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Hydrogen Fuel Cell Propulsion for Long Endurance Small UAVs

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Hydrogen fuel cells are demonstrated as the propulsion system for long-endurance, small, electric unmanned air vehicles (UAVs). Flight times of >24 hours were demonstrated for the 35-lb Ion Tiger fuel cell UAV while carrying a 5-lb payload. This paper describes the design criteria and development process used to meet these performance goals, including setting the specifications for the vehicle, fuel cell, cooling, and fueling systems.

I. Introduction

Small electric UAVs have many attractive attributes such as instant starting, high reliability and no electric generator. They are also quiet, and thus afford stealthiness, and provide the capability to fly closer to a target undetected. Electric vehicles to date have been hampered by the low specific energy of batteries, whereby even new lithium-ion technologies are limited to about 200 Wh/kg. Although new battery chemistries are emerging, a alternative route is to make an electric vehicle from a fuel cell system, and take advantage of hydrogen fuel, which has an energy of 33,410 Wh/kg (lower heating value).

Hydrogen fuel cells are under development worldwide as electric propulsion systems for automobiles, because they offer high efficiency (approximately 50%), relatively high power to weight, and rapid load following. The fuel cells comprise a polymer-based proton exchange membrane (PEM) coated with platinum-based catalysts that electrochemically convert the oxygen (O_2) in air and hydrogen (H_2) fuel into water, electricity and heat at operational temperatures between 50 and 80 °C. A full system includes a fuel cell stack which is made up of 10's to 100's of individual cells compressed between flow fields, which effectively deliver gases and transport away product water, and cooling channels for heat rejection. The stack operates within a "balance of plant," which typically comprises a water management system (e.g., humidifier), air blower, fuel delivery/conservation system, cooling pumps or blowers, and a start up battery, plus electronics to control the system components and regulate the power and voltage coming from the fuel cell. Effective coordination is required for all of the electrochemical, flow, mechanical and electrical systems to deliver optimum performance of the full fuel cell system.

NRL has been researching hydrogen-fuel-cell-propulsion for small unmanned air vehicles (UAVs) since 2003 with the objective to extend the flight time of electric vehicles. We started with the Spider Lion program, which was a simple 6-lb airplane kit powered by a 100-W fuel cell from Protonex Technology Corporation on 15-g of hydrogen stored in a paint-ball tank. This humble vehicle flew for 3 h and 19 minutes. Although a weight analysis proved that there was no benefit to this fuel cell system over a lithium battery,[1] we were encouraged enough to follow on. We then pursued the XFC program to tube-launch a 15-lb vehicle with a flight requirement of 6 hours and a 2-lb payload.[2] In this case, an equivalent battery system would only fly for 3 h. Finally in 2009, we pursued the Ion Tiger vehicle with the goal of a vehicle capable of 24-h flight endurance while carrying a 5-lb payload.[3,4] The Ion Tiger team comprised NRL, Protonex Technology Corporation, the University of Hawaii, HyperComp Engineering, and Arcturus. The program was overall successful, culminating in a 23 h 19 minute flight in October 2009, and a 26 h 1 min flight in November 2009. In a prior paper, we gave an overview of the Ion Tiger attributes.[3] This paper describes the design and development process that we used, as well of our future goals for extending flight times to 72 h by storing the hydrogen as a cryogenic liquid.

II. Air vehicle and propulsion system design

A. Vehicle design sizing

Design sizing was carried out for a fixed wing vehicle with a 5-lb payload and an approximate flight speed of 27 kts. A 5-lb payload was selected as the generic target, because this is the approximate size of a day/night camera, and many other electric payloads of interest. The payload weight drove the size of the vehicle, and was allocated 15% of the vehicle take off gross weight (TOGW). An additional 38 wt% was allowed for the propulsion system, including the fuel cell system and hydrogen tank and regulator. The cooling system was counted as part of the airframe. We also had to target a nominal cruise power near 300-W, based on preliminary analysis by the fuel cell vendor that they could provide a fuel cell with a power of 500 W. The break out of analysis is shown in Table I, and the result was a ~35 lb vehicle with a wingspan of 17 ft.

