7-2024

Engine Performance of an Electric Airplane with Partial Battery Capability

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Engine Performance of an Electric Airplane with Partial Battery Capability

by

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A thesis submitted to the College of Engineering and Science of
Florida Institute of Technology
in partial fulfillment of the requirements
for the degree of

Master of Science
in
Flight Test Engineering

Melbourne, Florida
July, 2024

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Abstract

Ground Test Engine Performance of an Electric Airplane with Partial Battery Capability

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As electric aircraft are developed and certified, knowledge of electric aircraft performance during complete or partial battery failures can be useful to determine an aircraft's limitations and capabilities of completing an emergency landing, especially during takeoff and low-altitude climbs, as well as fully characterizing the potential aircraft performance. The results of this research will be useful in developing regulations and procedures pertaining to energy reserves and emergencies. This paper presents the results of a Pipistrel electric airplane climb power ground test that was conducted by the author and Florida Tech faculty. In the test, one of the airplane's batteries was inoperative, and the airplane's engine was run at full and minimum climb power. The results were compared to the limitations, power settings, and engine output data presented in the pilot operating handbook. It was discovered that the maximum power and RPM produced by one battery was less than that produced by two batteries. The maximum full power produced by one battery was 2 kW to 9 kW less than the lowest full power given in the operating handbook, and the maximum full power RPM was closer to the minimum climb power RPM than the full power RPM limit in the handbook. Minimum climb power was achievable until a low battery state of charge. The flight time with one operational battery was less than 10 minutes due to the rapid decrease of battery state of charge and the increasing battery temperature, which rapidly reached the maximum limit stated in the pilot operating handbook. Comparing the results to previous climb test data of the airplane suggested that a typical pattern altitude could be achieved with the power produced by one battery, provided that the initial battery state of charge is high.

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Acknowledgement

I want to extend my thanks to Florida Tech's College of Engineering and Science for providing me the opportunity to earn my Master's degree in Flight Test Engineering, an amazing topic of study that I would have never considered at the start of my education at the university in 2018.

I also want to thank my thesis advisor and professor, Dr. Ralph Kimberlin, for sharing his expertise in and passion for flight test engineering, as well as his knowledge of aviation as a whole. I also thank Dr. Isaac Silver, who inspired my interest in Florida Tech's research in electric propulsion and assisted with data collection, and Dr. Brooke Wheeler from the College of Aeronautics for making it possible for me to participate in the research. Additional thanks go to Dr. David Fleming from the College of Engineering for his advice and support for my undergraduate and graduate education and projects at Florida Tech.

Research and tuition funding for this thesis has been graciously provided by Dr. Wheeler through the Florida Tech College of Aeronautics' IRI funding, the FAA through the Electric Aircraft Trajectory Flight Test Data and Trajectory (AWD00524) contract and Energy Management – Phase 3 contract, and the Office of Naval Research DON STEM Education and Workforce Grant (N00014-20-1-2669).

Lastly, I want to express my gratitude to my parents, Matthew Scrivens, Lynette Baney-Scrivens, and my sister, Lydia Scrivens, for their unwavering support, guidance, and encouragement throughout my education journey.

Soli Deo Gloria.

Chapter 1
Introduction

Background and Objectives

As electric aircraft enter commercial and private use in urban air mobility, general aviation, and flight training, their capabilities and limitations must be defined to create safety procedures and regulations [1,2]. Research on aircraft performance with a partial or complete loss of power in low-altitude flight phases, such as takeoff and climb, is crucial since electric aircraft batteries degrade quickly with frequent use, which increases risks [3,4].

Engine ground tests are a valuable way of determining an electric engine system's performance without the risks posed by actual flight tests at altitude. This thesis aims to determine an electric airplane's limitations and their potential effects on climb performance during cases when one of the batteries fails and is inoperative during takeoff. The airplane's pilot operating handbook states that the power provided by one battery is enough to sustain normal flight. The ground test described in the thesis was conducted to independently verify this claim and produce results and potential operation recommendations for pilots of the airplane. The results of an engine ground test conducted by the author and Florida Tech faculty will be compared to data from the pilot operating handbook and previous climb performance tests to determine the effect of partial battery power on battery health and the electric engine's output.

Acronyms and Definitions

AC – Alternating Current

CFR – Code of Federal Regulations

DC – Direct Current

FAA – Federal Aviation Administration

ISA – International Standard Atmosphere

kW – Kilowatts

Li-NMC – Lithium Manganese Cobalt

MCP – Minimum Climb Power

MPTOP – Minimum Performance Take-Off Power

MTOP – Maximum Take-Off Power

POH – Pilot Operating Handbook

ROC – Rate of Climb

RPM – Revolutions per Minute

SOC – State of Charge

SOH – State of Health

VFR – Visual Flight Rules

V_Y – Best Rate of Climb Airspeed

Previous Research

Since Florida Tech's acquisition of a Pipistrel Velis Electro in 2021, Florida Tech students and faculty have conducted ground and flight tests of the airplane. A summary of previous ground tests that took place in 2022 and their results are described here.

An initial ground test was done by Wheeler et al. [3] to observe the effects of battery discharge on motor performance, specifically the impact of battery temperature on the estimated remaining flight time shown on the airplane cockpit display. Motor power was also analyzed. After a flight test, the airplane was tied down and chocked on the ramp. The beginning battery state of charge (SOC) was 64%, and the batteries were discharged to 0%

SOC. The power lever, or throttle, was increased to maximum takeoff power (MTOP) at each 10% decrease in SOC and then reduced to minimum cruise power at 20 kW until the next full power test point. It was concluded from this test that motor power decreases as the batteries discharge, and the resulting temperature increases, could lead to unreliable system performance and flight time predictions.

Full battery discharge tests were then completed by Cunha et al. [4] to better understand the trends from the initial battery discharge test. A second ground test followed a similar procedure to the first one, but it had two test cases instead of one. Each full discharge test began with fully charged batteries at 100% SOC with a state of health (SOH) of 88% each. In the first test case, the power lever was set at MTOP and gradually reduced to idle until 75% SOC was reached. Then, like with the initial ground test, the power lever was increased to MTOP for each 10% decrease in SOC and reduced to idle between the MTOP test points. The second test case started with both batteries at 100% SOC and 88% SOH. The power lever was set to a constant cruise power of 27 kW, and the batteries were discharged to 0% SOC. The results from the test supported the initial observations that as the SOC becomes lower, the motor power output and its predictability decreases, sometimes without warning.

As the airplane was flown more, the batteries began to noticeably degrade. The battery decline led to one cell in the front battery, Battery 1, failing. A laboratory experiment for one of Florida Tech's flight test engineering courses, also a full battery discharge test, was conducted to determine the effects of the faulty battery on the motor's performance. This test began with a SOC of 99%. Battery 1 had a SOH of 88%, and Battery 2, the back battery, had a SOH of 86%. Like the previous ground tests, the power lever was set at MTOP. The power was reduced in 5-kW increments to 50 kW and then in 1-kW increments to 20 kW. Power and RPM were recorded at each test point, and the test continued until a SOC of 75% was reached. The power was then set at MTOP for each 10% SOC decrease from 75% to 28% SOC. Power, SOC, and RPM were read from the aircraft's instrumentation by the pilot and observer, and an outside observer read thrust via a fish scale connected to the airplane's back tiedown rope. The power was reduced to a range of 10 to 25 kW until the next test SOC was reached. As the SOC reached under 40%, Battery 1 failed completely, leading to a rapid decrease in maximum power output, motor RPM, battery charge, and flight time while the battery temperatures rose quickly. At the end of the test, both batteries had to be replaced. These results made it clear that more research must be done to gather information about motor performance in the event of a battery failure.

Test Aircraft Description

The test airplane in this report, shown in Figure 1, is the light sport Pipistrel Velis Electro, which is fully electric and powered by two battery packs. It has two seats, tricycle landing gear, and a T-tail, and the airframe is made of multiple composites that include Kevlar, carbon fiber, and fiberglass [5]. The airplane is certified as an electric light sport airplane in Europe [6], but it only has an experimental certificate in the United States [7].

Figure 1: Pipistrel Velis Electro Test Airplane [8]

The powerplant is the Pipistrel E-811-268MVLC engine, which has a liquid-cooled, alternating current (AC), axial flux Pipistrel 268MVLC VHML motor. The motor has a fixed three-phase magnet and runs with three-phase alternating current through the moving coils. The direct current (DC) from the battery packs is converted to AC by the H300C motor controller. The motor controller is connected to the data bus, which takes input from the power lever or throttle, data bus, and instruments. The liquid cooling system is connected to the motor controller and includes a coolant pump, the motor, and the batteries [5].

Figure 2 and Figure 3 show the labeled parts of the engine system installation.

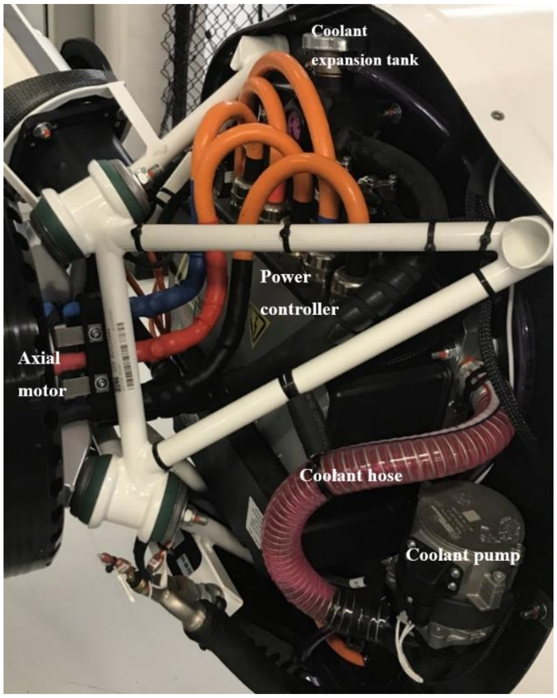

Figure 2: Left View of the Engine System

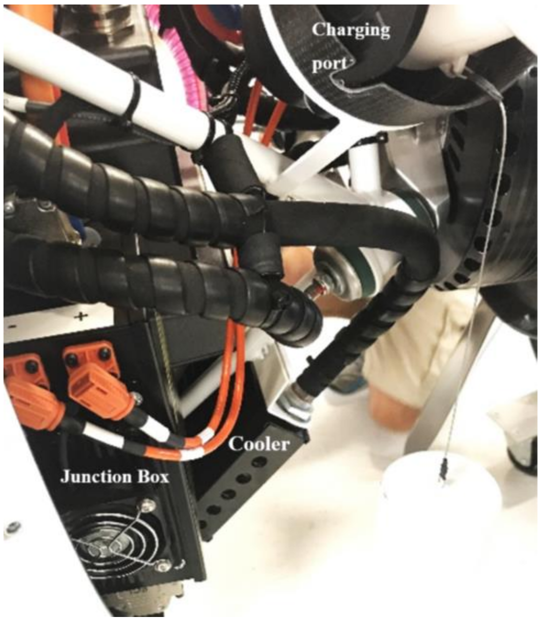

Figure 3: Right View of the Engine System

The Pipistrel P-812-164-F3A propeller is fixed-pitch and ground-adjustable. The blades have stainless steel roots and molded carbon fiber and fiberglass layers. They are attached to an aluminum hub with two M8 hex bolts, and the hub is attached to the motor's rotating plate [1]. Table 1 lists the specifications of the propeller and engine.

