2019-12

COMBINING A PROTON EXCHANGE MEMBRANE FUEL CELL AND ULTRACAPACITORS TO REPLACE BATTERIES AND EXTEND FLIGHT TIME FOR A VERTICAL TAKE-OFF UNMANNED AERIAL SYSTEM (UAS)

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http://hdl.handle.net/10945/64000

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

COMBINING A PROTON EXCHANGE MEMBRANE FUEL CELL AND ULTRACAPACITORS TO REPLACE BATTERIES AND EXTEND FLIGHT TIME FOR A VERTICAL TAKE-OFF UNMANNED AERIAL SYSTEM (UAS)

by

Justin A. Laddusaw

December 2019

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** December 2019	**3. REPORT TYPE AND DATES COVERED** Master's thesis

4. TITLE AND SUBTITLE
COMBINING A PROTON EXCHANGE MEMBRANE FUEL CELL AND ULTRACAPACITORS TO REPLACE BATTERIES AND EXTEND FLIGHT TIME FOR A VERTICAL TAKE-OFF UNMANNED AERIAL SYSTEM (UAS)

5. FUNDING NUMBERS

6. AUTHOR(S) Justin A. Laddusaw

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
N/A

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.	**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

This research investigated the combination of a fuel cell and ultracapacitors to create a hybrid powertrain for a vertical take-off unmanned aerial system (UAS). This replaced the more common battery-only powertrain or the hybrid fuel cell-battery powertrain. A secondary power source, such as a battery or ultracapacitors, is required to assist a fuel cell with immediate load requests because a fuel cell was unable to supply instantaneous power. The fuel cell-ultracapacitor was tested using a power profile that was experimentally determined using a battery-powered vertical take-off UAS during take-off, hover, and landing. This tabletop experiment is meant to lead to a more refined solution that can be easily scaled to fit into a smaller future vertical take-off UAS. The fuel cell-ultracapacitor powertrain was able to meet the power requirements while also supplying power to the fuel cell itself, without an external power supply. Future work opportunities include scaling for implementation into a UAS platform and coding the power management software to optimally manage the proposed hybrid powertrain.

14. SUBJECT TERMS
fuel cell, ultracapacitor, unmanned aerial system, hybrid powertrain

15. NUMBER OF PAGES 85

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UU

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
December 2019

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LIST OF ACRONYMS AND ABBREVIATIONS

DOD	Department of Defense
DOE	Department of Energy
DC	direct current
FAA	Federal Aviation Administration
ISR	intelligence, surveillance, and reconnaissance
Li-ion	lithium-ion
LiPo	lithium polymer
NPS	Naval Postgraduate School
PEM	proton exchange membrane
UAS	unmanned aerial system

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ACKNOWLEDGMENTS

I would first like to thank my wife, Caitlin, for her patience and love. She has been an inspiration and motivation to always strive harder. She is truly the best.

I would like to specifically thank Professor Anthony Pollman for his guidance and wisdom. I would also like to thank Professor Oleg Yakimenko along with Sondre Engebraten for their direct support. I am also grateful to everyone at the Turbopropulsion Laboratory, to include Professor Anthony Gannon, Andrea Holmes, and John Gibson. Assistance from James Calusdian and Warren Rogers from the Electrical Engineering Department was also very much appreciated; they are experts. I would also like to thank the Navy and the Naval Postgraduate School for this opportunity. Thank you all.

Also, a shout out to my parents. Thank you!

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I. INTRODUCTION

Fuel cells are a growing alternative to conventional combustion engines and solely battery powered units. Fuel cells have the potential to reduce energy costs and the amount of greenhouse gases from current energy sources. Currently, there are significant barriers to the large-scale commercialization and implementation of fuel cells. Among those barriers are cost, durability, fuel infrastructure, and fuel storage. However, on a smaller scale for specific applications such as unmanned vehicles, the current technology of fuel cells is applicable.

Fuel cells produce electrical energy electrochemically and do not require a recharge. They supply power as long as fuel is available. There are many kinds of fuel cells, but this thesis will focus on Polymer Electrolyte Membrane (PEM) fuel cells, also called Proton Exchange Membrane fuel cells (a Horizon 300 watt PEM fuel cell will be used). PEM fuel cells currently show the most promise in smaller scale operations.

A. BACKGROUND

Small UAS, those weighing less than 25 kilograms (55 pounds), are becoming more commonly used for recreation, commercial activities, and military applications as shown in Figure 1. As of September 2018 there were more than 900,000 owners who had registered their UAS with the Federal Aviation Administration (FAA) in the United States. The FAA saw an average of 8,000-9,000 new registrants during 2018 [1]. While most of these UAS are for recreation purposes, a growing number are being used to complete commercial tasks such as inspecting crops, infrastructure, and taking aerial photos. Future applications include package delivery which could include regular mail or even medical supplies [2]. Recreational UAS that are powered by batteries alone typically have an average flight time of 15–25 minutes. While this may be sufficient for the average user, commercial and military applications will require much longer flight times in order to be efficiently utilized.

Military use of UAS is also on the rise for intelligence, surveillance, and reconnaissance (ISR) gathering. In [3], the author states that, according to the Bard College

Center for the Study of the Drone, the Department of Defense (DOD) requested approximately $9.39 billion for UAS and associated technologies in the 2019 fiscal year budget. This article also stated that the Stinson Center assessed that the administration requested $3.4 billion for UAS procurement, research, development, testing and evaluation. The author concludes that these UAS are used by both the DOD and the Central Intelligence Agency. Most of the government's UAS are fixed wing that are used for ISR and are also often used to carry out strikes. The implementation of fuel cells in these drones could greatly reduce operating costs and improve efficiency.

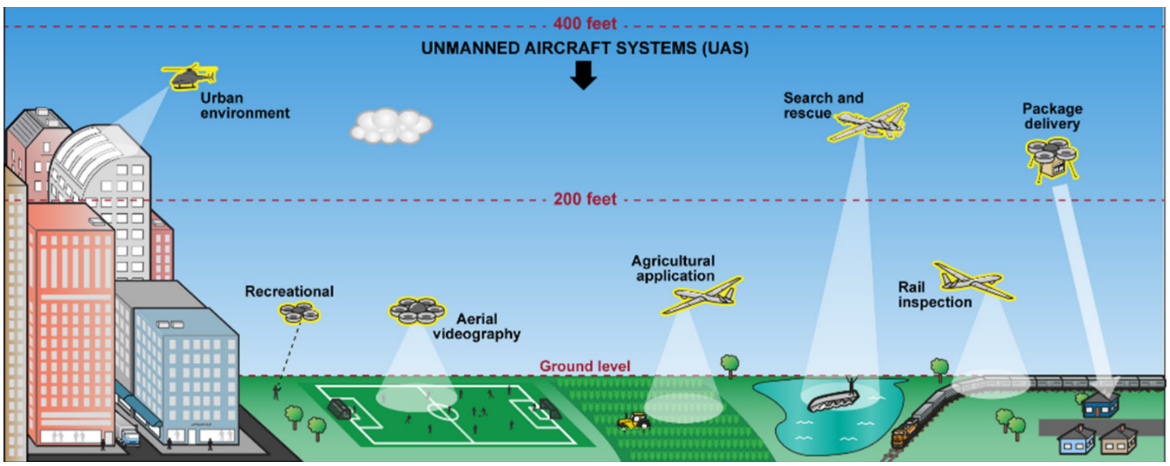

Figure 1. Applications of UAS. Source: [2].

Fuel cells, batteries, and ultracapacitors are an ever increasing alternative to normal power sources that use fossil fuels, such as combustion engines. Specifically, the use of batteries on their own, a combination powertrain of fuel cells and batteries, fuel cells and ultracapacitors, or a combination of the three are on the rise. Currently, the most commonly used powertrain, whether in automobiles or UAS, is the use of batteries and an internal combustion engine, batteries alone, or fuel cells and batteries. Batteries are limited on energy production from their available charge and can only be reused after a recharge, which can take a relatively long amount of time when compared to the capabilities of ultracapacitors. This is where the introduction of the fuel cell-ultracapacitor powertrain will be useful. A description of fuel cells, ultracapacitors, and batteries is further described in this introduction.

1. Ragone Chart Comparison

Fuel cells, batteries, and ultracapacitors all have different performance characteristics and capabilities. As shown in Figure 2, fuel cells have more specific energy than batteries and batteries have more specific energy than ultracapacitors [4]. The figure also shows that ultracapacitors have higher specific power than batteries and batteries have higher specific power than fuel cells. From the Ragone plot, it can be seen that, by combining fuel cells with ultracapacitors to create a hybrid powertrain, then specific energy and specific power levels equivalent to that of an internal combustion engine can be obtained.

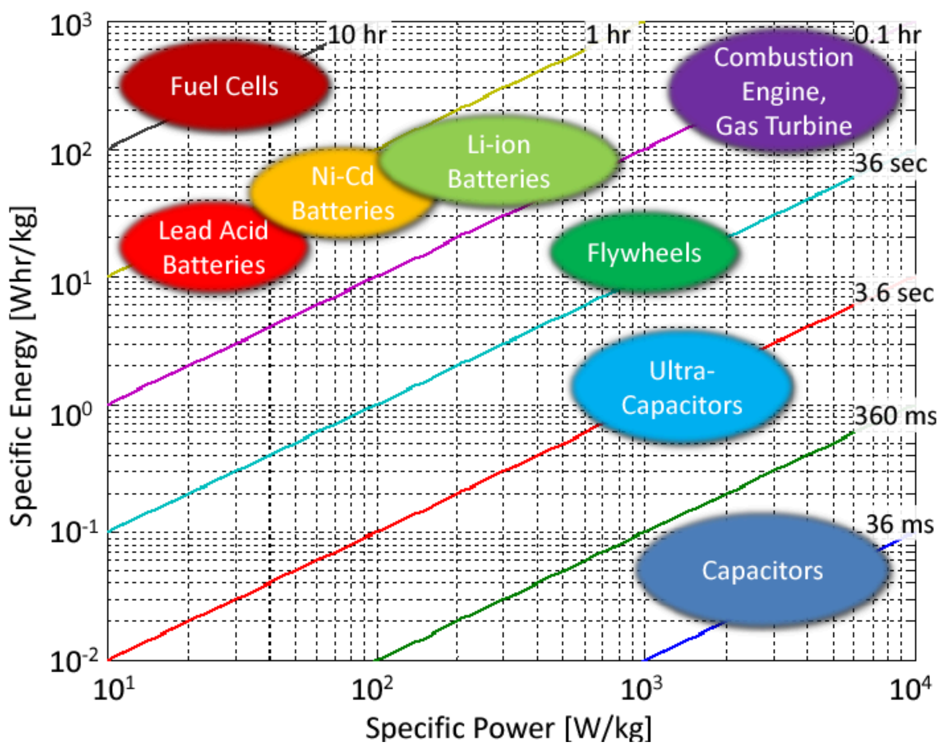

Figure 2. Ragone plot and charge/discharge times of energy devices. Source: [4].

2. Fuel Cells

Fuel cells are becoming more widely used and commercially available as automakers and other industries, such as UAS, continue to invest and develop them. Fuel cell technology has the potential to have a huge impact on the economy. They could replace many conventional power generation technologies in applications as small as automobiles and as large as power plants. According to the Department of Energy (DOE), fuel cells offer the following characteristics that would have the largest impacts: "efficiency improvements that could lead to considerable energy savings and reductions in greenhouse gas emissions, increased energy security and electric grid reliability, a significant improvement in air quality, and the potential for fuel cells to be used in a wide range of applications due to their modular capabilities" [5].

The type of fuel cell that generally gets the most attention is the proton exchange membrane fuel cell. PEM fuel cells use hydrogen as a fuel to generate electricity. Like a battery, they produce it electrochemically. Unlike a battery, they do not require a recharge and are only limited by the amount of hydrogen fuel available [5]. One of the first PEM fuel cells was built in the 1960s by General Electric for the Gemini spacecraft. This fuel cell was rated at 1 kilo-watt [6].

A single PEM fuel cell, shown in Figure 3, consists of an anode and a cathode with an electrolyte in between and bipolar plates on either side of the cell [7]. The DOE defines the process as the following: "Hydrogen is fed to the anode and air is fed to the cathode. A catalyst at the anode separates hydrogen molecules into protons and electrons. The electrons go through an external circuit, creating a flow of electricity. The protons migrate through the electrolyte to the cathode, where they unite with oxygen and the electrons to produce water and heat" [8].

