NORTH ATLANTIC TREATY ORGANIZATION

SCIENCE AND TECHNOLOGY ORGANIZATION

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STO TECHNICAL REPORT **TR-SET-173-Part-II**

Fuel Cells and Other Emerging Manportable Power Technologies for the NATO Warfighter – Part II: Power Sources for Unmanned Applications

(Piles à combustible et autres technologies portatives d'alimentation en énergie pour les combattants de l'OTAN – Partie II : Sources d'alimentation des applications sans pilote)

This is the Final Report of SET-173 "Fuel Cells and Other Emerging Manportable Power Technologies for the NATO Warfighter" on the use of fuel cells in four types of unmanned vehicles, Unmanned Aerial Vehicles (UAVs), Unmanned Ground Vehicles (UGVs), Unmanned Underwater Vehicles (UUVs) and Unmanned Surface Vehicles (USV).

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The NATO Science and Technology Organization

Science & Technology (S&T) in the NATO context is defined as the selective and rigorous generation and application of state-of-the-art, validated knowledge for defence and security purposes. S&T activities embrace scientific research, technology development, transition, application and field-testing, experimentation and a range of related scientific activities that include systems engineering, operational research and analysis, synthesis, integration and validation of knowledge derived through the scientific method.

In NATO, S&T is addressed using different business models, namely a collaborative business model where NATO provides a forum where NATO Nations and partner Nations elect to use their national resources to define, conduct and promote cooperative research and information exchange, and secondly an in-house delivery business model where S&T activities are conducted in a NATO dedicated executive body, having its own personnel, capabilities and infrastructure.

The mission of the NATO Science & Technology Organization (STO) is to help position the Nations' and NATO's S&T investments as a strategic enabler of the knowledge and technology advantage for the defence and security posture of NATO Nations and partner Nations, by conducting and promoting S&T activities that augment and leverage the capabilities and programmes of the Alliance, of the NATO Nations and the partner Nations, in support of NATO's objectives, and contributing to NATO's ability to enable and influence security and defence related capability development and threat mitigation in NATO Nations and partner Nations, in accordance with NATO policies.

The total spectrum of this collaborative effort is addressed by six Technical Panels who manage a wide range of scientific research activities, a Group specialising in modelling and simulation, plus a Committee dedicated to supporting the information management needs of the organization.

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These Panels and Group are the power-house of the collaborative model and are made up of national representatives as well as recognised world-class scientists, engineers and information specialists. In addition to providing critical technical oversight, they also provide a communication link to military users and other NATO bodies.

The scientific and technological work is carried out by Technical Teams, created under one or more of these eight bodies, for specific research activities which have a defined duration. These research activities can take a variety of forms, including Task Groups, Workshops, Symposia, Specialists' Meetings, Lecture Series and Technical Courses.

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Disclaimer

The information contained within this report has been compiled within the SET-173 Task Group from member inputs. It is recognised that this may not reflect the totality of the current and near future capabilities and does not encompass all of the available manufactured products whether representative of production or prototypes.

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Fuel Cells and Other Emerging Manportable Power Technologies for the NATO Warfighter – Part II: Power Sources for Unmanned Applications

(STO-TR-SET-173-Part-II)

Executive Summary

Goal: To identify and report on the state-of-the-art of fuel cell technology for application in unmanned ground, aerial and above/below water. Currently all these systems rely on either rechargeable batteries, an Internal Combustion Engine (ICE) or a combination of the two, depending on the size of the system, to provide power for propulsion, sensors and weapons. The major problem related to the use of batteries or an ICE is lack of time on station/mission endurance. Reducing the weight or increasing the energy density of the energy source frees up payload that can be applied to weapons/sensor packages of extended mission times.

A contributing factor in the potential solutions is that many of these platforms require a power source with both high power and high energy densities. Fuel cells offer a high energy density, and when combined with a rechargeable battery into a hybrid configuration, a high power density requirement. Fuel cells offer some advantages not seen in the current alternatives. For underwater platforms they offer a significant reduction in noise, thermal and mechanical signatures that reduce the potential for detection. The same can be said for ground systems, where silent watch is a desired trait for vehicles. For aerial systems the wieght saving couples with longer mission times allows for greater weapons and sensor packages and increased loiter times.

There are some challanges facing the adaptation of fuel cells, the largest being the ability to use logistic fuels. This challange is more significant in the smaller systems than in larger ones. Other issues are the intial cost and lack of proven reliability of the systems that have been demonstrated to date.

Underwater applicatons have their own unique challanges not faced by other unmanned systems, The two most significant are the high pressures that the systems may encounter and the fact that since they have no access to oxygen, they must either carry the oxident on board or generate it from the fuel source.

In conclusion fuel cells for unmanned systems have the potential for significant increase of energy density, and consequently endurance, compared to batteries and lower signature compared to ICE-systems. The potential increase of energy density is highly dependent on the mission scenario and the unmanned system, and needs to be calculated for each case. In general, fuel cell systems will be more favourable in systems with high energy demand and low average power. The report includes results of analysis of using fuel cells in different unmanned vehicles in different scenarios. Conclusions from these analyses are presented under each section.

Piles à combustible et autres technologies portatives d'alimentation en énergie pour les combattants de l'OTAN – Partie II : Sources d'alimentation des applications sans pilote

(STO-TR-SET-173-Part-II)

Synthèse

Objectif : identifier et rendre compte de l'état de la technologie des piles à combustible pour leur emploi dans les applications sans pilote, terrestres, aériennes et sous-marines / de surface. Actuellement, tous ces systèmes reposent sur des piles rechargeables, un moteur à combustion interne (MCI) ou une combinaison des deux, en fonction de la taille du système, pour alimenter la propulsion, les capteurs et les armes. Le grand problème de l'utilisation des piles ou d'un MCI est la durée réduite de disponibilité en mission / en place. Réduire le poids ou augmenter la densité d'énergie de la source d'alimentation libère une charge utile qui peut être occupée par des armes / boîtiers de détection ayant une durée de mission plus longue.

Les solutions potentielles ont besoin, pour beaucoup d'entre elles, d'une source d'alimentation présentant une grande densité de puissance et d'énergie. Les piles à combustible offrent une forte intensité d'énergie et, associées à une pile rechargeable en configuration hybride, une grande densité de puissance. Les piles à combustible présentent des avantages absents des alternatives actuelles. Dans les plates-formes sous-marines, elles permettent une réduction importante des signatures sonore, thermique et mécanique, ce qui réduit le potentiel de détection. Cela vaut également dans les plates-formes terrestres, où la surveillance silencieuse est une caractéristique souhaitée des véhicules. Dans les systèmes aériens, l'économie de poids associée à l'allongement de la durée de mission permet l'emport de plus grosses armes, et de plus de capteurs et des temps sur zone plus importants.

L'adaptation des piles à combustible présente un certain nombre de défis, le principal étant la capacité d'utilisation de combustibles courants. Ce défi est plus important dans les petits systèmes que dans les grands. Les autres problèmes sont le coût initial et le manque de fiabilité démontrée des systèmes testés jusqu'à présent.

Les applications sous-marines ont leurs propres défis, inconnus des autres systèmes sans pilote. Les deux principaux problèmes sont les hautes pressions auxquelles les systèmes peuvent être confrontés et le fait que, n'ayant pas accès à l'oxygène, ils doivent soit transporter l'oxydant à bord, soit le produire à partir de la source d'alimentation.

En conclusion, les piles à combustible destinées aux systèmes sans pilote pourraient permettre une hausse importante de densité d'énergie, et donc de durée de fonctionnement, par rapport aux piles, et une réduction de la signature, par rapport aux systèmes à MCI. L'augmentation potentielle de densité d'énergie dépend grandement du scénario de la mission et du système sans pilote et doit être calculée au cas par cas. En général, les systèmes de pile à combustible seront préférables dans les systèmes demandant beaucoup d'énergie et une faible puissance moyenne. Ce rapport inclut les résultats d'analyse de l'utilisation de piles à combustible dans différents véhicules sans pilote et différents scénarios. Les conclusions de ces analyses sont présentées à la fin de chaque section.

Chapter 1 – GENERAL INTRODUCTION TO UNMANNED VEHICLES

Unmanned Vehicles (UVs) are fast becoming the cornerstone of military operations. A large number of unmanned air, ground and sea vehicles are in the works and deployed around the world. Because of their lower cost, every military organization is developing systems in this domain. These UVs come in many sizes and varieties depending on operational function.

For example in the large Unmanned Aerial Vehicle (UAV) family is the U.S. Air Force Global Hawk surveillance aircraft that can give high-resolution Synthetic Aperture Radar (SAR) images. It can survey as much as 100,000 square kilometers in a day, with a maximum endurance of 35 hours and a payload of 1360 kg as well. Another example is the Predator, smaller than the Global Hawk and can carry offensive weapons such as smart bombs in addition to heavy sensor packages. The Predator's endurance of 14+ hours puts it in high demand in the field.

There are also many unmanned vehicles being designed for ground operations, which also come in various sizes. They range from the Dragon Runner, which weighs 4 kg, to larger ones like the Modular Advanced Armed Robotic System (MAARS) which can weigh up to 159 kg with a full sensor and armaments package. These types perform a range of applications, from explosive ordinance disposal to offensive capabilities.

Unmanned Underwater Vehicles (UUVs) tend to be more challenging because of the need for oxidant as well as fuel. UUVs have self-contained navigational systems and can be used for a wide variety of uses. There are a variety of commercial and military platforms and Autonomous Underwater Vehicles (AUVs) such as the Battlespace Preparation Autonomous Underwater Vehicle (BPAUV) built by Bluefin-21 and Remus 100. These designs follow that of torpedoes or submarines and utilize conventional propellers for propulsion.

Unmanned Surface Vehicles (USV) provides a capability on the surface of the water. An example is the Protector which operates atop the waves and can run autonomously or be remotely controlled. It can be used for many different missions, including; anti-terrorism force protection, Intelligence, Surveillance, and Reconnaissance (ISR), anti-surface warfare Anti-Submarine Warfare (ASW), and Anti-Mine Warfare (AMW). It can be used for long-range standoff surveillance or to patrol for naval vessels. One of the main advantages to UVs, either in the air, on the ground or surface of the water, is that these remote-control vehicles typically use wireless communication which means the operator can be located on the other side of the world. This provides the second advantage of UVs in that it eliminates a large amount of life support and hardware needed to support a human occupant. The lack of a human occupant makes these robotic vehicles more disposable than their manned counterparts, allowing for their use in more dangerous situations. A third advantage is specialists and operators work together and having a team available means they can be rotated and stay fresh even when the vehicle has been in the operation for days.

To enable the wider use of UVs, there is a need for more efficient, powerful, and logistically supportable power plant solutions for propulsion. The propulsion systems for unmanned vehicles are influenced by 5 main features, apart from size, whose requirements are different than those of manned ones. These requirements are endurance, operational usage (it may have longer stored periods before its use, shorter life requirements, longer operational schedule without rest, shorter and rougher take-off and land on situations), higher power to operate the payload and vehicle equipment, lower signature design and lower cost. The development of new engine technologies to improve the vehicle performance is focused in current UAS.

The characteristics that define the power plants are their thrust or power, weight, specific fuel consumption and cost. All new power plant developments are directed at improving these characteristics as much as possible. Depending of the vehicle size, the conventional engines used are gas turbines and reciprocating engines. The new initiatives are working on more efficient embedded turbine engines, IC engines operating with heavy fuels and, electric propulsion for smaller platforms. Some of the current trends for electric propulsion applications are: batteries, fuel cells, solar cells, capacitors. Even some initiatives on microwave electric propulsion, using a rectenna, have existed, but without enough success (SHARP project by Canadian Communications Research Center in 1987) [1].

Currently, all UVs are powered using batteries, an internal combustion engine or a combination of the two. Fuel cells are a good, and efficient, alternative to batteries and reciprocating engines. Fuel cells are devices that electrochemically combine fuel and air to produce high-quality electrical power. Because these systems do not generate power via combustion processes, they offer significantly lower Specific Fuel Consumption (SFC) rates relative to advanced heavy fuel engines or diesel power generators. Some options, such as Solid Oxide Fuel Cell (SOFC) systems offer high efficiencies and fuel flexibility, with low audible signature making them a compelling solution to power unmanned missions.

Be they large or small, airborne or aquatic, unmanned vehicles will continue to improve and be deployed more heavily in the future. Significant improvements are in the works, but major design challenges remain, especially as these robots move toward autonomous operation. Issues of response time, field reliability, bandwidth, and even congestion of frequencies used to control vehicles arise in the real world. Bandwidth will be an issue with any wireless solution and even some wired solutions.

Chapter 2 – UNMANNED AERIAL VEHICLES (UAVs)

2.1 INTRODUCTION

2.1.1 Definition of UAV

Unmanned Air Vehicles (UAVs) are aerial powered platforms with no on-board human operator. They are small aircrafts with an on-board computer or microprocessor together with control, sensor and communication electronics. They may be remotely-controlled or autonomous, using pre-programmed flight plans or more complex dynamic "shelf-thinking" systems[1]; and they may be recoverable or expendable. Remotely Piloted Vehicle (RPV) [2] UAVs have military and civil applications such as perform reconnaissance or attack missions and border surveillance. In general employing a UAV is considered useful for dull, dirty or dangerous missions. The UAV represents a cost effective, safer and more environmentally responsible approach compared in an internal combustion engine for light pay load aerial military and civil missions.

2.1.2 Description of Existing UAV Systems

There is a wide range of UAV types, from micro to small aircraft scale with a wide range of characteristics:

- Maximum take-off weight from grams to more than 15,000 kg;
- Maximum speeds from 10 m/s to more than 1,000 km/h;
- Flight endurances from minutes to months;
- Ranges up to 20,000 km and more;
- Rotor, fixed wing and lighter than air technology; and
- Controlled by pre-programmed, remote control or shelf-thinking methods.

UAVs can be classified by various performance parameters such as range, altitude, weight, wing load, engine type or power. They also can be classified by their mission or purpose as the six functional categories listed below from [3]:

- Target and decoy;
- Reconnaissance;
- Combat;
- Logistics;
- R&D, data collection; and
- Civil and Commercial applications.