Table 1: Velis Electro Propeller and Engine Specifications [1,5,9,10]

Component	***Specifications***
# Propeller Blades	3
Blade Pitch Angle	18°
Propeller diameter	1640 mm (64.57 in)
Propeller Weight	5 kg (11 lbs)
Max Propeller RPM (Clockwise)	2500
Max Continuous Power	49.2 kW
Max Takeoff Torque	220 N-m
Motor Operation Temperature	-20 °C to +110 °C (-4 °F to +230 °F)
Motor and Power Controller Weight	65.5 kg (144.4 lbs)

Each battery pack has 16 lithium nickel manganese cobalt (Li-NMC) cells [1]. The front battery (Battery 1), cooling system, and data bus are between the cockpit control panel and the engine, while the aft battery (Battery 2), data bus, and cooling system are behind the seats in the cockpit. The batteries are cooled using a mixture of 50% water and 50% glycol G12+, and the system radiator is located on the lower aft fuselage. The maximum battery operating temperature is limited to 58°C to prevent thermal runaway or overheating, in which case warnings are shown or the battery pack shuts down [5].

In the case of the climb power test described in this report, Battery 1 was operational while Battery 2 was not.

Chapter 2
Climb Power Test Procedure

Test Plan Development

Prior to testing, a test plan was made to present the objectives, applicable FAA regulations, test procedure, success criteria, and test cards to the test pilot and all observers. A sample test card is shown in Figure 4. The filled and modified test cards are shown in the Appendix.

5	**MAX T/O POWER TEST** Pipistrel Velis Electro Ground Test	Engineering Notes:
TIME: _______________ **AIRCRAFT CONFIGURATION** Baro — 29.92in 1. Throttle: Full, 65 kW - 69.5 kW		

Test Pt.	Power (kW)	RPM	SOC		SOH		Temp. (°C)			%Torque	Current	Voltage	Energy (kWh)
			#1	#2	#1	#2	M	#1	#2				

Figure 4: Sample Test Card

A test hazard assessment was also made to determine potential risks, rank the risks' initial severity in the form of a risk matrix, list mitigation procedures, and rank the risks' severity after mitigation actions are taken.

Propeller Airworthiness Standards

14 CFR Part 35.5 [11] was determined to be the applicable regulation for this ground test because the propeller and powerplant performance of the airplane would be tested and analyzed. Related portions of this regulation are listed below.

(a) Propeller ratings and operating limitations must:

(3) Be based on the operating conditions demonstrated during the tests required by this part as well as any other information the Administrator requires as necessary for the safe operation of the propeller.

(b) Propeller ratings and operating limitations must be established for the following, as applicable:

(1) Power and rotational speed:

(i) For takeoff.

(ii) For maximum continuous.

(iii) If requested by the applicant, other ratings may also be established.

(2) Overspeed and overtorque limits.

A test success criteria table was based on this regulation and is shown in Table 2 below.

Table 2: Ground Test Success Criteria

Parameter	***Description***	***Success Criteria***
Power, RPM, and torque limits not exceeded	Power does not exceed the engine power and RPM limits listed in the pilot operating handbook (POH).	The power does not exceed 49.2 kW for more than 30 seconds, and the RPM do not exceed 2500. [5]
Battery temperature does not exceed limits	Monitor battery temperature to ensure that the limit is not exceeded, and end the test if it is.	Battery temperature does not exceed 45°C [5]

Ground Test Procedure

The climb power ground test procedure and Test Hazard Assessment developed by the author and Florida Tech faculty is presented below.

Pre-Flight

The airplane must be fully charged before each ground test in order to ensure the maximum test duration.

1. Record the aircraft SOC before and after disconnecting the airplane from its charger.

2. Tie the airplane down and chock it in the test location.

Ground Test

1. Record the engine startup time, SOC, and SOH.

2. Set the power to the maximum takeoff power or MTOP (between 65 kW and 69.5 kW) and record the following.

    a. %SOC

    b. RPM

    c. Motor, inverter, and battery temperature, and

    d. Any audible or visual warnings, especially those related to the batteries and engine

3. Reduce the power to minimum climb power or MCP (49.2 kW or 49 kW) and record the parameters from Step 2. Hold MCP power until 80% SOC has been reached.

4. Once 80% SOC has been reached, repeat Step 2 for each 10% SOC decrease. Reduce the power to MCP and repeat Step 3 after collecting the MTOP power data.

5. Continue the test until the battery SOC has reached 20% or the battery or engine temperatures are about to exceed their limits.

6. Turn off the engine and move it to the hangar for storage and charging.

Test Hazard Assessment

A test hazard assessment documents risks and their mitigation procedures for the benefit of the flight test crew during planning and pre-flight briefings. Risk matrices are used as a way to categorize hazards in one graphic. To categorize the risks, the risk's severity is ranked from No Safety Effect to Catastrophic (second column on the left), and the risk's probability is ranked from frequent to improbable (bottom row). The cells are color coded from green (low risk) to black (extreme risk) to indicate the total level of risk for each severity/probability combination. The cell at which the risk's severity and probability rankings intersect has enlarged bold and underlined text to make the risk's ranking stand out from the rest of the cells.

Mitigation and emergency procedures are then listed, as well as weather, minimum crew, and parachute requirements to reduce the risk. The risk's severity after mitigation is then ranked from Low to Avoid.

Hazard 1 Risk Matrix:

Hazard Number: 1	**Severity**	**Risk Assessment**				
Test Plan: Pipistrel Velis Engine Test	Catastrophic	**Avoid**	**High**	**High**	**Medium**	**Low**
Flight Test Technique: Ground Test	Hazardous	**Avoid**	**High**	**Medium**	**Medium**	**Low**
Hazard: Wind or rain damage	Major	**High**	**High**	**Medium**	**<u>Medium</u>**	**Low**
Cause: Thunderstorms	Minor	**Medium**	**Medium**	**Medium**	**Low**	**Low**
Effect: Damage to the aircraft	No Safety Effect	**Low**	**Low**	**Low**	**Low**	**Low**
	Probability	Frequent	Probable	Occasional	Remote	Improbable

Mitigations and Minimizing Procedures:

1. Check the current weather and forecast for the test location and surrounding area for forming or active thunderstorms.

2. Do not conduct the test if the storms will develop around the airport or in the test location during the expected flight time.

3. All members of the crew observe weather during flight to alert pilot of potentially hazardous weather.

Emergency Procedures:

1. End the test if thunderstorm activity is noticed in the vicinity of the airport.

Weather Requirement and/or Flight Conditions: VFR conditions

Minimum Flight Crew: Yes

Parachutes Required: No

Risk After Mitigations: Low

Hazard 2 Risk Matrix:

Hazard Number: 2	**Severity**	**Risk Assessment**				
Test Plan: Pipistrel Velis Engine Test	Catastrophic	Avoid	High	High	Medium	Low
Flight Test Technique: Ground Test	Hazardous	Avoid	High	**Medium**	Medium	Low
Hazard: Complete or partial loss of power	Major	High	High	Medium	Medium	Low
Cause: Battery overheating, unsteady battery thermal control, failed battery pack	Minor	Medium	Medium	Medium	Low	Low
Effect: Potential battery fire	No Safety Effect	Low	Low	Low	Low	Low
	Probability	Frequent	Probable	Occasional	Remote	Improbable

Mitigations and Minimizing Procedures:

1. Monitor the engine instruments display.

2. Make sure the motor, inverter, and battery temperature limits are not exceeded.

Emergency Procedures:

Temperature limits exceeded:

1. Reduce the power to idle

2. Turn off the engine

3. Evacuate the airplane

Weather Requirement and/or Flight Conditions: VFR conditions

Minimum Flight Crew: Yes

Parachutes Required: No

Risk After Mitigations: Low

Chapter 3
Test Results

Data Reduction

Using the data collected on the test cards as a guide, the full climb power and MCP test results were identified and compiled from the airplane's data files. The test time in minutes, battery state of charge, motor power, estimated remaining flight time, average, minimum, and maximum battery temperature, and battery voltage and current were selected for analysis.

Results Discussion

The full climb power data was collected in 30 seconds or less to stay within the full power time limit recommended by Section 3.5.7 of the POH [5]. Figure 5 compares the maximum full power by SOC for the climb power test.

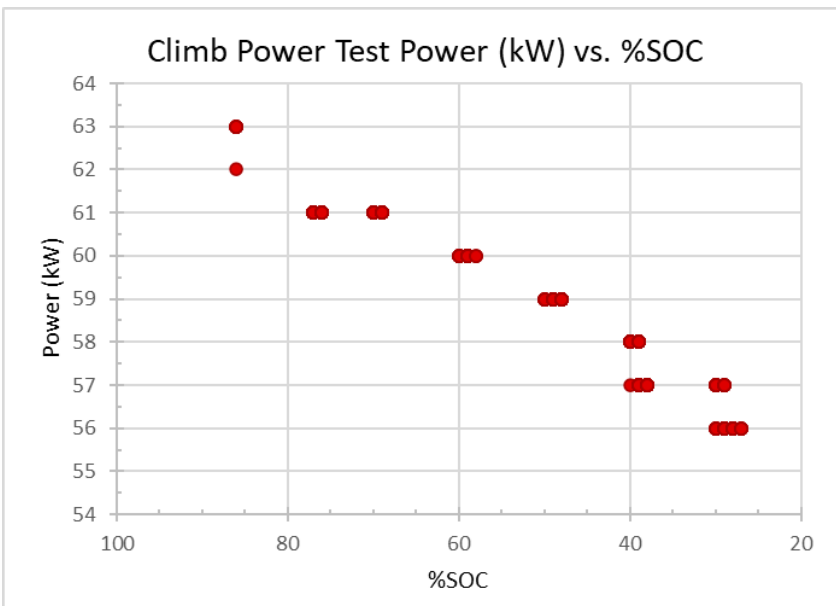

Figure 5: Climb Power Test Power vs. %SOC Plot

From Figure 5, the maximum power of 63 kW is less than the maximum power range supported by of two batteries, which is 65 kW to 69.5 kW according to the POH [5]. Section 7.6.2 of the POH states that one battery produces enough power to the engine to climb or continue a flight [5]. The results presented in Figure 5 show that this is the case since 56 kW to 64 kW was produced at the full power setting from 86% to 26% SOC. The power output range provided by one battery is above 50 kW, which Section 1.7.3 of the POH states is the minimum performance takeoff power or MPTOP at low SOC values or when the batteries reach the end of their service life [5]. Therefore, it can be assumed that MPTOP was successfully maintained and exceeded with the full power setting.