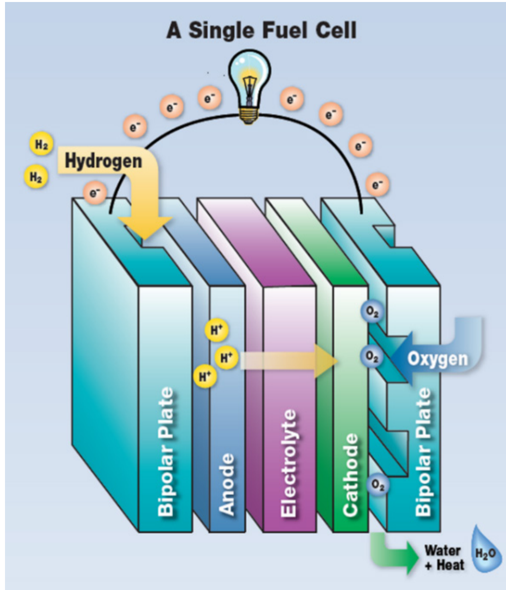

Figure 3. Basic framework of a PEM fuel cell. Source: [7].

Fuel cells have many unique characteristics which include the ability to be stacked into different configurations making them desirable for manufacturing, fairly high efficiencies, especially when compared to internal combustion engine, high reliability, and the ability to control them remotely with no supervision [9]. A fuel cell's only byproducts are heat and water. They do not have the same harmful emissions as combustion engines. PEM fuel cells are much more energy efficient than internal combustion engines. Hydrogen fuel cell systems use 40–60 percent of the fuel's energy while an internal combustion engine is less than 20 percent efficient in converting the chemical energy in gasoline to power [7].

Fuel cells will continue to be an emerging technology. They are currently being developed by companies in the automobile industry to include Toyota, Honda, Hyundai, and Mercedes [10], but the bulk of the technology maturation and development will occur in smaller scale markets, such as the UAS market.

3. Ultracapacitors

Ultracapacitors, also known as electronic double layer capacitors, were created to deliver quick bursts of energy during peak power demands in a complement to conventional primary power sources such as internal combustion engines, batteries, and fuel cells. Ultracapacitors store energy by physically separating opposite charges. They store positive and negative charges on two parallel plates that are separated by an insulator as shown in Figure 4. The small separation between these electrodes give the ultracapacitor its high energy density characteristics.

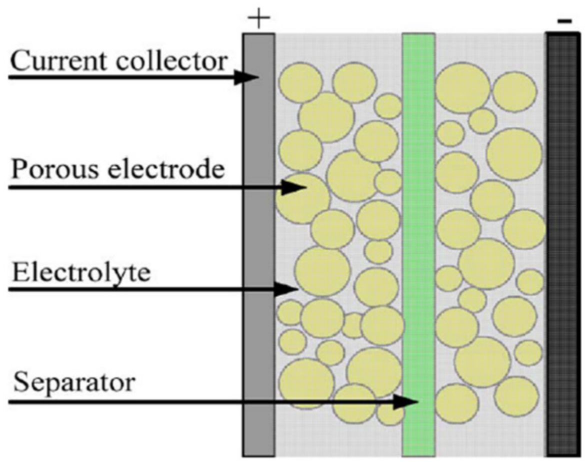

Figure 4. Individual ultracapacitor cell. Source: [11].

While batteries have a significantly higher energy density than ultracapacitors, ultracapacitors are superior in many applications. Ultracapacitors have better power densities than batteries and can be easily placed in series or parallel to increase voltage capability or capacitance respectively. Ultracapacitors can be designed for capacitance from a few Farads to many thousand Farads in each cell [12]. However, ultracapacitors are generally low in voltage, typically 2.7 volts, and must be placed in series in order to increase the voltage to a level desired, depending on the application. When placing ultracapacitors in series, the voltage is increased but the capacitance is decreased. This relationship is shown in equations 1 and 2. When placing ultracapacitors in parallel, their capacitance is increased but the maximum applied voltage can only be as high as the lowest individual cell's voltage. This relationship is shown in equations 3 and 4.

$$C_{total} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \ldots + \frac{1}{C_n}} \quad (1)$$

$$V_{maximim} = V_1 + V_2 + \ldots + V_n \quad (2)$$

$$C_{total} = C_1 + C_2 + \ldots + C_n \quad (3)$$

$$V_{maximim} \leq V_{lowest\ cell} \quad (4)$$

Because of these relationships, ultracapacitors are often placed in series until the required voltage is obtained and then multiple strings of ultracapacitors are then placed in parallel to achieve the desired capacitance.

According to Maxwell Technologies, the top 10 advantages for using ultracapacitors are: “very high efficiency, high current capability, wide voltage range, wide temperature range, condition monitoring [state of charge and state of health], long cycle life, long operation life, life extension for other energy sources, ease of maintenance, and straightforward integration” [13].

The largest economic advantages of ultracapacitors are that they have a long shelf life and cycle life. Over time, batteries will degrade severely due to self-discharge and corrosion. While on a shelf, ultracapacitors will also self-discharge over time. However, their characteristics, such as capacitance, will not degrade and they can be recharged as before [14]. An ultracapacitor will not experience an end of life. Over time, there will be an increase in resistance and a decrease in capacitance, but this is slight in comparison to the degradation batteries experience [15]. Ultracapacitors can be cycled at high rates, up to 1,000,000 cycles, and only degrade approximately 20%, which is not true of batteries [14], [15].

Unlike batteries, an ultracapacitor does not use a chemical reaction so their charge and discharge rates can take place at the same rate as shown in Figure 5 [15]. This allows ultracapacitors to be a good supplement in systems that require quick pulse responses for peak power and transient power scenarios where the primary energy source is unable to meet those needs.

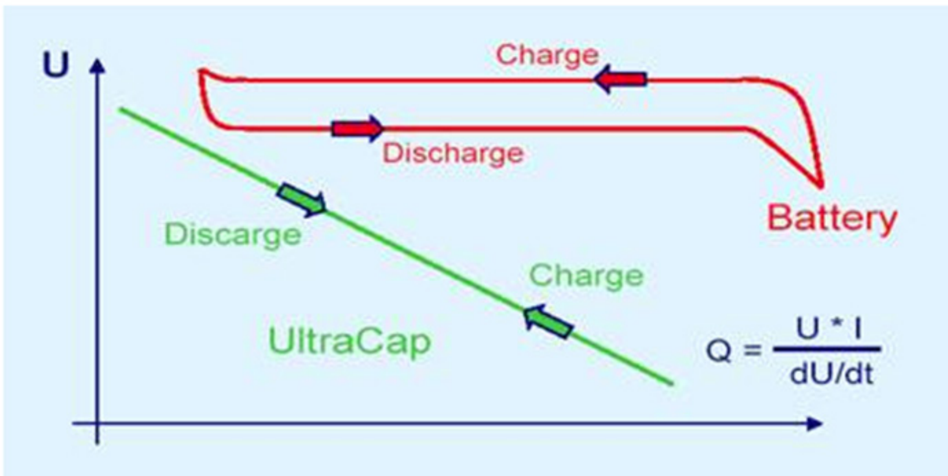

Figure 5. Discharge/charge rates of batteries and ultracapacitors.
Source: [16].

4. Batteries

Batteries convert chemical energy into electricity. A simple battery consists of three parts; the cathode, anode, and electrolyte. The chemical reactions in a battery cause electrons to accumulate on the anode which creates an energy potential, or voltage, between the anode and cathode. There are generally two types of batteries, primary and secondary. Secondary batteries are rechargeable while primary batteries are not rechargeable. For hybrid powertrains, secondary batteries are needed.

Secondary batteries are rechargeable because the electrochemical reaction can be reversed. During discharge, the chemical energy is converted to electricity and during charging, electrical energy from an external power source is converted into chemical energy. This process can be repeated over and over again and represents the cycle life. The discharge process of a battery is not completely reversible and thus the battery will degrade in capacity over time [17].

Currently, lithium-ion (Li-ion) and lithium-polymer (LiPo) are the most commonly used batteries in portable devices. In lithium batteries, the anode is typically made from carbon, the cathode is made from a metallic oxide, and the electrolyte is made from a lithium salt in an organic solvent. Their advantages over other rechargeable batteries include higher energy densities, higher power output, lower self-discharge rates, faster charging and discharging, wider operating temperature ranges, longer cycle life, and more environmentally friendly. LiPo batteries have a few advantages over Li-ion batteries which include; more flexible casings, better safety and reliability, and longer cycle life [17].

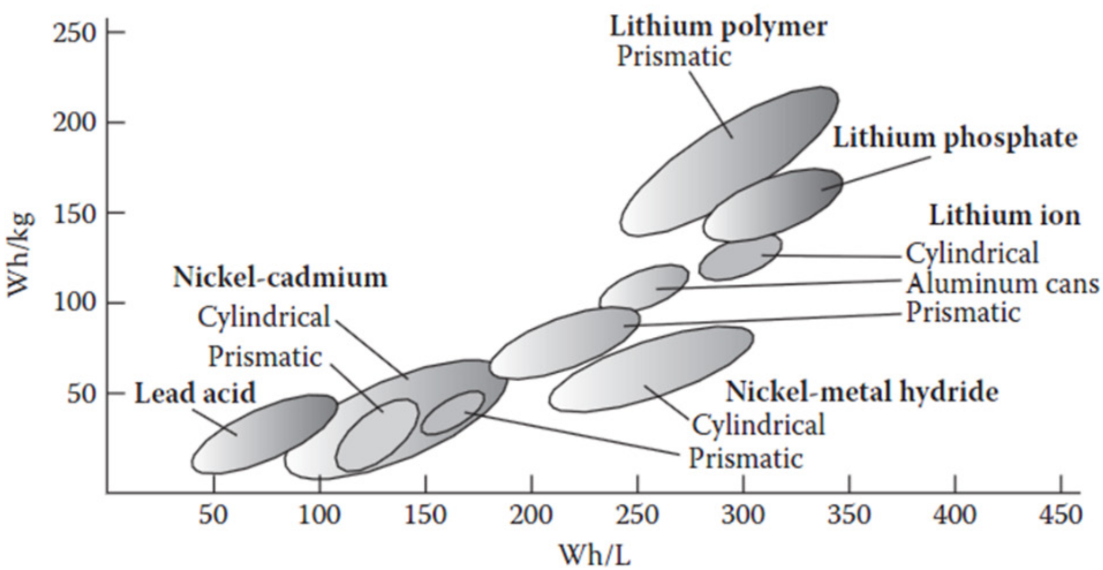

Figure 6. Ragone plot of commonly used batteries. Source: [9].

Batteries come with numerous disadvantages that have been accepted due to their ease of use and lack of other technologies. These disadvantages include toxic and hazardous materials used are detrimental to the environment if not recycled properly, limited cycle life when compared to ultracapacitors, and smaller energy densities and power densities when compared to fuel cells and ultracapacitors, respectively. Lithium batteries are also fragile and must be handled with extreme care.

B. FUEL CELL USE IN MODELS AND SIMILAR APPLICATIONS

Fuel cell applications are becoming an increasingly attractive alternative to both internal combustion engines and battery operated vehicles. They have been modeled in numerous studies and physically used in many applications.

The key concept behind the hybrid powertrain is that during high power demands, power is supplied both by the fuel cell and the battery or ultracapacitor. In periods of low demand, the fuel cell will supply all of the power and whatever power remains will be utilized to recharge the battery or ultracapacitor. Once the battery or ultracapacitor is fully charged, the fuel cell system will directly carry the load until the cycle is repeated. When customizing a powertrain for vertical take-off UAS, the power required for hover should be taken into account and a fuel cell that will meet this power requirement should be selected. In [18], the authors recommend that there should be some additional power overhead considered as well in order to recharge the battery or ultracapacitor at a sufficient rate. With this consideration in mind, and to be discussed in the equipment section, batteries or ultracapacitors should be selected based on the performance of the fuel cell and the power requirements of the system. The selection should equal or exceed the voltage output of the fuel cell at peak power in order to not degrade any of the fuel cells' output performance and in order to not risk overcharging of the batteries or ultracapacitors.

1. Modeled Powertrains

There have been a numerous amount of models and studies of both fuel cell-battery powertrains and fuel cell-ultracapacitor powertrains completed over recent years. These models have involved various sizes and types of fuel cells, batteries, and ultracapacitors depending on the model's intended application.

Key takeaways from these models include ensuring the fuel cell power output is rated over the constant power requirement, the use of DC/DC converters to manage the voltage of the powertrain, utilizing a programmable load to simulate different power requirements, and utilizing a diode to protect reverse flow from the battery or ultracapacitor to the fuel cell if such protections are not already built into the fuel cell [11], [12], [19], [20].