Another method of grouping UAVs is shown in Table 2-1 extracted from [3].

[1] EP/EXPO/B/SEDE/FWC/2006-10/Lot4/05. UAVS AND UCAVS: DEVELOPMENTS IN THE EUROPEAN UNION. October 2007.

Table 2-1: UAV Grouping Adapted from [3].

UAS CATEGORY	MAXIMUM GROSS TAKE-OFF WEIGHT (kg)	NORMAL OPERATING ALTITUDE (m)	SPEED	CURRENT/FUTURE UAS (Examples, not all Inclusive)
GROUP 1	0 – 9	< 370	< 185 km/h	WASP, Future Combat Systems Class I, Pointer
GROUP 2	10 – 25	< 1000	< 460 km/h	ScanEagle, Silver Fox, Aerosonde, Skylark II
GROUP 3	25 – 600	< 5500	< 460 km/h	Shadow 200, Neptune, STUAS, Camcopter
GROUP 4	> 600	< 5500	Any Airspeed	Hunter, VTUAV, A-160
GROUP 5	> 600	> 5500	Any Airspeed	Reaper, Global Hawk. Global Observer, N-UCAS

However, the most comprehensible classification is derived from the 2006 EU briefing paper on UAVs [2], where 6 categories are defined although the boundaries between them are not clear, because some features belong to two different categories. The following examples are some of the more relevant UAVs in each classification.

Group 1 – Micro-UAV: "Mostly portable, hand-launched, very short range / low altitude (± 2 km / 600 m) with a simple propulsion system and payload of less than 1 kg (small video camera)".

Some examples from [3], [4] and [5] (many of them are already in production but some are still in development) are:

- WASP (AeroVironment Inc. – USA): 0.3 kg; altitude 3000 m and 1-hour endurance powered by electric motor and lithium-ion battery (10DC W).[2]
- PD100 (Prox Dynamics – Norway): 16 g rotary-wing UAV; in operation (UK and Norway); video and GPS; Powered by electric motor and rechargeable Lithium polymer batteries.
- CAROLO P50 (Mavionics GmbH – Germany): 550 g; 0.5 h; 500 m ceiling; 50 W Li-poly battery, electric motor (in development).
- GOLDEN EAGLE (Cradance Services Pty Ltd – Singapore): 850 g (80 g); 1 hr and 200 m ceiling; powered by rechargeable batteries; brushless motor.
- MICROB (Bluebird Aero Systems Ltd. – Israel): 1 kg (200 g); range 15 km and 1 h of endurance; 4000 m; electrical powered.
- RAVEN RQ-11B 7 (AeroVironment): 1.9 kg (200 g); 90 min; 10 km.; Aveox brushless 27/26/7 electric motor.
- RECCE D6 (CE Stephansen – Norway): 2.8 kg; range 10 km and 0.55 h endurance (70 km/h; powered by 200 W LiPoly battery and a brushless motor.

[2] UAV Handbook Shephard 2008.

- Aladin ((EMT – Germany): 3.2 kg UAV with ±5 km range and 30 minutes endurance; small surveillance camera payload; powered by electric motor and rechargeable Lithium polymer batteries.
- PUMA (AV Inc. – USA): 5.5 kg; 4 h endurance, 3000 m of ceiling; range speed up to 90 km/h; powered by 600 W DC electric motor; there is also a prototype, powered by a hybrid fuel cell / lithium-ion battery with an endurance of 9 hours.
- Bird Eye 400 (IAI – Israel): 5.6 kg (1.2 kg); endurance 80 min; ceiling max. 300 m; 10 km range.
- CAROLO T200 (Mavionics GmbH – Germany): 6 kg (1.5 kg); 1 h; 4000 m; 40 km; 2 x 250 W battery or twin electrical brushless motor.

(a) Wasp **(b) Aladin** **(c) Puma**

Figure 2-1: Examples of Micro-UAVs.

Group 2 – Mini- or Close-UAV: Very short range / low altitude (max. 10 km / 2000 m) with a payload of several kg (high resolution large video or thermal camera):

- AEROSONDE 4 (Aerosonde Pty Ltd. (AAI Corporation) – USA): 15 kg; 1000 m radius and more than 24 hours of endurance, 112 km/h; powered by 24 cc H type 1 kW unleaded petrol fuel injected.
- ALO (INTA – Spain): 20 kg (6 kg payload); 200 km/h; endurance and range powered by a 4.85 kW gasoline 2-stroke engine.
- BAT 3 (MLB Company – USA): 9 kg; 6-hour endurance; 23 cc gasoline 2-stroke engine (1.64 kW).
- BOOMERANG (BlueBird Aero Systems – Israel): 9 kg (1.2 kg); 6 hour; 40 km; electrical power (batteries and fuel cells).
- JAVELIN (L-3 BAI Aerosystems – USA): 9 kg (1.45 kg payload); 2 hours; 300 m ceiling; 1 single 2-stroke engine.
- AZIMUT (Alcore Technologies–/ France): 9 kg (2 kg payload); 2 h / 300 m; 10 km.; 600 W Li-poly and one brushless electric motor.
- ION TIGER (NRL – USA): 17 kg (2 kg); 26 h; 550 W fuel cell.

(a) ALO **(b) BAT 3** **(c) AZIMUT**

Figure 2-2: Examples of Mini- or Close-UAVs.

Group 3 – Short range, NATO-type or Tactical UAV: Short range / low – medium altitude (50 – 150 km / max. 4500 m) with a payload of up to 100 kg:

- LUNA (EMT – Germany): 40 kg; 6 h; 5000 m; 70 km/h; 5 kW 2-cylinder 2-stroke engine; driving pusher propeller.
- FUTURA (Alcore Technologies – France) : 70 kg (10 kg); 1.1 h; 300 m; 50 lb turbojet.
- CRECERELLE (Sagem – France: 145 kg; 5 h; 3100 m; 160 km/h; 20 kW (26 hp) rotary engine (WAE342).
- HERMES 180 (Elbit – Israel): 195 kg (32 kg); 10 h; 4500 m; 38-hp rotary UEL engine.
- SIVA (Inta – Spain): 290 kg (45 kg); 7 h; 4000 m; 250 km/h; 36 kW 4-cylinder, 2-stroke engine; there is a prototype powered by electric brushless motor and a 20 kW hydrogen fuel cell.

(a) LUNA

(b) SIVA

Figure 2-3: Examples of Short Range Tactical UAVs.

Group 4 – Medium range or tactical UAV: Medium range / medium altitude (200 km / 6000 m) UAV with a payload of up to 150 kg:

- SPERWER (Sagem – France): 350 kg; 12 h; 6100 m; 160 km/h, 70-hp 2-stroke engine.
- HERMES 450 (Elbit – Israel): 450 kg; 20 h; 5500 m; 130 km/h: 39 kW (52-hp) wankel engine.

(a) SPERWER (www.danskpanser.dk)

(b) HERMES 450 (Wikipedia)

Figure 2-4: Examples of Medium Range UAVs.

- MALE (Medium Altitude, Long Endurance): UAV – long range / medium altitude (200 km / 10000 m) UAV with up to 300 kg payload.
- PREDATOR (General Atomics Aeronautical Systems Inc. – USA): 1000 kg (340 kg); 40 h; 7250 m; 220 km/h; powered by ICE Rotax 914 hp turbo (115 hp).
- HERON/EAGLE (IAI/EADS – Israel/France): 1200 kg (250 kg); 40 h; 7750 m; 230 km/h 180 km range; powered by a Rotax 914, 86 kW (115 hp) 4 cycle, 4 cylinder.

(a) PREDATOR (http://defense-update.com)

(b) HERON (http://defense-update.com)

Figure 2-5: Examples of Medium Range UAVs.

Group 5 – HALE (High Altitude, Long endurance) UAV: Long range / high altitude (1000+ km / 10000+ m) UAV with over 300 kg payload, in some cases. Solar HALE UAVs are included although they do not allow for much of a payload:

- REAPER MQ-9 (General Atomics Aeronautical Systems Inc. – USA): 4700 kg (1700 kg); 5800 km; 15000 m; 370 km/h; Honeywell TPE331-10GD turboprop engine.
- TALARION (EADS – France): 7000 kg (800 kg); 3000 – 15000 m; 20 h; 555 km/h; twin jet engines.
- GLOBAL HAWK (Northrop Grumman – USA): 14600 kg (1360 kg); 18000 m; 35 h; 635 km/h; Rolls-Royce AE3007H Turbofan.

(a) TALARION

(b) GLOBAL HAWK

Figure 2-6: Examples of Extended Range UAVs.

- PATHFINDER PLUS (Aerovironment Inc./NASA – USA): 400 kg (45 kg); 20000 m; 14 h; 37 km/h; 8 brushless direct-current electric motors (7.5 kW) powered by solar energy.

- HELIOS (Aerovironment Inc./NASA – USA): 635 kg; 30000 m; 40 km/h; 14 electric motors powered by solar energy using thin film solar cells.
- ZEPHYR (QinetiQ – UK): 45 kg; 21400 m; 14 days; 2 (1 kW) brushless electric motors with propeller powered by solar energy using thin film solar cells.
- GLOBAL OBSERVER (Aerovironment Inc./NASA – USA): Up to 4500 kg (450 kg); 21000 km; 2 weeks; liquid hydrogen propulsion system powering electric motor propeller system.

(a) PATHFINDER **(b) GLOBAL OBSERVER** **(c) ZEPHYR**

Figure 2-7: Examples of High Altitude UAVs.

Based on fuel cell capabilities and the various classifications we are going to focus on the following UAVs types and definitions:

- Conventional UAVs. In this range three size categories are specified:
  1) Micro (up to 100 Watts);
  2) Mini (up to 10 kW); and
  3) Tactical (10 – 50 kW).

2.1.3 UAVs Propulsion and Power Systems

The Power system is a key component in these aerial vehicles. It has to provide the thrust to propel the vehicle and the electricity to power the various on-board electronic devices (flight control, sensors, weapons, etc.). The demand for electrical energy is ever increasing as better performance is sought. Examples where better performance is desired are longer endurance, higher power extraction, lower signature design, lower specific fuel consumption, greater pay loads, and lower unit and operating costs. Many of these features can only be accomplished with more efficient and higher energy output power sources.

As stated earlier, the most common technology currently used to power the micro-UAVs is electric propulsion where the energy needed is stored in batteries; The mini-UAVs are powered both by electric motors and small piston engines; but in UAVs that comprise Groups 3 and 4 (i.e., MALE and some HALE configurations) most of the propulsion systems are based on internal combustion engines (piston, rotary, turboprop) or jet engines. Internal combustion power systems also generate the electricity that is stored in rechargeable batteries. The disadvantages of batteries are weight and limited endurance, and the primary disadvantage of an internal combustion engine is weight and volume. Since our subject deals with fuel cells a focus on electric propulsion seems appropriate.

No matter if the energy source is a battery, fuel cell, or some form of internal combustion engine, the goal is to perform mechanical work that not only propels the UAV but provides electricity for the electronic devices. So the use of these technologies does not only involve their own development to generate electricity in an efficient and light way, but also it involves the development of other components such as electric motors and energy storage devices. Table 2-2 from UAS Roadmap 2005 – 2030 published by DoD [6], shows its forecast on the propulsion and power technologies.

Table 2-2: Propulsion and Power Technology Forecast.

	Now	2010	2015
Turbine Engine	Turbofan, turboprop, Integrated High Performance Turbine Engine Technology (IHPTET)	Versatile Affordable Advanced Turbine Engines (VAATE-1)	VAATE-II Note: VAATE ends in 2017
Hypersonics Scramjets	AF Single Engine Scramjet Demo, Mach 4-7, X-43C Multi-engine, Mach 5-7	Robust Scramjet: broader operating envelope and reusable applications (e.g. turbine-based combined cycles)	Hypersonic cruise missiles could be in use w/in operational commands. Prototype high Mach (8-10) air vehicles possible
Turboelectric Machinery	Integrated Drive Generator on Accessory Drive, Integrated Power Unit – F-22	No AMAD, Electric Propulsive Engine Controls, Vehicle Drag Reduction/Range Extension	Enabling electrical power for airborne directed energy weaponry
Rechargeable Batteries	Lead Acid, NiCd, in wide use, Lithium Ion under development –(B-2 battery – 1st example)	Lithium Ion batteries in wide use (100-150 WH/kg)	Solid State Lithium batteries initial use (300-400 WH/kg)
Photovoltaics	Silicon based single crystal cells in rigid arrays	Flexible thin films Multi-junction devices – Germanium, Gallium based	Concentrator cells and modules technologies (lens, reflectors)
Fuel Cells	Prototypes demonstrated in ground-based assets.	Production PEM/SO fuel cells available for UA Begin UA integration	Fuel cells size/weight reductions Fuel flexible reformers

The Specific Power (SP), defined as the maximum rated power of the propulsion system divided by the mass of the propulsion system (including the engine and all the auxiliary systems but not the fuel storage system), indicates the potential eligibility of each technology. The current trends are illustrated below in Figure 2-8 which was excerpted from the same DoE report.