The conclusion of the design sizing study is that we would need to carry 1.1 lbs (500 g) of hydrogen to enable the Ion Tiger to fly at 300 W for 24 hours, or 7200 Wh. With a 45%-efficient fuel cell, we would need 16,000 Wh of H_2. Based on the lower heating value of hydrogen, 33,410 Wh/kg at room temperature, 500 g of H_2 allows adequate energy plus a ~4% fuel reserve.

TOGW	*35.5 (lbs)*
Fuel cell	2.2
Fuel tank	8.0
Fuel	1.1
Regulator	0.4
Cooling system	1.5
Propulsion system	0.9
Avionics	1.0
Airframe	15.5
Payload	5.0

Dimensions	
Wing area	16.9 ft3
Span	17.0 ft
Aspect ratio	17
Length	7.9 ft
L.D	17

Total Cruise Power	*267 W*
Propulsion	200 W
Avionics	20 W
Flight controls	20 W
Payload	20 W
Conversion losses	7 W

Table I: Weight allocations and design sizing for the Ion Tiger, within the constraints of a 5-lb payload, 300-W cruise power, and 24 h endurance.

The other weight assignments were made with some rational knowledge of the typical weights of components. The 0.4-lb regulator weighing was developed already for the XFC fuel cell UAV program. A target weight of 2.2 lbs was allocated for the fuel cell, and 1.5 lbs was allocated for the cooling system, e.g. radiator and coolant.

B. Hydrogen storage selection

We carried out a study to determine the best way to store hydrogen for a 24-h flight. We had previously used compressed hydrogen for our Spider Lion project,[1] but wanted to make sure that we were taking a fresh look at the technology. As noted in section IIA, our target was to carry 1.1 lbs of hydrogen in a 8.4-lb container (fuel tank and regulator), or have a hydrogen storage weight of 13%.

Eight trade study criteria were used and technologies were ranked from 1 to 10, with 1 being the best, and 10 being the worst, and each had a weighting factor, with higher weighting factors indicating greater importance. The most important criterion was weight, and the least was novelty. The eight criteria are listed below and divided into qualitative and quantitative assessments. The weighting factor for each criterion is listed in parentheses. Note that we did not use volume as the criteria for this sizing, as we had the option to build a new airframe and thus could accommodate a wide range of component volumes, as long as their weight was acceptable.

Qualitative criteria:

- Development Risk: Likelihood of tank satisfying 8.0 lb maximum weight and 1.1-lb minimum H_2 storage. (8)
- Logistics: Complexity or difficulty involved in obtaining fuel, fueling, setting up and running the system. (2)
- Novelty: Relative degree to which we are pushing doing novel research. (1)
- System Complexity: Number of components and interconnections, control requirements. (4)
- Safety (handling): Risk of someone getting hurt when assembling, fueling, starting, defueling, etc. While we do not *expect* anyone to get hurt, the use of high pressures and/or cryogenic liquids does impart some degree of risk. (2)

- Failure Risk: Risk of the system not delivering hydrogen, or not delivering enough, or otherwise ending a flight prematurely. (6)

Quantitative criteria:

- Estimated Program Cost per Tank: Cost of each containment vessel, scaled so that the least expensive is 1 and the most expensive is 10. (1-10)
- Weight: Whether or not the containment vessel is expected to weigh less than or equal to 8.0 lb dry. If it is expected to, it scores a 1, if it is not expected to, it scores a 10. (1,10)

Discussions with vendors, experts, and our own knowledge and experience were used to rank the following 6 hydrogen-storage technologies:

- carbon overwrapped aluminum pressure vessels (target pressure 5000 psi)
- carbon overwrapped titanium pressure vessels (target pressure 5000 psi)
- linerless carbon pressure vessels – Vendor 1
- linerless carbon pressure vessels – Vendor 2
- cryogenic hydrogen
- sodium borohydride

The results of the trade study are shown in Figure 1.