An additional benefit to batteries and ultracapacitors in other vehicle applications but not yet applicable to UAS is the ability to utilize regenerative braking. Regenerative braking converts the vehicles kinetic energy back into energy that can recharge the battery or ultracapacitor. This recharging is recovered energy that does not have to be supplied by the fuel cell and creates better efficiencies [12].

2. Existing Powertrains

Both fuel cell-battery and fuel cell-ultracapacitor hybrid powertrains have been investigated. While fuel cell-battery powertrains are more common, there are instances where fuel cell-ultracapacitor powertrains have been tested. Ultracapacitors have an advantage over batteries because they are able to quickly charge and discharge at large currents [21].

a. Fuel Cell-Battery Powertrain

HES Energy Systems currently has its HYCOPTER for sale commercially, shown in Figure 7. This UAS has six-rotors and uses a fuel cell-battery powertrain. The fuel cell used is the AEROSTAK 1500, which is a PEM fuel cell that outputs 1500 watts and weighs 3000 grams. The batteries used are two 4S LiPo batteries connected in series, each rated at 14.8 volts. The "4S" means that there are four LiPo cells in series in each battery. The batteries weigh 776 grams total. This UAS has an estimated flight time of 3.5 hours, which is dependent on the size of the hydrogen tank attached [22].

Figure 7. HES Energy Systems' HYCOPTER 2.0. Source: [22].

Intelligent Energy sells fuel cell power modules that can be integrated onto existing UAS platforms, shown in Figure 8. It offers a range of modules rated from 650 watts to 2400 watts that integrate a lithium battery. Intelligent Energy also offers fuel cell power modules that can be integrated into vehicles and fuel cells that can be integrated into other stationary applications [23].

Figure 8. Intelligent Energy's fuel cell power module mounted on a UAS. Source: [23].

Ballard Power Systems is a leading developer in the fuel cell technology effort. It is involved in the development of fuel cells for many different markets which include: transit bus, automotive, rail, truck, material handling, UAS, infrastructure, and marine applications. Ballard created a prototype UAS, shown in Figure 9, which incorporates its liquid-cooled 1200 watt PEM fuel cell in parallel with an 8S LiPo battery. Ballard also offer a 600 watt PEM fuel cell [24].

Figure 9. Ballard H2-6 hex-rotor VTOL platform. Source: [24].

b. Fuel Cell-Ultracapacitor Powertrain

Fuel cells are superior to batteries in specific energy and ultracapacitors are superior to batteries in specific power. Combining both of these superior power sources to create a hybrid powertrain will create increased performance over other hybrid powertrains. Ultracapacitors have a lower cost per Farad and require less maintenance [12].

In [25], the author compared a fuel cell-battery powertrain to a fuel cell-ultracapacitor powertrain to operate an electric scooter. The experiment concluded that both powertrains were superior to that of an internal combustion engine, approximately three times the energy efficiency. The results also concluded that the powertrains were nearly identical in fuel consumption by the fuel cell; however, the fuel cell-ultracapacitor powertrain yielded a more stable bus voltage to the motor and power electronics when operating at a lower average power but a greater voltage variation when operating at a higher average power. Overall. the ultracapacitors were advantageous to the batteries due to lower maintenance costs and significant weight savings, especially in a compact design such as a scooter or UAS where weight is a large factor in design [25].

C. PROBLEM FORMULATION

The purpose of this thesis is to create a hybrid powertrain utilizing a fuel cell and ultracapacitors. Specifically, this powertrain will be applied to match the flight profile of a battery powered small vertical take-off unmanned aerial system (UAS). The fuel cell requires an alternate energy source to handle the transition required during peak power and pulsed power intervals, and in this study that alternate energy source will be ultracapacitors.

II. PROFILE AND EQUIPMENT

This chapter identifies a model for the fuel cell-ultracapacitor powertrain to attempt to fit to. The equipment that was utilized is also identified along with the relevant characteristics, applications, and how it is all integrated into a working system.

A. UAS FLIGHT PROFILE

In order to realistically model what power profile the fuel cell-ultracapacitor powertrain would have to follow, a UAS was used in real time conditions and was not simulated. To get a reasonable flight profile across the multiple aspects of flight, the UAS was taken from the landed position to a hover position approximately five feet off the ground and held in the hover position for approximately 20 seconds prior to returning to the landed position. This was repeated a total of five times.

1. UAS

The UAS utilized for this experiment was the Solo quadcopter manufactured by 3DR, shown in Figure 10. It utilizes a 5200 mAh, 14.8 volt LiPo battery with an estimated flight time of 25 minutes [26]. The Bluetooth payload consumed approximately 14 watts of power while the UAS was on the ground.

Figure 10. 3DR Solo quadcopter used to acquire flight profile

2. Data Acquisition

The payload on the UAS used a Bluetooth connection with the operator's laptop that recorded the time, voltage, current, and battery percentage in ROS. The data was then exported into an Excel spreadsheet for additional processing in MATLAB for analysis and presentation.

3. Results

The data acquired from this testing is displayed in Figures 11–13. These figures show the voltage, current, and power for the duration of the test which lasted approximately five minutes. The power was calculated by multiplying the voltage times the current at a given time. Figure 14 shows the five flight profiles overlapped. This figure shows that the flight profiles were generally the same.

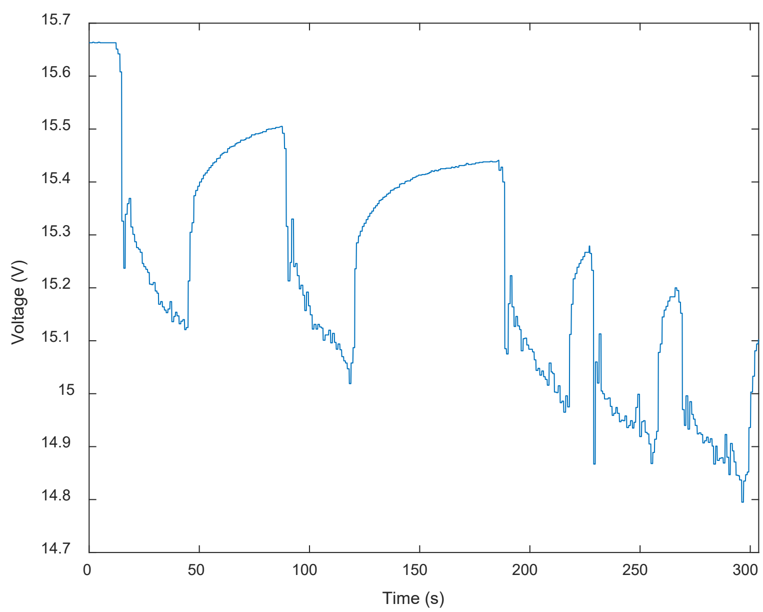

Figure 11. Voltage versus time plot from profile test flight data

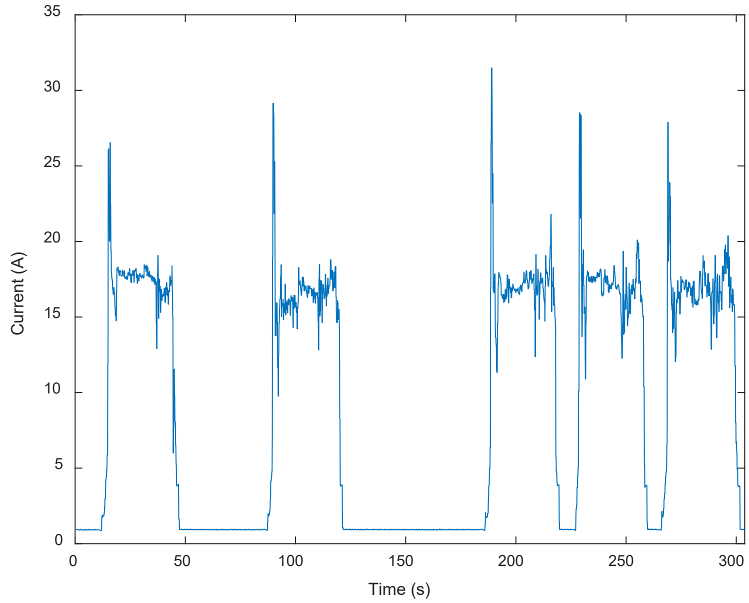

Figure 12. Current versus time plot from profile test flight data

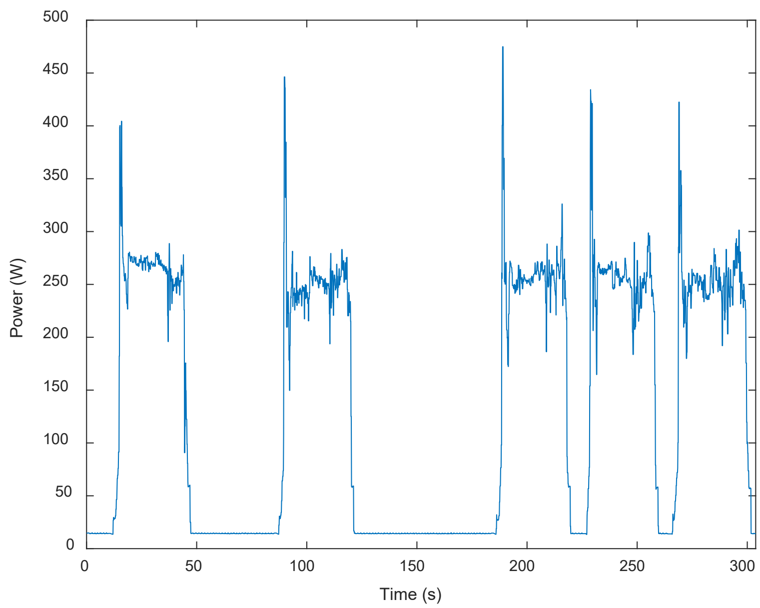

Figure 13. Power versus time plot from profile test flight data

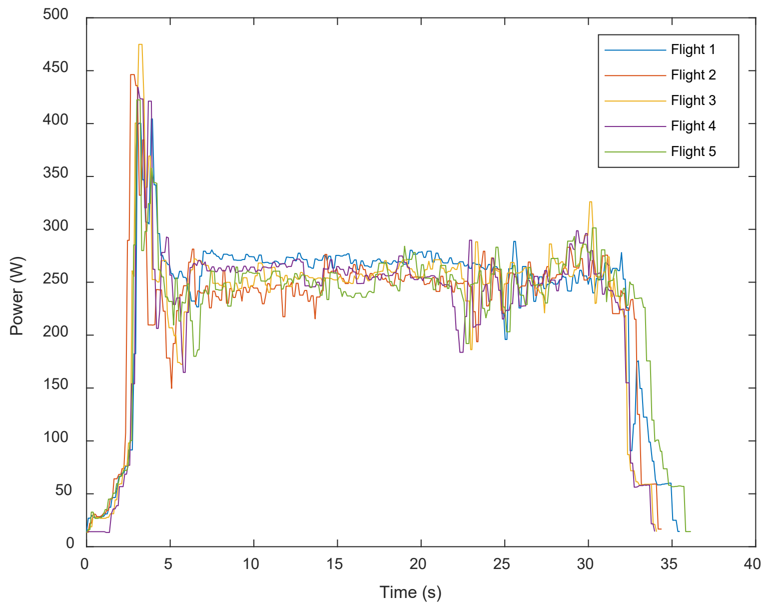

Figure 14. Overlapped power versus time plot from profile test flight data

Peak power consumption occurred during take-off. The peak power in watts for each iteration is shown in Table 1 along with the average peak power.

Table 1. Peak power for each flight

	Voltage (volts)	Current (amps)	Power (watts)
Flight 1	15.237	26.54	404.39
Flight 2	15.316	29.14	446.3082
Flight 3	15.085	31.48	474.8758
Flight 4	14.867	28.33	421.1821
Flight 5	15.152	27.88	422.4378
Average Power			433.8388

During hover, the UAS uses less power than the maximum power of the fuel cell being utilized, approximately 250 watts. During this period, the fuel cell will have extra power available to recharge the ultracapacitor bank for the next pulse of power.

B. EQUIPMENT

The powertrain was built to be able to swap different hardware in and out to produce a quality first iteration. The intention was not to use expensive aeronautic equipment, but rather equipment available in order to keep costs down. Once the powertrain is optimized, it can be configured so that commercial off-the-shelf aeronautic equipment can replace the heavier items used in order to create a system that is light enough for flight.