In addition to the full power results, the MCP test results for the climb power test must also be analyzed to determine if MPC is achievable when one battery fails. Figure 6 shows the MCP power vs. SOC plot.

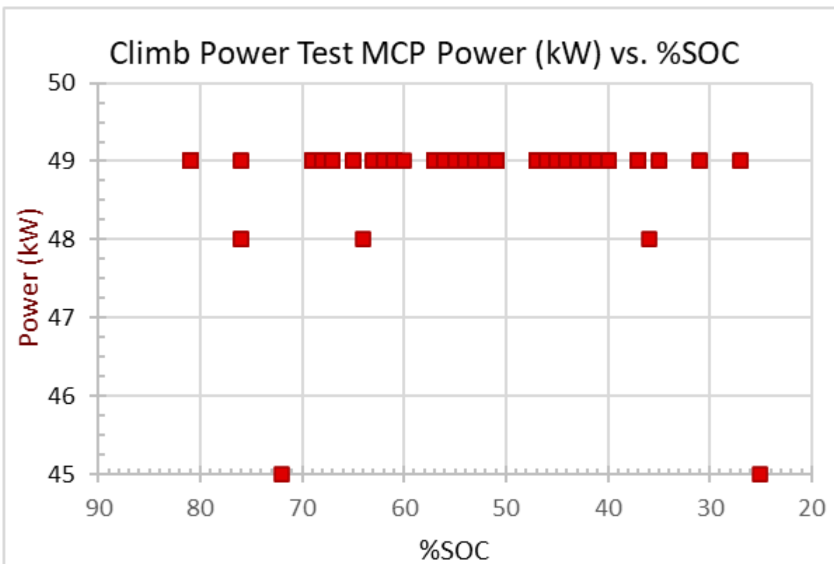

Figure 6: Climb Power Test MCP Power vs. %SOC

The MCP power range of 48 kW to 49.2 kW is steadily achieved for most of the test, except when the SOC is low. Therefore, in the event of a single battery failure during takeoff, it may be possible that setting the throttle to MCP will provide enough power for the airplane to climb to a safe altitude to attempt an emergency landing as long as the SOC is above 25%. The cause of the two outliers at 72% and 25% are uncertain. The outlier at 72% may be due to throttle adjustment errors. However, the outlier at 25% was the maximum power reached near the end of the final MCP run, so there is a chance that the power could only reach 45 kW because of the reduced output at that SOC and not because of throttle setting errors.

Figure 7 plots the decrease in full power over elapsed time.

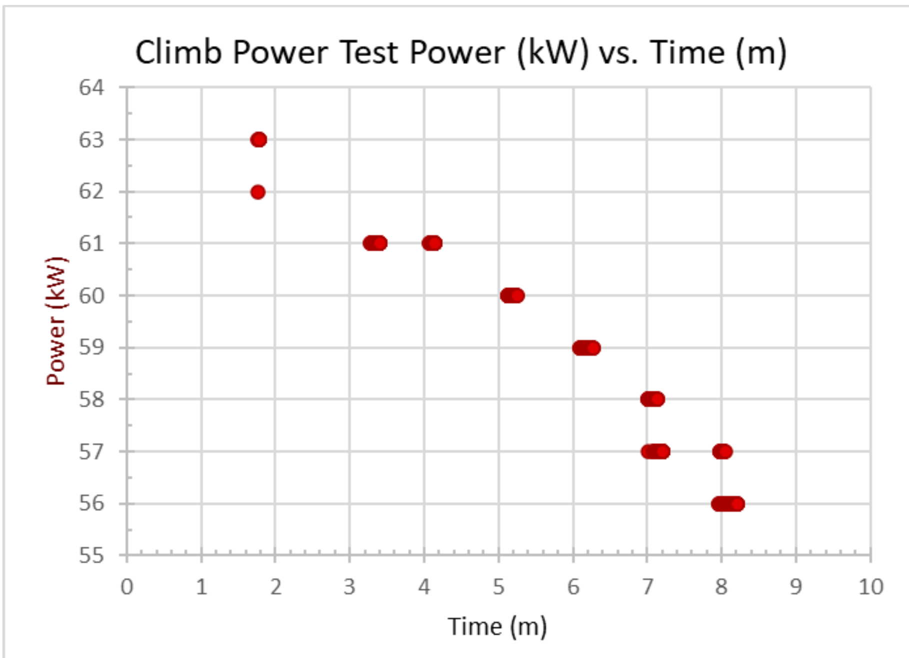

Figure 7: Climb Power Test Power vs. Elapsed Time

Note how in Figure 7, there are no data points until an elapsed time of around 1.6 minutes. This is because the onboard data collection system began counting the elapsed time when the engine was turned on at the start of the test session, not at the first power input.

In addition to the maximum power produced at each full power test point, Figure 7 shows how quickly the motor lost power as the SOC decreased. The last full power test was completed at about 8.3 minutes after the start of the test.

This result shows that the power output decreases quickly when one battery provides power to the engine. A short battery discharge time creates a high potential of risk in emergency situations since the amount of time available to accomplish a forced landing may not be enough when one battery fails, depending on how far the airplane is from a safe landing location.

Figure 8 shows the power vs. elapsed time plot for the MCP test runs.

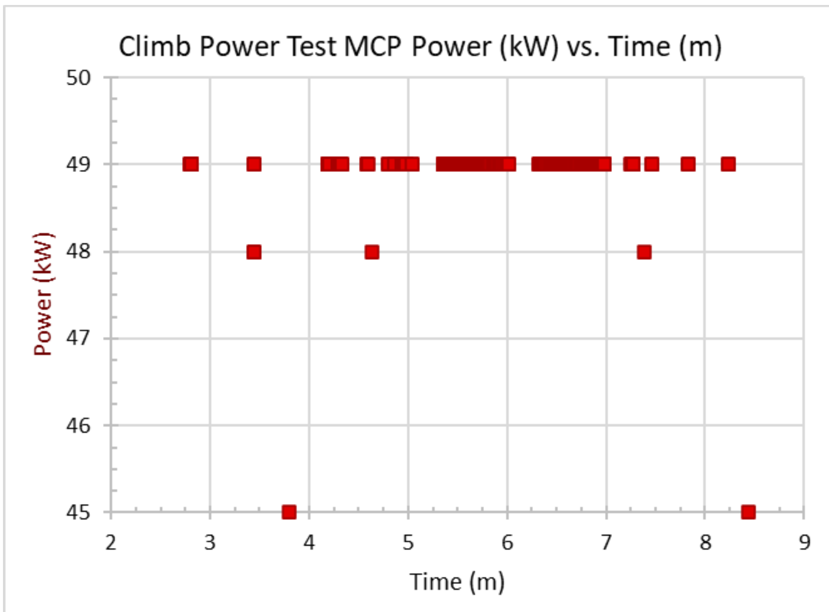

Figure 8: Climb Power Test MCP Power vs. Elapsed Time

As in Figure 6, Figure 8 shows how MCP can be constantly maintained for the most part.

So far, the results showing that full motor power decreases with SOC and time further reiterate the observations by Wheeler et al. [4] that the performance of an electric airplane is different from what pilots of fuel-powered airplanes expect. With fuel-powered aircraft, the aircraft's weight decreases as fuel is used, increasing its performance until the fuel levels reach their minimums [3]. In contrast, the electric airplane's performance decreases as the SOC decreases while the weight remains unchanged. Therefore, pilots of non-electric aircraft must be informed of the differences in electric and non-electric aircraft performance and how they practically affect climb and other performance-related impacts.

These topics can be addressed in electric airplane proficiency training, in addition to studying the recommended operating procedures in the POH.

Since it is clear from Figures 5 to 8 that the motor being powered by one battery severely limited the test's duration to a little over 8 minutes, the airplane's estimated flight time will be analyzed to determine its accuracy since pilots rely on the flight time estimates to make decisions. Figure 9 plots the estimated flight time against the elapsed test time for the test's full power runs, Figure 10 plots the SOC against elapsed time for reference.