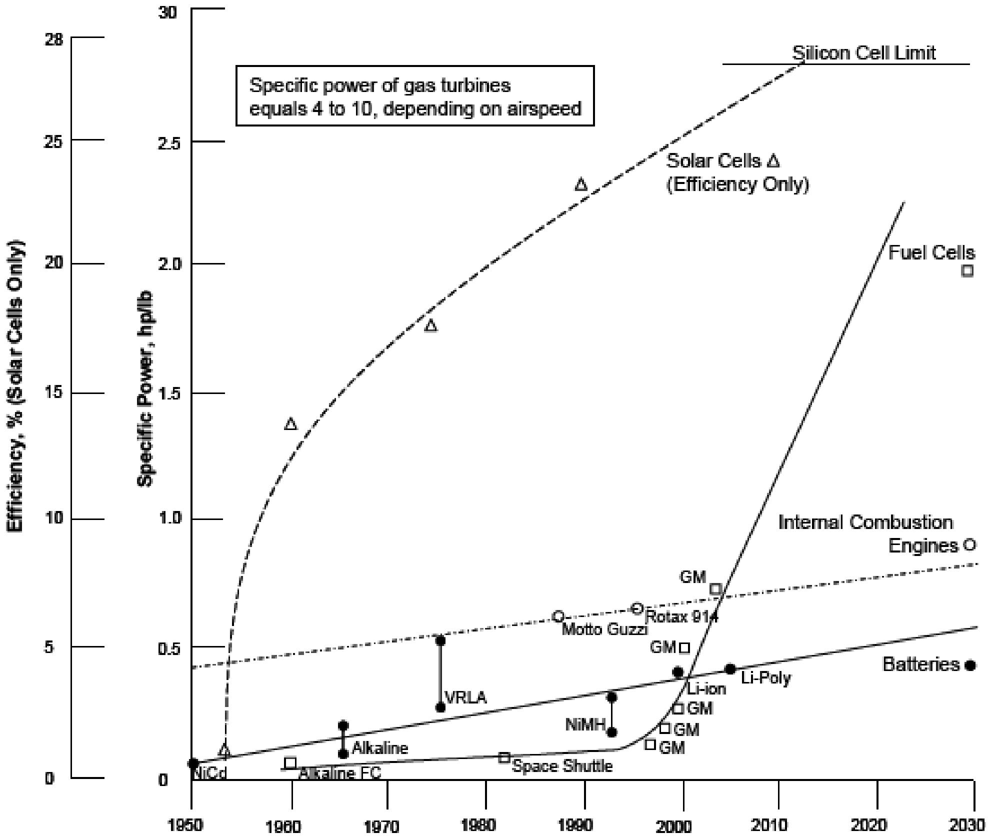


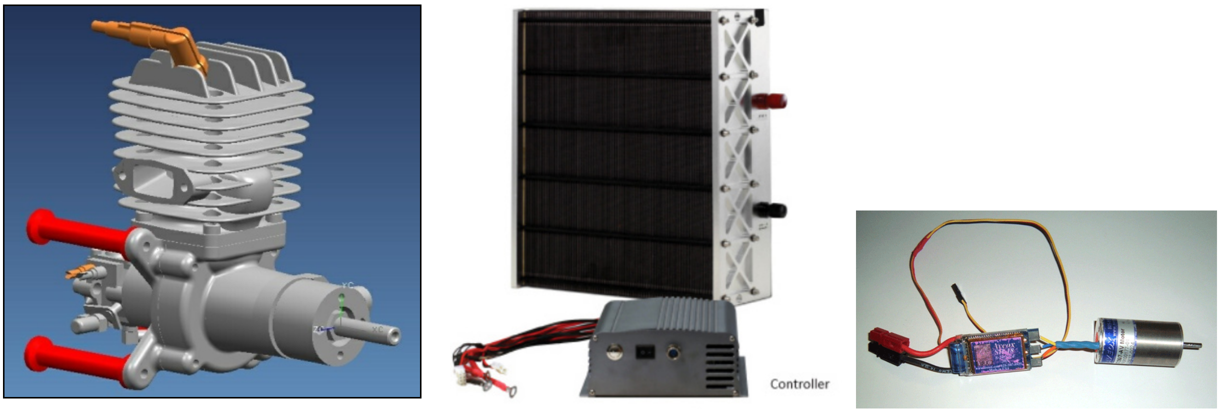
Figure 2-8: Mass Specific Power Trends.

The desirable solution is higher specific power, in order to reduce the weight of the propulsion system but also lower Specific Fuel Consumption (SFC), defined as the mass of fuel required to produce one unit of power per time so as to reduce the amount of fuel than must be carried onboard to fulfill the mission.

Fuel cell technology may be a good alternative as it can provide the required electricity to power electric motors and the rest of the electronic devices that are on-board from one fuel rich in Hydrogen with high energy density. [7] But fuel cell technology has to prove a longer endurance, less cost and higher efficiency compared with traditional power technologies for it to be a viable alternative to existing technologies.

Fuel cell system efficiencies (over 40% LHV)) have been proven, which is higher than ICE efficiencies (around 30%) [8], [9] which translates into a lower SFC. However the fuel cell System Specific Power (SP) are still under 600 W/kg (some examples are the 80 kW H_2 Transport FC described in [10] with system SP of 400 W/kg, or the Horizon 1 kW FC [11] with 227 W/kg. In comparison, we have small ICE engines with power over 3 kW that weight less than 1.5 kg or 15 kW engines weighting 5 kg. This means it has an engine SP over 2 kW/kg [9]. The result is that the general trend in fuel cells is to improve the fuel consumption and efficiency while sacrificing the specific power.

For smaller non-manned vehicles, the current fuel cell technology may be more compelling as the specific fuel consumption is not very good for small combustion engines. For example the 15 kW two strokes Desert Aircraft engine has a SFC over 500 g/kWh of gasoline, while a fuel cell system (from 1 to 75 kw) has a SFC under 90 g/kWh of hydrogen (Ballard ElectroGen [8] or Horizon [9]). However it is important to consider the total mass for hydrogen systems, including the mass of the hydrogen source. Examples of these power sources are shown in Figure 2-9.



(a) (b)

Figure 2-9: Small Propulsion Systems: (a) Desert Aircraft Engine DA-50 (3.7 kW_1.5 kg); (b) Horizon Fuel Cell H-3000 (3 kW_17.5 kg Controller Inc.) + Aveox 27/26 Electric Motor and Controller (0.26 kg).

2.2 FUEL CELL SYSTEMS IN UAV APPLICATIONS

The dramatic increase in the deployment of all kind of unmanned systems has led in a growing demand for efficient, powerful, portable, and logistically supportable solutions for unmanned system propulsion and power plant requirements.

The new generation of UAVs will be the result of the evolution in the various enabling technologies that comprise the power system as well as the whole vehicle. Progress on innovative electric motors, fuel storage systems, electronic power modules miniaturization, advance cooling, among others, are keys to get the integration of fuel cell systems onboard. Also optimization on vehicle design, materials and structural concepts will result in a more efficient airframe with less power required to keep the UAV in flight.

Fuel cells offer a solution for propulsion in small size unmanned vehicles due to their higher efficiency and low specific fuel consumption compared to internal combustion engines. This allows for greater endurance and payloads. However there are some handicaps to overcome such as the requirement to use logistic fuels. Some fuel cell types, such as the Solid Oxide Fuel Cells (SOFC), have revealed great improvements in fuel tolerance providing a path forward for electrochemical logistic fuel operation [12].

The use of fuel cells in aircraft also contributes to the "More Electric Aircraft" initiative. This concept tries to simplify the driving aircraft sub-systems, it converges the hydraulic, pneumatic and mechanical power upon electric power. The target is to optimize the military aircraft war fighting capability or payload and its life cycle cost.

2.2.1 Benefits of FC Systems in UAVs

Some of the main benefits made available by the use of fuel cells come from the electrification concept or its high performance:

- Electrification reduces weight (not necessarily electric propulsion);
- Electrification allows the UAV to increase endurance thanks to the use of hybrid systems from alternative electrical energy sources (fuel cells, solar energy, batteries, capacitors);
- Increased reliability vs. IC engines;

- High efficiency;
- Low acoustic signature – (only propeller noise);
- Easy maintenance;
- Reduced life-cycle costs; and
- Low or NO EMISSIONS if using pure hydrogen.

2.2.2 Fuel Cell System Components – UAV's Requirements

Current state of FC technologies, using Commercial-Off-The-Shelf (COTS) fuel cells, has yet to prove these advantageous capacities. Technology demonstrators have been flown as proof of "concept type vehicle" using automotive derived components. Recent projects have tried to develop specific airborne components with aerial requirements but failed to **reduce** enough **weight and cost** and **increase reliability** to make these technologies successful for UAVs. It is anticipated that these problems will be overcome as there is an increased interest by the automotive industry on the use of fuel cells. An example of the state of fuel cells for automotive applications is provided in Figure 2-10.

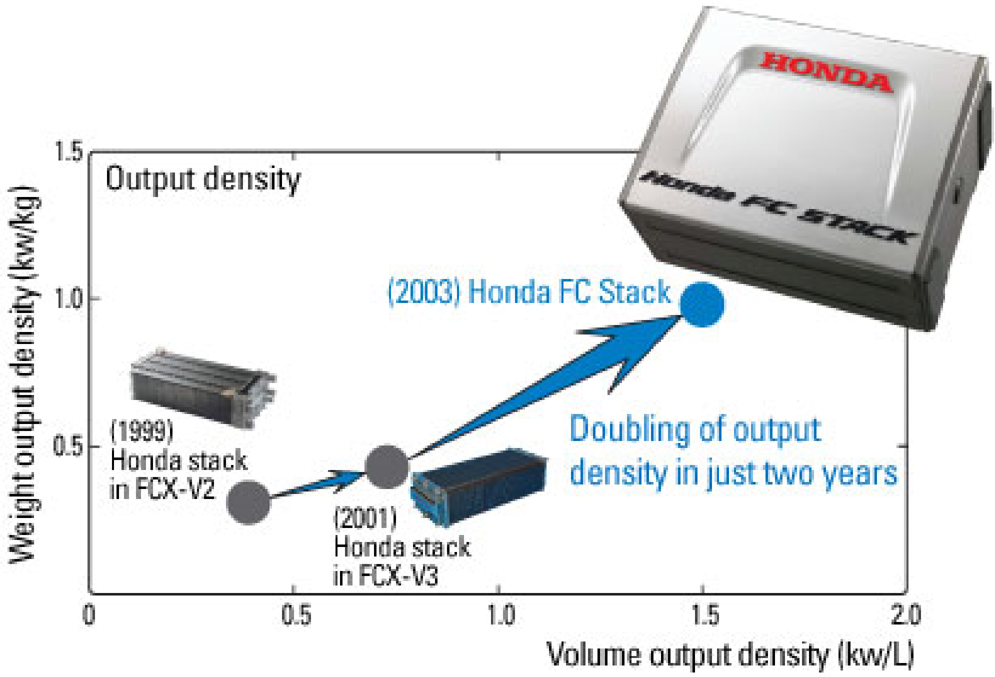


Figure 2-10: Honda Fuel Cell SP and Power Density Development Over Three FC Generations [13].

For fuel cells to succeed in UAV applications they will have to improve or prove performance for the following characteristics:

- High efficiency;
- High power density;
- Low cost;
- Regenerative performance (for HALE applications where solar power is available);
- High reliability; and

- Reformed fuels use. Pure hydrogen requirement have some disadvantages as the lack of H_2 supply infrastructure, the potential hazard of H_2 storage. A logistic military requirement of "only one fuel" is requested, as JP-8 for example.

PEM and SOFC fuel cell types offer the greatest potential for aircraft power plants. The Polymeric Exchange Membrane Fuel Cells can be operated at low temperatures (80 – 160 °C), it offers a quick start up, but it requires relatively pure hydrogen fuel. The Solid Oxide Fuel Cells operate at higher temperature (700 – 1000 °C); it may be fed by reformed hydrocarbon fuels because it tolerates higher levels of impurities. SOFC has the potential of making a direct partial reforming internally, and potentially it could achieve higher efficiencies, although it still has lower specific power than PEMFC. Both FC types are in current development for automotive applications. The targets for the new developments are focused mainly on higher power densities, more tolerance on impurities, durability and lower cost.

One of the barriers to the introduction of fuel cell technology in military applications is the requirement of a hydrogen supply even though it has the most energy per unit mass of any known fuel involving high specific energies. Other fuels rich in hydrogen, such as the hydrocarbons, require reformers that add mass and lower the efficiency of the power system. Only the internal reforming in SOFCs is an attractive option for UAV applications, but this technology has not been demonstrated for heavy hydrocarbons as jet fuels. For this reason the fuel considered in this report for small UAV applications will be hydrogen, although the way to store it is a great barrier in this application.

A brief categorization of the different technologies to store hydrogen depending on the UAV size is provided below:

1) The metal and chemical hydrides containers, such as the Sodium Borohydride generator, provide a solution to store low amounts of hydrogen. This method can hold up to 5% or 7% of H_2 by weight with active heating. The use of adsorption techniques in small UAVs has the advantage of lower pressures and lower volumes versus other storage methods. However, the recharge times for the tanks are longer and heat input is typically needed to provide an adequate flow rate for high power applications. This storage technique has been used in several commercial mini-UAVs. The declared system energy density was 446 Wh/kg for a 900 Wh device and higher for device of more than 2000 Wh [14], which amounts to less than 6% of H_2 by weight. Other concepts under development include the Cella technology which is based around the encapsulation and nano-structured chemical hydrides in plastic pellets. The pellets can be handled in air and release the hydrogen quickly and cleanly upon heating. According to its manufacturer heating one gram of Cella pellets will produce one litre of hydrogen (at normal pressures and temperatures). But this technology remains to be proven in aerial applications [15].

2) The more common method of storing hydrogen is in gaseous form by pressure vessels. However high pressures (currently 35 to 70 kPa) are required to store significant amounts of hydrogen. The lightest compressed hydrogen tanks are made of composite materials (Type III and IV), high performance carbon fibers prototypes have demonstrated that they can store up to 11% of H_2 by weight, but at very high cost [16]. This is illustrated in Figure 2-11. The current commercial technologies seem to store less than 6% of H_2. But if we focus on small tanks, around 1.1 litres and operating by 30 kPa we store no more than 2.3% of H_2 by weight or 2% if we include the regulator (Horizon Energy systems). If we use the 9 liters at 30 KPa in a carbon fibre reinforced seamless aluminium alloy Luxfer cylinders we can get 4% of stored H_2. In the latter case it is important consider the weight of the pressure regulator needed to decrease the operational pressure from 30 KPa to 0.03 KPa. as it can add significant weight (130 g) for the smaller applications.