1. Hydrogen

The Horizon fuel cell requires hydrogen input between 0.45 and 0.55 bar (6.5 and 8 PSIG). Tank pressure can be anywhere from 0 to 137.9 bar (0 to 2000 PSIG). The tanks utilized for this experiment are from the NPS Rocket Laboratory and are often given to the Turbopropulsion Laboratory after they have been depleted to approximately 1000 PSIG. Because of the pressure differential between the hydrogen tank and the inlet pressure required, a regulator is needed as shown in Figure 15.

Hydrogen use requires preventative safety measures to be taken. Hydrogen is a colorless, odorless gas. It is non-toxic and lighter than air, so when using in a well ventilated space it will dissipate rapidly. However, hydrogen has a wide range of flammable conditions and a lower ignition energy than gasoline, meaning it may ignite more easily than other fuel sources. Material selection is important when dealing with hydrogen in order to avoid any effects of hydrogen embrittlement [27].

Because of these safety considerations, the fuel cell is operated in a well ventilated space with a hydrogen detector available to detect any potentially dangerous levels. Furthermore, all wiring and connections are encased to prevent any sparking. Stainless steel lines and connections from Swagelok were also used to avoid any effects of embrittlement.

Figure 15. Regulator used to bring tank pressure to 0.5 bar for fuel cell use

2. Fuel Cell

As discussed, because of their advantages over other power sources and other fuel cells, the PEM fuel cell was utilized for this experiment; specifically, the Horizon 300 watt PEM fuel cell. It has 60 cells and is rated at 300 watts with its peak power output at 36 volts and 8.3 amps. It also comes with a controller. The remaining technical specifications are shown in Table 2.

Table 2. Horizon 300 watt PEM fuel cell technical specifications. Adapted from [28].

External temperature	5–30ºC
Max stack temperature	65ºC
H2 inlet pressure	0.45–0.55 bar
Hydrogen purity required	≥99.995% dry H2
Humidification	Self-humidified
Cooling	Air (integrated fan)
Stack weight	2790 grams (±50 grams)
Controller weight	400 grams (±30 grams)
Dimensions	11.8cm x 26.2cm x 9.4cm
Flow rate at max output	3.9L/min
Efficiency of stack	40% at 36V
External power supply	13V (±1V), 5A

The Horizon fuel cell, Figure 16, comes with everything needed to operate with the exception of an external power supply, a source of hydrogen, and a hydrogen regulator. This includes a controller, hydrogen supply valve, purge valve, short circuit unit, on/off switch, blower, tubing for hydrogen input and output, controller connectors and connectors for power in and out.

Figure 16. Horizon 300 watt PEM fuel cell and fuel cell controller

3. Ultracapacitors

Determining the correct ultracapacitor for this application needs to factor in sizing, maximum operating voltage, average current or power, operating temperature, run time, and required life time. The greatest factors for this application are sizing and voltage. For this scenario the fuel cell's voltage at peak power is 36 volts, which means that the ultracapacitor bank will have to be at least 36 volts in order to allow that voltage to be passed on to the load. If the ultracapacitor bank was less than 36 volts, the fuel cell would need to be limited in order to not overcharge the ultracapacitors. Because the average ultracapacitor rated voltage is 2.7 volts and the voltage of the fuel cell is 36 volts at peak power, at least 14 ultracapacitors will be needed in series in order to achieve a voltage greater than or equal to this amount.

a. 56 Volt 130 Farad Maxwell Ultracapacitor Module

Due to availability, the ultracapacitor used was the Maxwell Technologies BOOSTCAP 56 volt energy storage module, shown in Figure 17. The module is rated at 56 volts and 130 Farads. It is made up of 23 individual cells in series with each cell rated at 2.7 volts and 3,000 Farads. However, the module weighs 18 kilograms, and for this reason is not a feasible candidate for a small UAS. This module is being used to prove the concept that a fuel cell requires the addition of ultracapacitors for transient and peak power. Additional technical specifications for this module are found in Table 3.

Figure 17. Maxwell Technologies 56 volt ultracapacitor module. Source: [29].

Table 3. Maxwell Technologies 56 volt ultracapacitor module technical specifications. Adapted from [29].

Rated Capacitance	130F
Rated Voltage	56V
Absolute Maximum Voltage	62V
Absolute Maximum Current	1,900A
Capacitance of Individual Cells	3,000F
Number of Cells	23
Operating Temperature	-40 to +30ºC
Mass	18kg
Usable Specific Power	2,600W/kg
Specific Energy	3.1Wh/kg
Dimensions	68.3cm x 17.7cm x 17.5cm

b. Tecate Group Type TPLH 2.7 Volt Threaded Model

A smaller ultracapacitor was also used to create a more realistic model. For the smaller model, the 2.7V TPLH threaded ultracapacitor was used, shown in Figure 18. In order to meet voltage requirements, 14 of these cells were placed in series for a total voltage of 37.8 volts, which reduced the capacitance from 650 Farads for a single cell to 46.43 Farads for the 14 cells in series. The ultracapacitors were put in series by connecting the negative terminal of the first to the positive terminal of the next using a brass connecter with holes punched in them for the terminals to fit through, shown in Figure 19. These ultracapacitors are significantly lighter than the Maxwell Technologies module that was utilized initially. Additional technical specifications for these ultracapacitors are found in Table 4.

Figure 18. Tecate Group 2.7 volt 650 Farad ultracapacitor

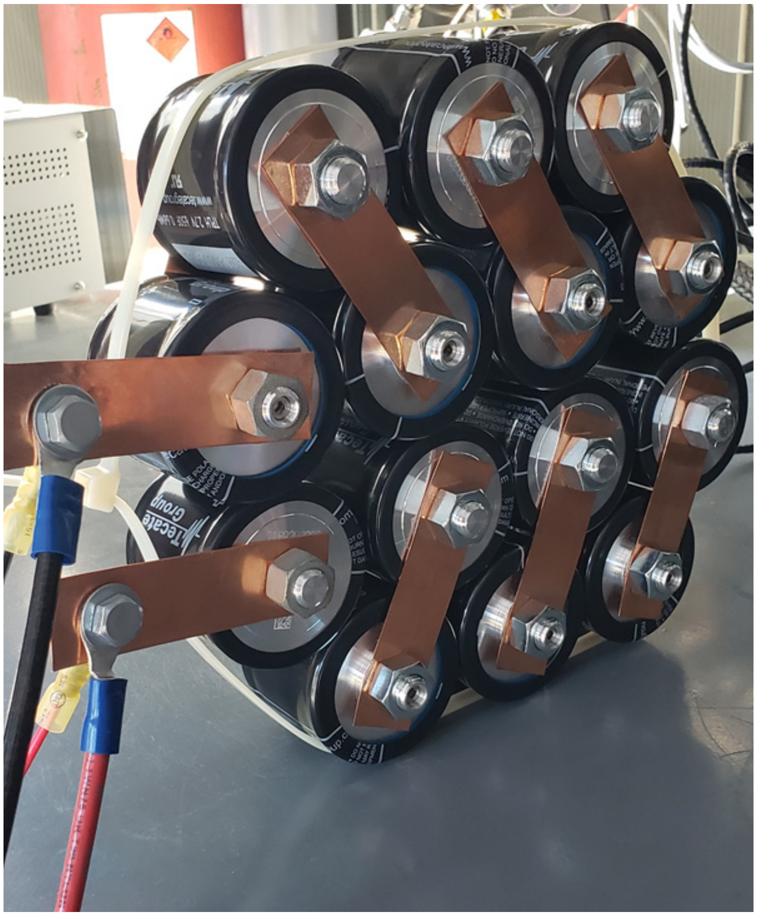

Figure 19. 14 Tecate Group ultracapacitors in series

Table 4. Tecate Group 2.7 volt TPLH threaded ultracapacitor technical specifications. Adapted from [30].

Capacitance of Individual Cells	650F
Voltage of Individual Cells	2.7V
Number of Cells	14
Rated Capacitance (Series)	46.43F
Rated Voltage (Series)	37.8V
Maximum Current	590A
Operating Temperature	-40 to +65ºC
Total Mass	2.94kg
Dimension of Individual Cell	51.5mm (L) x 60.7mm (D)

c. Maxwell Technologies 2.7 Volt 350 Farad D Cell Ultracapacitor

The Maxwell Technologies 2.7 volt 350 Farad ultracapacitor was utilized after the Tecate Group ultracapacitor, shown in Figure 20. This ultracapacitor is smaller in both size and capacitance than the Tecate Group ultracapacitor. Similar to the Tecate Group ultracapacitor, 14 of these cells were placed in series in order to reach a voltage of 37.8 volts. The ultracapacitors were connected in series by soldering wire from the negative terminal of the first to the positive terminal of the next and continuing this for all 14 cells, shown in Figure 21. This reduced the capacitance of the ultracapacitor bank to 25 Farads. Additional technical specifications for the Maxwell Technologies model can be found in Table 5.

Figure 20. Maxwell Technologies 2.7 volt 350 Farad D Cell ultracapacitor

Figure 21. 14 Maxwell Technologies ultracapacitors in series

Table 5. Maxwell Technologies 2.7 volt 350 Farad D Cell ultracapacitor technical specifications. Adapted from [31].

Capacitance of Individual Cells	350F
Voltage of Individual Cells	2.7V
Number of Cells	14
Rated Capacitance (Series)	25F
Rated Voltage (Series)	37.8V
Maximum Current	170A
Operating Temperature	-40 to +65ºC
Total Mass	0.84kg
Dimension of Individual Cell	61.5mm (L) x 33.3mm (D)

4. External Power Supply

Because the fuel cell needs 13 volts for start-up, an external power supply was utilized, shown in Figure 22. After start-up, the fuel cell in the setup is able to power itself and the external power supply is turned off.

Figure 22. External power supply used for fuel cell start-up

5. DC to DC Buck Converter

In order to regulate voltage and current from the fuel cell to the ultracapacitors and from the fuel cell back to itself, DC/DC buck converters were used. A buck converter allows voltage and current to be stepped down from the source. Bidirectional DC/DC buck converters are commonly used to manage power flow [11]. The downside to DC/DC converters are that they increase cost, mass, and size of the system [32]. Because this was experimental, it was necessary to use buck converters that were adjustable in order to swap different equipment in and out. The specific model used was made by Drok, shown in Figure 23.

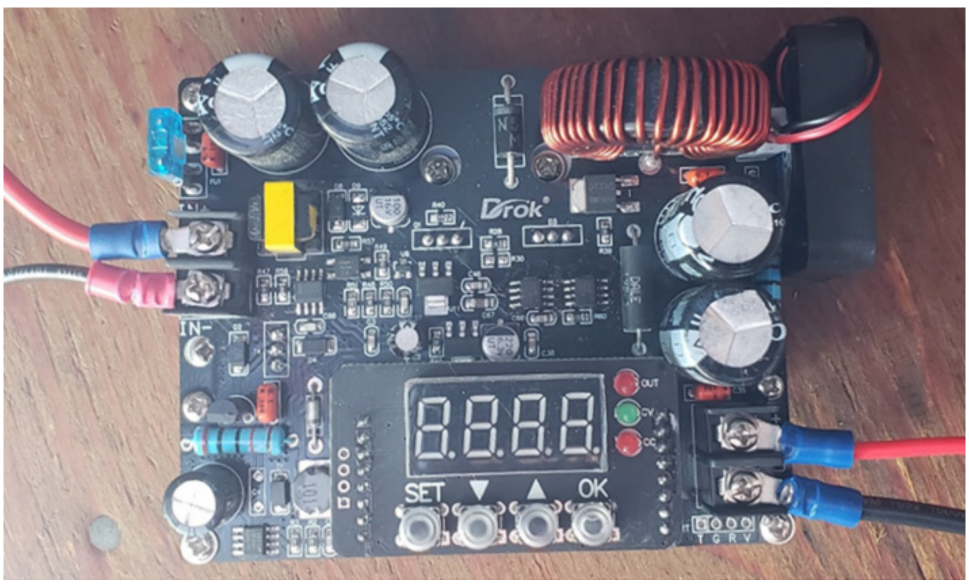

Figure 23. Drok DC/DC buck converter

The adjustable buck converter displays the real-time current and voltage as well as the set output current and voltage. The technical specifications for this model are displayed in Table 6. Operating instructions for this model are contained in [33].

Table 6. Drok DC/DC buck converter technical specifications. Adapted from [33].