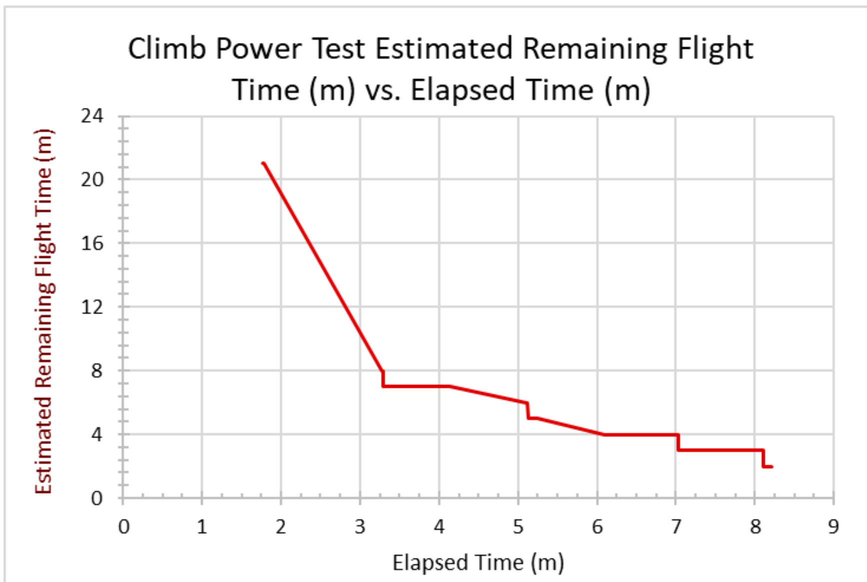

Figure 9: Climb Power Test Estimated Remaining Flight Time vs. Elapsed Time

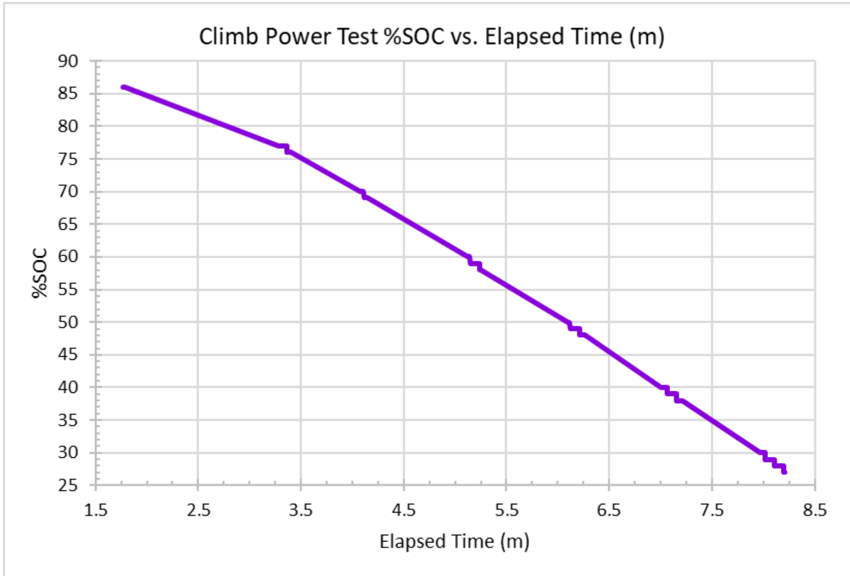

Figure 10: Climb Power Test %SOC vs. Elapsed Time

In Figure 9, the initial estimated flight time was 21 minutes, which was clearly inaccurate considering that the ground test lasted for about 8.5 minutes from engine start to shutdown. The estimate then decreases to as low as 7 minutes during the first 10% SOC decrease that occurred from 1.75 to 3.25 minutes elapsed time, according to Figure 10. The reduced remaining flight time estimate is due to the calculations being readjusted to reflect the motor being run at the full power setting and therefore depleting the battery faster than if the motor was run at a lower setting.

Since the estimated remaining flight time fluctuates throughout the duration of the test as presented in Figure 9, the fluctuations must be compared to the actual remaining flight time. Figure 11 is a plot of the estimated remaining flight time against the actual remaining flight time during the full power portions of the ground test. The actual remaining flight time is included as a reference line to illustrate how the estimated remaining flight time is consistently greater than the actual remaining flight time.

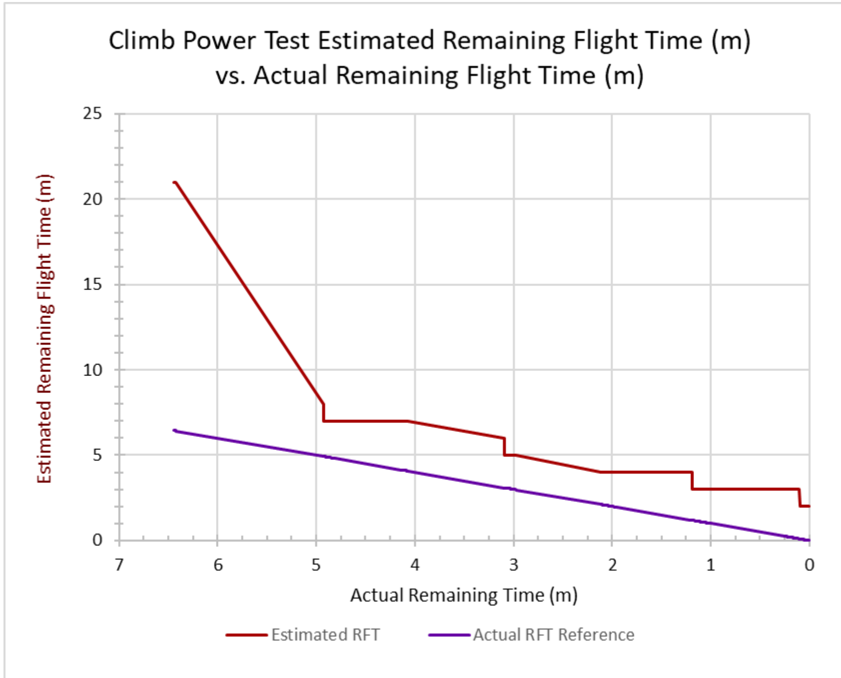

Figure 11: Estimated Remaining Flight Time (m) vs. Actual Remaining Flight Time (m) with Actual Remaining Flight Time Reference Line

The difference between the estimated and actual remaining flight times was then calculated and plotted by the actual remaining flight time in Figure 12. This plot was created to make it easier to see how much the airplane's flight time estimates overshot the actual remaining flight time.

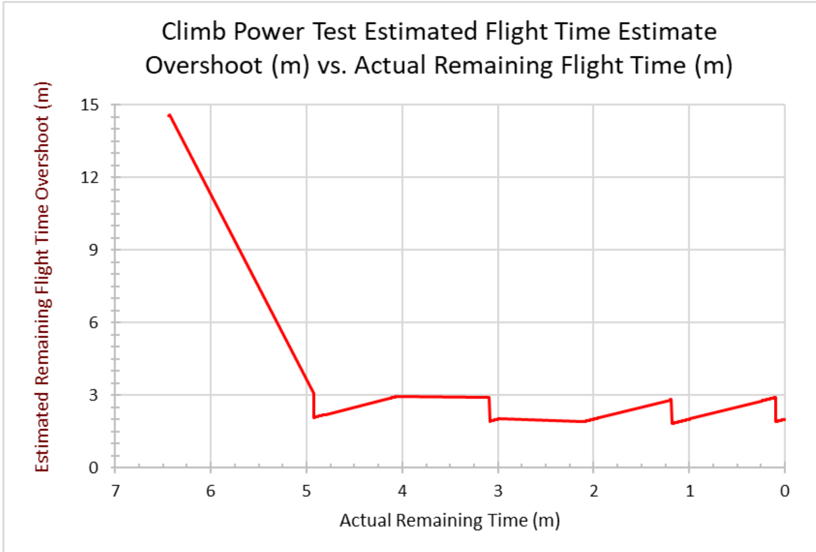

Figure 12: Estimated Remaining Flight Time Overshoot (m) vs. Actual Remaining Flight Time (m)

Figure 11 illustrates that at the time the first power input was made, the estimated remaining flight time was 21 minutes when the actual remaining flight time was about 6.5 minutes. The trend of the estimated flight time being overestimated, or overshot, by 2 minutes or more compared to the actual remaining time continued throughout the test, according to Figure 12. The remaining flight time mostly decreased during each full power run due to the power lever being set at MCP in between full power runs instead of at a lower power setting. This steady decline in the remaining flight time estimate is why the POH suggests breaking up extended climb periods with periods of a lower climb power setting to conserve energy and therefore flight time [5].

Figures 13 to 16 are the same plots as those in Figures 9 to 12, but for the test's MCP runs.

