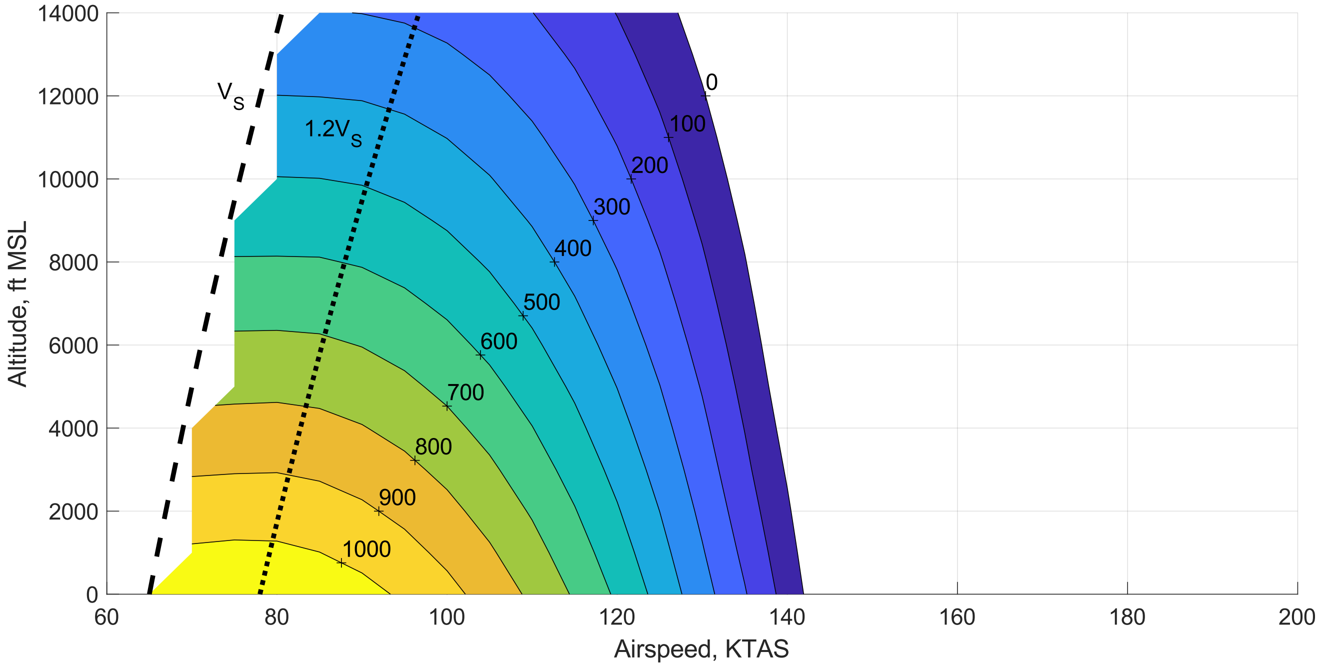

Figure 11 – X-57 Mod I rate of climb estimates (ft/min) in cruise configuration at MCP, standard day.