Input voltage range	10–75V
Output adjustable voltage range	0–65V
Output adjustable current range	0–12A
Typical efficiency	94%
Response time	< 50ms
Operating temperature	0 – 40ºC
Dimensions	3.97in x 2.95in x 1.89in

This model is optimal because of the large variation of input and output capabilities for both voltage and current. The fuel cell voltage range is between the allowable input range and the output range so the buck converters do not limit the fuel cell at all. The current adjustable output range also does not limit the fuel cell, as the fuel cell maximum current is 8.3 amps.

6. Diode

Because ultracapacitors have low internal impedance, they are able to deliver a large amount of current at one time. At the time of the experiment, it was unknown as to whether or not the fuel cell and fuel cell controller had current protection already installed, so a diode was used to ensure current would not go from the ultracapacitor back into the fuel cell, shown in Figure 24.

However, after speaking with a Horizon employee, it was noted that the fuel cell controller already has reverse current protections installed and thus the diode was unnecessary. The use of a diode is always recommended when it is unknown if the system has its own protections, especially if the system is expensive.

Figure 24. Diode used to restrict current flow from ultracapacitors back into the fuel cell

7. Self-Power Loop

As described in the external power supply section, after start-up the external power supply was shut off and the fuel cell was able to power itself. This was done using a DC/DC buck converter, a switch, and wiring from the fuel cell to the converter back to the fuel cell, shown in Figure 25. The converter was set to 13 volts and 5 amps, and once the fuel cell was running, the switch was turned on and the external power supply was turned off. The wiring and switch are shown in Figures 26 and 27, respectively. Normally start-up power is supplied by a battery. While this experiment uses a bulky external power supply, a battery could also be utilized for start-up and then disconnected once the fuel cell is running. This will save valuable weight on the UAS and will allow start-up anywhere a small battery can be carried.

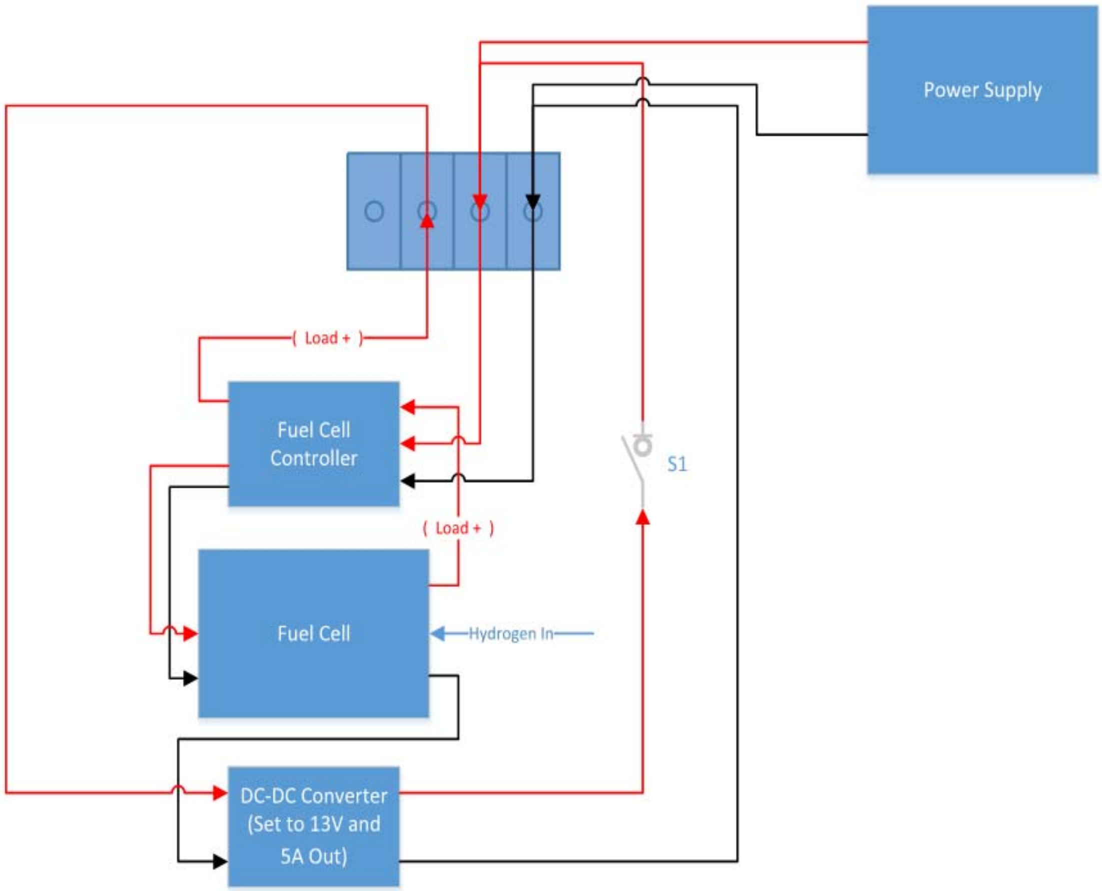

Figure 25. Self-power loop

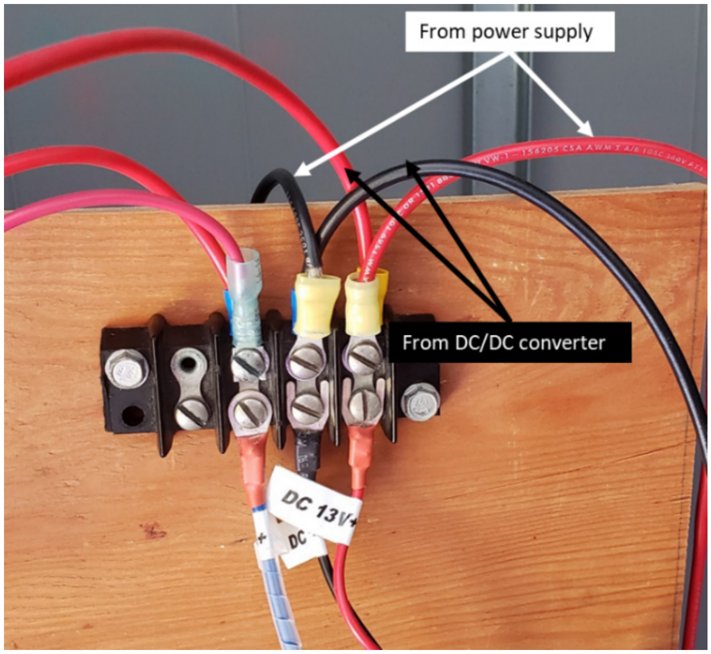

Figure 26. Wiring connections from power supply and DC/DC converter back to fuel cell

Figure 27. Switch to allow self-powering of the fuel cell

8. DC Programmable Electronic Load

In order to simulate the flight profile obtained from earlier in this chapter, a DC programmable electronic load was utilized; specifically, the Array 3751A 2.0kW, 0–240 volt, and 0–150 amp programmable DC electronic load, shown in Figure 28. The programmable load has many features, including constant current, voltage, and power. It also has modes where the current, voltage, or power can be set to change to different levels of output at user input times.

Figure 28. Array 2 kilo-watt DC programmable electronic load

The programmable load is able to connect to a computer in order to interface with the program through software, shown in Figure 29. This interface enables the user to see current and historical data of the current, voltage, and power demands. It also allows the user to more easily utilize the different modes and quickly adjust parameters. The data acquired from the programmable load is capable of being exported to an Excel spreadsheet, which can later be used in MATLAB or another program for further analysis and presentation.

Figure 29. Computer interface for DC programmable electronic load

C. VISUAL EXAMINATION

The equipment listed in this chapter was utilized to make the hybrid powertrain. A drawing of this is shown in Figure 30. The finished product is shown in Figure 31 and the fuel cell and DC/DC buck converters are expanded in Figure 32.

When handling electricity and hydrogen, extreme caution should be taken. For this experiment, the start-up and shutdown procedures listed in Appendix A were utilized. Essentially the external power supply needs to be at 13 volts ± 1 volt and the hydrogen input needs to be between 0.45 and 0.55 bar. Two buck converters were used, as described. The first allows the fuel cell to power itself and the second to properly charge the ultracapacitors without limiting the fuel cell's capabilities at peak power output.