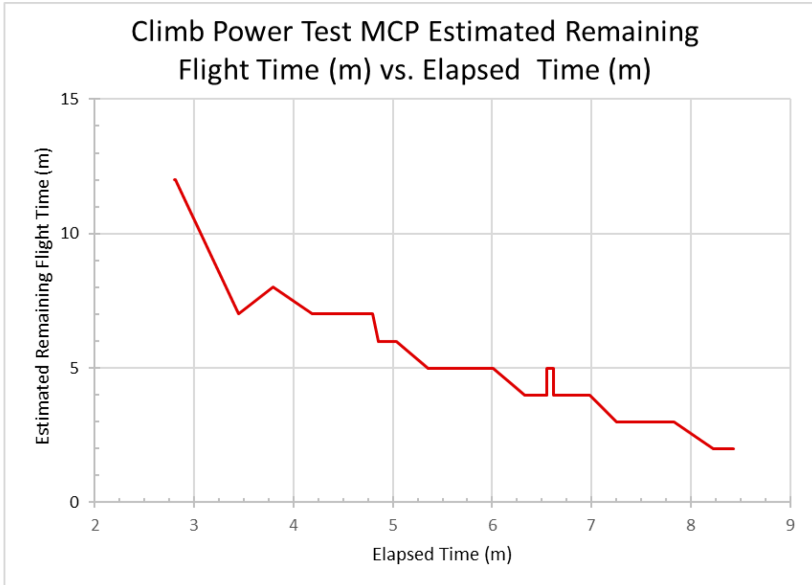

Figure 13: Climb Power Test MCP Estimated Remaining Flight Time vs. Elapsed Time

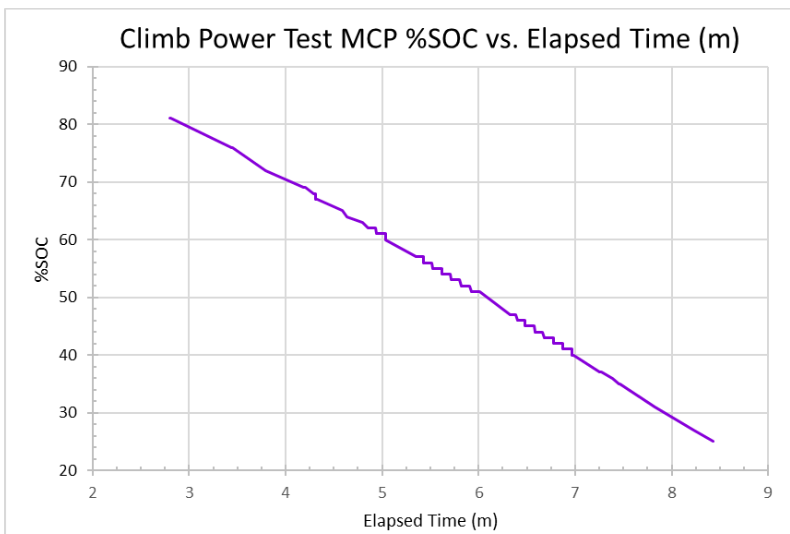

Figure 14: Climb Power Test MCP %SOC vs. Elapsed Time

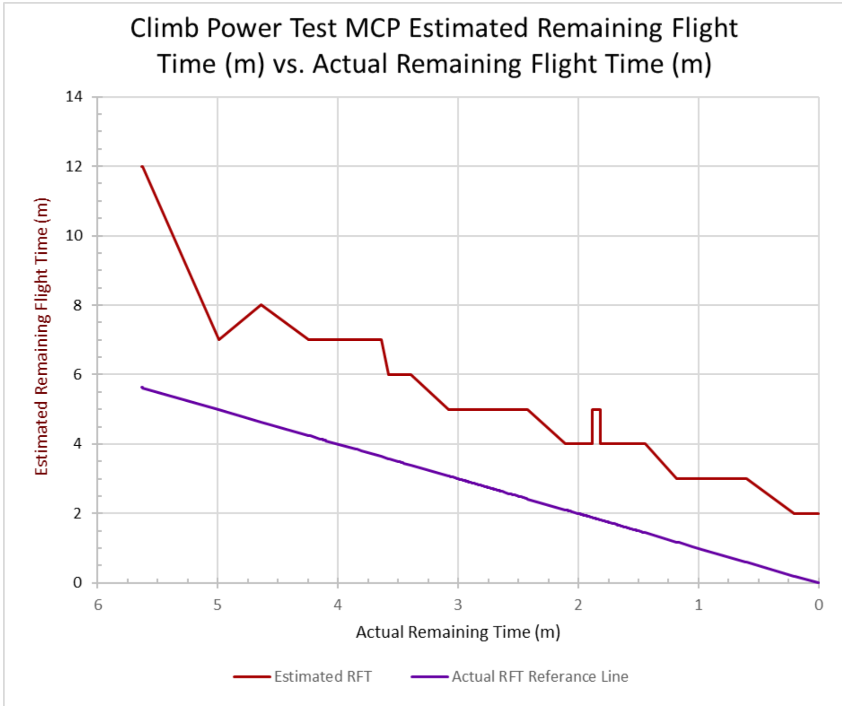

Figure 15: MCP Estimated Remaining Flight Time (m) vs. Actual Remaining Flight Time (m) with Actual Remaining Flight Time Reference Line

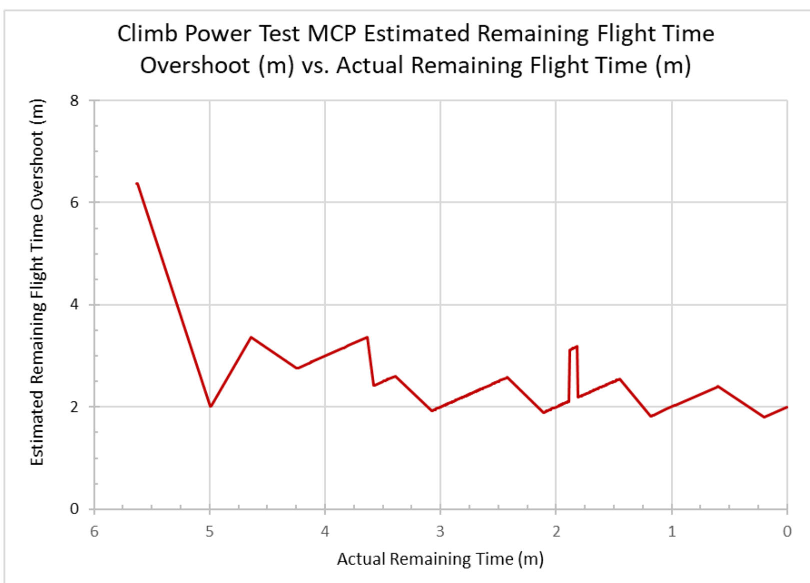

Figure 16: MCP Estimated Remaining Flight Time Overshoot (m) vs. Actual Remaining Flight Time (m)

Like with the full power plots in Figures 9 and 11, the estimated remaining flight time in Figures 13 and 15 also decreased significantly after the initial estimate spike but was overestimated during the MCP runs. The remaining flight time values tended to be overestimated by 2 or more minutes compared to the actual remaining test time, according to Figure 16. Estimate inaccuracies like these must be considered when operating the airplane in routine or emergency situations since flight profiles have many phases that require very different power settings, such as taxi, climb, cruise, and landing.

These remaining flight time results are crucial since they imply that climbing for extended periods of time, especially with one operational battery, will increase the risk of the airplane not having enough time to make an emergency landing. Additionally, the fact that the remaining flight time was consistently overestimated is concerning since the estimates would lead pilots to assume that they have more time than they really have for decision making. It is also expected that any remaining flight time estimates calculated by an airplane's system should reflect the minimum or worst-case scenario to ensure a power reserve.

Given that battery heating degrades the lifetime and performance of batteries, it is worth analyzing the increase in battery temperature throughout the test. Figures 17 and 18 plot the average battery cell temperature against time for both the full power and MCP test runs.

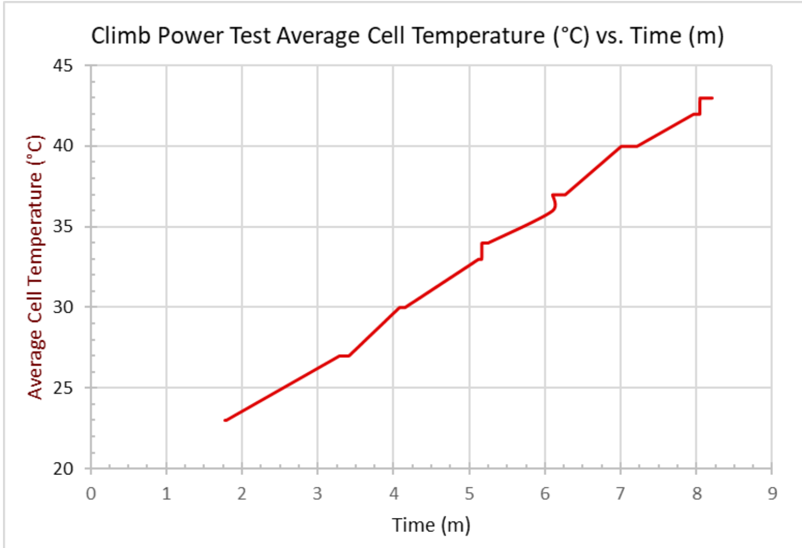

Figure 17: Climb Power Test Average Cell Temperature vs. Time

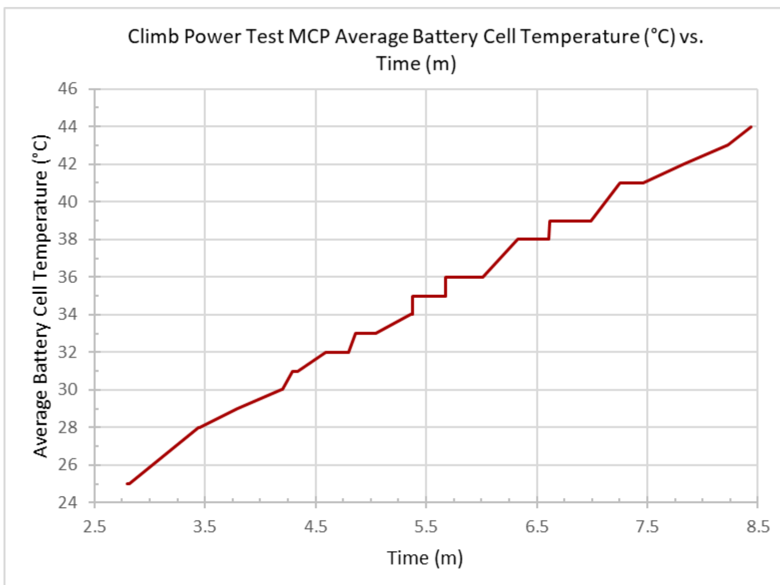

Figure 18: Climb Power Test MCP Average Cell Temperature vs. Time

The maximum average cell temperature was 44°C at the end of the MCP test run, close to the 45°C temperature limit given by the POH [5]. This temperature was 21°C higher than the starting average cell temperature of 23°C. Using Figure 17 and the assumption that the average cell temperature increased linearly, the temperature increase rate was calculated to be 3.57°C/min. The high temperature rise partially occurred because the test began with a high SOC value of 91%, allowing the battery to run for close to its maximum duration with one battery. Therefore, it can be assumed that the batteries have a high chance of exceeding their temperature limits at low SOC values after prolonged use.

Figures 19 and 20 plot the minimum and maximum battery temperatures against test time for the full power and MCP test runs, further illustrating the effect that operating the airplane with one working battery has on battery temperature. The minimum and maximum battery temperatures are recorded by the data collection system separately from the average cell temperatures discussed previously.