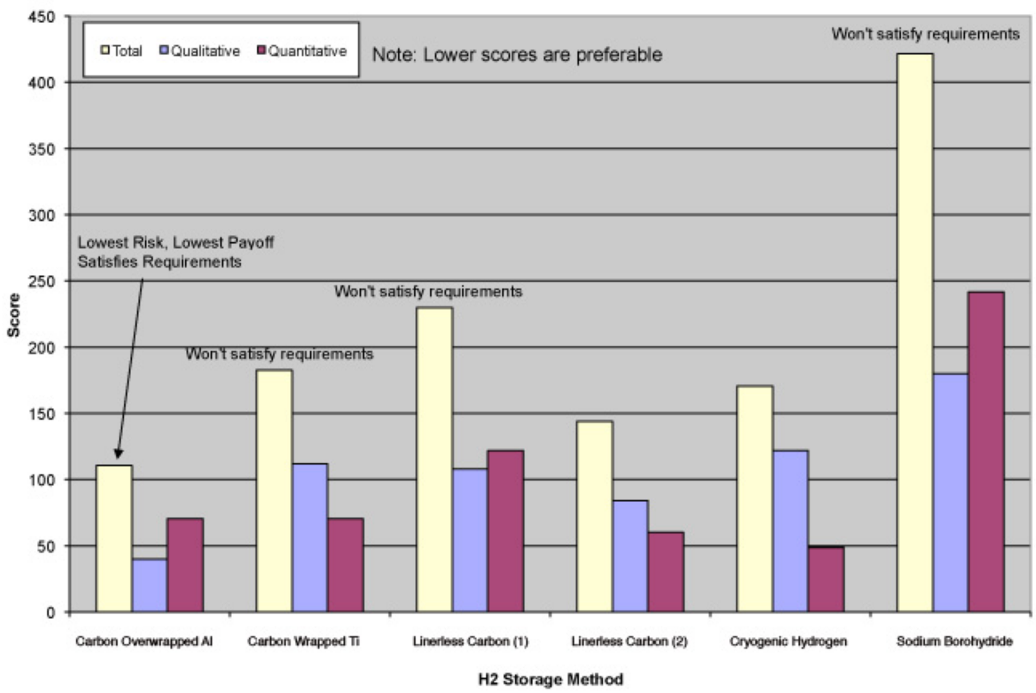

Figure 1. Scoring from study to determine best way to store hydrogen for 24-hour Ion Tiger flights.

The conclusion of the study is that we should continue to pursue storing compressed, gaseous hydrogen in a carbon overwrapped aluminum pressure vessel. We found that titanium tanks were inadequate because they were very expensive, and had long development lead times. With more development time, these might be an option.

The linerless carbon tanks available from one vendor were too heavy, while another vendor quoted a reasonable weight. We pursued linerless carbon tanks for a short period, and had some test tanks made, but for our target weight they leaked too much. These might also be an option with more development time and funding.

Sodium borohydride storage, by which H_2 is release from $NaBH_4$ upon reaction with water to make $NaBO_2$, was inadequate because the theoretical wt % of H_2 was only 12% based on the final weight of the $NaBO_2$ and not including any weight for the storage vessel or balance of plant to operate. Thus fueling with $NaBH_4$ was deemed a non-responsive option for the Ion Tiger.

We therefore settled on traditional carbon-overwrapped pressure vessels with an aluminum liner to block H_2 diffusion. Additional steps were taken to reduce the weight of the system to 8 lbs.

The cryogenic hydrogen option looked compelling, and we opted to look at this as a longer-term program. Cryogenic, or liquid, hydrogen must be stored in an insulated dewar, to keep the gas at 3K. The cryogenic hydrogen boils off continuously, and the amount that boils off is determined by the quality of the insulation. Because of the persistent boil off of liquid H_2, it has been abandoned by the automotive industry. However, there may be an opportunity for cryogenic hydrogen for flight, and cryogenic hydrogen is being pursued as a fuel for high altitude long endurance (HALE) aircraft in development by AeroVironment and Boeing.

As part of a separate effort, we have modeled the boil off rates vs. insulation quality to match to the hydrogen consumption of the Ion Tiger,[5] and we are pursuing extension of the Ion Tiger vehicle to 3 days by carrying 1.5 kg of cryogenic hydrogen in an 8-lb insulated dewar.