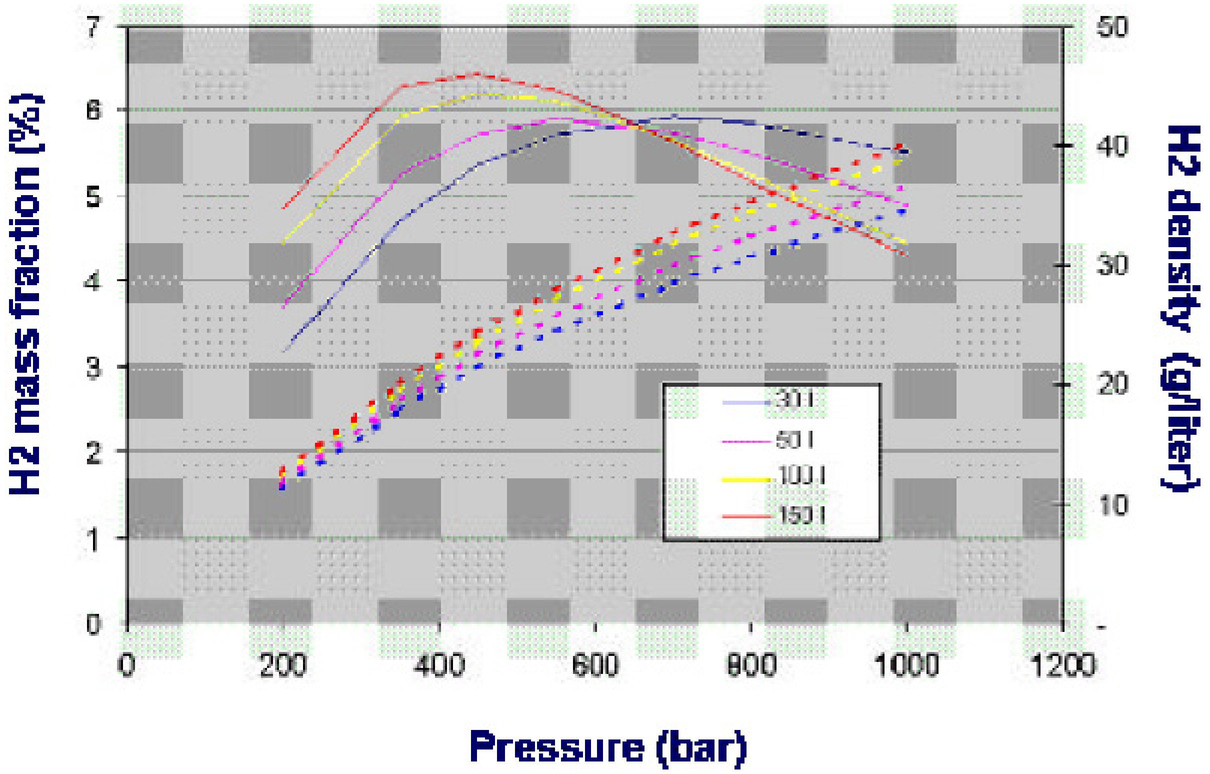


Figure 2-11: H_2 Mass Fraction of Pressure Vessels Type III and IV vs. Pressure [16].

2.3 UAV APPLICATIONS RELEVANT FOR FC SYSTEMS

An analysis of using fuel cell technologies for different types of UAVs was performed and examined the advantages and barriers and compared them to conventional power systems. The intent was to document the development required compete with conventional power sources. The main potential advantage to use fuel cells should be an increase of pay load and autonomy. The examples used for the analysis are as follows:

- Group 5 – High altitude and Long Endurance missions (HALE_10 kW):
  - Fuel cells and nuclear-based power schemes [6] are in the portfolio of future efforts.
- Conventional UAVs. In this range three size categories are specified:
  - Group 1 – Micro (up to 10 Watts):

    An example of micro-UAV that has gone through with the FC technology is the HORNET Fuel cell MAV by Aeroenvironment shown in Figure 2-12.

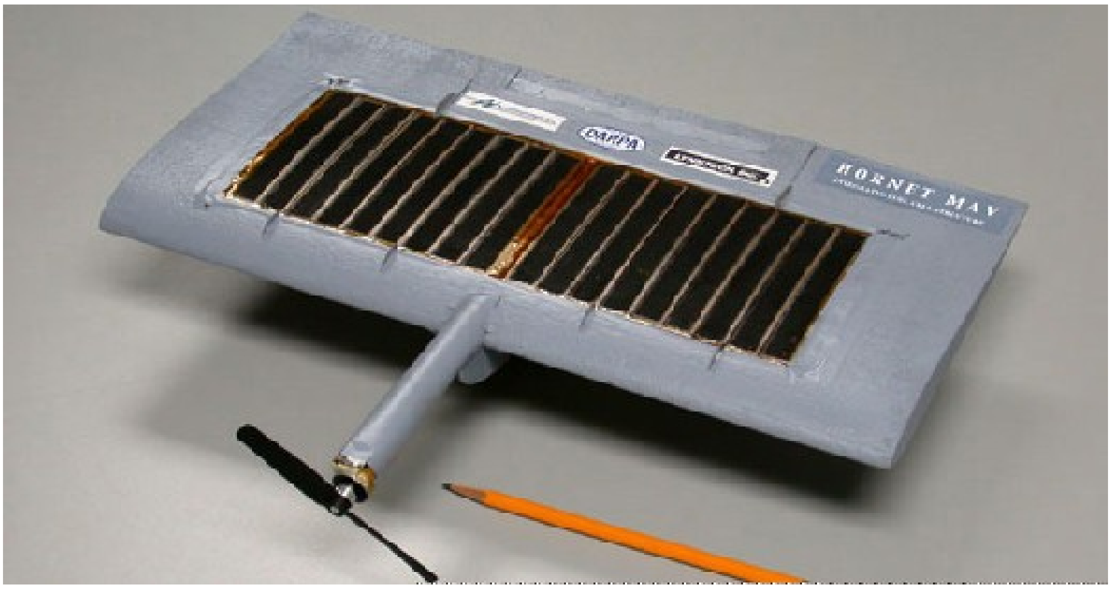


Figure 2-12: Hornet Fuel Cell-Powered Micro Air Vehicle.

Another example that is under development in this range is the DELFLY UAV shown in Figure 2-12, a flapping-wing Micro unmanned Air Vehicle (MAV) weighing just 17 g and with a wingspan of 330 mm (13 in). It has been designed and built by 11 students from Delft's faculty of aerospace engineering (Netherland). The Delfly Figure 2-13 has flown at about 1.5 m/s for 12 min, powered by a 3.7 V lithium polymer battery [17].

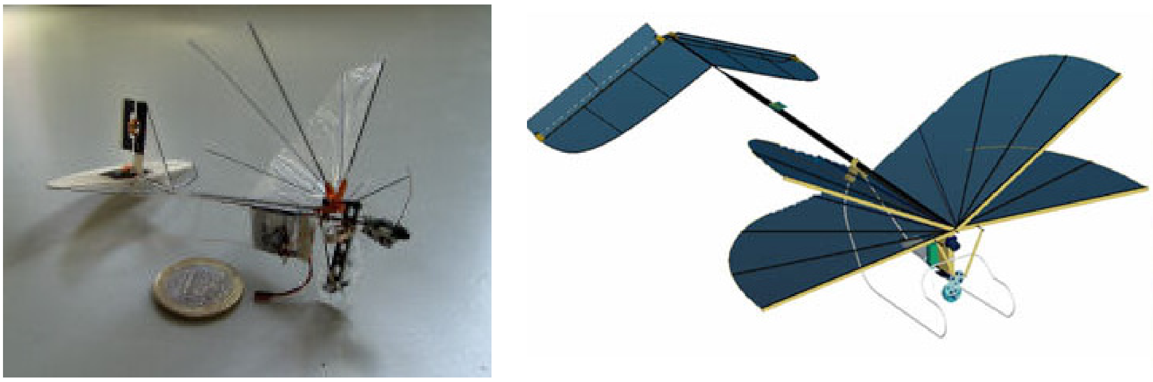


Figure 2-13: Delfly Micro.

- Group 2 – Mini (up to 1 kW):

  This kind of UAV has been changing from two cycle engines to battery power. The main advantage is its lower noise signature despites the lower energy content and specific power of the conventional batteries. New battery developments are focused on higher durability by energy and power to weight ratios.

  UAVs in the power range of 100 – 1000 watts offer an opportunity for fuel cells. Figures of 450 Wh/kg of specific energy have been reported in fuel cells (Horizon Fuel Cell Technologies) powering a mini-UAV [11]. The 2011 DoE technical plan points 250 Wh/kg of specific energy in a fuel cell system between 100 – 250 watts in 2011. These data show much better performance than the best batteries (around 220 Wh/kg).

Several Group 2 UAVs powered by fuel cells has been tested. Some examples that weigh less than 10 kg are the "SPIDER LION" powered by a 100 watt FC, and the "SKYLARK" and the "PUMA" which are powered by more than 500 watts power. Horizon Fuel Cell Technologies has powered, among others, the German "HYFISH" [11], the US "PTEROSOAR" and the Russian CIAM-80. Most of them have demonstrated flights of 1 – 3 hours. One of them reached the official record of 5 hours flying in 2010 [14] and flights up to 10 hours, have been reported. Flights up to 2 hours can be expected using battery packs. The ION TIGER of Group 2, developed by Naval Research Laboratory (NRL) in the United States, is a bigger mini-UAV of nearly 18 kg, has flown for more than 24 hours with a 550 watt PEM fuel cell built by Protonex. Examples of mini-UAVs are shown in Figure 2-14.

PUMA

ION TIGER

Figure 2-14: Examples of Mini-UAVs.

The acceptance of fuel cells for this type of UAV is dependent on the ability to increase their flight endurance, lower the price, and accommodate fuel logistics.

Currently there are commercial hybrid FC and battery "packs" fed by H_2 with a peak power of up to 1000 W. Its technical sheet warrants 500 hours of durability and flights of more than 10 hours. Companies as EnergyOr, Horizon Fuel Cell Technology and Protonex offer these types of products for UAVs applications.

Figure 2-15 shows the Horizon Energy Systems Aeropak, which is capable of producing 200 W continuously. It has a weight/volume ratio of 470 g / 1.2 L not including fuel weight [18].

Figure 2-15: Horizon Energy Systems Aeropak.

- Group 4 and 5 (1 kW – 50 kW):

  Reciprocating internal combustion engines are widely used in this kind of aerial vehicles. The main advantage of the reciprocating internal combustion engine is its low cost. Other technologies as gas turbines are proved to be less efficient in these size ranges while are widely used in bigger UAVs. But the present high investments on electric propulsion in the automotive sector may boost the use of FC and batteries instead of internal combustion engines.

  There are some manned aircraft that have flown with fuel cells electric power plants, (Boeing Fuel Cell Demonstrator, DLR Antares, Enfica-FC, Fast Company Fuel Cell Powered Aircraft). Most of them have used hybrid batteries-fuel cell systems fed by compressed hydrogen. Their powers were in the range of 20 – 50 kW, and the flights lasted less than an hour. Figure 2-16 shows the Boeing Fuel Cell Demonstrator.

Figure 2-16: Boeing Fuel Cell Demonstrator.

According to [19] the current Specific Power for a FC stack of 80 kWe on pure hydrogen is 1.2 kW/kg while the specific powers of current UAVs reciprocating engines is around 1.16 kW/kg [4]. But if we look at the technical targets for 2020, the FC specific power may reach 2 kW/kg while the ICE cannot overcome the 1.6 kW/kg barrier.

A complete chart on the published demonstrated projects of UAVs using fuel cells is found in the Table 2-3.

Table 2-3: Published Fuel Cell Powered Aircraft Demonstrations [10].

System Integrators	Aircraft Name	Type	Fuel Cell Manufacturer	Fuel Storage	Wingspan (m)	GTOM (kg)	Max Power (W)	Endurance (hr)	Year
Lynntech/AeroVironment	Hornet	PEM	Lynntech	H_2 Sodium Borohydride	0.381	0.17	-	0.25	2003
AeroVironment	Global Observer	PEM	-	Liquid H_2	15.24	-	-	24	2005
FH-Wiesbaden	Hy-Fly	PEM	Heliocentris	Gaseous H_2	2	1.75	65	0.025	2005
Naval Research Lab	Spider-Lion	PEM	Protonex	Gaseous H_2	2.2	3.1	115	3.3	2005
Adaptive Materials (AMI)	-	SOFC	AMI	Propane	-	-	60	4.3	2006
Georgia Inst. of Tech.	-	PEM	BCS	Gaseous H_2	6.58	16.4	550	0.75	2006
Cal State LA	-	PEM	Horizon	Gaseous H_2	5.49	12.9	513	0.25	2006
SmartFish/DLR	HyFish	PEM	Horizon	Gaseous H2	1	6.1	1300	0.25	2007
AFRL/AeroVironment	Puma	PEM	Protonex	Sodium Borohydride	2.6	6.5	-	9	2007
Cal State LA/Oklahoma State Univ.	Pterosoar	PEM	Horizon	Gaseous H_2	4	5	150	12	2007
Korea Advanced Institute of Science and Tech.	-	PEM	-	Sodium Borohydride	1.2	2	-	10	2007
Boeing	Dimona	PEM	Intelligent Energy	Gaseous H_2	16.3	841		0.5	2008
AMI/AeroVironment	Puma	SOFC	AMI	Propane	2.6	-	-	7	2008
United Technologies Research Center	FC Helicopter	PEM	UTRC	Gaseous H_2	-	-	-	-	2008
Adaptive Materials/U. of Michigan	Endurance	SOFC	Adaptive Materials	Propane	1.524	5.3		10.25	2008
DLR	Antares	PEM	BASF	Gaseous H_2	20	660	25000	5	2009
BlueBird Aero Systems	Boomerang	PEM	Horizon	H_2 Hydride	2.75	9	500	9	2009
Naval Research Lab	XFC	PEM	Protonex					6	2009
Naval Research Lab	Ion Tiger	PEM	Protonex	Gaseous H_2			500	24	2009

2.4 CHOICE OF OPERATIONAL SCENARIOS

In order to analyse in detail the viability of Fuel cells to power the UAVs propulsion systems some examples of operational requirements are showed in two different type scenarios: Group 2 (Mini-UAVs) and Group 3 Tactical UAVs.