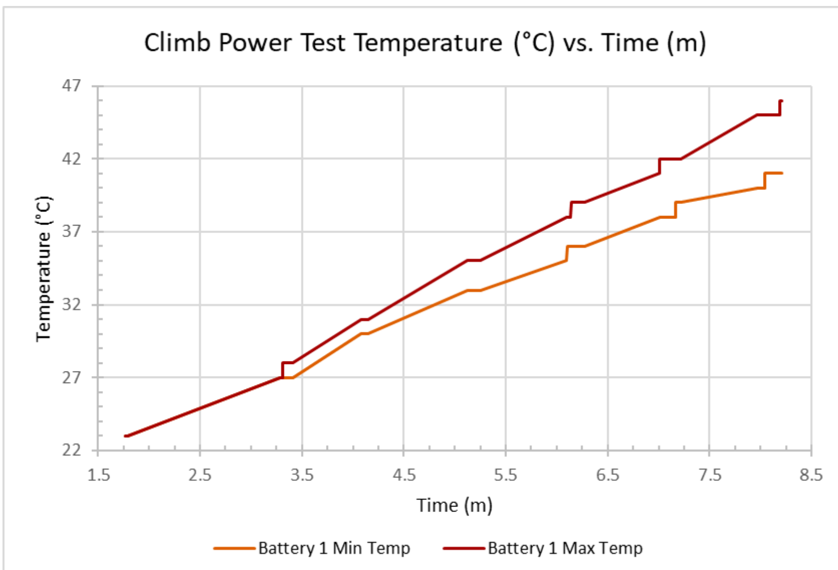

Figure 19: Climb Power Test Minimum and Maximum Battery Temperature vs. Time

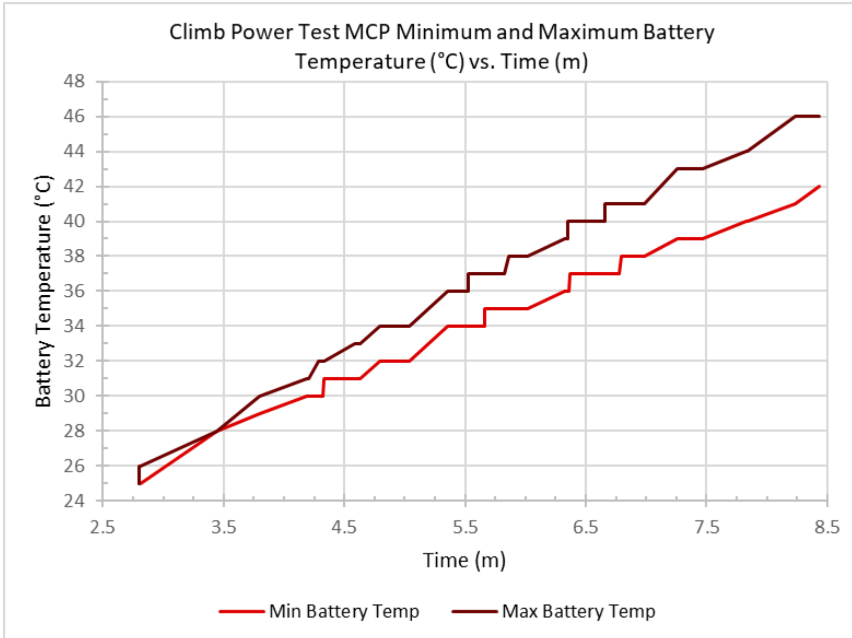

Figure 20: Climb Power Test MCP Minimum and Maximum Battery Temperature vs. Time

The minimum and maximum temperatures are both 23°C at the beginning of the test since the battery had not heated up yet. As time progresses, the difference between the minimum and maximum temperatures increases as the battery becomes hotter. This indicates that the cooling system works harder to maintain a low temperature at lower SOC values and cannot always keep up with the temperature increase. Both figures show that the maximum and minimum temperature difference is as much as 6°C near the end of the test. Comparing the maximum battery temperature with the average cell temperature shows that the difference between the start and end average cell temperatures does not accurately reflect how much the battery temperatures actually increase. For example, the average cell temperature in Figures 17 and 18 increased by 21°C from 23°C to 44°C. However, the maximum battery temperature in Figures 19 and 20 increased by 23°C from 23°C to 46°C due to 2 of the 16 battery cells reaching 46°C while the rest remained between 42°C and 45°C. Therefore, while the average cell temperature of the one operational battery did not exceed the temperature limit of 45°, the maximum battery temperature did because of the two cells.

This difference in the average cell and maximum battery temperatures are a concern in engine failure scenarios since the average cell temperature is displayed to the pilots and not the maximum cell temperature, which could mislead the pilot about the true battery temperature. This somewhat inaccurate temperature reporting could result in pilots not ending a flight before or when battery temperatures are exceeded because they are unaware of how hot one or more battery cells really are. Extreme battery temperatures, even in one or two cells like in the ground test, are a serious hazard since they reduce the battery's lifespan and may eventually lead to thermal runaway, which is often a cause of battery fires. Lithium-ion battery fires are especially dangerous because they are self-sustaining and not extinguished until the chemical reaction has run its course. Because of this concern, Section 3.5.7 of the POH states that a maximum of 40 kW must be used when one battery is operational and that full power must not be used for more than 30 seconds in emergencies [5].

Increases in battery temperature are linked to voltage and current. Figures 21 and 22 show the voltage vs. SOC plot for the full power and MCP runs.

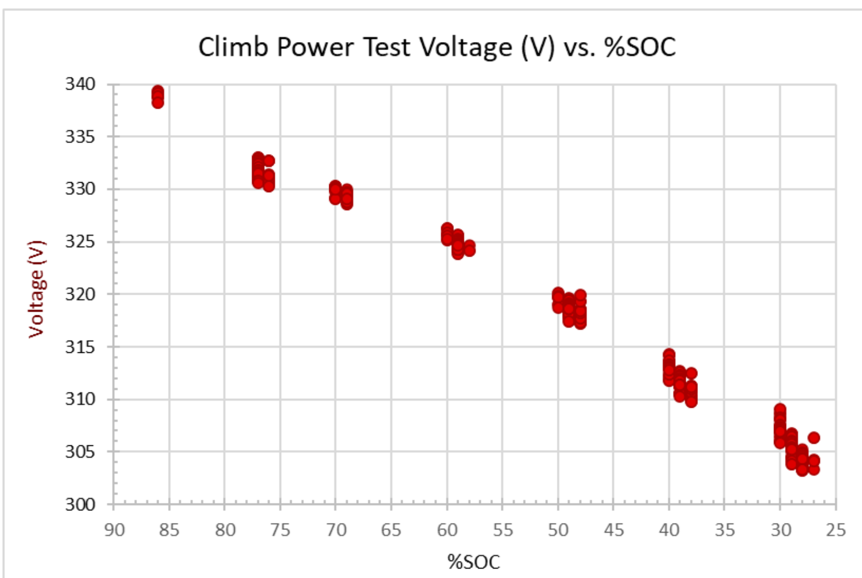

Figure 21: Climb Power Test Voltage vs. %SOC

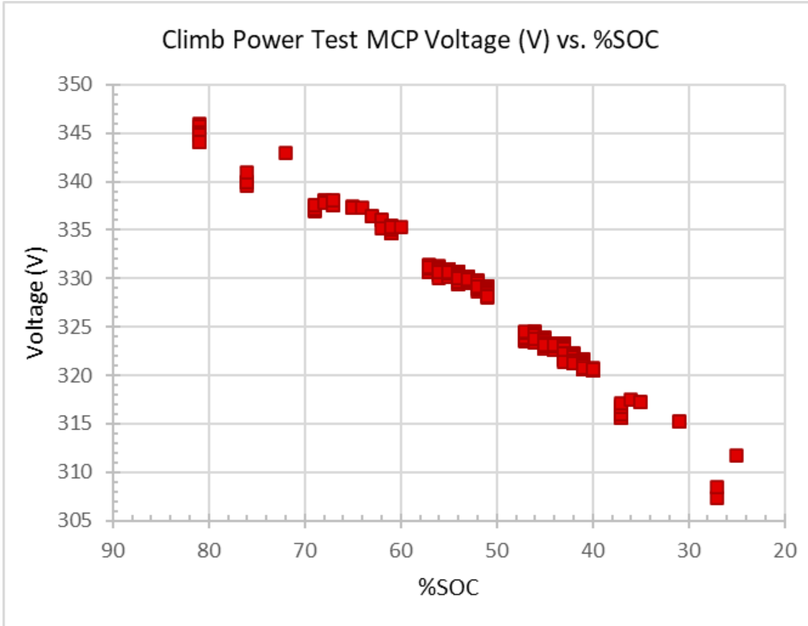

Figure 22: Climb Power Test MCP Voltage vs. %SOC

Figures 23 and 24 show the current vs. SOC plots for the full power and MCP runs.

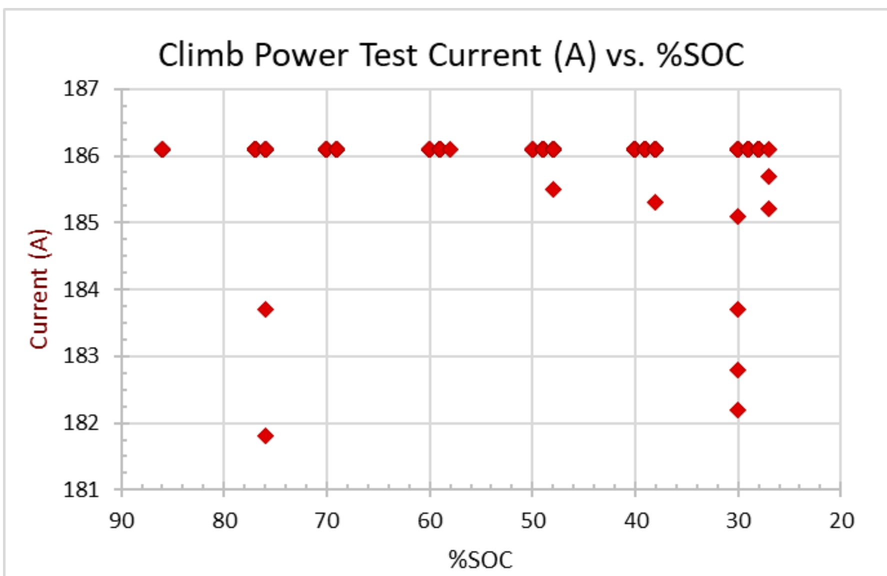

Figure 23: Climb Power Test Current vs. %SOC

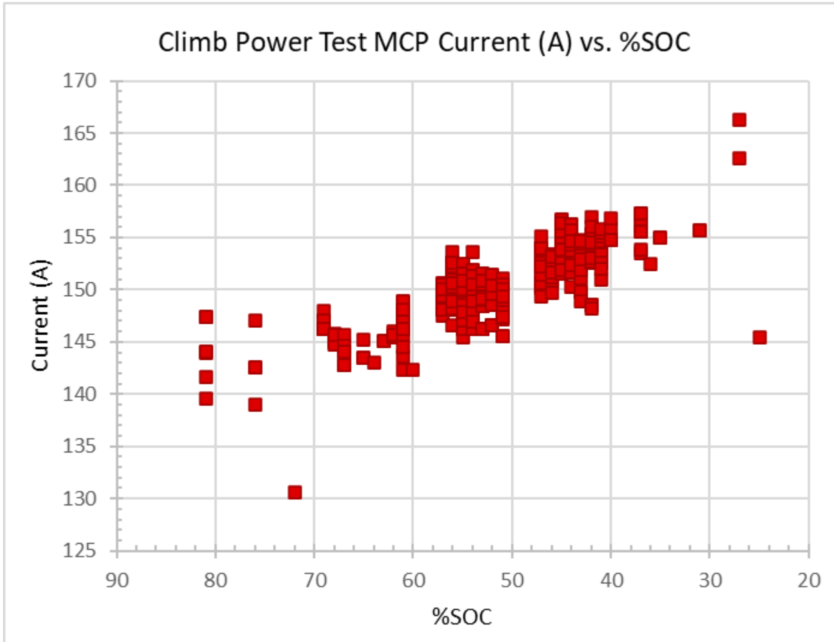

Figure 24: Climb Power Test MCP Current vs. %SOC

As explained in the report about the full battery discharge test by Cunha et al. [4], voltage and current are inversely proportional, and a battery's voltage decreases as the battery discharges. Therefore, the current must increase to maintain a constant power as the SOC decreases. Figures 21 to 24 mostly demonstrate that the current increases as the voltage decreases until SOC is about 30%. The drop in current at 30% SOC seems to indicate the point at which the temperature was high enough to cause a high internal resistance in the battery, which limited the battery's ability to carry current. This is why the cockpit engine and battery temperature displays must be monitored, and the flight must be stopped before the temperature limits are exceeded, unlike what happened during the test. It must be noted that the current remained mostly constant in Figure 23 during the full power runs instead of increasing like in the MCP runs. The reason for this behavior is unclear, but it may be a result of the current being limited by the battery system.

