Advanced Propulsion for Small Unmanned Aerial Vehicles

The Role of Fuel Cell-Based Energy Systems for Commercial UAVs

WHITE PAPER

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1 Introduction

Although they have been primarily used by the military, unmanned aerial vehicles (UAVs), also known as drones, have also recently become significant tools in the consumer and commercial sectors. According to recent reports, the U.S. Pentagon now has some 7,000 aerial drones, compared with fewer than 50 a decade ago.[1] Currently, these unmanned systems are being used primarily in the role of intelligence, reconnaissance, and surveillance (ISR) from hand-launched to passenger airplane-sized systems, with the capability to carry significant payloads.

In June 2016, the U.S. Department of Transportation's Federal Aviation Administration finalized the first operational rules for routine use of small UAVs, opening the door to expanded commercial uses. The new regulations streamline the process to legally operate a UAV and create the opportunity for as many as 600,000 commercial drones to be flying in the United States within the next year.[2] Internationally, Teal Group estimates there were 2.25 million UAVs produced for civil applications and operating around the world in 2016.[3]

Small UAVs, with a gross take-off weight of less than 25kg, are dominating the commercial uses. There are significant gains to be had with UAVs performing the dull, dirty or dangerous operations previously performed by larger platforms with humans in the cockpit or that were not previously possible with manned aviation. However, with the growing interest in UAVs and their potential for a host of military, commercial and civilian applications, limitations in the current state-of-the-art propulsion systems are coming to light. In the small UAV space, batteries or internal combustion engines have been primarily used for propulsion. Both of these technologies will limit the use and efficacy of UAV systems as the technology continues to evolve and its capabilities expand, requiring gains in autonomy, range, and reliability.

An alternative technology, hydrogen fuel cells, has come to the forefront as a solution to these challenges. First demonstrated in military UAVs, fuel cell systems now been proven from a reliability, durability, and range perspective, opening doors to commercial and civilian applications.

Fuel cell-powered systems offer compelling value for unmanned aerial vehicles due to improved reliability over small internal combustion engines, enhancing safe and low maintenance operation. UAV systems powered by fuel cells operate longer than their battery counterparts, with the same benefits of low thermal and noise signature. Ballard, through our wholly-owned subsidiary Protonex, has demonstrated fuel cell-based propulsion as an alternative to battery and small engines on a number of small UAV platforms. This paper discusses the applicability of fuel cell-based propulsion in the next phase of UAV commercialization; particularly in platforms with a gross takeoff weight (GTOW) of 3-25 kilograms.

[1] https://www.fcnl.org/updates/understanding-drones-43
[2] http://www.usatoday.com/story/news/2016/08/29/faa-drone-rule/89541546/
[3] http://www.uasmagazine.com/articles/1573/uas-numbers-of-the-future

2 Commercial Uses of UAVs

UAVs are versatile tools that can be used in a range of surveying and monitoring applications. To date, businesses have primarily used UAVs largely to collect video and photographs, but there are many other applications of UAV technology that are poised to save commercial operations time and money while also enhancing safety and security.

Here is how some businesses are using UAVs and how they might use the technology in the future:

Infrastructure Monitoring
UAVs can survey vast swathes of critical infrastructure to assess the soundness of power transmission lines, hydroelectric dams, railroad tracks, mining operations, seaport operations, oil and gas pipelines and platforms from the air. Engineering firms use UAVs to map out future infrastructure projects.

Agriculture
UAVs can be used to take inventory of crops and identify failing crops or equipment, as well as be equipped to spray pesticides, fertilizers or water on crops. Unmanned aircraft avoid exposing pilots to toxic pesticides and the increased risk of injury due to low altitude flying where collisions occur with greater frequency.

Environmental Monitoring and Conservation
UAVs can operate discretely, monitoring wildlife populations and their habitat for health and migration habits without disturbance. UAVs equipped with night vision are also used to monitor wildfires and track and intercept poachers.

Real Estate
Drones are used to record and stream high definition video for aerial fly-over views of properties for sale or up for development.

Delivery
Door-to-door delivery by drones is a much talked about future application for UAVs. This is especially useful in regions with poor road infrastructure, making travel by ground onerous.

Wireless Internet Access
Large corporations have publicized efforts to bring internet access to the developing world with the help of UAVs conducting long-duration, high altitude flights over communities.