Group 2 (Mini-UAV) requirements:

- Maximum weight: 4.5 kg (take-off);
- Airplane empty weight, without engine = 1.7 kg;
- Flight ceiling: 2000 m;
- Range of operation ambient conditions: from ISA (International Standard Atmosphere) – 35 to ISA +25;
- Launching Altitude: 0 m to 500 m;
- Capability to start in: 30 seconds in the range of ambient conditions;
- Take-off: Launched by catapult;
- Climbing: 2 min 90% Max power. R/C 3 m/s;
- Cruise: 1 h 50% Max altitude. Flight speed 12 m/s;
- Recovery. During the recovery phase, the required power parameters are the same as the cruise phase; and
- Electrical extracted power: 100 – 200 W.

In order to reach the operational requirements with an aerial vehicle where the aerodynamic and weight performances are known, it is necessary to have a propulsion system, including the fuel; that will provide the required thrust without exceeding the Maximum Take-Off Weight (MTOW).

Required power, during different flight steps (example):

- Take-off: 0 (power to take-off comes from a catapult);
- Climbing: 300 W for 2 min;
- Cruising speed: 100 W for 1 hour; and
- Auxiliary systems: about 150 W.

Required energy to carry out the mission:

- If the UAV mission is defined by the previous flight step example for a total mission time of 1 hour, the required energy for this mission may reach 300 Wh.

2.4.1 Required Energy Density

According to the previous numbers the airplane weight available to integrate the whole fuel cell propulsion system is 2800 g, this means that the energy density of this system should be 300 Wh / 2.8 kg ≈ 110 Wh/kg.

This specific energy for the whole system is reachable with the current hybrid fuel cell technology: US DOE[3] 2011 technology status is around 250 Wh/kg [8], so we can plan a flight mission that is twice as long. The specific power of the current fuel cell system, including batteries and fuel storage, is over 25 W/kg and it should increase in next few years.

2.4.1.1 Group 3 Tactical UAV Mission Requirements

Regular UAV Requirements:

- Aerial platform:
  - Maximum weight: 300 kg (take-off).
  - Airplane empty weight, without engine = 190 kg.
  - Load Factor: 3,5 g (Landing) and 4,4 g (Symmetrical Operation).
  - Max. pitch: 21° and Max. roll: 60°.
- Mission description:
  - Flight ceiling: 4000 m.
  - Range of operation ambient conditions: from ISA-35 to ISA +25.
  - Launching Altitude: 0 m to 1000 m.
  - Capability to start in: 30 sg in the range of ambient conditions.
  - Take-off: 2 min 100% Max power. Min angle 5 degrees.
  - Climbing: 20 min 90% Max power. Flight speed 130 km/h (1.2 Vs). R/C 3.3 m/s.
  - Cruise: 1 h 30 min 50% Max power. Flight speed 150 km/h (1.3 Vs). 3000 m.

[3] http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/fuel_cells.pdf.

- Observation: 6 h. 60% – 75% Max power or nominal power minimum consumption. Flight speed 150 km/h. 2500 m Recovery. During the recovery phase, the required power parameters are the same as the cruise phase.
- Electrical extracted power: 1.5 – 2 kW.

In order to reach the operational requirements with an aerial vehicle where the aerodynamic and weight performances are known, it is necessary to have a propulsion system, including the fuel; that will provide the required thrust without exceeding the MTOW.

Required power, during different flight steps:

- Take-off: 27 kW during 2 min.
- Climbing: 21 kW during 20 min.
- Cruising speed: 16 kW for not less than 6 hours.
- Auxiliary systems: about 1.5 kW.

Required energy to carry out the mission:

- If the UAV mission is defined by the previous flight step a total mission of 7 hours flying is set, the required energy for this mission should be 114 kWh.

2.4.1.2 Required Energy Density

If we use the design numbers of MTOW (300 kg) and empty vehicle weight (120 kg), we have only 180 kg available to build the whole fuel cell propulsion system, this means that the energy density of this system should be 114 kWh / 180 kg ≈ 640 Wh/kg.

This is nearly reachable using current fuel cell technology for this size of fuel cells and systems (over 20 kW). However we also have to consider that this UAV did not allocate weight available for the payload.

Current data provided by US DOE[4] show a fuel cell stack power density of around 1 kW/kg and that does not include the storage system or the balance of plan. The 2017 DOE Targets for 80 kW integrated transportation fuel cell power systems operating on direct hydrogen are 650 W/kg gravimetric density, while the 2011 status in this category is validated up to 400 W/kg but these targets exclude hydrogen storage, power electronics and electric drive.

So if we try to provide a "Regular" UAV, similar to this one, with a COTS FC propulsion system we would have to significantly reduce its performance or its mission. A state of the art fuel cell cannot compete with the conventional technologies in this UAV size.

Fuel Cell System Description for Chosen Scenarios

Some of the examples of fuel cell propulsion systems described in this chapter apply to the different UAV types. Although in some case it is evident that the mission cannot be reached, the systems are characterized to illustrate the current state of the art.

Group 2 Mini-UAV Power System Description

Figure 2-17 shows the main components required to power a Group 2 UAV by a hybrid FC system.

[4] http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/fuel_cells.pdf.

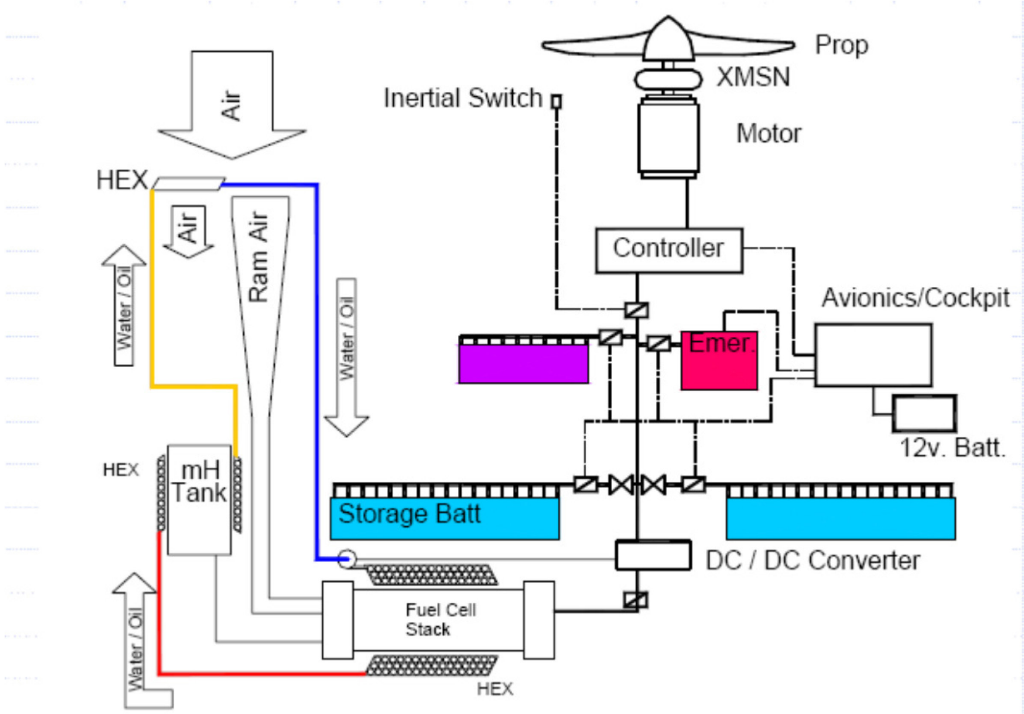


Figure 2-17: Hybrid Fuel Cell Propulsion System.

2.4.1.2.1 Fuel Cell Stack

An example of a fuel cell system package that is being developed to meet the requirements of a Group 2 UAV is the Horizon Aeropak hybrid system as shown in Figure 2-18. The peak power available is 600 W, 200 W in continuous output provided by the fuel cell and 400 W provided by a Lithium Polymer rechargeable during 5 minute peak load intervals. The total weight of fuel cell stack plus battery and auxiliary equipments such as blowers and controllers, is around 700 g. This provides a peak system specific power of 850 W/kg. The output voltage range is from 20 to 32 volts, so a DC/DC converter is not needed. Its efficiency is 46%.

FUEL CELL SYSTEM SPECS

Continuous Output Power:	200W
Peak Power (hybrid battery):	600W for 2 min.
Continuous Output current:	10A
Output Voltage Range:	20V-32V
FC System Weight:	**470g (1.04 lbs)**
Dimensions (mm):	126 X 116 X 138
Operating environment:	0C-40C / 0-95% humidity
Max altitude with no change:	2000m (can be adjusted)

Figure 2-18: Aeropak Horizon Performances – www.hes.sg.

2.4.1.2.2 H_2 and Air Systems

This company also offers a fuel cartridge pack to feed the fuel cell. It is made up of a fuel tank, where the hydrogen rich NaBh4 is contained; and a reactor to produce the pure hydrogen through the use of a specific catalyst. Its total weight with 1 liter of fuel is 1.570 g. The net energy is up to 900 Wh, which amounts to an energy density of 570 Wh/kg. If the whole system can be under the maximum weight of the airplane, we could extend the flight mission three times the purposed mission with this storage system. The oxidant used is air and it requires an air flow of 2000 L/min. The operating altitude affects the fuel cell performance decreasing the cell voltage and the output power, over 10% at 1000 meters above sea level.

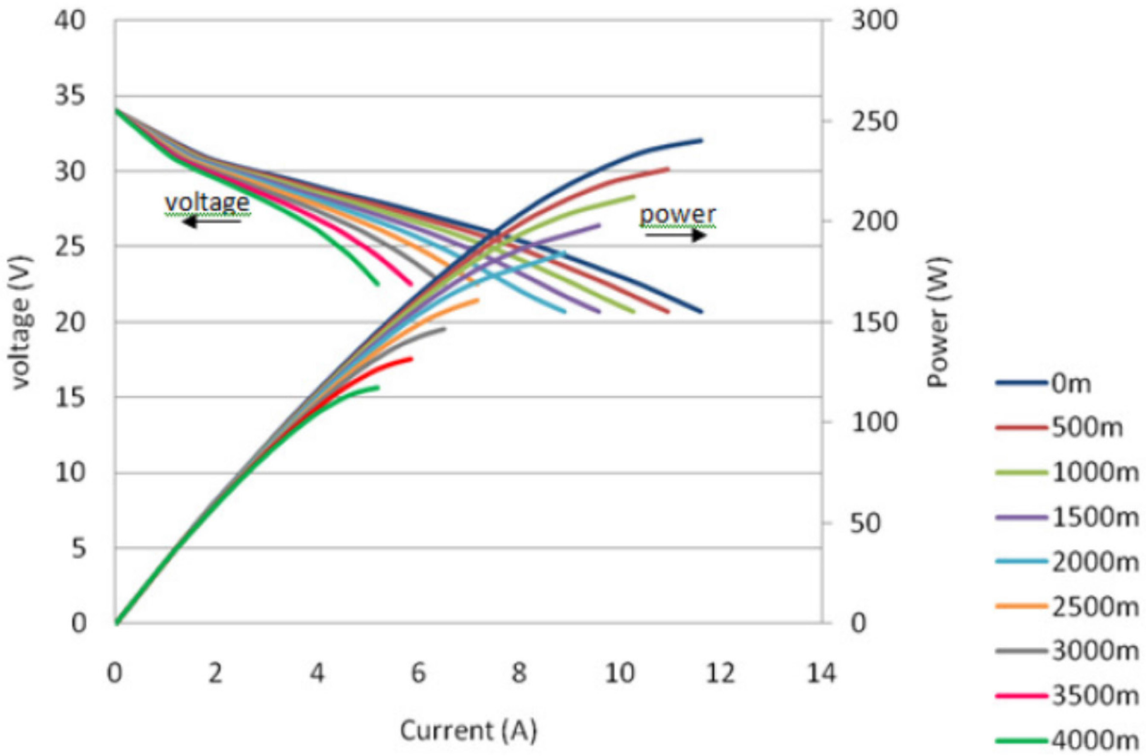


Figure 2-19: Aeropak Performance at Various Altitudes – www.hes.sg.

2.4.1.2.3 Electric Motor

Small DC electric motors that are commercially available, thanks to the RC airplanes, have been chosen to transform the electricity into torque. It provides the torque needed at the propeller speed, so it doesn't need a gearbox. It does require an engine controller. The total weight of this system is 170 g, including the light composite propeller.

2.4.1.2.4 Avionics

Some other auxiliary equipment must be included in airframe to pilot and control the vehicle. The avionics may include the receptor and servo, the flight control system, GPS, and a radio modem. This adds around 100 g more.

2.4.1.2.5 Total Weight

The total weight of the designed propulsion system according to the products commercially available is 2550 g as illustrated in Table 2-4. This is slightly under the maximum designed weight (2800 g) but it has an energy of 900 Wh, three times the required energy for 1 hour flight. This means that with this technology we can extend the mission to three hours of cruise flight and some payload could be included.

Table 2-4: Weight of Fuel Cell Sub-Systems and Total Weight of Mini-UAV Propulsion System.

Component	Weight (g)
Fuel cell stack +Li-Po batteries	700
Hydrogen and oxygen system (with 1 liter of fuel)	1570
Total Power System Weight	**2270**
Electric motor with propeller	170
Avionics	100
Total Weight	**2540**

2.4.1.2.6 Energy Density

With the mass of 2.27 kg of the power system and total energy of 900 Wh, the power system energy density is 400 Wh/kg. The energy density of the total system, including the electrical motor, is 350 Wh/kg. For this particular scenario and flight mission fuel cells provide a favourable alternative compared to batteries.

Group 3 Regular UAV Fuel Cell Propulsion System Description

Based on the mission requirements stated earlier an assessment of the current state of development for this technology and the barriers that need to be overcome will be examined.

2.4.1.2.7 Fuel Cell Stack

According to the mission profile, the propulsion system should provide at least 24 kW to take off. A hybrid fuel cell and battery system has been designed for this UAV. A 27 kW PEM fuel cell stack, fed by pure hydrogen and oxygen, with no humidification required has been developed. Its Power density is around 1.4 kW/kg. It can use oxygen or air, but the oxidant must be fed at constant pressure, so instead of using free air an onboard compressor must be utilized. The fuel cell stack is operated at a nominal power of 20 kW, while the peak power is provided by a battery pack of 8.8 kW.