Due to damage caused by the high battery temperatures and the additional stress on Battery 1 from operating without Battery 2, Battery 1 did not accept any charge after the test was completed and the engine was shut off for charging. The charger would automatically shut off up to 30 seconds after starting a charging session. Because Battery 2 was inoperative before and after the test, it also did not accept any charge. Therefore, replacing both batteries with new batteries post-flight after experiencing a battery failure would be a reasonable recommendation.

Climb Performance Comparison

Figure 25 shows the full power RPM vs. power plot for the full power runs of the test.

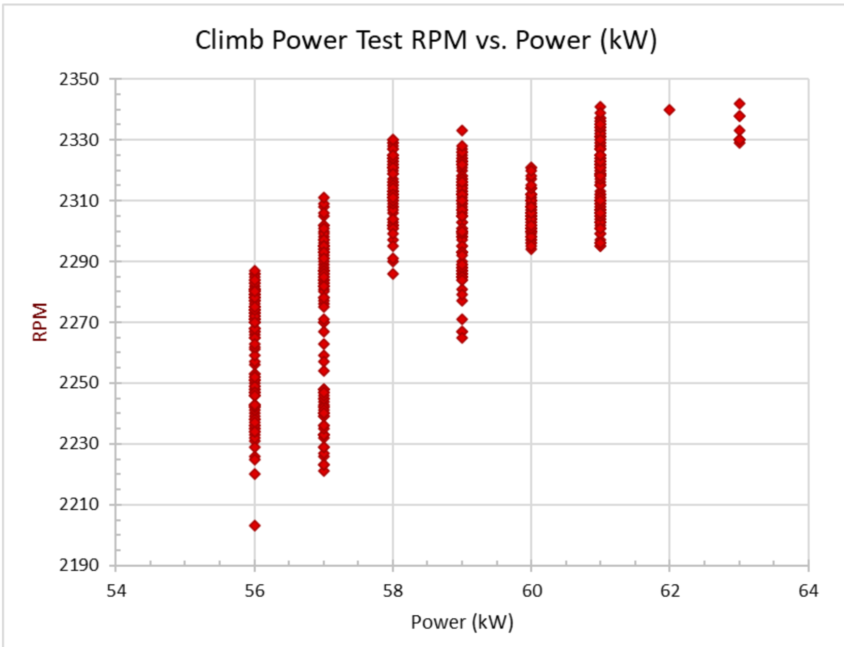

Figure 25: Climb Power Test RPM vs. Power

The maximum RPM was below 2,500 RPM, which passes the RPM limit test criteria. As expected, the climb power test produced a fairly low range of RPM values from 2,225 to 2,345 due to only one battery operating. For comparison, the MCP RPM is 2,300 in the POH [5].

Figure 26 plots the MCP RPM vs. power for all of the MCP portions of the test.

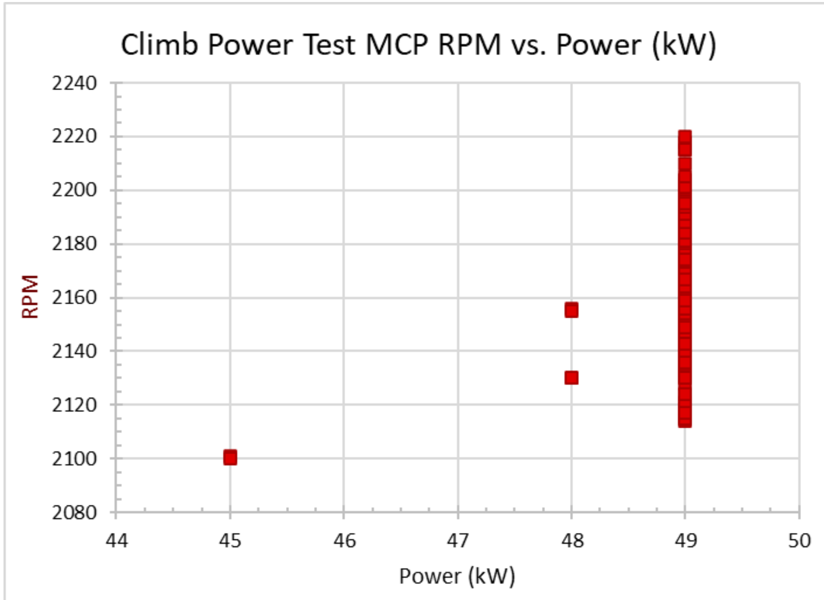

Figure 26: Climb Power Test MCP RPM vs. Power Plot

As shown in the full power plot in Figure 25, the RPM decreased as the motor lost power from the decreasing battery charge, even though the throttle was kept at a constant setting position. While the MCP power setting produces 48 kW to 49.2 kW in most cases in Figure 8, the RPM remains between around 2,105 and 2,220 RPM. This range is lower than the defined MCP RPM of 2,300, which was easily reached and exceeded when the throttle was set to full power.

As a comparison, the POH states that cruise power settings from 25 kW to 36 kW at sea level result in an RPM range from 1,780 to 2,300, where 2,300 is the maximum cruise RPM as well as the MCP RPM [5]. The comparison implies that even if the power is set at MCP, the resulting RPM may be similar to that provided by cruise power settings. This characteristic is important for pilots to note since, in addition to airspeed, power setting adjustments are often made using the RPM shown on the tachometer in non-electric airplanes. In the case of the Velis Electro, however, motor power is just as critical as RPM when adjusting the throttle, if not more so. The operating procedures listed in the POH also suggest this, where airspeed and motor power are emphasized while RPM values tend to be presented as limits and guidelines. However, if the RPM with a MCP setting is lower than 2300, the airplane could potentially not climb well.

In the full power tests, the RPM first went below 2,300 at about 61 kW. The power vs. %SOC plot in Figure 5 shows that these power values correspond with 75% SOC. This means that at the time when the RPM went below 2,300, the SOC decreased by 25% in about 2 minutes from 86% to 75%, as shown in Figure 11. For comparison, a mission planning calculation example in Section 5.12 of the POH estimates that the SOC used for takeoff with no wind is 5%. The SOC used for a climb at MCP and 2,300 RPM from sea level to 2,000 ft is 18%, with a start SOC of 80%. Therefore, it is reasonable to assume that with a complete failure of one battery, the airplane can reach a pattern altitude of 1,000 ft as long as the battery failure occurs at a SOC over 80%. It must be noted, however, that no climb duration was given in the example.

These results suggest that while MCP is achievable with a failure of one battery, an RPM of 2,300 during an extended climb may decrease to the point where 2,300 RPM cannot be constantly maintained relatively early in a flight. A similar result may be expected even if both batteries are functional, which is why the POH suggests separating climb periods with periods of cruise power to save battery charge [5]. A reduced climb RPM output after short periods of time may limit the maximum altitude the airplane can reach during an extended climb. This is especially critical if the airplane experiences a partial battery failure at takeoff speed and must climb to safely circle back to the runway or land in a location straight ahead of the runway.

Suggested minimum altitudes for emergency landings after takeoff include 200, 500, and 1000 ft AGL [12]. The rates of climb (ROC) at sea level for the best rate of climb airspeed (V_Y) are used to determine the altitude that would be reached in the time period where the RPM was at or above 2300 at MCP. The Velis Electro POH ROC table, shown in Figure 27, lists ROC values for various pressure altitudes and temperature ranges, measured in terms of standard temperature or International Standard Atmosphere (ISA) [5], which is 15°C [13, 14].

MASS/ AIR SPEED	Pressure Altitude (PA)	RATE OF CLIMB [ft/min]				
	ft	ISA -15°C	ISA -5°C	ISA	ISA +5°C	ISA +15°C
600 kg/ V_Y 75 KIAS	0	683	658	647	636	615
	4000	602	580	570	560	541
	8000	439	423	415	408	393
	12000	276	265	260	255	246

Figure 27: POH V_Y Rate of Climb Table [5]

Using the ROC values from the POH table, the maximum altitude is calculated for the duration at which the RPM was 2,300 or more in the climb power test, which was about 2 minutes. These results are shown in Table 3.

Table 3: ROC and Maximum Altitude Table

ROC	***Altitude in 2 minutes***
683 ft/m *(0°C, H_P = 0 ft, 600 kg/1323 lbs)* [5]	1366 ft
658 ft/m *(10°C, H_P = 0 ft, 600 kg/1323 lbs)* [5]	1317 ft
647 ft/m *(15°C, H_P = 0 ft, 600 kg/1323 lbs)* [5]	1294 ft
636 ft/m *(20°C, H_P = 0 ft, 600 kg/1323 lbs)* [5]	1272 ft
615 ft/m *(30°C, H_P = 0 ft, 600 kg/1323 lbs)* [5]	1230 ft

Using the POH ROC values, the maximum altitudes are between 1,000 ft and 2,000 ft pressure altitude after 2 minutes. These altitudes are above the common traffic pattern altitude of 1,000 ft, which is useful for an emergency approach and landing that involves the airplane circling back to the runway [12].

It must be noted that errors from the propeller blade cavitating due to excessive speeds during ground tests render the RPM values inaccurate for comparison to actual flight data, where the dynamic air pressure reduces the propeller speed in flight. To determine what the RPM at altitude might be for the ground test's full power range, the ground test data will be compared to the data in an RPM vs. power plot from a previous level acceleration flight test, shown in Figure 28.