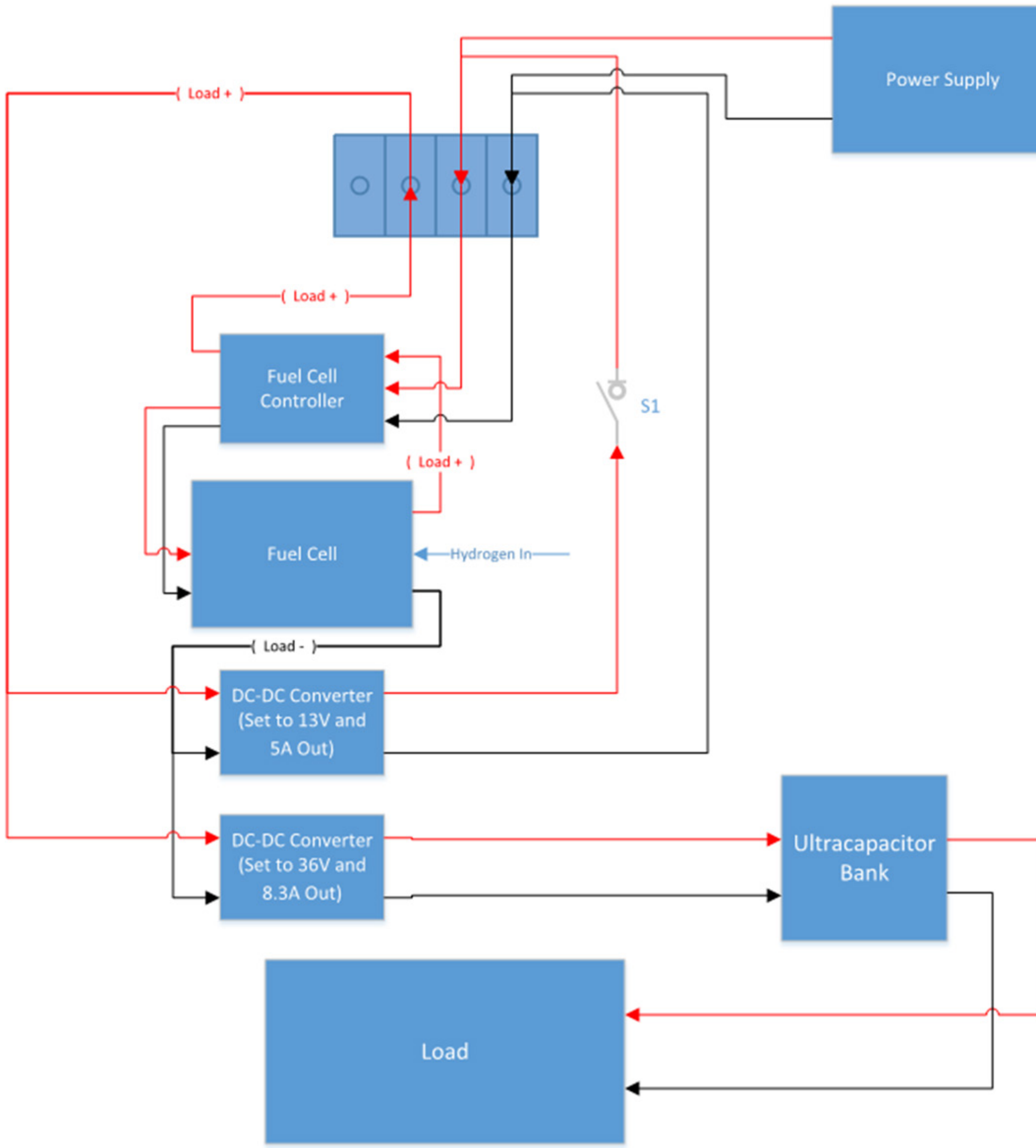

Figure 30. Drawing of fuel cell and ultracapacitor hybrid powertrain

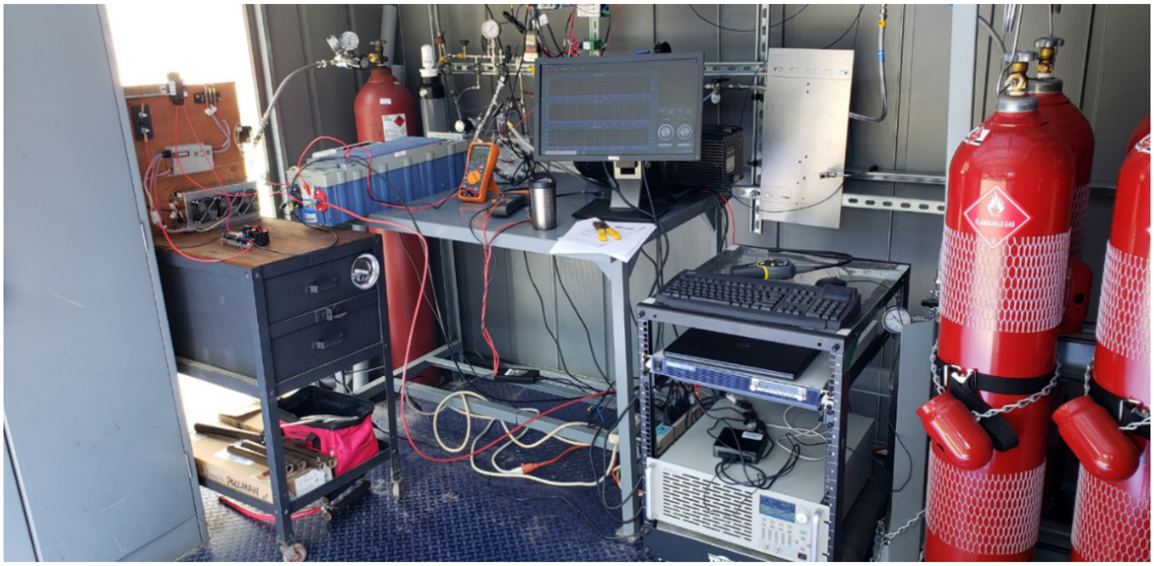

Figure 31. Complete experimental set-up

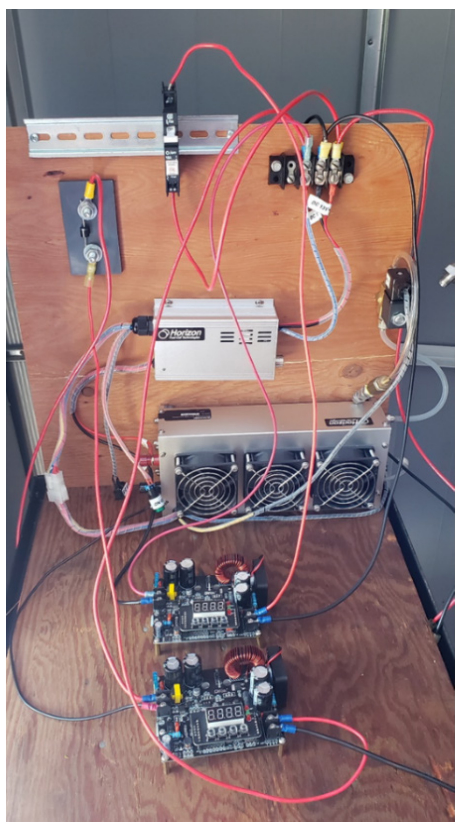

Figure 32. Fuel cell and DC/DC buck converters

III. RESULTS AND DISCUSSION

This chapter displays the results of the tests conducted on the systems outlined in the previous chapter. The fuel cell was tested alone and then in parallel with the individual ultracapacitor banks. The results are then compared to show which system is optimal.

A. FUEL CELL ONLY

The first experiment conducted was to test the fuel cell alone. It was assumed that the fuel cell could not sufficiently react to meet the power demands. This assumption was tested by subjecting the fuel cell to different power demands utilizing the programmable load to see how it would react. From Figure 33, it can be seen that the fuel cell overshoots when first responding, and then settles to output a constant power. It also has some delay in responding to the power demand. This can be seen when the actual power output is plotted against the commanded power, shown in Figure 34. These plots solidify the assumption that the fuel cell does not have power density required to respond quickly enough to rapid transitions of power requirements.

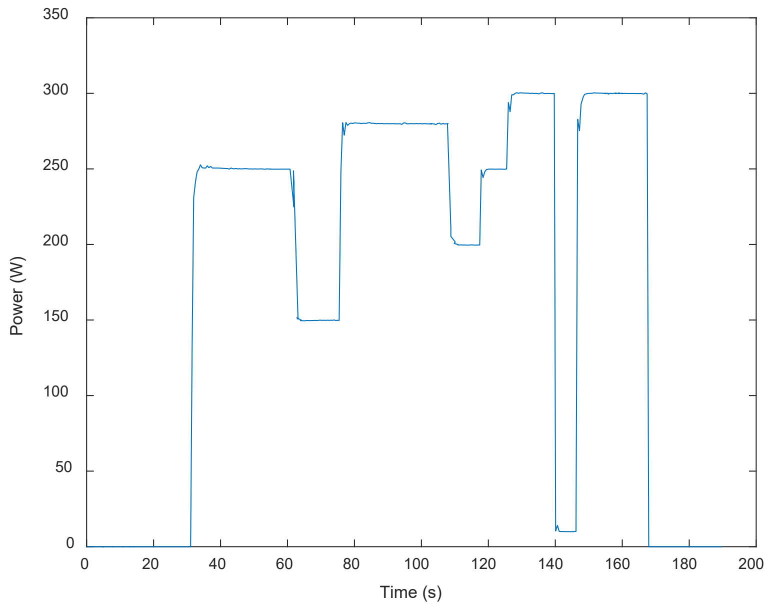

Figure 33. Power profile of fuel cell alone without ultracapacitors in parallel

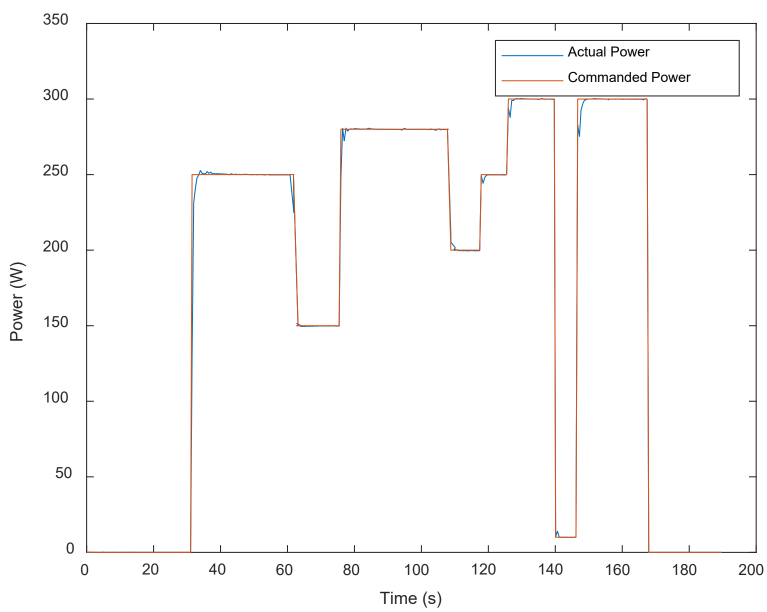

Figure 34. Commanded power versus actual power output of fuel cell without ultracapacitors in parallel

B. MAXWELL TECHNOLOGIES 56 VOLT ULTRACAPACITOR MODULE

Because it was shown that the fuel cell requires a secondary energy source in order to meet peak and transient power profiles, the Maxwell Technologies 56V ultracapacitor module was placed in parallel as described in the equipment section. This module provided sufficient power to meet any commanded power shifts, as shown in Figure 35. As seen in the figure, the fuel cell-ultracapacitor hybrid was able to transition immediately from 0 watts to 250 watts, simulating the initial power demand from the UAS. The system was able to then transition from 250 watts to 450 watts with no noticeable variance that had been exhibited by the fuel cell when tested without the ultracapacitor in parallel. The system was able to sustain 450 watts for approximately 63 seconds and the module only dropped 2.5 volts. The fuel cell was then able to power the system at 250 watts while simultaneously charging the ultracapacitor bank. This simulates the UAS in hover mode while having sufficient overhead capacity in the fuel cell to charge the ultracapacitor. The fuel cell was able to sustain the 250 watts and charge the ultracapacitor bank from 33 volts to 34 volts in approximately 231 seconds. The second 450 watt power consumption dropped the ultracapacitor bank from 34 volts to 33 volts in approximately 24 seconds and then recharged back to 34 volts in approximately 380 seconds while at 250 watts.

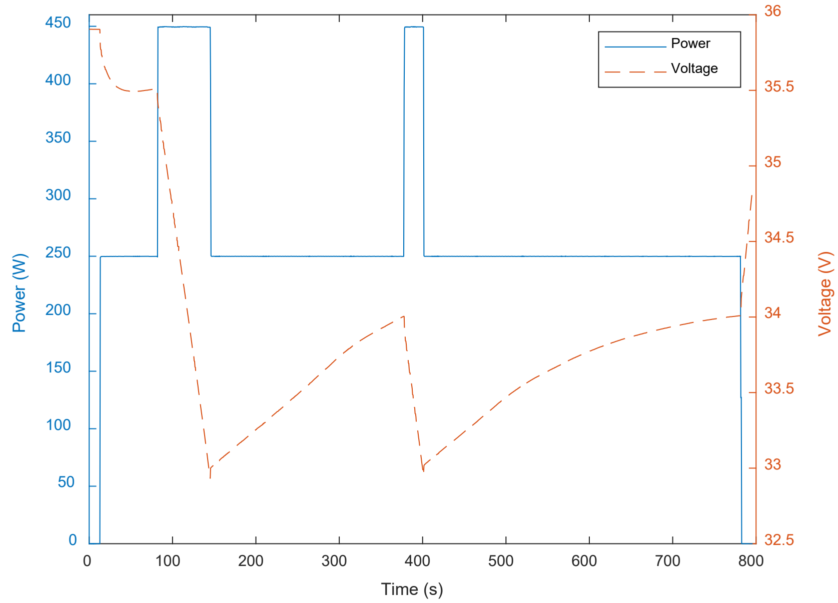

Figure 35. Power profile with Maxwell Technologies 56 volt module in parallel with the fuel cell

Figure 36 shows the voltage versus current for the same scenario as described above. Due to the fact that the Maxwell Technology module that was used was much larger than required, the ultracapacitors are able to easily power the profile at the peak power for a relatively long time with minimal voltage drop.

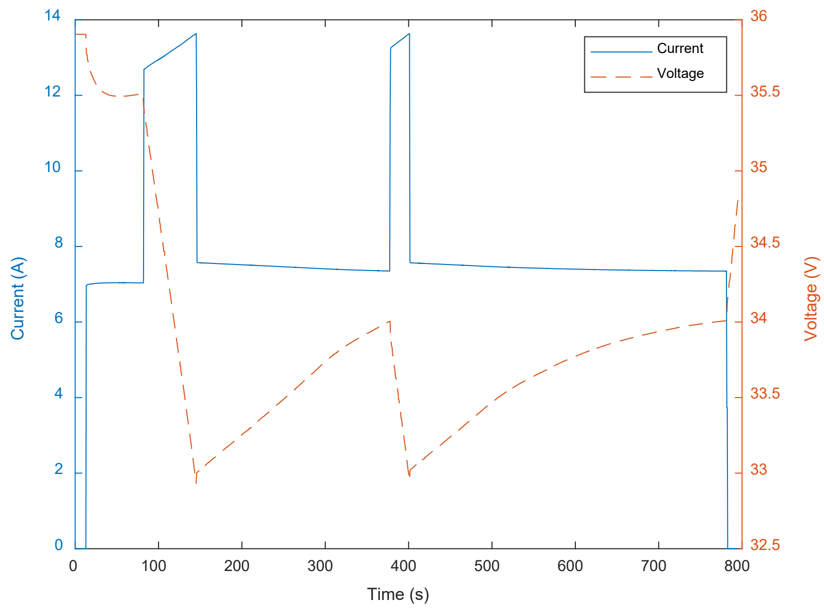

Figure 36. Voltage and current versus time for power profile of Maxwell Technologies ultracapacitor module in parallel with the fuel cell

C. TECATE GROUP 2.7 VOLT ULTRACAPACITORS

Since the previous ultracapacitor module proved that an ultracapacitor was sufficient to be paralleled with the fuel cell in order to meet power requirements, the smaller Tecate Group 2.7 volt ultracapacitors were utilized. As described in the equipment section, 14 2.7 volt 650 Farad cells were placed in series creating an ultracapacitor bank that was 37.8 volts and 46.43 Farads. The ultracapacitor bank was fully charged by the fuel cell with no load applied. After the bank was fully charged, 250 watts was applied followed by 450 watts until the ultracapacitor bank reached approximately 30.4, volts at which point 250 watts was applied again. This was repeated a total of three times.