For these applications, the payload (i.e. thermal-imaging equipment) can be heavy, and gusty winds, hilly terrain or other unfavorable environmental conditions can make the UAVs difficult to operate. Propulsion systems providing sufficient power, range and maneuverability are essential.

3 Challenges with Incumbent Technologies

3.1 Battery Propulsion

Many small UAVs, and nearly all with a GTOW of under 10 kilograms, are based on lithium battery propulsion. This includes both multi-rotor and hand launched, fixed wing platforms. The attractiveness of batteries in these platforms is based on the simplicity of the propulsion, which requires minimal power system knowledge to implement. In addition, systems integrators have turned to electric propulsion for UAVs for a number of other benefits to the platform:

- 100% throttle flexibility, including mid-air start-stop capability
- Low observability – noise and thermal signature
- Payload flexibility and the ability to divert power from the drive train to the payload
- Flexibility in propeller and motor combinations to improve efficiency
- Zero emission operation

While these battery-based systems are sufficient for many consumer hobbyist applications, the energy density of batteries limits the platforms' range and endurance for commercial uses. Battery technology is receiving considerable attention with steady improvements in capacity, but even optimistic projections for capacity will not meet many of the UAV use cases contemplated. Additionally, as has been highlighted by several recent events, the quest for improved battery energy density often sacrifices some level of stability and, ultimately, safety. From a sustainability perspective, when batteries are not properly disposed of the toxic chemicals within can leach into the surrounding environment

3.1.1 Fuel Cells vs. Batteries

Fuel cells provide an attractive alternative to the battery-powered unmanned aerial vehicle as they maintain the simplicity and benefits of an all-electric architecture while taking advantage of highly energy-dense fuels. To compare fuel cell- and battery-based systems it is important to understand the fundamental differences in the two technologies (Table 1). A fuel cell resembles a battery in that it provides direct electrical current. However, unlike a battery, the fuel cell utilizes separate fuel (hydrogen) and oxidant (air) streams that are not contained in a discrete case. This makes a fuel cell system inherently safer than advanced high energy density battery technologies. The fuel cell itself is a way to convert the fuel and oxidant but does not store any energy. In general, because air is used as the oxidant and not stored with the fuel, the energy content of the fuel system well exceeds traditional battery systems.

Similarities	Differences
• Both directly generate electricity through electro-chemical reactions	• A battery stores energy, while a fuel cell generates energy on demand
• Both have an anode and a cathode in contact with an electrolyte	• A fuel cell does not need to be recharged; it is refueled by hydrogen and ambient air
• With both, individual low-voltage DC cells are combined in series to attain higher voltage and power	• In a fuel cell, the anode and cathode gasses (hydrogen and air) are kept separate; while in a battery they are in close proximity which can be a safety issue

Table 1: Comparison of fuel cells to batteries

The advent of fuel cell-based propulsion allows for the benefits of electric propulsion while maintaining enhanced range on most small UAV platforms. Fuel cell power systems typically will surpass batteries in stored energy if the mission duration is long enough to amortize the fuel cell system. To increase the endurance of a battery-powered UAV, additional batteries are added, growing the overall power system mass at a rapid rate. In comparison, to add additional endurance to a fuel cell powered system, only a larger hydrogen fuel tank is installed, adding run time with relatively minimal added mass (Figure 1).

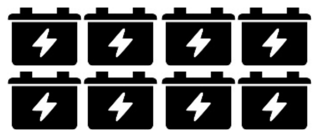
	SYSTEM MASS	
RUNTIME	*Battery Power System*	*Fuel Cell System*
x hours		
8x hours	 *Battery system mass increases at a rapid rate to add runtime*	 *Fuel cell system mass remains static, and only fuel storage increases to add runtime*

Figure 1: Impact of endurance demands on power system mass

3.1.2 Case Study – Ion Tiger

As an illustrative example, Protonex has collaborated with the Naval Research Laboratory (NRL) over the past ten years to demonstrate the utility of fuel cell-based propulsion systems on a number of UAV platforms. Each of these platforms was custom designed around the fuel cell propulsion system and the fuel storage subsystem, optimizing the outcome. The Ion Tiger UAV demonstrates the endurance advantages offered by hydrogen powered fuel cell systems. The Ion Tiger is a 16-kilogram system with a 3-meter wingspan designed around a composite hydrogen tank (300 bar). It has the capability to carry a 2.2-kilogram payload. When fuel was stored onboard the vehicle as compressed gaseous hydrogen, the Ion Tiger platform demonstrated 26 hours of flight. For comparison, an equivalent weight of batteries would provide an endurance of approximately 4 hours. Separately, the Ion Tiger was outfitted with a liquid hydrogen storage subsystem and demonstrated 48 hours of flight time (Figure 2).