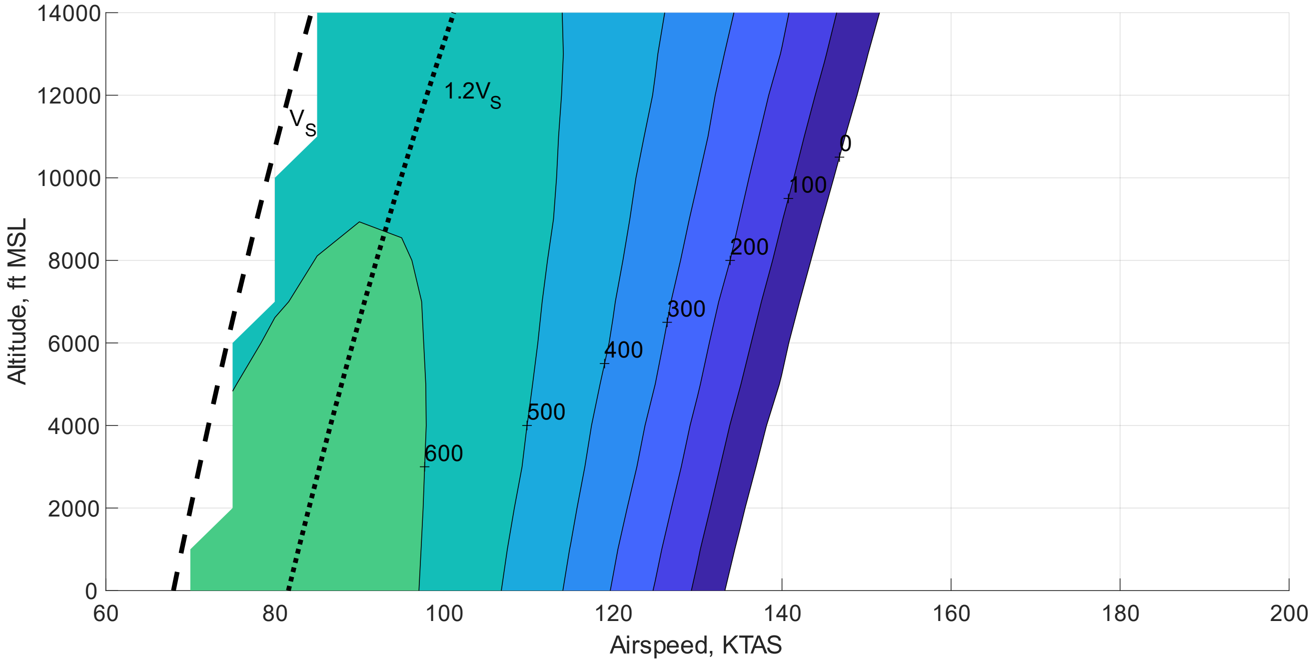

Figure 12 – X-57 Mod II rate of climb estimates (ft/min) in cruise configuration at MCP, standard day.

The stall speeds are superimposed on the rate of climb contours in both Figure 11 and Figure 12. The V_S and $1.2V_S$ contours are shown on both plots, as the former is the absolute slowest speed to climb, and the latter is one of limiting (minimum) climb speeds allowed for aircraft certified under 14 CFR §23. The drag model used to generate these plots did not fully account for the separated flows that can develop around the aircraft near stall, so the rate of climb contours to the left of the $1.2V_S$ contour should be considered optimistic. Given these factors, the best rate of climb for Mods I and II was constrained by the $1.2V_S$ contour.

Comparison of Figure 11 and Figure 12 shows that, although Mod II has a lower overall maximum rate of climb at lower altitudes due to the higher takeoff mass and lower thrust of the cruise motors, the Mod II aircraft has a higher rate of climb above approximately 8000 ft MSL due to power lapse of the Mod I engines with altitude. The 0 ft/min contour of the Mod I configuration shows a significant lapse with altitude; this trends with the Mod I V_H contour seen in Figure 9 and Figure 10.

Figure 13 explores the differences in thrust lapse behavior between Mod I and Mod II further by evaluating the best rate of climb versus altitude for project standard day and hot day conditions. The air density would be lower for the project hot day conditions. In the Mod I case, the impact of density lapse rate with altitude is apparent—the lower density leads to lower power production as well as a higher true airspeed for a given flight condition, which leads to a reduction in propeller thrust. For Mod II, the only difference between standard day and hot day is associated with the airspeed-induced propeller thrust lapse, so the corresponding rates of climb are less affected by the lower air density on project hot days.