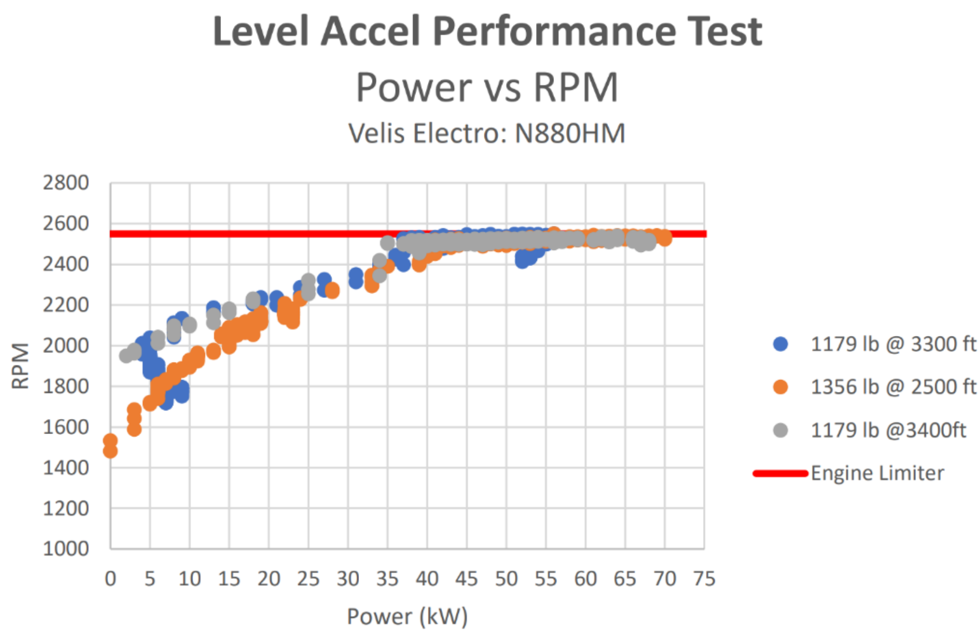

Figure 28: Level Acceleration Power vs. RPM Plot [1]

In the power range from 65 kW to 48 kW, the RPM values range from 2,400 to the maximum RPM of 2,600. The range is higher than those shown for the same power settings in Figures 25 and 26, which makes sense since the air is less dense at the level acceleration test altitudes and atmospheric conditions of that day. It may be reasonable to assume that the RPM values could be slightly lower at lower altitudes where the air is denser, which lends some credibility to the climb power test RPM results.

Chapter 4
Conclusions

This thesis analyzed the engine and battery performance of a Pipistrel Velis Electro during a ground test with one operational battery. The results were compared to the limitations and output of the recommended climb settings described in the pilot operating handbook. This investigation aimed to determine performance limitations and potential risks of operating the airplane with one battery at climb power settings, which are critical to understand to improve safety.

As expected, the maximum power produced to the motor by one battery is less than the power output when both batteries are operational. However, minimum climb power or MCP can be maintained until a low state of charge. The test was ended a little after 8 minutes since the single battery's SOC decreased rapidly, and the battery temperature reached its limit due to the power being set at the minimum and maximum climb power settings. The reduced flight time due to only one battery operating is a concern because there may not be much time for a pilot to return to the runway if a battery fails during takeoff. The POH states that the power provided by one battery is enough to sustain a climb and continue a flight [5]. However, the data produced from this test has shown that the battery provides only enough power to make an emergency landing in under 10 minutes. The high battery temperatures near the end of the test also pose a risk of thermal runaway, which could lead to a battery fire.

When comparing the power and RPM data for the ground test to data from actual flight tests of the same airplane, it was determined that the minimum climb RPM of 2,300 could be achieved at full power with one battery as long as the remaining battery's SOC was above 75% and the temperature limit of 45°C is not exceeded. Climbing at V_Y with one failed battery may also be enough to reach an altitude of 1,000 ft pressure altitude as long as the battery failed at a high SOC.

Replacing both batteries with new ones after a flight where one battery failed is recommended due to the damage caused by high battery temperatures.

Future Research and Suggestions

To further determine the airplane's performance limitations during a battery failure, more ground tests like the one discussed in this report could be done for different power settings and power adjustments. Instead of running the engine at MCP in between full-power test runs, the power could be reduced to 40 kW as recommended by the POH [5]. The differences in power and RPM output, actual and estimated flight time, and battery temperature could be compared to the results from this and other ground tests.

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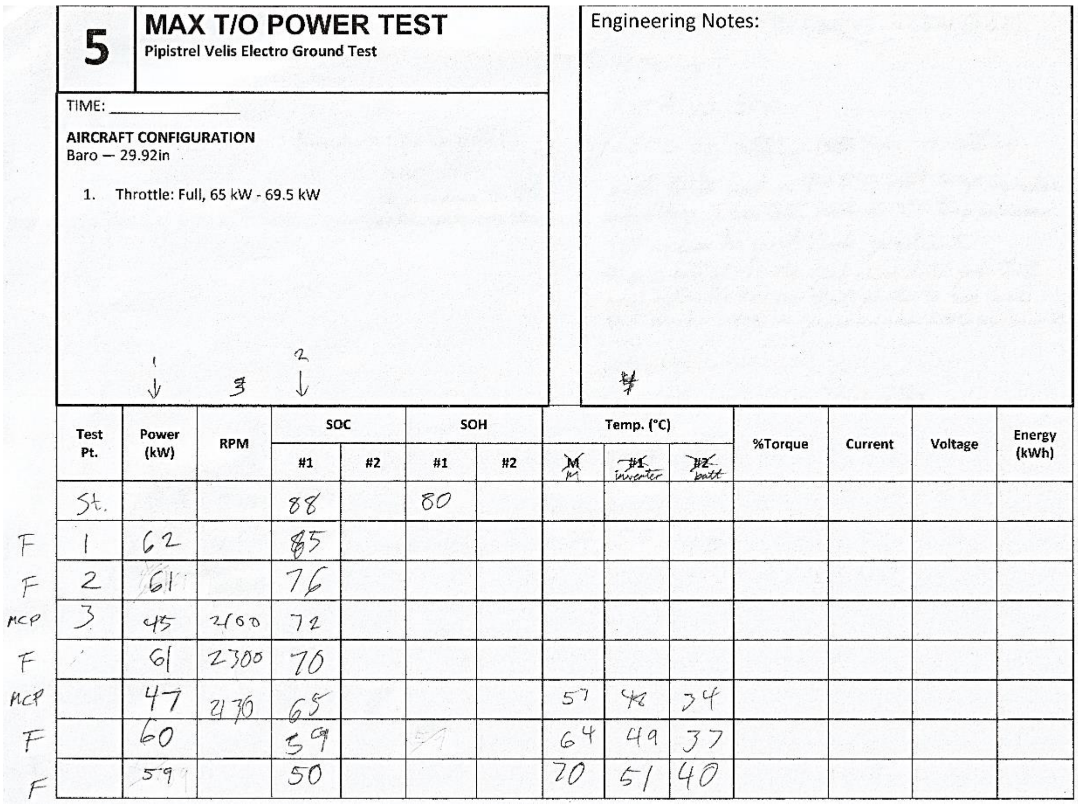
Appendix

Used Test Cards



5	MAX T/O POWER TEST Pipistrel Velis Electro Ground Test

TIME: ______________

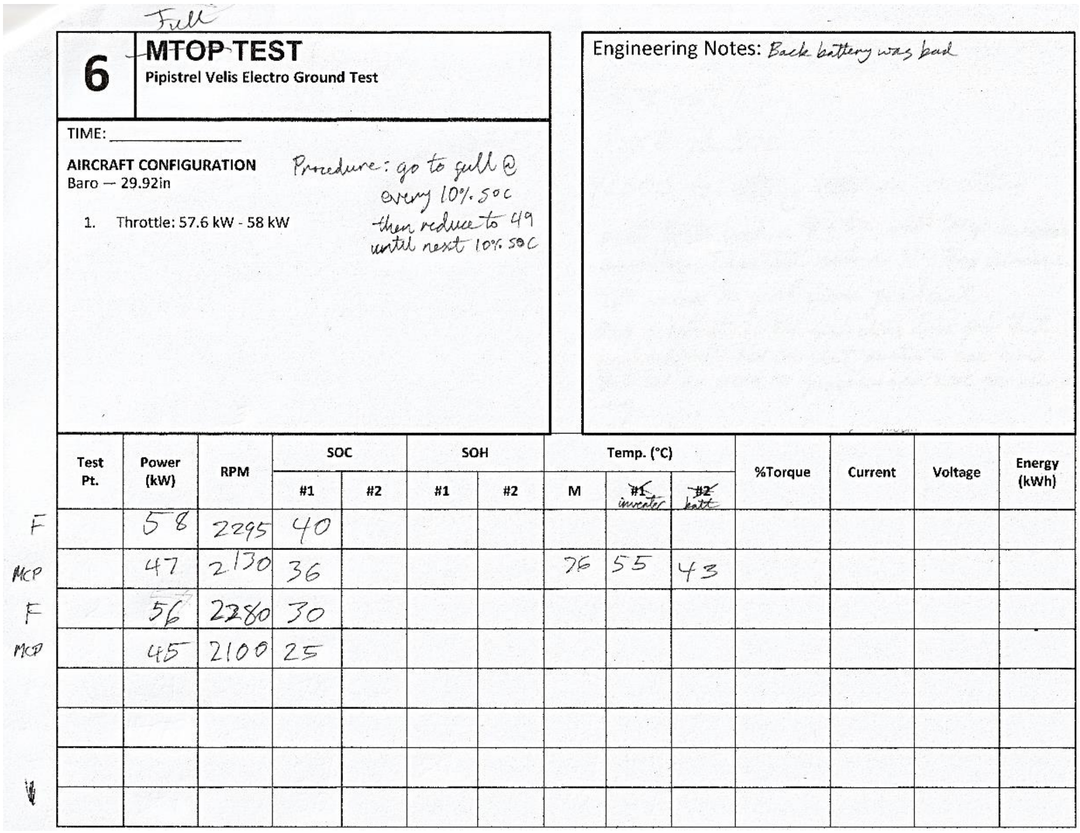
AIRCRAFT CONFIGURATION
Baro — 29.92in

1. Throttle: Full, 65 kW - 69.5 kW

Engineering Notes:

	Test Pt.	Power (kW)	RPM	SOC #1	SOC #2	SOH #1	SOH #2	Temp. (°C) ~~M~~ M	Temp. (°C) ~~#1~~ inverter	Temp. (°C) ~~#2~~ batt	%Torque	Current	Voltage	Energy (kWh)
	St.			88		80								
F	1	62		85										
F	2	61		76										
MCP	3	45	2160	72										
F		61	2300	70										
MCP		47	2170	65				57	48	34				
F		60		59				64	49	37				
F		59		50				70	51	40				

Figure 29: First Used Test Card



Full

~~MTOP TEST~~

6

Pipistrel Velis Electro Ground Test

TIME: ______________

AIRCRAFT CONFIGURATION
Baro — 29.92in

1. Throttle: 57.6 kW - 58 kW

Procedure: go to full @ every 10% SOC then reduce to 49 until next 10% SOC

Engineering Notes: Back battery was bad

	Test Pt.	Power (kW)	RPM	SOC #1	SOC #2	SOH #1	SOH #2	Temp. (°C) M	Temp. (°C) ~~#1~~ inverter	Temp. (°C) ~~#2~~ batt	%Torque	Current	Voltage	Energy (kWh)
F		58	2295	40										
MCP		47	2130	36				76	55	43				
F		56	2280	30										
MCP		45	2100	25										

Figure 30: Second Used Test Card