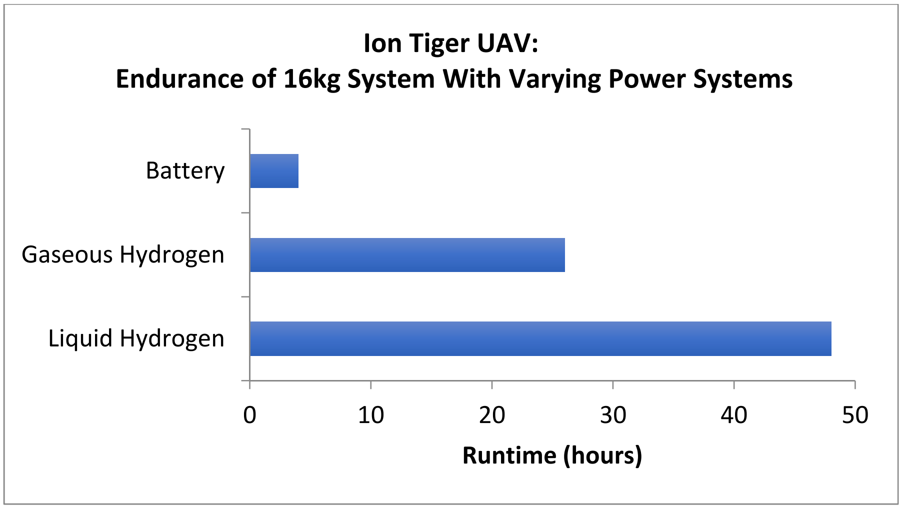


Figure 2: Ion Tiger UAV

Based on current improvements in fuel storage and the efficiency of the fuel cell, this platform could stay aloft for 3 to 4 days based on liquid hydrogen. Details regarding this project have been published in papers entitled, "Hydrogen Fuel Cell Propulsion for Long Endurance Small UAVs"[4] and "Projecting the Impact of Aircraft Design Decision on the Performance of a Fuel Cell Power and Energy System in Unmanned Aircraft Systems".[5]

3.2 Small Internal Combustion Engine Propulsion

UAV platforms traditionally powered by small internal combustion engines (ICEs) have different advantages than those powered by batteries. Given the high energy density of liquid hydrocarbons, ICE-powered UAVs have very good endurance versus battery-powered vehicles. That said, small engines have numerous deficiencies even after considerable investments in improving reliability and predictability. In operation, small engines are noisy and polluting with a high thermal signature, making them less suitable for applications where stealth is valued, such as environmental monitoring and conservation. The small engines have a narrow band of fuel efficient operation and poor load following capabilities, with an electric alternator sized to specific power and payload requirements.

3.2.1 Fuel Cells vs. ICE

In addition to the advantages provided by electric propulsion enumerated above, systems integrators are also attracted to fuel cells as a replacement to ICE systems for the following advantages:

- Significant improvement in the expected MTBF (mean time between failures), up to five times of traditional small engine systems
- Altitude flexibility; unlike traditional ICEs, fuel cells have positive control of the airflow so power derating with altitude can be effectively managed without grossly oversizing the propulsion system
- Extremely low thermal, acoustic and vibration signatures
- Flexible application of on-aircraft power

[4] https://www.nrl.navy.mil/lasr/content/hydrogen-fuel-cell-propulsion-long-endurance-small-uavs
[5] http://papers.sae.org/2012-01-2178/

- Significant reduction in pollutants emitted during operation (water vapor being the only exhaust in pure hydrogen systems)

The following table provides a comparison of the two technologies (Table 2).

ATTRIBUTE	FUEL CELL	ICE
• Low MTBF	+	−
• Payload flexibility	+	−
• Altitude flexibility	+	−
• Load following capability	+	−
• Low noise, vibration and thermal signature	+	−
• Low environmental emissions	+	−
• Endurance	+	+
• Fuel efficiency	+	−

Table 2: Comparison of fuel cells to internal combustion engines

3.2.2 Case Study – ScanEagle®

In conjunction with Insitu, Protonex designed a hybrid fuel cell propulsion module to augment propulsion system offerings for the ScanEagle® unmanned aerial system (Figure 3). The propulsion module fits within the existing airframe without modification, so it is compatible with the considerable number of ScanEagle® systems in the field. Flight testing is planned for the fuel cell-based ScanEagle® at Insitu's test facilities to demonstrate many of the attributes of electric propulsion listed above.