C. 550-W Ion Tiger fuel cell

The Ion Tiger fuel cell was developed by Protonex Technology Corporation under a contract with the Naval Research Laboratory. The development focused around the following performance goals for a PEM fuel cell system:

- 500 W maximum continuous power
- 50-W minimum continuous power
- 1 kg total weight

Another goal was to have the fuel cell operate at as high efficiency as possible, particularly at the average cruise power near 300 W, to make the best use of the stored hydrogen. Based on our thermal models, we also targeted a minimum stack temperature of 60 °C (see section II-D).

Another design criterion for naval platforms was for a propulsion system that would allow the vehicle to fly continuously into a persistent headwind, so we opted for a fuel cell design that could fly continuously at full power and which was not hybridized. We also wanted a system that could fly continuously at low power (50 W), in the event that the vehicle was gliding in a tail wind or thermal, and only needed power for the avionics and payload.

A photograph of the Ion Tiger fuel cell is shown in Figure 2. It includes a fuel cell stack, air and coolant pumps, humidifier, H_2-recirculation system, and electronics. It is mounted on an aluminum frame. The air pump provides around 1 psi of pressure to the cathode. The H_2 side of the fuel cell is dead-ended, and is kept near 10 psi. The pressure in the fuel cell cathode was kept low (1 psi) to keep down the parasitic power of the pump.

A polarization curve of voltage vs. current from the stack, measured by Protonex is shown in Figure 3. The 36-cell stack operates near 25 V and 15 A near the average cruise power of 300 W. Thus, the average cell voltage is 0.7 V, and the voltage efficiency of the stack is about 55% (based on the ΔG value of 1.25 V for the LHV of hydrogen). The stack puts out 600 W with a stack voltage of 19 V, or 0.53 V/cell with 42% voltage efficiency. Note that the net power and efficiency of the system is lower due to losses in powering the balance of plant (pumps, etc.) and the fuel utilization, however the stack efficiency is the main driver for the system.

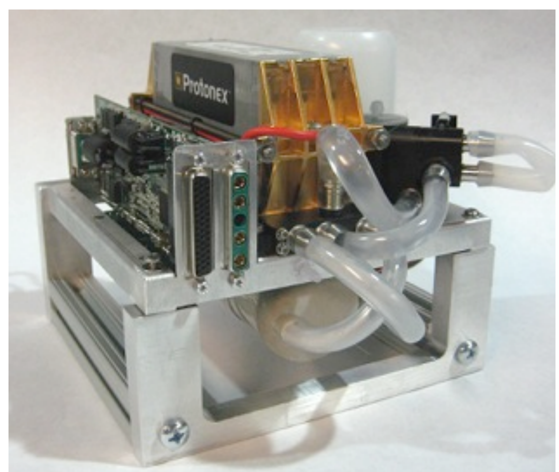

Figure 2. Ion Tiger 550-W fuel cell by Protonex Technology Corporation. (Used by permission from Protonex Technology).