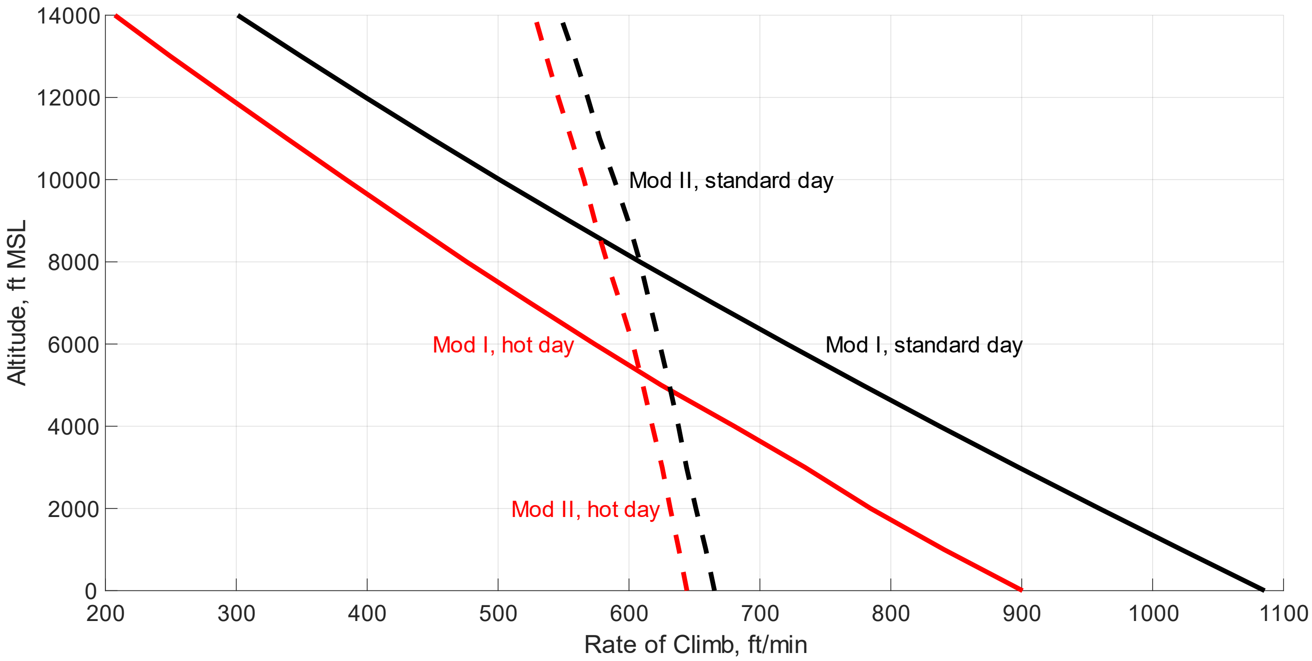

Figure 13 – Mod I and Mod II best climb rates at MCP versus altitude for project standard day and project hot day conditions.

The estimated rates of climb for Mod III are shown in Figure 14. Like Mod II, the Mod III rates of climb show little lapse with altitude; in fact, the climb ceiling could be above 40,000 ft if there were no other limiting factors [1]. The highly loaded Mod III wing exhibited better predicted climb rates above the $1.2V_S$ contour. A significant challenge with the Mod III configuration was the poor rate of climb in the takeoff configuration; a companion paper discusses the techniques used to mitigate these climb rate issues by essentially treating Mod III as only a cruise configuration and leveraging the high-lift propellers in Mod IV along with reduced power for the cruise motors to mitigate controllability issues due to failures [19].