Figure 3: Boeing Insitu ScanEagle®

3.3 Other Approaches

Much attention has been drawn to solar-battery driven UAVs, especially in the quest for flight durations of weeks or months. In particular, the potential for UAVs to augment satellite-based systems is particularly attractive but requires extensive flight times to become an economic reality. Solar-based systems are a good solution for platforms that can fly consistently above cloud cover but will have limited practical utility for lower flying craft. [6] Solar powered UAVs still require an energy storage component to keep aloft when the sun is not shining. Batteries are the simplest solution, but as the total energy stored increases beyond approximately 100-kilowatt hours, a fuel cell/electrolyzer based system can decrease weight and improve the platform performance. A fuel cell/electrolyzer system stores the excess electricity from solar via water electrolysis to hydrogen and oxygen. These gasses can be compressed and stored in composite pressure vessels. When the solar subsystem is not providing enough energy, the hydrogen and oxygen are fed into the fuel cell.

4 Fuel Cell Powered UAV Design Considerations

Historically all-electric propulsion meant battery-based energy storage, with a significant reduction in range and endurance over engine-based systems. The advent of fuel cell propulsion allows for the benefits of electric propulsion while maintaining sufficient range on most small UAV platforms. That said, there are certain factors to consider when designing a fuel cell powered UAV.

4.1 Size Matters

Fuel cell propulsion systems are not applicable to all UAV platforms or applications. At present, the power density of traditional engines cannot be rivaled by fuel cell systems. As such, the use of fuel cells in larger UAVs (group IV, >600kg) is more exploratory and focused on emissions reduction at present. Given the amount of active investment in fuel cell technology, there is no doubt that fuel cells will gain additional markets as these systems are transitioned to high volume manufacturing. Initial experiments with small manned aircraft are a hint to what lies ahead for fuel cell-based propulsion.[7]

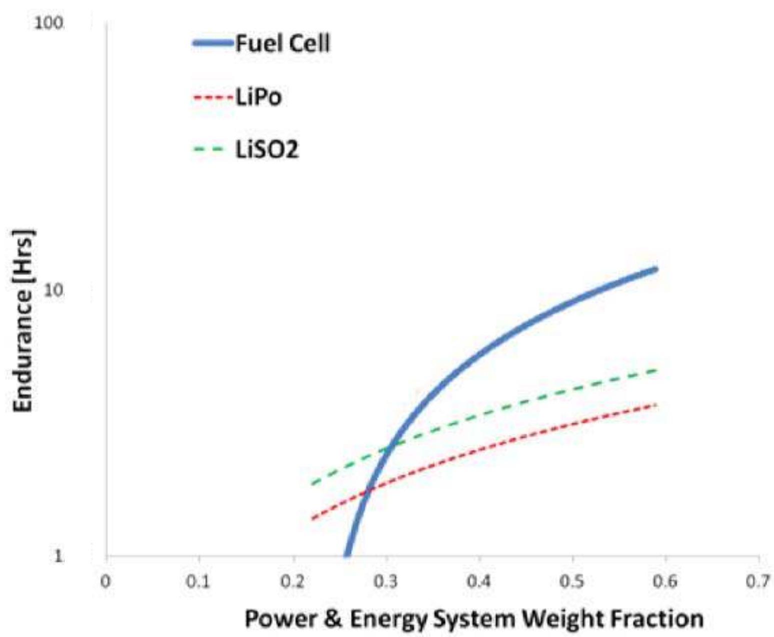


Figure 4: System weight fraction

[6] https://www.yahoo.com/tech/historic-solar-impulse-team-planning-drone-174129042.html

[7] https://airbusdefenceandspace.com/our-portfolio/military-aircraft/uav/zephyr/

At the other end of the scale, Protonex has looked extensively at the applicability of fuel cell propulsion for small quadcopters and other vertical take-off and lift (VTOL) UAVs. The significant power required for maneuvering and lack of traditional lift surfaces favors batteries for smaller craft and shorter missions. Most hobby activities are dominated by batteries and would show no material improvement with fuel cell-based propulsion. Commercial missions based on small VTOL UAVs of under-five kilograms are not good candidates for fuel cells given the limited weight dedicated to energy storage (Figure 4).