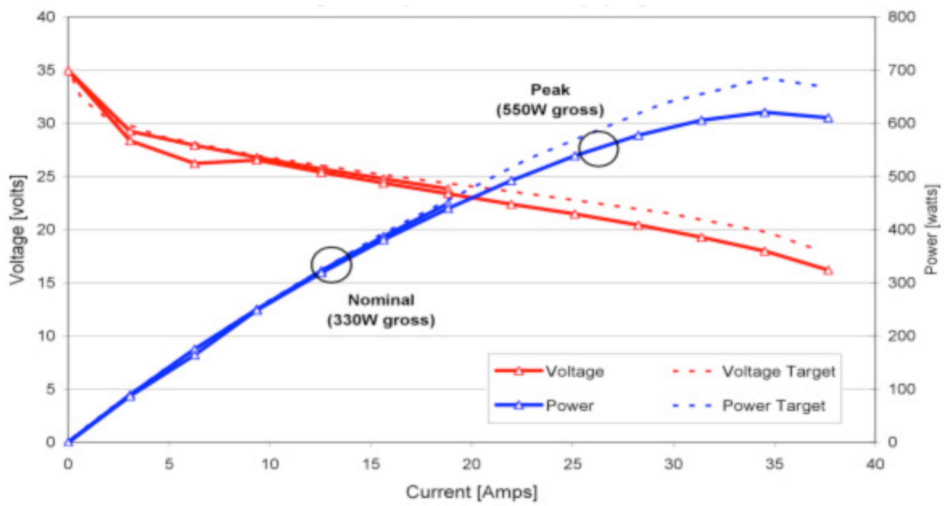

Figure 3. Polarization curve for 36-cell proton exchange membrane fuel cell stack for the Ion Tiger.

D. Radiator sizing

An effective radiator is critical to success of the flight, as inadequately cooled fuel cells overheat, dry out, and then fail to produce power. The key to good thermal management is to have a significant temperature difference between the fuel cell and the ambient temperature, and then put the heat from the fuel cell through an effective radiator.

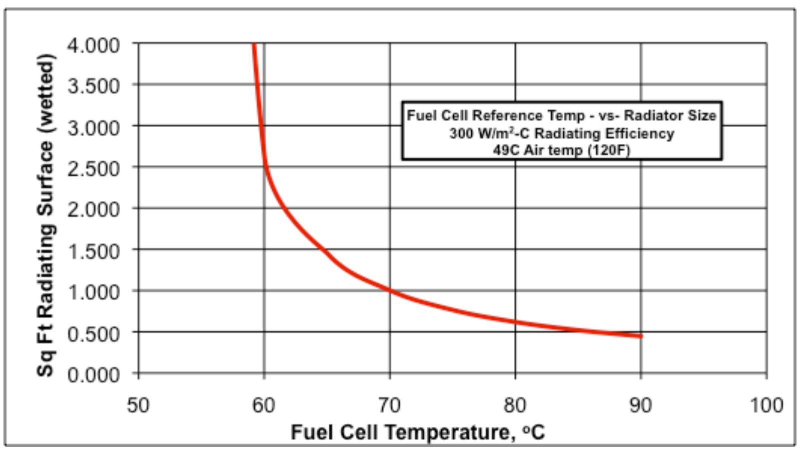

Figure 4. Thermal model showing that for an ambient temperature of 49 °C, the radiator temperature increases exponentially as the fuel cell temperature decreases below 60 °C.

Our target air temperature was 49 °C (or 120 °F). A simple thermal model, shown in Figure 4, shows that for a radiator with a standard radiating efficiency of 300 W/m^2-°C, 2.5 ft^2 of radiating surface area is needed for operation at 60 °C, and only 0.6 ft^2 is needed for operation at 80 °C. If the fuel cell temperature needs to be kept below 60 °C, the amount of radiator area increases exponentially in a 49 °C environment.

The maximum temperature for the fuel cell operation is determined predominantly by the fuel cell membrane, in our case a perfluorosulfonic acid (e.g. Nafion). The membranes operate by conducting protons by a water mechanism, which requires that the membranes have a certain level of hydration. The membrane design and chemistry affects how much hydration is needed to keep it conductive with increasing temperature. The membrane hydration is also determined by the pressure at which the fuel cell is maintained.

We studied both surface and internal radiator designs.[6] The surface radiators were proven in wind tunnel tests to have heat-transfer coefficients of 200 to 300 W/m^2-°C. But to reject about 760 W, the heat rejected by the fuel cell at full power (assuming 42 % efficient at 550 W), we would need 2.5 to 4 m^2 of radiator area. This amount of surface area was not available on the skin of the Ion Tiger body, and use of the wing required extensive plumbing.

A more weight-effective solution was a fin-and-tube radiator with an external fan, reminiscent of the radiators used in automobiles. This assembly had a heat transfer coefficient near 1500 W/m^2-°C under a free stream of air at speed of 27 kts. The heat transfer coefficient improved to 1700 W/m^2-°C by increasing the air speed with the additional of a fan. Assuming a heat transfer coefficient of 1500 W/m^2-°C for the radiator, rejection of 760 W of heat demands a fin-and-tube radiator with a wetted area of about 0.5 m^2.