During the test the voltage of the ultracapacitor bank was manually not allowed to drop below 30.12 volts. This is because the maximum amperage output of the fuel cell is 8.3 amps and when at a 250 watt load, 30.12 volts are required to create that power output. If the ultracapacitor bank drops below 30.12, theoretically the fuel cell will not be able to recharge it. The data acquired is shown in Table 7 and displayed in Figure 37. Figure 38 shows the voltage versus current for the same scenario.

Table 7. Data from Tecate Group 2.7 volt ultracapacitor bank testing

	Starting Voltage (V)	Ending Voltage (V)	Voltage Change (V)	Time (s)	Charge/Discharge Rate (V/s)
Charge with no load	0	36.9427	36.9427	225.001	0.1642
1st Discharge @ 450W	36.4409	30.3677	6.0732	56.055	0.1083
1st Charge @ 250W	30.3677	36.7111	6.3434	438.838	0.0145
2nd Discharge @ 450W	36.7111	30.3698	6.3413	63.165	0.1004
2nd Charge @ 250W	30.103	36.657	6.554	460.229	0.0142
3rd Discharge @ 450W	36.657	30.3993	6.2577	62.699	0.0998
3rd Charge @ 250W	30.2661	36.6972	6.4311	416.993	0.0154
Average Discharge Rate			6.2241	60.640	0.1028
Average Charge Rate			6.4428	438.687	0.0147

The data in Table 7 shows that the Tecate Group ultracapacitor bank in parallel discharged, on average, 6.2241 volts in 60.640 seconds. This results in an average discharge rate of 0.1028 volts/second when the load was 450 watts. When the load then shifted back to 250 watts, the ultracapacitor bank was able to recharge at an average rate of 0.0147 volts/second, which took approximately 438.687 seconds to reach approximately 36.7 volts.

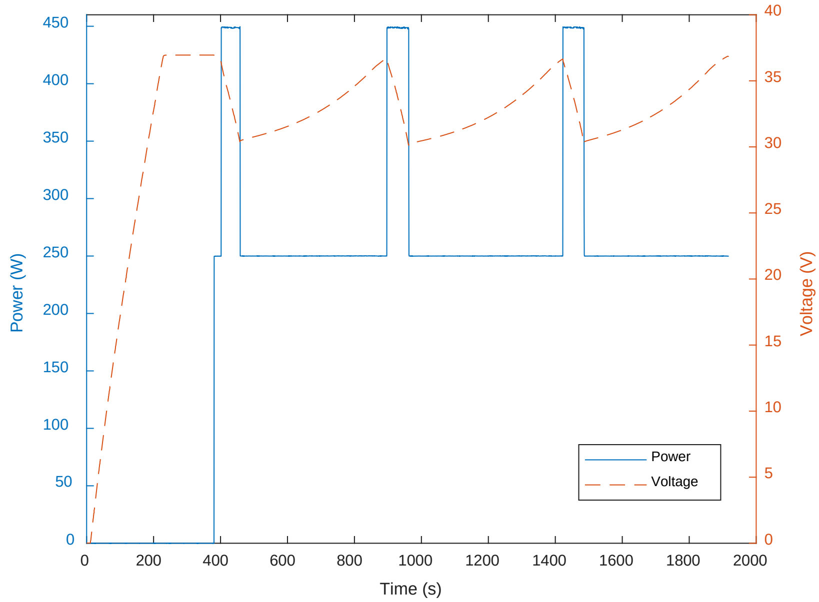

Figure 37. Power profile with Tecate Group 2.7 volt ultracapacitor bank in parallel with fuel cell

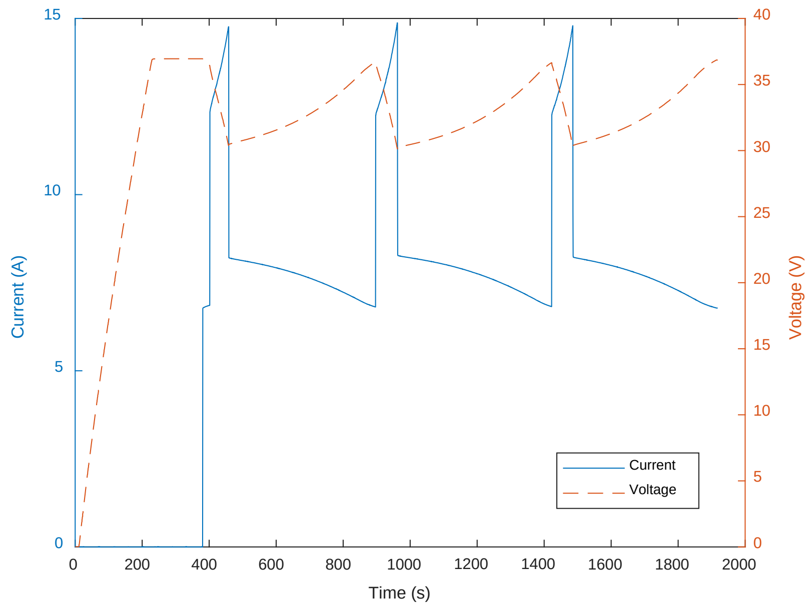

Figure 38. Voltage and current versus time for power profile of Tecate Group 2.7 volt ultracapacitor bank in parallel with fuel cell

D. MAXWELL TECHNOLOGIES 2.7 VOLT ULTRACAPACITORS

As a smaller option than the Tecate Group ultracapacitors used, the Maxwell Technologies ultracapacitors were tested in a similar fashion. 14 2.7 volt 350 Farad cells were placed in series creating an ultracapacitor bank that was 37.8 volts and 25 Farads. The same test as used previously with the Tecate Group ultracapacitor bank was used with this ultracapacitor bank. The ultracapacitor bank was fully charged by the fuel cell with no load applied. After the bank was fully charged, 250 watts was applied followed by 450 watts until the ultracapacitor bank reached approximately 30.4 volts, at which point 250 watts was applied again. This was repeated a total of three times. The data acquired is shown in Table 8 and displayed in Figure 39. Figure 40 shows the voltage versus current for the same scenario as described above. As was the case with the previous scenario, the ultracapacitor bank cannot be allowed to drop below 30.12 volts, otherwise the fuel cell will not be able to recharge it. Because these ultracapacitors are much smaller than those previously used, the voltage drop is more rapid when at peak power demands.

Table 8. Data from Maxwell Technologies 2.7 volt ultracapacitor bank testing

	Starting Voltage (V)	Ending Voltage (V)	Voltage Change (V)	Time (s)	Charge/Discharge Rate (V/s)
Charge with no load	0	36.947	36.947	116.984	0.3158
1st Discharge @ 450W	36.4245	30.3473	6.0772	34.416	0.1766
1st Charge @ 250W	30.3473	36.8023	6.455	197.187	0.0327
2nd Discharge @ 450W	36.8349	30.3812	6.4537	34.88	0.1850
2nd Charge @ 250W	30.1474	36.8386	6.6912	203.265	0.0329
3rd Discharge @ 450W	36.8386	30.3606	6.478	34.869	0.1858
3rd Charge @ 250W	30.2463	36.8343	6.588	196.376	0.0335
Average Discharge Rate			6.3363	34.722	0.1825
Average Charge Rate			6.5781	198.943	0.0331

The data in Table 8 shows that the Maxwell Technologies ultracapacitor bank in parallel discharged on average 6.3363 volts in 34.722 seconds, which is an average discharge rate of 0.1825 volts/second when the load was 450 watts. When the load then shifted back to 250 watts, the ultracapacitor bank was able to recharge at an average rate of 0.0331 volts/second and took approximately 198.943 seconds to reach approximately 36.8 volts.

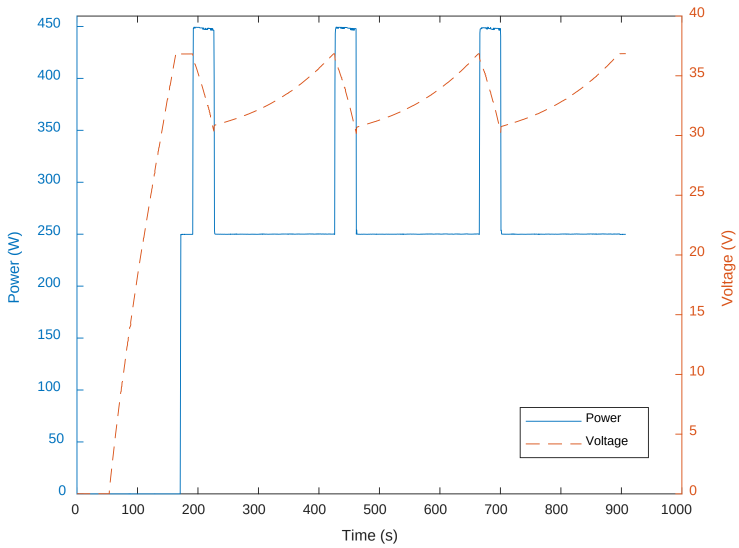

Figure 39. Power profile with Maxwell Technologies 2.7 volt ultracapacitor bank in parallel with fuel cell

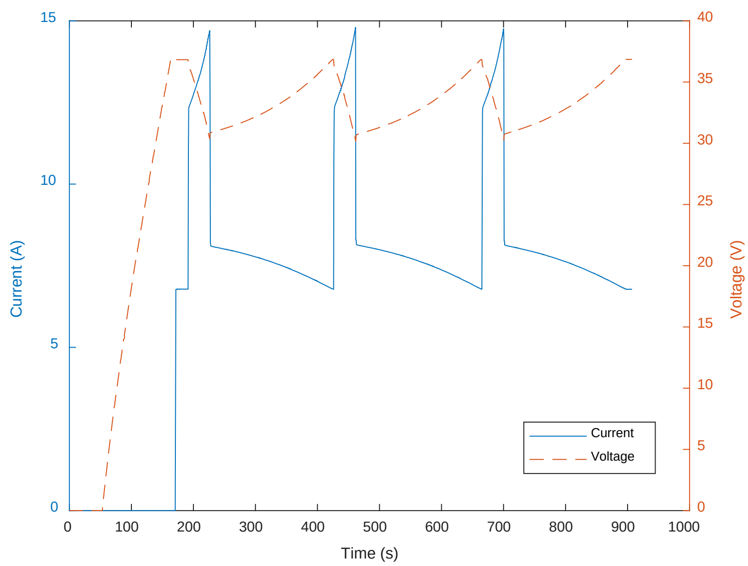

Figure 40. Voltage and current versus time for power profile of Maxwell Technologies 2.7 volt ultracapacitor bank in parallel with fuel cell

E. COMPARISON OF 650 FARAD ULTRACAPACITOR BANK VERSUS 350 FARAD ULTRACAPACITOR BANK

Comparing the Tecate Group ultracapacitor bank to the Maxwell Technologies ultracapacitor bank yields the results displayed in Table 9.

Table 9. Comparison of both ultracapacitor banks

	Bank of 650F Ultracapacitors	Bank of 350F Ultracapacitors	Versus
Capacitance	46.43 F	25 F	650F bank has 85.72% more capacitance
Rated Voltage	37.8 V	37.8 V	
Mass	2.94 kg	0.84 kg	350F bank weighs 71.43% less
Capacitance per kg	15.79 F/kg	29.76 F/kg	350F bank has 88.46% more capacitance per kg
Average Discharge Rate	0.1028 V/s	0.1825 V/s	650F bank discharges 77.53% slower
Average Charge Rate	0.0147 V/s	0.0331 V/s	350F bank charges 125.17% faster
Average Discharge Time	60.64 s	34.722 s	650F bank has 42.74% more discharge time
Average Charge Time	438.687 s	198.943 s	350F bank takes 54.65% less time to charge
Average Discharge Rate per kg	0.0350 V/s/kg	0.2173 V/s/kg	650F bank discharges at a rate of 521.35% slower per kg
Average Charge Rate per kg	0.005 V/s/kg	0.0394 V/s/kg	350F bank charges at a rate of 688.10% faster per kg
Average Discharge Time per kg	20.626 s/kg	41.336 s/kg	350F bank has 100.41% more time to discharge per kg
Average Charge Time per kg	149.213 s/kg	236.837 s/kg	650F bank charges 58.72% faster per kg

Depending on the importance of characteristics for a specific application, either the 650 Farad bank or the 350 Farad bank may be better. The 350 Farad ultracapacitor bank is significantly lighter, has more capacitance per kilogram and charges faster or more rapidly. However, the 650 Farad ultracapacitor bank has more capacitance overall and discharges at a much slower rate per kilogram, which results in being able to output 450 watts for a significant more amount of time.