Larger VTOL craft, over five kilograms, could have significant endurance improvements based on fuel cell propulsion, but care must be taken to provide the power required for full maneuverability. Underpowered systems can be demonstrated under controlled conditions, but are of limited utility in real world applications.

Range and endurance for VTOL UAVs will always be shorter than fixed wing aircraft of similar GTOW. Transitioning fixed wing aircraft with VTOL capabilities can be significantly improved by fuel cell propulsion. In fact, fuel cell propulsion may make applications like package delivery and remote medical support possible given the combination of requirements including range, payload capability, and VTOL.

4.2 Hybridization

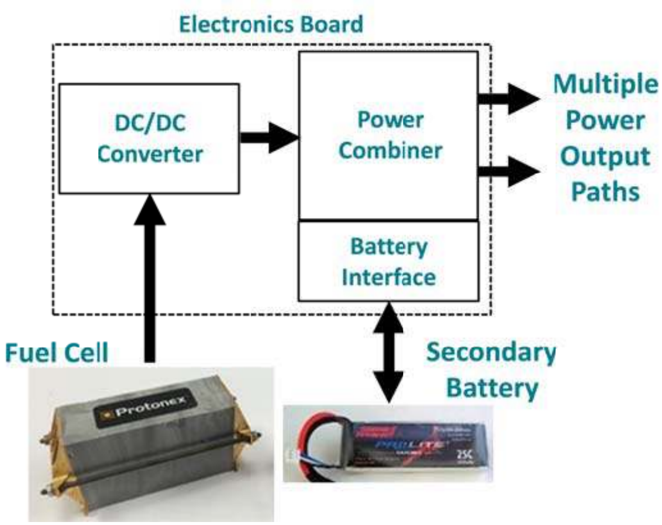


Figure 5: Energy management scheme

Often the best propulsion solution includes both fuel cells and batteries with appropriate power management electronics. Generally, batteries have better power density (power per unit weight) than fuel cells. In contrast, fuel cell systems typically provide higher energy density than batteries, assuming long enough flight duration. The attributes of both these systems can be combined in a hybrid propulsion system to good effect, although it does increase the complexity (Figure 5). The power management electronics monitors the battery state of charge and the fuel cell output relative to the vehicle and payload requirements. In periods of high power demand, power is supplied both by the fuel cell and the battery. In periods of low demand, some of the fuel cell power will recharge the battery. Once the battery is fully charged, the fuel cell system can be directly output to the vehicle load.

Take for example small hand-launched UAVs like the Lockheed Martin Desert Hawk. The fuel cell system provides power up to two times the cruise power required. Any additional power required is provided by the battery. This is especially useful for takeoff where additional power makes hand launching easier. Hybridization can also be useful in managing diverse payload power requirements including payloads that might traditionally overwhelm other power sources, such as active radar.

4.3 Fueling Options

Fuel cell systems consume hydrogen fuel. Hydrogen can be produced in large “central production” plants and transported to the point of end-use and stored until use. Liquid hydrogen is the most cost-effective form of hydrogen to transport. Hydrogen may also be produced in smaller “distributed production” facilities, very near or at the point of end-use. Hydrogen required to operate the UAV could be generated on-site and on-demand using available water and a portable electrolyzer driven by a ground-based generator; by this approach, the system is multi-fuel capable, including JP-8, a type of diesel.

Various means for storing the hydrogen fuel onboard the UAV have been evaluated. Compressed hydrogen storage systems have been demonstrated in hundreds of prototype fuel cell vehicles and are available commercially at low production volumes. Storage of hydrogen as a gas typically requires high-pressure carbon-composite tanks (350–700 bar [5,000–10,000 psi] tank pressure). Storing liquid hydrogen in tanks takes special handling and materials to contain and keep the fuel cool, to prevent waste via “boil-off.”

One convenient way to store hydrogen for smaller UAV platforms is based on chemical hydride cartridges. In general, a chemical hydride can store hydrogen at low pressure with minimal packaging that can be liberated as the fuel cell consumes the hydrogen. Typically these systems run at low pressures, so the weight of a compressed hydrogen storage tank is not necessary. One drawback is the added cost and complexity of the fueling subsystem that is required to liberate the hydrogen.