The performance of our radiator design was recently validated in wind tunnel testing at an ambient temperature of 120 °F (49 °C) and a wind speed of 27 kts. The results are shown in Figure 5. At the cruise power of 300 W, the temperature of the coolant at the fuel cell inlet is 55 °C, and the temperature at the coolant at the fuel cell outlet is 59 °C, while the fan is off. The temperature of the air entering the radiator is between 46 and 49 °C during this test. When the fuel cell is operated at its full power of 550 W and the radiator fan is on, the fuel cell inlet temperature is 60 °C and the outlet is 71 °C; if the fan is off, the inlet and outlet temperatures increase to 63 and 74 °C respectively. Although the temperature increase with the fan off is only a few degrees, these small temperature variations can be critical to the state-of-health of the fuel cell, and might be necessary for adequate cooling.

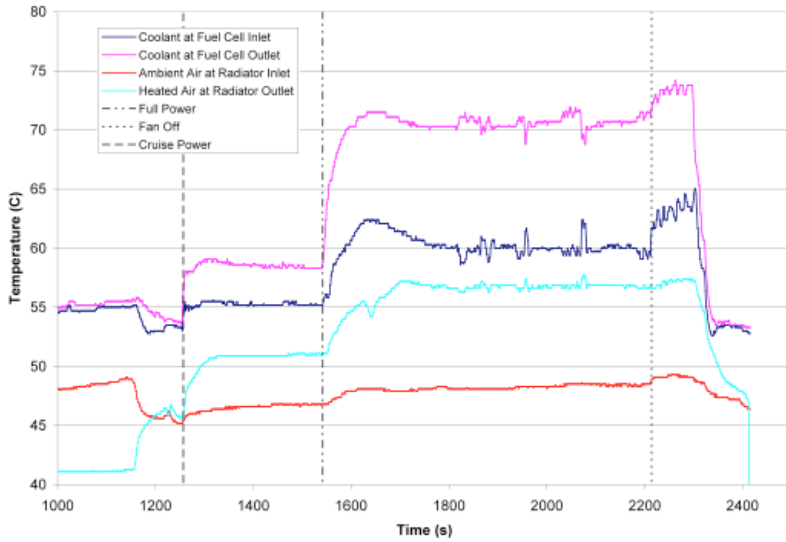

Figure 5. Results of thermal tests of fuel cell operating fin-and-tube internal radiator in wind tunnel tests at 120 °F ambient. Cruise power is 300 W, and full power is 550 W.

E. Vehicle design

We initially sought to purchase an airframe for flight testing the fuel cell system, but found no kits that offered the volume needed for the fuel cell system and hydrogen storage, along with the high L/D needed for low drag efficient flight, along with low weight construction.

NRL designed a simple, monoplane built with carbon fiber and Kevlar construction to meet the design goals in Table I. During the design phase, we had input from Protonex on the size of the fuel cell system, and we also used preliminary designs for the hydrogen pressure vessels to determine the fuselage diameter and volume.

The NRL design for Ion Tiger was built by Arcturus. A drawing of the design and photograph of the final vehicles are shown in **Figure 6**. The first Ion Tiger airframe was built for battery flight, so that the airframe could be tested prior to integration of the fuel cell system. Once the airframe was proven to match the design criteria for L/D and weight, new ones were built exclusively for fuel cell flight, notably with adequate vents for cooling.

III. Flight test results

In October 2009, our team flew the Ion Tiger for 23 h and 19 minutes in windy conditions. This vehicle carried a 4-lb payload. In November 2009, we went onto fly for 26 h and 1 minute carrying a 5-lb payload. The primary difference between the flights was that the October flight was in windy conditions, forcing the Ion Tiger to fly at higher power, and burn its hydrogen fuel at a higher rate. These long-endurance flights were preceded by several one to 2 hour flights in which the vehicle flight speed and controls were optimized, and a "dawn to dusk" flight in August 2009. In all cases, the vehicle took off and landed safely, with no mishaps.