2.4.1.2.8 Balance of Plant

In order to operate the fuel cell stack some other components are needed to move air (blowers/compressors), fuel (pumps), and the associated piping and control systems. The main ones are:

- Cooling System to Cool the Fuel Cell and Electronic Equipments: In this case fans are not necessary, but collectors to carry the outside air to the system are installed. Also radiators and pumps to move the water coolant are required. The total weight of the cooling system is 10 kg.
- Ancillary Components: The batteries, wires, control system and converters must be ruggedized to meet the environmental conditions, so are relatively heavy. The total weight of these equipments is nearly 40 kg. The main component responsible of this weight is the HV/LV converter which weights around 20 kg. The battery module which is composed of lithium-ion cells connected in series to obtain the appropriate voltage has an energy density is 88 Wh/kg and weighs around 10 kg.
- Mechanical Parts: These parts cover the elements needed to attach this equipment to the aircraft. This is an important part on the weight balance due to structural requirements. These parts add 10 kg to the total weight.

- Gases Fuels Storage System:
  - Storage Tanks: The fuel cell is fed by compressed pure hydrogen and pure oxygen. This means that at least two cylinders are needed. The initial designs are to validate the basic vehicle design, and are therefore not optimized.
    - H_2: Two 9 litres and two 6.9 litres over 300 bars carbon fibre reinforced seamless aluminium alloy cylinder tanks, the total weight is 18 kg total. Total H_2 available = 660 g.
    - O_2: Two 9 litres 200 bars tanks, the total weight is 9,6 kg total. Total O_2 available = 5350 g.
- Components of gas circuits: regulators, sensor to measure the control parameters (voltage, temperature, pressure), shut-off valves, purge valves and pipes add a total weight around 3 kg.

2.4.1.2.9 Electric Motor

Among the different types of electrical engines, brushless permanent magnet is considered the best solution for the propulsion system of this application at the moment. A 35 kW, 380 Nm electric motor of this type has been chosen as it provides a continuous power of 24 kW, torque of 150 Nm, has a maximum efficiency of 90%, and a power density of 875 W/kg. But this motor needs a controller that adds 16 kg to the carried weight. These equipments are designed for automotive applications so great efforts will have to be taken to develop lighter systems for aerial applications.

2.4.1.2.10 Total Weights

Table 2-5 shows the total weight of the propulsion system. The Fuel cell system, without the gas cylinders weighs 81.5 kg and has a power density of 430 W/kg. This power density decreases to 247 W/kg when we add the electric motor system.

Table 2-5: Weight of Fuel Cell Sub-Systems and Total Weight of Regular UAV Propulsion System.

COMPONENT	WEIGHT (kg)
Fuel cell stack	18,5
Cooling line	10
Circuit line (H_2+O_2)	3
Electro-technical parts	40
Mechanical parts	10
TOTAL FC system	81,5
Electrical Motor system	60
TOTAL wo Fuel	141,5
Hydrogen storage	18,5
Oxygen storage	15
TOTAL	175

2.4.1.2.11 Energy Density

Given the hydrogen consumption of around 0.3 g/s (16 kW), and the total available hydrogen of 660 g approximately 10 kWh can be achieved. The energy density of the total system for this particular scenario (including the electrical motor) is only 50 Wh/kg. The energy density of the power system is 85 Wh/kg, which is a much lower energy density than with lithium-ion batteries. The time we can fly with the available H_2, and O_2, is not more than 30 minutes. So the regular UAV powered by a fuel cell is a long way from being practical.

2.5 BOTTLENECKS AND CHALLENGES IN CHOSEN SCENARIOS

As we can conclude with the previous sections the main bottlenecks in these applications it is not the fuel cell technology but instead the hydrogen storage systems and the auxiliary equipment needed to integrate the technology. The electric motors can be improved thanks to the development of electric cars, but the electronic converters for airborne applications continue to be a challenge.

2.6 CONCLUSION

Fuel cell technology may be a good way to improve the UAVs performance, but it depends on the mission and the type of UAV. The mission will determine the needed endurance and payload weight, which in turn will determine the size of the vehicle and energy needed for the mission. In general, fuel cells will be favoured over batteries for longer missions and lower average power demands.

Chapter 3 – UNMANNED GROUND VEHICLES (UGVs)

3.1 INTRODUCTION

Unmanned Ground Vehicles (UGVs) are the vehicles that operate on the ground without any driver/operator onboard. In most cases UGVs are tele-operated – which means they are remotely controlled by the operator equipped with the console allowing them to command the vehicle and giving the visual (or in some cases also audio and/or tactile) feedback and the reading from specific sensors installed onboard. Some UGV applications, however, feature the full or partial autonomy mode, which allows it to perform its tasks with minimal involvement of operator. UGVs are usually deployed where human life may be endangered or when the required task is particularly dull or time-consuming and repetitive.

An autonomous operation of land-based vehicles tends to be more challenging than operation of air or water-based vehicles because of variable terrain and obstacles that are major issues. Although fully autonomous military vehicles with limited intelligence like cruise missiles are in use already, applications such as ground vehicles require better sensors and greater intelligence to have the same autonomy.

Historically, the focus on unmanned systems has steadily grown since the Second World War, but there was limited use of Unmanned Ground Vehicles (UGVs) in the decades that followed. Research in the 1980s met with some success and set the conditions for the employment of robotic EOD (explosive ordnance disposal/destruction) and mine clearance systems in the first Gulf War conflict. Application of UGVs in non-military operations was largely disregarded until the World Trade Centre attack of 2001 where robots were used very effectively in the clean-up operation.

In recent years, there has been an acceleration of the development of robots for the military and the police to identify and eliminate risks of terrorism (e.g., dangerous substances, improvised explosive devices). In the very beginning these robots were simple makeshift devices created by individuals committed to safely countering these IED pyrotechnics. Further on, this development was institutionalized resulting in increasingly advanced robots to counter more sophisticated IEDs. In the subsequent years, the form of these devices was mainly the result of technical considerations, but as users became more aware and comfortable of robots capabilities and their potential applications, the design was increasing focused on user's operational needs and tactics.

Rapid growth of UGV's application came during the period of military missions in Iraq and Afghanistan. To this day, the main application for unmanned ground vehicles is EOD and Improvised Explosive Device Disposal (IEDD) operations. However, the range of applications is rapidly expanding in such areas as logistics, reconnaissance, surveillance, patrol and even support in combat missions. CBRN threat situations are another example of where the UGVs may be deployed in order to detect, identify, sample and neutralize the hazardous material, without exposing a human operator.

Special Forces are users with specific requirements. These include the requirements for low weight, small size and the good speed of the robotic device (both the rate of movement and the time at which they are switched on, deployed and ready for use). Other requirements such as low-noise operation or long-range operation may also come to play. UGVs are currently expected to be used both in asymmetric operations, low-intensity conflicts and classic combat operations.

It is important that the military capability planners consider the uses and benefits that UGVs offer the military of tomorrow. Unmanned ground systems offer several opportunities for improved performance at lower risk to human life in a number of different applications through optimization, increased survivability, and increased stand-off.

UGVs offer a tremendous potential for reduction of costs, greatly reduced soldier workloads, increased mission endurance and time on station. Above all they represent the potential to change the nature of military operations themselves.

The US Army has identified the following capabilities for unmanned systems research and development. In order of priority:

- Reconnaissance;
- Mine detection and countermeasures;
- Precision target location and designation;
- Chemical, Biological, Radiological, Nuclear and Explosive (CBRNE) weapons reconnaissance;
- Weaponization and strike;
- Battle management;
- Communications;
- Data relay;
- Signals intelligence;
- Covert sensor insertion counter concealment; and
- Camouflage and deception.

The US Army is leading the militaries on developing UGVs over a wide size/scale. Some examples are the Soldier Unmanned Ground Vehicle (SUGV – a 30-pound, man-portable scout that comes equipped with weapons and sensors), the Multi-function Utility/Logistics and Equipment (MULE – two-and-a-half-ton truck for carrying supplies into battle or soldiers out of it), and the Armed Robotic Vehicle (ARV, a five-ton mini-tank that could be equipped with missiles or a .30 caliber (.762 mm) chain gun). The SUGV is the most prominent UGV in operation today and prime role is conducting missions ranging from surveillance to weapons carrying systems.

The next generation of UGVs being developed is the Mobile Detection Assessment and Response (MDARS) program. MDARS has successfully fielded the first semi-autonomous ground robot as an exterior patrol unit vehicle. It is an advanced UGV employed by logistics forces capable of self-guided navigation using differential GPS and inertial sensors, along with Laser Detection and Ranging (LIDAR) based obstacle detection and avoidance capabilities, to autonomously patrol high value storage facilities.

General classification of UGVs may be aligned in different aspects. The most common is weight-based classification and application-based classification. Unmanned ground platforms can be divided into the following weight classes:

- Backpack: 12 – 25 kg;
- Man-portable: 25 – 60 kg;
- Light: 60 – 150 kg;
- Average: 150 – 500 kg; and
- Heavy: > 500 kg.

Main applications of robots include:

- Support for patrol teams (i.e., IEDD/EOD missions);
- Engineering support for combat operations in urban areas;

- Engineering patrol of infrastructure;
- Engineering patrol of the area;
- Engineering patrol of roads;
- Paving roads;
- Roadblocks and engineering barriers reconnaissance; and
- Breaching the ground barriers.

3.2 FUEL CELL SYSTEMS IN UGV APPLICATIONS

3.2.1 Present Capabilities

Researchers in the US have developed two fuel cell solutions for UGVs targeted at soldiers for longer missions times, greater flexibility and improved safety and security of the operator. Efforts to meet these requirements are being led by the engineers from the U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) at the Detroit Arsenal in Warren, Mich., in conjunction with Adaptive Materials Inc. They are developing new fuel cell applications for small unmanned ground vehicles and have been demonstrated on the iRobot PackBot and the QinetiQ Talon UGVs.

Most of the smaller UGVs, such as those used for EOD missions are operated off batteries. For these UGVs, batteries will always be required to enable the system to respond to instantaneous increases in the demand for power such as when the vehicle is climbing a steep incline. The advantage of adding a fuel cell in these vehicles in a hybrid configuration is to increase operation times by extending the time between having to replace the on-board rechargeable batteries (which often stop the mission). The PackBots are primarily designed to detect roadside bombs or conduct camera surveillance. One solution uses a 150-Watt propane-powered fuel cell although propane is not considered a standard logistic fuel for forward operations. However, it does drastically extend the mission length compared to a rechargeable battery. The Talon robot solution uses a 205-Watt propane-powered fuel cell to increase operational time over the standard lead acid batteries by almost 5 times. TARDEC is working to develop a JP-8 based fuel cell power system at the 250-Watt power level which will help eliminate the non-logistics fuel based solutions and increase likelihood of transition to the field. The solution is being developed in conjunction with CERDEC and the Air Force Research Lab, Wright-Patterson Air Force Base, Dayton Ohio.

PACBOT FasTac

TALON IV

Talon IV With Fuel Cell

Figure 3-1: Examples of UGVs.

3.2.2 Advantage of Fuel Cells

Performance is the most powerful driving force for the adoption of fuel cells by the world's armed forces. Low noise and a low heat signature represent two good examples, providing specific benefits to military users that may not be as important to other customers. The most attractive attribute of fuel cell systems is their high energy density, particularly when compared to standard military batteries. Today, a typical UGV battery lasts about two hours. Comparing UGVs powered by fuel cell to the ones supplied from batteries, fuel cell technology offers shorter charging time of a power source, which can be crucial in long-lasting military operations.

3.2.3 Disadvantage

Use of non-logistic fuels (optimal fuel source for fuel cell) is a major disadvantage. In addition at the current state of fuel cell maturity, reliability is reduced and cost is high compared with batteries or combustion engines.

3.2.4 Future Development

R&D on fuel cells and unmanned systems is truly an international effort that goes beyond military interests. At least 50+ countries are currently developing unmanned systems technology – including Iran, Russia, and China.

In addition to the issues related to the power plant, widespread applications of autonomous ground-based unmanned systems have been limited due to the level of task complexity and the nature of the operational environment, required computing power, and integration of sensors and perception technologies required to perform more dynamic missions. There are two chief limitations on the use of robots at the moment. First, computers and sensors are incapable of delivering anything close to the situational awareness of a human being. Second, a shortage of bandwidth limits the number of systems that can be remotely controlled at any one time.

The desired end state for power generation is 72 hours of continuous operation without refueling or recharging batteries. It should also be a requirement that power generation systems, whether fossil-fuel fired generators or some other source, be equipped with some sort of noise suppression system. Selection of an energy source for the system is important as it will be an important factor in achieving requisite scaling of mission duration and system size, weight, and power.

3.3 UGV APPLICATIONS RELEVANT FOR FC SYSTEMS

One obvious use of a fuel cell in an UGV, is as a very high energy density power source for sensors. The sensor platform moves to a position and stays there observing for a long period of time, using, e.g., a direct methanol fuel cell to power its sensors. This application is independent on the propulsion system, whether the UGV is powered by a battery, a fuel cell hybrid or a combustion motor.

3.4 CONCLUSION

Fuel cells are providing clear operational benefits, including silent operation and weight reduction compared to batteries and mission duration improvements for unmanned vehicles. A number of companies are advancing unmanned vehicles for the military. One fuel cell manufacturer, Adaptive Materials, has demonstrated a successful unmanned ground vehicle which operated for 12 hours, traveling 40 miles with all cameras and computers activated. At present, fuel cells systems are superior to batteries in terms of energy density and the best systems are comparable to combustion engines in this respect. Given the importance of low signature for military systems combined with the ease of control of electric power drives, hybrid systems are expected to be a common power source for small military UGVs in the near future.