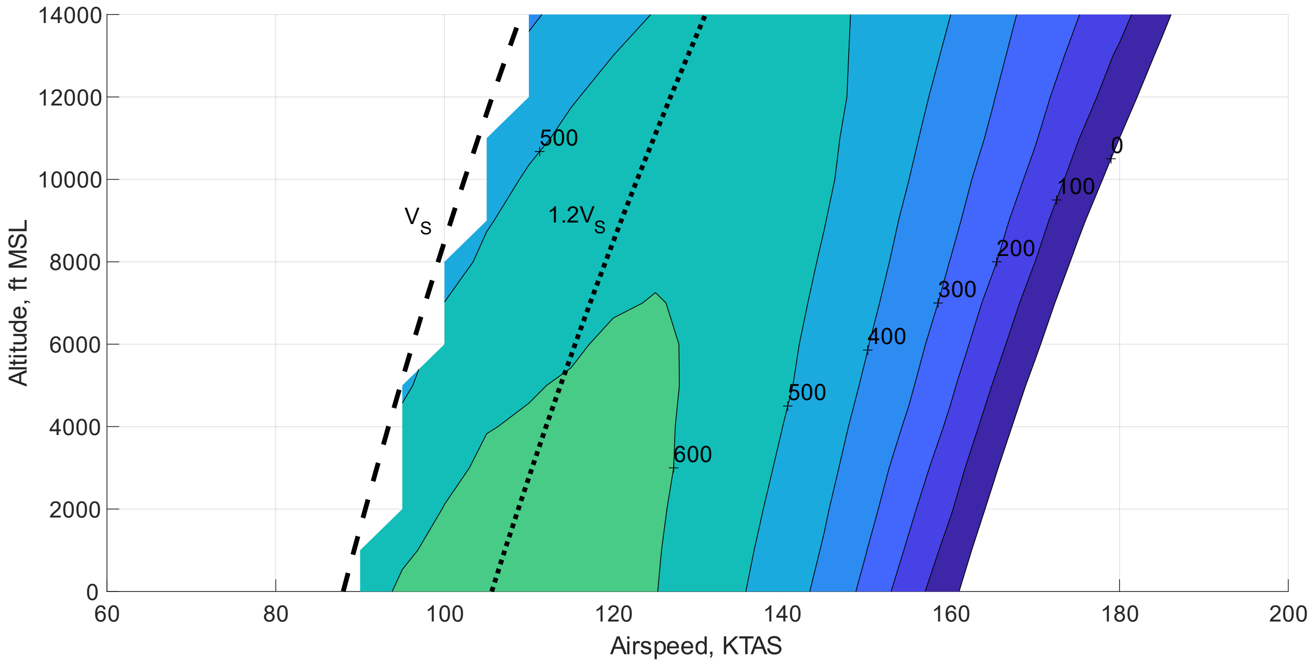

Figure 14 – X-57 Mod III rate of climb estimates (ft/min) in cruise configuration at MCP, standard day.

3.4 Flight Envelopes

The flight envelope of the X-57 was determined by some of the factors described earlier, including the minimum steady flight speed (stall speed) V_S and the maximum level flight speed at maximum power V_H. In addition, the flight envelope was limited by the never-exceed speed, V_{NE}, and the aircraft altitude ceiling of 14,000 ft MSL. The resulting flight envelopes for all four Mods are given in Figure 15.