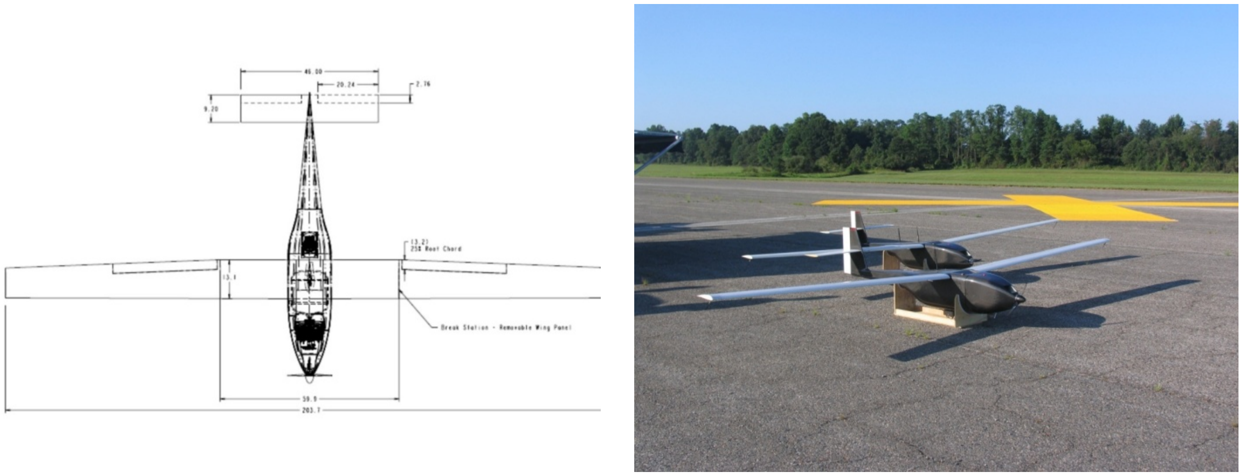

Figure 6. (a) Drawing of Ion Tiger, (b) two completed Ion Tiger vehicles at a flight range.

A. 23-hour flight

The flight profile for the 23-h 19 min flight is shown below in **Figure 7**. It was carried out on 09-10 October 2009 at Philips Airfield at Aberdeen Proving Grounds. The flight path was 3,000 ft in diameter, 2,000 ft AGL, varying throughout flight. The average air speed was 29 kts. The weather was windy with periods of wind ranging from 20 to 35 kts. The mean temperature was 69 °F, with a high of 71 °F and a low of 59 °F.

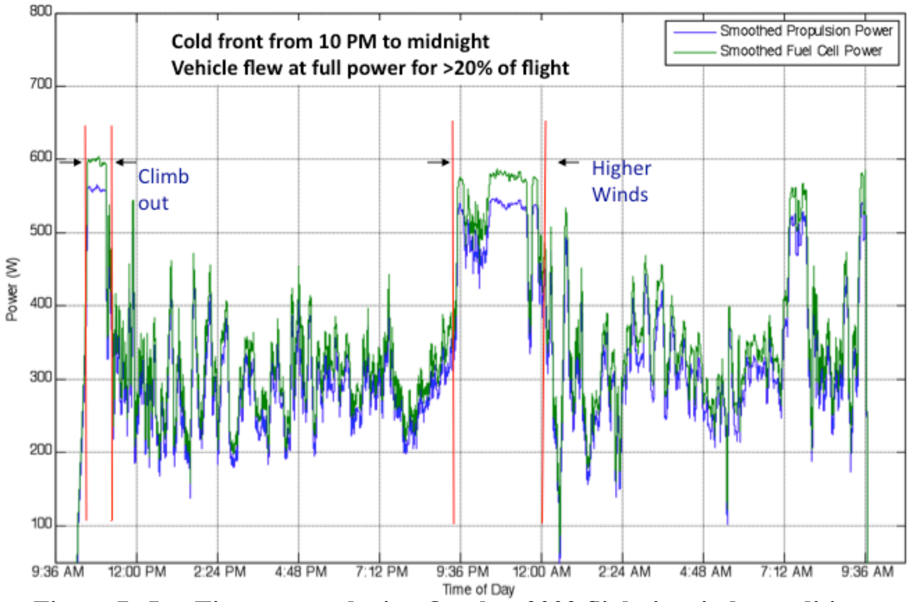

Figure 7. Ion Tiger power during October 2009 flight in windy conditions.