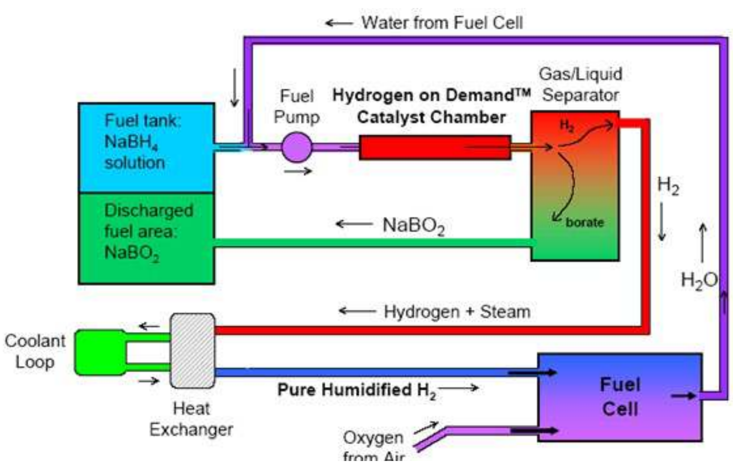


Figure 6: Sodium borohydride system flow diagram

Figure 7: Sodium borohydride cartridges (1350 watt hours)

Protonex has worked extensively with the chemical hydride, sodium borohydride, which has a large hydrogen content, is readily available and cost effective. The chemical hydride is stored in a water based solution that is non-flammable. By pumping the sodium borohydride solution over a catalyst bed, the hydrogen is liberated as needed by the fuel cell system (Figure). This system is completely load-following and can be ramped from no hydrogen production to full output in 3-5 seconds. Similarly, hydrogen production can be idled instantly without loss of hydrogen. See Table 3 for a comparison of hydrogen storage methods.

H2 Storage Method	H2 Mass Percentage* (%)	Specific Energy* (Wh/g)	H2 Density* (g/L)	Energy Density* (Wh/L)
Compressed Gas (5,000-10,000 psia, 25°C)	100	20	23 - 39	450 - 770
Cryogenic Liquid (50 psia, Tsat = -248°C)	100	20	64	1270
Aqueous Sodium Borohydride (15psia, 25°C)	4.0 – 6.4	0.8 – 1.3	41 - 64	810 - 1270

**Estimates do not include the mass and volume of tank/containment structure*

Table 3: Comparison of Hydrogen Storage Methods

The chemical hydride system is packaged as a cartridge that can be installed prior to flight (Figure). Once primed on the ground, the system interfaces with the fuel cell to provide hydrogen as needed. Once completed the cartridges can be discarded or returned for remanufacturing.

5 Path Forward for Fuel Cell-Based Propulsion

5.1 Fuel Cell UAV Demonstrations

The attributes of fuel cell-based propulsion have been demonstrated in a variety of UAV platforms, and the technology is rapidly being matured for commercial and military applications. Systems integrators interested in extended duration and/or reliability improvements over traditional propulsion system have additional choices. After ten years of pioneering work on fuel cell-based propulsion systems, Protonex has extensive experience integrating the technology into a variety of all-electric small UAVs (Table 4).

Unmanned System	Endurance	Weight	Fuel Type	Fuel Cell Power
NRL Ion Tiger	26 hours	16 kg	Pressurized hydrogen	550W
NRL Ion Tiger	48 hours	16 kg	Liquid hydrogen	550W
NRL XFC-Submarine Launch	7 hours	9 kg	Pressurized hydrogen	550W
Lockheed Martin Desert Hawk EER	6-8 hours	6.8 kg	Chemical hydride	350W
Insitu ScanEagle®	4-10 hours	22 kg	Pressurized or liquid hydrogen	1,200W

Table 4: Launched UAV platforms

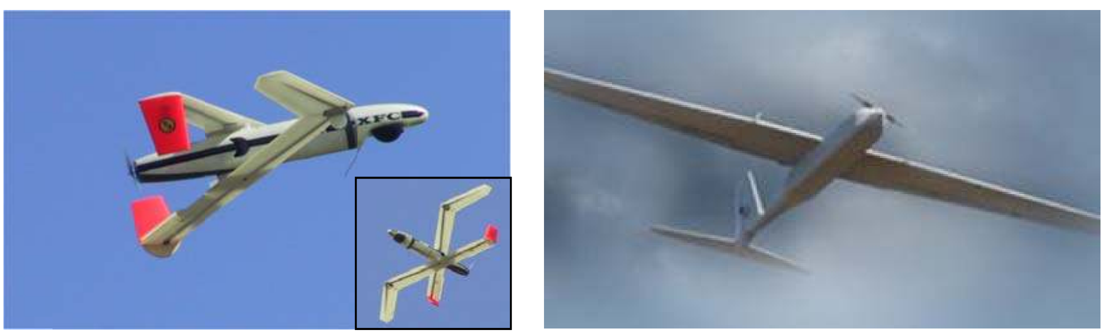


Figure 6: NRL XFC-Submarine Launch (left) and Lockheed Martin Desert Hawk EER (right)