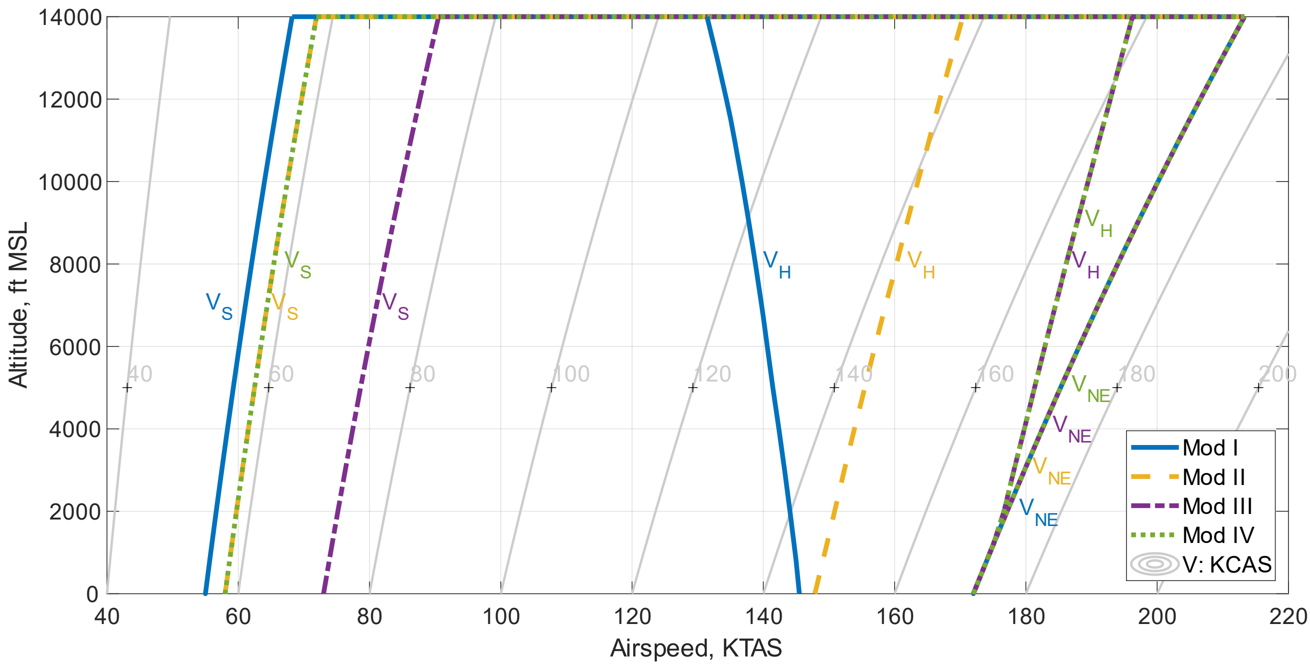

Figure 15 – Flight envelopes for X-57 Mods I through IV in KTAS for project standard atmosphere shown with contours of KCAS. Note that some limits overlap.

The never-exceed speed was set to 172 KCAS for all configurations. This speed limit was set because the original Tecnam P2006T has a V_{NE} of 172 KCAS at 1230 kg. Although a higher V_{NE} may have been possible, particularly with the radically different wing configuration of Mods III and IV, the X-57 team did not know what component was critical for setting V_{NE}. The V_{NE} could have been set by the wing, empennage, or fuselage components. Since all X-57 Mods shared the same fuselage and empennage, the project made the decision to keep the V_{NE} of the original aircraft.

The project ceiling was set by supplemental oxygen requirements. An example of these requirements is in 14 CFR §91.211, which states that supplemental oxygen is required for the crew for operations exceeding 30 minutes above 12,500 ft MSL and for any duration above 14,000 ft MSL. The X-57 team did not wish to carry supplemental oxygen due to mass and safety concerns. The flight duration for X-57 Mods II through IV was limited by onboard battery energy storage, which ultimately constrained X-57 flight planning to missions of less than 30 minutes. As such, operation up to 14,000 ft MSL would be possible without violating the guidelines[7] for supplemental oxygen.

4. Summary and Concluding Remarks

The X-57 project used four different aircraft configurations to illustrate the progression of performance benefits associated with DEP technology. The first configuration, Mod I, was a production gasoline-fueled aircraft. Mod II replaced the gasoline engines and fuel tanks with electric motors and batteries, respectively, to determine the impact of moving from a combustion propulsion system to a battery-electric system. Mod III introduced a highly loaded wing with wingtip-mounted cruise propellers to the aircraft, which were designed to increase high-speed cruise efficiency and show a beneficial aero-propulsive interaction with the wingtip vortex. The highly loaded wing of Mod III was an interim step to Mod IV, which introduced 12 stowable high-lift propellers used only at low speeds to recover the minimum steady flight speed of the Mod II configuration while using the highly loaded Mod III wing.

This paper explored the performance differences between the X-57 Mods. Mod II used less stored energy at cruise than Mod I for the same flight conditions. This was attributed to the increase in efficiency of the powertrain—the combustion powertrain of Mod I was approximately 30% efficient at converting onboard stored energy to shaft work, whereas the electric powertrain of Mod II was approximately 90% efficient. Mod II also exhibited increased climb performance at higher altitudes and for hot days due to the lack of power lapse from the electric motors. Mod III exhibited combined aero-propulsive efficiencies, yielding an additional 53% improvement in cruise efficiency as compared to Mod II at the project high-speed cruise point of 150 KTAS and 8,000 ft MSL. Mod IV was able to recover the minimum steady flight speed of Mod II while yielding the cruise benefits of the Mod III wing.

Though the X-57 project was concluded prior to demonstrating these performance features in flight, this paper showed the performance differences associated with unique features of distributed and electric propulsion. These include a change in power lapse behavior, aero-propulsive coupling, propulsors used for only particular stages of flight, and integrated distributed propulsion and aerodynamic benefits.

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6. Copyright Statement and Acknowledgements

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This work was funded by NASA's Aeronautics Research Mission Directorate. Initial funding came from the Convergent Aeronautics Solutions Project within the Transformational Aeronautics Concepts Program, and funding for later efforts was provided by the Flight Demonstrations and Capabilities Project within the Integrated Aviation Systems Program.

[7] The NASA X-57 team was not bound by civil airworthiness or operating rules due to operation as a Public Use aircraft; however, these guidelines were still considered prudent for selection of the X-57 operating envelope.

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