Chapter 4 – UNMANNED UNDERWATER VEHICLES (UUVs)

4.1 INTRODUCTION

Unmanned devices are increasingly used in order to keep the human out of harm's way as well as to reduce the cost of an operation. Underwater vehicles are no exception to this development. The Unmanned Underwater Vehicles (UUVs) may be tethered or untethered. If controlled via the tether, they are usually called Remotely Operated Vehicles (ROVs). In an ROV power may or may not be transferred via the tether. An untethered UUV may be controlled over an acoustic link or it may be completely autonomous. According to Christopher von Alt (Kongsberg Hydroid) the definition of an Autonomous Underwater Vehicle (AUV) is:

> *"A robotic device that is driven through the water by a propulsion system, controlled and piloted by an onboard computer, and maneuverable in three dimensions."*

This definition includes torpedoes but excludes gliders, as they are propelled by gravity in decent and buoyancy in ascent and thus not freely maneuverable. Gliders with their low average power consumption may be powered by a fuel cell / battery hybrid whereas the specific power density requirements of torpedoes are orders of magnitude above present technology level for fuel cells. Thus torpedoes will not be discussed, but a short introduction to gliders will be given.

The range and speed of an AUV is determined by its energy content and propulsion efficiency as well as the drag of the vehicle and the power capability of the propulsion system. To state the obvious: The target is to get maximum energy per weight and volume at a minimum cost and without sacrificing the safety of the crew of the support vessel, the support vessel or the AUV.

Underwater vehicles are different from ground and air vehicles in both control- and available energy systems:

1) Bandwidth in seawater is lower than in air (kbits/s versus Gbist/s);
2) Signal propagation is slower (1500 m/s versus $3*10^8$ m/s) and attenuation larger;
3) Refraction may make communication difficult; and
4) No free oxygen for combustion.

The lack of communication is a strong drive for autonomy and the lack of air a strong drive for efficient energy sources, at present mainly batteries.

Figure 4-1 shows a typical survey AUV, the HUGIN 1000 HUS owned by the Norwegian Defence Research Establishment (FFI). It has a maximum operational depth of 3000 m, a maximum speed of 6 knots, and a typical speed of 4 knots (2.1 m/s). The propulsion system is a low speed brushless motor operating at ambient pressure and directly coupled to the propeller. The energy source is a pressure tolerant lithium-ion polymer battery of ca 18 kWh. The sensors are synthetic aperture sonar (both sides), a multi-beam echo-sounder, a sub-bottom profiler, an optic camera and a navigation suite. Some applications are:

- Mine Reconnaissance (MR);
- Intelligence, Surveillance and Reconnaissance (ISR);
- Anti-Submarine Warfare (ASW);
- Seabed mapping and characterization;
- Pipeline inspection;

- Oceanography;
- Fishery research; and
- Underwater archaeology.

Figure 4-1: HUGIN 1000 Ready to be Deployed (Courtesy of FFI).

In a typical scenario, the AUV cruises at 4 knots 15 m above the seabed, following a "lawn-mover" pattern. After the initial survey it then may inspect objects of interest at closer range for optical documentation. Similar AUVs are used by navies and civilian offshore survey companies.

The power used by the control and navigation system and the sensors are commonly lumped together into the term "hotel load" in contrast to the power used for propulsion, termed "propulsion power". Typically, propulsion power and hotel power are of the same order of magnitude and the speed is selected to maximize the surveyed area. The drag of the vehicles increases approximately with the square of the speed thus power consumption increases with the speed cubed. This usually restricts AUV speed to between 3 and 5 knots.

Power for propulsion is given by:

$$P(u) := \frac{1}{2}\cdot\rho\cdot u^2\cdot c_d\cdot Aref\cdot u\cdot\frac{1}{\eta_{propeller}}\cdot\frac{1}{\eta_{motor}}\cdot\frac{1}{\eta_{controlle}}$$

where ρ is the density of seawater, C_d is the drag coefficient and Aref the area on which the drag coefficient is based, u is AUV speed. Commonly used reference area is the projected frontal area or the AUV displacement in power two thirds. Propulsion efficiency η is the product of the efficiencies of the propeller, motor and motor controller.

It is evident from Figure 4-2 that for maximum track covered, the AUV speed should be between 2 and 4 knots where hotel load and propulsion power are of the same order of magnitude.

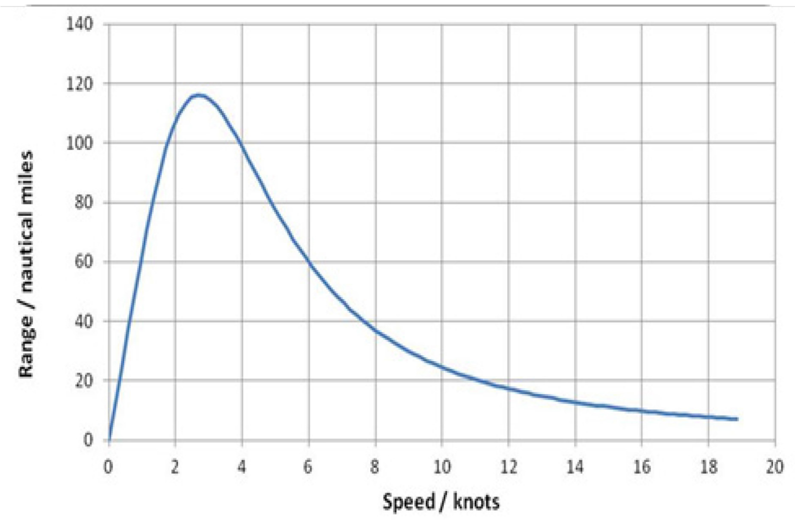


Figure 4-2: Range (Track) in Nautical Miles versus Speed in Knots Given a Projected Frontal Area-Based Drag Coefficient C_d of 0.13, a Diameter of 750 mm, a Total Energy of 18 kWh and a Hotel Load of 293 W. Propulsion efficiency η = 0.63.

Gliders are commonly even slower, their propulsion system being buoyancy regulation: Initially negatively buoyant, they sink until their turning depth where they pump out a liquid from their buoyancy tank, then ascend until the top turning point, etc. The liquid may be seawater or more commonly oil that fill a bladder and displace an equivalent volume of seawater. A power source for a glider could be a fuel cell that charges a battery during the gliding phases. This battery must then have sufficient power and energy to operate the pump at the deep turning point. Figure 4-3 shows a Spray glider.

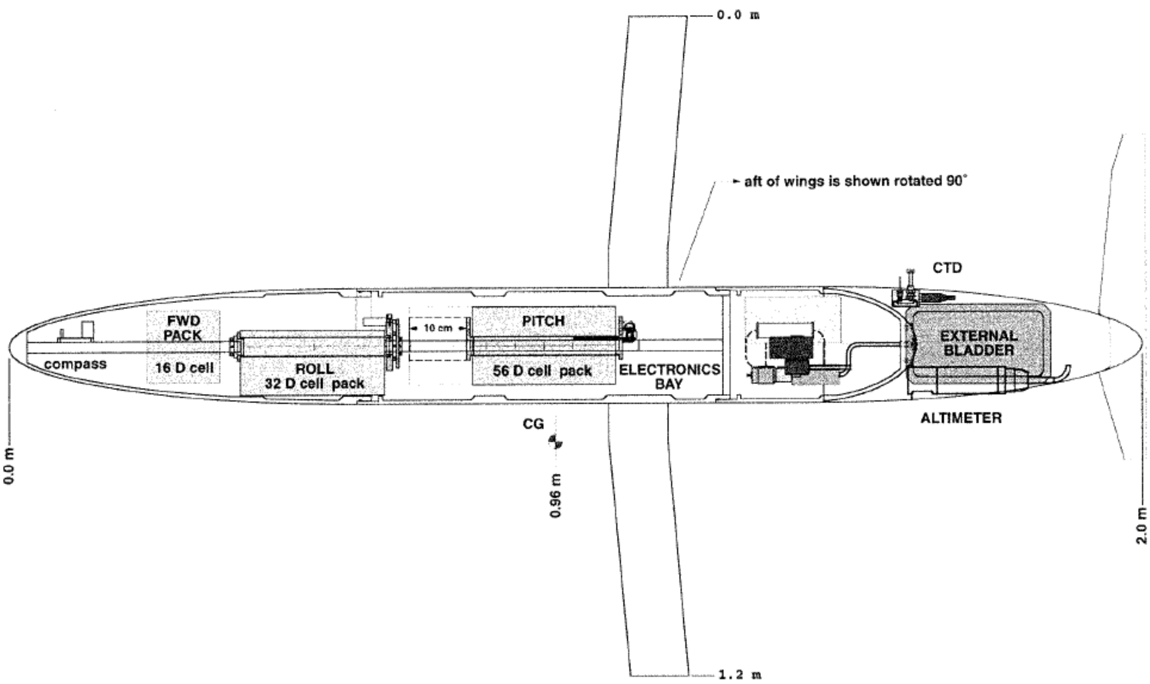


Figure 4-3: The Spray Glider (from Sherman et al., IEEE Journal of Oceanic Engineering, Vol. 26 No. 4 (2001) pp. 437-447). The gliders pitch and roll is controlled by moving the battery packs (the centre of gravity) and the buoyancy is controlled by pumping oil in and out of the bladder in the flooded section in the aft end. (The wings have been rotated 90° in the figure for clarity).

The propulsion efficiency of the glider is determined by the lift to drag ratio of the vehicle and the efficiency of the pump. (Hydraulic work done equals the pumped volume times the ambient pressure.) A common misunderstanding caused by the long range typical of low speed gliders is that gliders are more efficient than AUVs with propellers. Going from A to B, a glider must follow a longer path and the hydrodynamic work done (drag times path) will be larger given the same drag. One major advantage of gliders however is the low noise during the gliding phase. This zig-zag pattern is also useful for oceanography.

An AUV still in the water is neutral if the weight of the displaced water equals the weight of the AUV and it will have a neutral trim if the center of gravity is vertically below the centre of buoyancy. If the AUV moves, dynamic lift may compensate for wrong trim or buoyancy, but at the cost of increased drag. For battery operated AUVs trim and buoyancy considerations have been simple as the weight and centre of gravity of the power source do not change during discharge. For fuel cell powered vehicles however, this is not necessarily the case.

In order to successfully introduce fuel cells to the AUV community, the following must be true:

a) It must increase the energy content of the vehicle compared to a battery operated vehicle;

b) It must have sufficient operational reliability;

c) Buoyancy and trim must be controlled;

d) Logistic requirements and cost must be acceptable; and

e) It must give an acceptable feeling of safety to the user.

Other obstacles to the introduction of fuel cells may be rules and regulation, especially regarding use and storage of hydrogen on board ships. It makes no difference whether the perceived risks are real or not, the common public feeling of danger poses a significant obstacle to the acceptance of the use of hydrogen.

Fuel cells have been in use for Air Independent Propulsion (AIP) in manned combat submarines for a decade, e.g., the German 212A and 214 classes. Both are using a reversible metal hydride for hydrogen storage and oxygen stored as a Liquid at Low Temperature (LOX). For unmanned underwater vehicles however, batteries have been the preferred power source with few exceptions. For small UUVs and gliders primary batteries are commonly used, but with increasing size the operating cost becomes excessive and rechargeable batteries, e.g., lithium-ion, are used. Present state of the art for the specific energy is 400 to 500 Wh/kg for primary lithium-based cells and up to 200 Wh/kg for some lithium-ion cells. Depending on the design depth and construction, the achievable figures for complete power supply modules are typically 50% of the figures for the cells. Both pressure tolerant batteries working at ambient pressure and conventional batteries in a pressure hull are in use. The battery remains an important part of the working fuel cell system as it is required for start-up and shutdown as well as for load leveling.

4.2 FUEL CELL SYSTEM COMPONENTS UNIQUE FOR UUVs

Different fuel cells, their chemistry and applications have been given a thorough treatment in the report from the Applied Vehicle Technology Group (AVT-103) 2004 [12]. The work by the AVT group also describes technologies for hydrogen storage and hydrogen generation as well as oxygen storage and generation. This chapter assumes familiarity with the earlier AVT work and only discusses system components properties that differ in UUVs compared to ground and aerial systems.

The maximum energy density of a fuel cell system for UUV is to a large degree influenced by the source of oxygen, the design endurance and the design depth of the AUV. With increasing design depth, the weight of the pressure hull increases and reactants that can be stored outside the pressure hull gets more advantageous.

Examples are hydrogen peroxide and solutions of chemical hydrides (e.g., $LiBH_4$) or methanol. A pressure tolerant technology is used in the HUGIN 3000/4500 AUV. It is powered by a semi-fuel cell using aluminum as fuel, an alkaline electrolyte and hydrogen peroxide as oxidant or oxygen source. The complete system operates at ambient pressure down to a design depth of 4500 m (Hasvold et al., 2002) [20]. This system was introduced in 1998 and is operational in a number of commercial survey AUVs.

Because of the requirement of oxidant storage, the difference between the alternative fuels is moderate as shown in Table 4-1.

Table 4-1: Heating Value of Fuels and Specific Energy of Different Fuels in Combination with Pure Oxygen. Net energy to the user depends on the efficiency of the conversion system.

Chemistry	**Heating Value of Fuel** Based on the formation of water vapor, "lower heating value"	**Theoretic Specific Energy** "Lower heating value" and including the weight of oxygen
Hydrogen + oxygen $2\ H_2 + O_2 \Rightarrow 2\ H_2O$	120.1 MJ/kg 33.36 kWh/kg	15.86 MJ /kg 4.407 kWh/kg
Propane + oxygen $C_3H_8 + 5\ O_2 \Rightarrow 3\ CO_2 + 4\ H_2O$	46.39 MJ/kg 12.89 Wh/kg	10.79 MJ/kg 2.998 kWh/kg
Diesel + oxygen $C_7H_{16} + 11\ O_2 \Rightarrow 7\ CO_2 + 8\ H_2O$	47.800 MJ/kg 13.27 kWh/kg	10.64 MJ/kg 2.959 kWh/kg
Methanol + oxygen $CH_3OH + 2\ O_2 \Rightarrow CO_2 + 2\ H_2O$	22.320 MJ/kg 6.20 kWh/kg	9.069 MJ/kg 2.519 kWh/kg

It is evident from the table that with the exception of hydrogen, the figures for specific energy when the weight of oxygen is included are quite similar and that the selection of reactant should be based on the ease of use of fuel and the achievable efficiency of the complete system. The system weight should also include the necessary means to achieve constant buoyancy and trim of the AUV. For systems using stored pure oxygen and pure hydrogen, constant buoyancy is achieved just by containing the water produced in a separate, internal tank. For other combinations of stored fuel and oxidant, a more complex buoyancy control system may be mandatory.