5.2 Fuel Cell UAV Development

Manufacturers eager to accelerate the introduction of a fuel cell powered UAV to the marketplace should consider a PEM fuel cell propulsion module developed by Protonex (Figure 7). The scalable module includes the fuel cell stack and key balance of plant components that make for straightforward integration into the UAV. Alternatively, the module can serve as a starting point for product customization. The high-level project plan below outlines the phases of a typical integration project:

- **Phase 0 – Technology Evaluation:** Protonex engineers have developed a methodology to estimate the weight fraction required to be devoted to the power system based on common conceptual design inputs, thereby allowing aircraft designers to determine the suitability of utilizing a fuel cell system early in the design process.

- **Phase 1 – Aircraft Integration:** This phase focuses on the integration of the Protonex fuel cell system into an all-electric UAV. Development and testing of the system and system components will validate usage profiles, system design, and operating strategies.

Figure 7: Protonex PEM fuel cell propulsion module

- **Phase 2 – Integrated System Ground Testing:** The objective of this phase is to demonstrate overall system performance on the ground. An extensive test program will evaluate system performance over the full range of load conditions expected in flight.

- **Phase 3 – Integrated System Flight Testing:** In this phase, the system design is optimized based on Phase 2 feedback. A fully operational UAV will undergo multiple test events at a closed flight test facility to demonstrate the capability of the system.

- **Phase 4 – Pilot Deployment:** In this phase, the system design is optimized based on Phase 3 testing feedback. Prototype systems are delivered for testing at a customer site to validate the design under real-world conditions.

- **Phase 5 – Commercial Deployment:** This phase includes scale-up of production and delivery to a broad customer base at volume.

Through the life of the program, from concept until delivery of the fully integrated and operational UAV, Protonex's highly skilled engineering team supports the UAV manufacturer in the acceleration of fuel cell product development and deployment efforts. As experts in portable power solutions, Protonex understands the needs of unmanned systems when it comes to power. To learn more about what Protonex can do to keep UAVs in flight longer, contact us today at www.protonex.com.

6 About Ballard Power Systems

Ballard Power Systems is recognized as a world leader in the design, development and manufacture of clean energy fuel cell products. Ballard is located in Burnaby, British Columbia, Canada, where the company operates a fully equipped R&D, engineering and test facility, as well as a high-volume fuel cell manufacturing facility. Ballard's proprietary technology which draws on intellectual property from our patent portfolio together with our extensive experience and know-how in key areas of fuel cell stack operation, system integration, and fuel processing.

There are approximately 450 employees at Ballard with half made up of Ph.D.'s, engineers, scientists, and technologists focused on developing fuel cell products primarily for motive applications and providing engineering services to key customers and markets. Ballard also has sales, R&D and manufacturing facilities in the United States and Denmark.

To learn more about Ballard, please visit www.ballard.com.

7 About Protonex Technology Corporation

Protonex Technology Corporation, a wholly owned subsidiary of Ballard, is a leading designer and manufacturer of advanced power management products and portable fuel cell solutions. Protonex develops, tests, and manufactures portable power management products in Southborough, Massachusetts. Protonex has commercialized and deployed several products designed for end-users in military and commercial markets that are currently underserved by batteries and small generators and has received development programs from U.S. military and U.S. government organizations. Recently, Protonex's family of fuel cell propulsion systems were designated as EAR99 (Export Administration Regulations 99) compliant by the U.S. Department of Commerce, creating a path for commercial export and deployment in a variety of civilian unmanned vehicle applications.

For more information about Protonex power managers, chargers and fuel cells please visit www.protonex.com.

8 Patents

Protonex products are protected by patents in the U.S. and elsewhere. To view the list of these patents, visit https://protonex.com/company/protonex-patents/. The list of Protonex products published on the website may not be all-inclusive, and other Protonex products not listed may be protected by one or more patents.