IV. CONCLUSION

The focus of this thesis was to create a hybrid powertrain consisting of a fuel cell and ultracapacitors in order to sufficiently match the flight profile of a battery-powered, vertical take-off UAS. The prototype hybrid powertrain designed, constructed, and tested during this research utilized a 300 watt PEM fuel cell made by Horizon and a 56 volt, 130 Farad ultracapacitor module made by Maxwell Technology. A second ultracapacitor module was designed using 14 2.7 volt , 650 Farad Tecate Group ultracapacitors connected in series and a third module using 14 2.7 volt, 350 Farad Maxwell Technology ultracapacitors connected in series. Initial experimentation showed that the fuel cell was unable to respond to quick power transients on its own and required a secondary power source capable of delivering a large amount of power instantaneously. Hence, the power requirements during peak power periods, such as take-off, could not be met by the fuel cell alone. The experimentation showed that the ultracapacitors in parallel with the fuel cell were able to meet the peak power demands and the fuel cell was able to recharge the ultracapacitors during times of lesser power consumption, like when hovering.

NPS recently purchased a HYCOPTER UAS made by HES Energy Systems. This UAS uses two 4S LiPo batteries that have a combined weight of 776 grams and provide 29.6 volts [22]. The HYCOPTER uses a 1500 watt fuel cell that is also capable of outputting 45 amps. These power specifications remove the restrictions seen in this research on how low the voltage of the ultracapacitor bank can get. The Maxwell Technology 2.7 volt ultracapacitor bank utilized in this study provides 37.8 volts and weighs a mere 840 grams. The ultracapacitor bank has proven to be a suitable replacement for the LiPo batteries installed on the HYCOPTER.

There are opportunities for follow on work. In order to implement this design, proper scaling needs to be conducted. There are fuel cells made specifically for UAS avionics that are much more powerful than the fuel cell utilized in this thesis and that weigh significantly less. There will also need to be power management implementations in order to properly maintain and manage the load between the fuel cell and ultracapacitors based on the unique demands of a quadcopter or hex-copter.

Overall, this concept can be applied to future UAS designs. A fuel cell is able to meet all power demands of the UAS, with the exception of short-duration peak power demands. Replacing batteries with fuel cell-ultracapacitor hybrid system will reduce the pre-payload weight of the UAS. A reduced pre-payload weight allows a heavier payload which could hence increase mission capabilities of the UAS. It will also reduce maintenance costs to the UAS since ultracapacitors last for exponentially more cycles than batteries.

APPENDIX A. START-UP AND SHUTDOWN PROCEDURES

Start-up Procedure

1. Ensure there is an adequate amount of pressure in hydrogen tank.
2. Connect all required wires.
3. Connect hydrogen tubing to hydrogen tank.
4. Set self-power loop switch to 'off'.
5. Turn power strip that powers all supporting equipment on.
6. Ensure proper ventilation in space.
7. Turn on the external power supply and set to 13 volts.
8. Open hydrogen tank.
9. Set outlet pressure between 0.45 and 0.55 bar.
10. Hold the on/off button on fuel cell and wait for start-up process to complete.
11. Set self-power DC/DC buck converter output to 13 volts and 5 amps.
12. Turn self-power loop switch to 'on'.
13. Turn off external power supply.
14. Set ultracapacitor DC/DC buck converter to voltage and current as desired based on ultracapacitor configuration.
15. Charge ultracapacitor bank.
16. Use powertrain as desired.

Shutdown Procedure

1. Turn on external power supply and set to 13 volts.
2. Set self-power loop switch to 'off'.
3. Hold the on/off button on fuel cell and wait for shutdown process to complete.
4. Turn off external power supply.
5. Close hydrogen tank.
6. Disconnect hydrogen tubing from hydrogen tank.
7. Safely dissipate power from ultracapacitors.
8. Turn power strip that powers all supporting equipment off.

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APPENDIX B. MATLAB SCRIPT FOR FLIGHT PROFILE DATA ANALYSIS AND PLOTTING

```
clc
clear all
load('batterytest.csv');

%% Original Plot
amps  = batterytest(:,3);
voltage = batterytest(:,2);
watts = abs(amps.*voltage);
time = batterytest(:,1);
timeN = time - time(1); %normalize time
seconds = timeN/1000000000; %scales from nanoseconds to seconds
figure(1)
grid on
plot(timeN/1000000000,watts)
ylabel('Power (W)')
xlabel('Time (s)')
%title('Power Usage of a Vertical Take-off Drone for Take-off,
Hovering, and Landing')
xlim([0,303.8229]);
figure(2)
plot(seconds,voltage)
ylabel('Voltage (V)')
xlabel('Time (s)')
xlim([0,303.8229]);
figure(3)
plot(seconds,abs(amps))
ylabel('Current (A)')
xlabel('Time (s)')
xlim([0,303.8229]);

%% Take off profiles--single
%toXt is the time during that flights take-off
%toXw is the power usage at during that time
to1t=seconds(94:162);
to1w=watts(94:162);
to2t=seconds(822:889);
to2w=watts(822:889);
to3t=seconds(1761:1829);
to3w=watts(1761:1829);
to4t=seconds(2150:2209);
to4w=watts(2150:2209);
to5t=seconds(2521:2589);
to5w=watts(2521:2589);
figure(4)
plot(to1t,to1w,to2t,to2w,to3t,to3w,to4t,to4w,to5t,to5w)
grid on
legend('Flight 1','Flight 2','Flight 3','Flight 4','Flight 5')
title('Comparison of Each Take-off Profile')
ylabel('Power (W)')
xlabel('Time (s)')
```

```
%% Take off profiles--stacked
%toXt is the time during that flights take-off
%toXw is the power usage at during that time
to1t=seconds(94:172)-seconds(94);
to1w=watts(94:172);
to2t=seconds(822:899)-seconds(822);
to2w=watts(822:899);
to3t=seconds(1761:1839)-seconds(1761);
to3w=watts(1761:1839);
to4t=seconds(2150:2219)-seconds(2150);
to4w=watts(2150:2219);
to5t=seconds(2521:2599)-seconds(2521);
to5w=watts(2521:2599);
figure(5)
plot(to1t,to1w,to2t,to2w,to3t,to3w,to4t,to4w,to5t,to5w)
grid on
legend('Flight 1','Flight 2','Flight 3','Flight 4','Flight 5')
title('Comparison of Each Take-off Profile Stacked')
ylabel('Power (W)')
xlabel('Time (s)')

%% Total flight profiles--single
%tXt is the time during that flights duration
%tXw is the power usage at during that time
t1t = seconds(94:444);
t1w = watts(94:444);
t2t=seconds(822:1162);
t2w=watts(822:1162);
t3t=seconds(1761:2099);
t3w=watts(1761:2099);
t4t=seconds(2150:2477);
t4w=watts(2150:2477);
t5t=seconds(2521:2879);
t5w=watts(2521:2879);
figure(6)
plot(t1t,t1w,t2t,t2w,t3t,t3w,t4t,t4w,t5t,t5w)
grid on
legend('Flight 1','Flight 2','Flight 3','Flight 4','Flight 5')
title('Comparison of Each Test Flight Profile')
ylabel('Power (W)')
xlabel('Time (s)')
%% Total flight profiles--stacked
%tXt is the time during that flights duration
%tXw is the power usage at during that time
t1t = seconds(94:444) - seconds(94);
t1w = watts(94:444);
t2t = seconds(822:1162) - seconds(822);
t2w=watts(822:1162);
t3t=seconds(1761:2099)-seconds(1761);
t3w=watts(1761:2099);
t4t=seconds(2150:2477)-seconds(2150);
t4w=watts(2150:2477);
t5t=seconds(2521:2879)-seconds(2521);
t5w=watts(2521:2879);
```

```
figure(7)
plot(t1t,t1w,t2t,t2w,t3t,t3w,t4t,t4w,t5t,t5w)
grid off
legend('Flight 1','Flight 2','Flight 3','Flight 4','Flight 5')
%title('Comparison of Each Test Flight Profile Stacked')
ylabel('Power (W)')
xlabel('Time (s)')
```

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APPENDIX C. MATLAB SCRIPT FUEL CELL DATA ANALYSIS AND PLOTTING

```
clc
clear all
load('fcalone.csv');

%% Fule Cell without capacitors = 3
t3 = fcalone(:,7);
amp3 = fcalone(:,4);
volt3 = fcalone(:,3);
apower3 = fcalone(:,5);
cpower3 = fcalone(:,6);

figure(1)
yyaxis left
%title('Power Profile with Fuel Cell Alone')
plot(t3,apower3)
xlabel('Time (s)')
ylabel('Power (W)')
ylim([0 460])
yyaxis right
plot(t3,volt3)
ylabel('Voltage (V)')

figure(2)
plot(t3,apower3,t3,cpower3)
%title('Fuel Cell')
xlabel('Time (s)')
ylabel('Power (W)')
legend('Actual Power','Commanded Power')

figure(3)
plot(t3,apower3)
%title('Fuel Cell')
xlabel('Time (s)')
ylabel('Power (W)')

figure(4)
yyaxis left
plot(t3,amp3)
ylabel('Current (A)')
yyaxis right
plot(t3,volt3)
ylabel('Voltage (V)')
%title('Fuel Cell')
```

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APPENDIX D. MATLAB SCRIPT FOR MAXWELL TECHNOLOGIES 56 VOLT ULTRACAPACITOR MODULE DATA ANALYSIS AND PLOTTING

```
clc
clear all
load('wselfpowerloop.csv');

%% 56V Module Selfpower = 1
t1 = wselfpowerloop(:,7);
amp1 = wselfpowerloop(:,4);
volt1 = wselfpowerloop(:,3);
apower1 = wselfpowerloop(:,5);
cpower1 = wselfpowerloop(:,6);

figure(1)
yyaxis left
%title('Power Profile with 56V/500F Capacitor and Selfpower Loop On')
plot(t1,apower1)
xlabel('Time (s)')
ylabel('Power (W)')
ylim([0 460])
yyaxis right
plot(t1,volt1,'--')
ylabel('Voltage (V)')
legend('Power','Voltage')

figure(2)
yyaxis left
plot(t1,amp1)
ylabel('Current (A)')
xlabel('Time (s)')
yyaxis right
plot(t1,volt1,'--')
ylabel('Voltage (V)')
legend('Current','Voltage')
%title('Selfpower Loop On')
```

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APPENDIX E. MATLAB SCRIPT FOR TECATE GROUP 2.7 VOLT ULTRACAPACITOR BANK DATA ANALYSIS AND PLOTTING

```
clc
clear all
load('tecatethree.csv');

%% With self-power loop on
t1 = tecatethree(:,7);
amp1 = tecatethree(:,4);
volt1 = tecatethree(:,3);
apower1 = tecatethree(:,5);
cpower1 = tecatethree(:,6);

figure(1)
yyaxis left
%title('Power Profile with 2.7V/650F Capacitor and Selfpower Loop On')
plot(t1,apower1)
xlabel('Time (s)')
ylabel('Power (W)')
ylim([0 460])
yyaxis right
plot(t1,volt1,'--')
ylabel('Voltage (V)')
legend('Power','Voltage')


figure(2)
yyaxis left
plot(t1,amp1)
ylabel('Current (A)')
xlabel('Time (s)')
yyaxis right
plot(t1,volt1,'--')
ylabel('Voltage (V)')
legend('Current','Voltage')
```

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APPENDIX F. MATLAB SCRIPT FOR MAXWELL TECHNOLOGIES 2.7 VOLT ULTRACAPACITOR BANK DATA ANALYSIS AND PLOTTING

```
clc
clear all
load('maxwellthree.csv');

%% With self-power loop on
t1 = maxwellthree(:,7);
amp1 = maxwellthree(:,4);
volt1 = maxwellthree(:,3);
apower1 = maxwellthree(:,5);
cpower1 = maxwellthree(:,6);

figure(1)
yyaxis left
%title('Power Profile with 2.7V/350F Capacitor and Selfpower Loop On')
plot(t1,apower1)
xlabel('Time (s)')
ylabel('Power (W)')
ylim([0 460])
yyaxis right
plot(t1,volt1,'--')
ylabel('Voltage (V)')
legend('Power','Voltage')


figure(2)
yyaxis left
plot(t1,amp1)
ylabel('Current (A)')
xlabel('Time (s)')
yyaxis right
plot(t1,volt1,'--')
ylabel('Voltage (V)')
legend('Current','Voltage')
```

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