The specific energy of the hydrogen fuel cell propulsion system can be estimated from the October and November 2009 flights. In both cases, about 500 g of H_2 was consumed. The weight of the propulsion system at take off was about 7 kg (including fuel cell system, hydrogen fueling system, and cooling system). For the October 2009 flight, the average propulsion power of the fuel cell system was 326 W. Over 23 h and 19 min, the vehicle propulsion system consumed a total of 7600 Wh, giving a specific energy of 1090 Wh/kg. For the November 2009 flight in calmer wind conditions, the vehicle flew at an average propulsion power of 314 W for 26 h, delivering 8160 Wh of propulsion power at a specific energy of 1170 Wh/kg. The difference in the specific energy values is due to the decreased efficiency of the fuel cell in the October 2009 flights when flying at full power for extended periods. Nonetheless, the fuel cell propulsion system has 5 to 6x more capacity than lithium-ion batteries (~200 Wh/kg). Note that the full capacity of a Li-ion battery is likely to be unmet for high power flight, so the estimate of 200 Wh/kg for Li-ion batteries is generous. Considering that there is no battery technology on the horizon with a specific energy of 1000 Wh/kg, that can also deliver the power needed for flight, hydrogen fuel cell propulsion systems appear to be an attractive option for propulsion of small electric UAVs.

B. Hybridization studies

The flight test results above give us the opportunity to examine our decision to not hybridize the vehicle to reach peak power. The vehicle cruised near 300 W, as expected, and flew at around 550 W continuously for about 2.5 h when a cold front came through, and power was needed to stay aloft in the high winds.

Simple estimates predict that hybridization is a poor choice for the Ion Tiger. If the fuel cell had instead been designed for maximum propulsion power of net 300 W, and the peaks over 300 W had been left to a battery, the remaining 250 W for 550-W flight in sustained winds would have been needed from the battery. The battery would therefore have to deliver 625 Wh over the 2.5 h of sustained winds. For a lithium-ion battery with a specific energy of 200 Wh/kg, we would need at least 3.1 kg of lithium batteries to augment the high power flight, which is appreciable considering that the entire hydrogen system weighs about 3.8 kg (8.4 lbs). Although a smaller fuel cell on the order of 350 W would be used, the weight savings between the Ion Tiger's 1-kg 550 W and a 350-W fuel cell would likely be no more than about 300 g. The vehicle would additionally have to carry the additional weight for DC-DC electronics for the hybridization scheme and power electronics for the lithium battery.

Hybridization strategies were examined quantitatively in a separate project with the University of Hawaii through hardware in the loop and analysis with Simulink models. The Ion Tiger fuel cell system was modified as a hybrid system in the modeling to accommodate 23-30V batteries, with the associated DC-DC converters needed for battery charging. To keep the system as consistent as possible, the model was run at a higher cruise power to account for the higher weight of the hybridized propulsion system. The model tested whether keeping the fuel cell operating at lower power (high voltage per cell, and thus higher efficiency) could offset the other system losses. In no case did we find increased endurance with hybridization, and direct load following with the fuel cell proved to be the best choice for long endurance.

IV. Conclusions

This paper shows some of the steps needed to make a long endurance fuel cell powered UAV, the Ion Tiger. We focused on the weight reduction of components and maximal output from the fuel cell system to achieve a high specific power propulsion system in a custom vehicle. We found that carbon-overwrapped aluminum pressure vessels were the optimal method for making a lightweight storage vessel for high-pressure hydrogen. A fin-and-tube radiator was the most effective at providing cooling. Hybridization with a battery was not useful for long endurance or withstanding persistent head winds. The final product has about 6× the endurance of an equivalent system using Li-ion batteries.

Future work is focused on using liquid hydrogen for flights up to 3 days. We are also pursuing higher power fuel cell systems, up to 1.5 kW that would enable the small UAVs to fly faster and in poor weather.

Acknowledgments

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