4.3 HYDROGEN STORAGE OR GENERATION

4.3.1 Compressed Hydrogen

Compressed hydrogen is commercially available in metal cylinders. Metal cylinders are advantageous as they may be exposed to water and external pressure. Given their weight however, metal cylinders are not an attractive option. Carbon fiber composite cylinders are much lighter, developed for the automobile industry and commercially available in different sizes and pressure ratings, at present up to a pressure of 70 MP (700 atm). A typical average density of an empty 70 MPa cylinder is less than 500 kg/m^3, thus they may be used both as a buoyancy element in the design of the AUV and for hydrogen storage. For applications where they will be exposed to external pressure they need a waterproof coating as the carbon fiber composite is permeable. Gas sealing is an internal cylinder, "liner" made from thin metal or plastic. Corrosion in seawater must also be taken into account as well as rules and regulations and the need of certification of the cylinders after modification. Composite cylinders have a long and successful record as gas bottles for divers and the associated problems due to the use of hydrogen should not be insurmountable, but use in deep water and the resulting high external pressure demands a water proof coating and a test and certification process. For extreme deep diving a strengthening of the composite shell may become necessary as the strength for external pressure is significantly less than the strength for internal pressure. Table 4-2 provides some typical figures for hydrogen cylinders.

Table 4-2: Commercially Available Bottles for Compressed Hydrogen. In calculating buoyancy, a density of 1500 kg/m^3 has been assumed for the carbon fiber / epoxy composite material.

	Internal Volume (L)	Empty Weight (kg)	Hydrogen Mass (kg)	% H_2 kg/kg (%)	Weight in Water (kg Check)
Aluminum 200 bar Linde, AL050	50.0	58	0.82	1.4	-12.5
Composite 350 bar, Lincoln Composites "Tuffshell"	55.7	21.9	1.3	5.6	-46
Composite 700 bar "Tuffshell"	118.4	84.2	4.8	5.4	-85
Composite 350 bar "DyneCell"	202	93	4.26	4.4	-166

The positive buoyancy of the gas cylinders may be used to an advantage in the design of the AUV as most other components are heavier than water.

4.3.2 Reversible Hydrides

Hydrogen can be absorbed reversibly by some metal alloys that form hydrides under pressure in an exothermal reaction. The hydrogen is then released by a combination of reduced pressure and added heat. Depending on the composition of the hydride forming alloy, between 4 and 7 % by weight of hydrogen can be stored. But adding the weight of the container, heating tubes and heat exchangers, the practical hydrogen densities easily end up closer to 1%. As the volumetric storage density is quite good however and the system delivers highly pure hydrogen, it is in common use, e.g., in the AUV Urishima and in the U212 and U214 UVB-classes.

4.3.3 Liquid Hydrogen

Liquid hydrogen boils at 20 K, has a density of only 70 kg/m^3 and is not very easy to handle. It has however been used as a rocket fuel for decades and the aerospace industry is evaluating it as a fuel for commercial airplanes. This has resulted in the development of lighter and better insulated Dewars with reduced wall thickness. Figure 4-4 shows a liquid hydrogen system developed for automobiles. With minor modifications, this may be used for an AUV as well. As seawater can be regarded as an infinite source of heat for evaporation and heating of cryogen liquids to gas at "ambient" temperature, the low temperature is not an energy problem. For heat transport helium may be used. The low temperature may be an engineering challenge however as ice formation in and on the AUV must be avoided. It is assumed that containers for cryogen hydrogen storage are inside a pressure hull and separated from other systems.

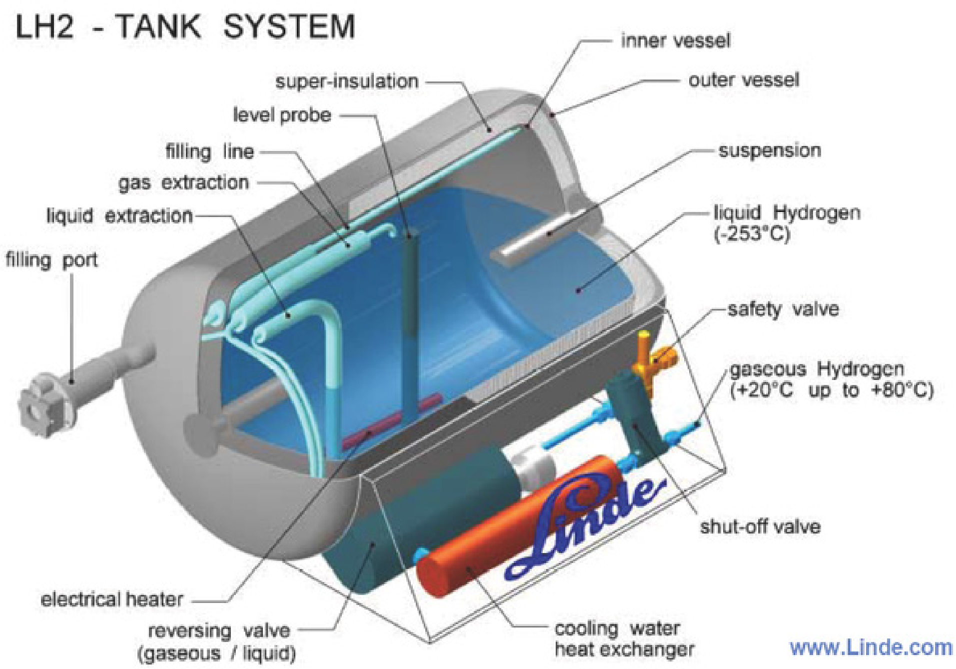


Figure 4-4: Liquid Hydrogen System Developed by Linde AG for BMW. A similar design may be used for liquid oxygen.

As the container insulation is not perfect, the heat flux leads to an unavoidable "boil-off" that makes venting necessary and limits the storage time.

The possibility of valve failures must be taken seriously as the pressure increase from liquid hydrogen to gaseous hydrogen at ambient temperature and constant volume is enormous.

4.3.4 Chemical Hydrides

Pure hydrogen can be generated from catalytic decomposition of a solution of chemical hydrides such as a sodium or lithium borohydride:

$$NaBH_4 + 4\ H_2O \Rightarrow NaB\ (OH)_4 + 4\ H_2$$

The hydrogen must be cleaned to remove traces of solution as cations such as sodium or lithium adsorbs to the membrane in PEM fuel cells, decreasing its conductivity.

Protonex Inc. (former Millenium Inc.) claims 7% hydrogen by weight from their hydrogen generator, close to the 8% based on the formula above (22% based on the weight of sodium borohydride).

4.3.4.1 Metals Reacting with Water

Alkali metals react rapidly with water forming alkaline solutions of metal hydroxides:

$2\ Li + 2\ H_2O \Rightarrow 2\ LiOH + H_2$ giving 14.5% hydrogen relative to lithium weight

$2\ Na + 2\ H_2O \Rightarrow 2\ NaOH + H_2$ giving 4.5% hydrogen relative to sodium weight

Both metals are easily extruded into a reactor where they may react with seawater in a batch process. The high solubility of the reaction products is highly advantageous as it simplifies the engineering of the hydrogen producing reactor. Precipitates of calcium and magnesium from the seawater will form however and may clog the system. Lithium is by far the best candidate in terms of weight and volume, but sodium is a much cheaper fuel and can be extruded more easily at low temperature.

Also aluminum, magnesium and silicon alloys have been studied as candidates for hydrogen production [20], but solid reaction products as well as large change in specific volume going from metal to hydroxide, may make these alloys more interesting for hydrogen generation on land.

In the case of aluminum:

$$Al + 3\ H_2O \Rightarrow Al\ (OH)_3 + 3/2\ H_2$$

This reaction gives 11.2% hydrogen relative to aluminum weight, but note that more water is consumed than generated from the fuel cell. The heat of reaction ΔH based on reaction with liquid water is -390.6 kJ/mol or 4.82 kJ/g, which is quite high, making it possible to operate the reactor at high temperature as a water vapor / aluminum system.

The volume increase from aluminum to aluminum hydroxide (hydrargelite) is 322%, thus the metal should be in a highly porous form. Ideally the kinetics of the reaction should be fast so that the production of hydrogen can be controlled by the rate of water addition. Also, in order to avoid clogging from the reaction products, soluble aluminum species should not be present. This is avoided in a system based on water vapor (superheated steam) and a highly porous aluminum alloy having only solid and gas phases. The calculated effective storage density of hydrogen, even at a high porosity of the aluminum alloy is still higher than in liquid hydrogen.

Recently, a hydrogen generator based on the reaction of sodium silicide Na_4Si_4 with water has been developed [21]:

$$2\ NaSi + 5\ H_2O \Rightarrow Na_2Si_2O_5\ (aq) + 5\ H_2$$

How efficient this reaction is largely dependent on the necessary water excess. (This holds for the other reactions as well and makes evaluation based on non-experimental information difficult.)

One advantage of the above mentioned systems for hydrogen generation is the high purity of the produced gas compared to hydrogen from reformers. Storability and safety is also excellent. The obvious disadvantage is system complexity and fuel cost.

4.3.5 Reforming of Hydrocarbons

Both steam and auto-thermal reforming of hydrocarbons are intensively studied. Irrespective of the fuel, a system for elimination of CO_2 must be incorporated in the AUV. In contrast to reforming of “logistic fuels” such as JP-8, methanol reforming takes place at much lower temperature and the reformate contains no sulfur. This makes the reforming process simpler and less energy consuming. This compensates for the slightly lower energy density of the complete system.

Neglecting side reactions [22] methanol is reformed according to:

$$CH_3OH + H_2O \Rightarrow CO_2 + 3\ H_2 \qquad \Delta H = +\ 49.4\ kJ/mol$$

giving 18.9% hydrogen relative to the methanol weight assuming that water produced from the fuel cell stack is used for the reforming reaction. The reaction is endothermic and heat must be supplied to the reformer and for the evaporation of water and methanol. Typical reaction temperature is 250°C and an excess of water is used (Steam to Carbon Ration (SCR) > 1.2, typically > 1.5), so as to keep the amount of CO formed low:

$$CO_2 + H_2 \Rightarrow CO + H_2O\ \Delta H = +\ 41.2\ kJ/mol \qquad \Delta G = +\ 28.6\ kJ/mol$$

In total, 1 to 5% CO may be present in the reformate after the steam reforming step. The energy for the reforming reaction can be generated in an auto-thermal reactor where a sufficient amount of oxygen is added to the mix of methanol and water vapor. The amount of oxygen x, is such that the heat of partial oxidation is sufficient to supply the required amount of heat to the steam reforming reaction:

$$CH_3OH + H_2O + (x/2)\ O_2 = CO_2 + (3\text{-}x)\ H_2 + x\ H_2O \qquad \Delta H = 0 \text{ kJ/mol}$$

Alternatively external heating of the reformer by an off-gas burner (off-gas = anode gas after going through the fuel cell) can be used. In both cases, a certain amount of fuel and oxidant is used for the reforming reaction.

Reformate gas is composed of H_2 and CO_2 as well as CO and water vapor and traces of methane and other contaminants. Depending on the type of fuel cell, the CO presence varies widely. SOFC can use CO as fuel, HTPEM can tolerate up to 3% (3000 ppm) whereas PEM typically require less than 10 ppm CO. Preferential catalytic oxidation can be used to remove CO where the reformate is mixed with the proper amount of oxygen and led over a catalyst. Unfortunately, an amount of hydrogen will also be oxidized.

An alternative is catalytic reduction to methane (methanation):

$$CO + 3\ H_2 \Rightarrow CH_4 + H_2O \qquad \Delta H = -205.9 \text{ kJ/mol}, \qquad \Delta G = -141.9 \text{ kJ/mol}$$

As methane is inert to the anodic oxidation in the PEM fuel cell, it must be removed by combustion in the off-gas burner. If not, it will accumulate in the system.

Membrane Hydrogen Purification

As low temperature PEM fuel cells perform best with pure hydrogen, the reformate may be cleaned with the help of palladium silver alloy membrane. Hydrogen diffuses through the membrane whereas the contaminants in the reformate do not. The process is well known, but energy consuming and the membranes are expensive. The contaminants, e.g., CO, CH_4 and CO_2 plus residual hydrogen are concentrated at the high pressure side of the membrane and must be disposed of. Thus a part of the hydrogen will also be lost.

Direct Methanol Fuel Cell (DMFC)

DMFC can be used in an UUV, but the low efficiency of present designs results in a high oxygen consumption compared to the Reformed Methanol Fuel Cell Systems (RMFC). As with RMFC systems, a CO_2 disposal system must be integrated.

CO_2 Removal

CO_2 may be removed from reformate ahead of or after the fuel cell stack. As the partial pressure of CO_2 is less than 25% ahead of the stack, physical separation is more difficult and chemical adsorption such as adsorption on calcium oxide is easier:

$$CO_2 + CaO = CaCO_3 \qquad \Delta H = -179.2 \text{ kJ/mol}$$

$$CO_2 + Ca(OH)_2 = CaCO_3 + H_2O \qquad \Delta H = -113 \text{ kJ/mol}$$

This is possible with standard adsorbers as used commercially in closed cycle diver breathing apparatus and in submarine systems. An alternative is to use this reaction to supply heat to the reforming reaction, making a mix of reforming catalyst and CaO:

$$CH_3OH(g) + H_2O(g) + CaO = CaCO_3 + 3\ H_2 \qquad \Delta H = -128.9 \text{ kJ/mol}$$

This reaction gives 6% hydrogen per weight unit of reactants.

Other systems for CO_2 scrubbing using lithium hydroxide and reversible systems based on amines are also well known.

A different technology is to cool the exhaust gas after the off-gas burner, recycle part of the water for use in the reforming process and then compress the mix of nearly pure CO_2 and water (if liquid it is expelled to the ocean). For shallow operating AUVs, an alternative might be to mix the CO_2 with seawater before expelling it. As pure CO_2 is liquid at ca 60 atm at room temperature, the amount of hydraulic work required to compress CO_2 is small. The efficiency of the system however might also be small, in which case chemical absorption might be the better solution.

4.4 OXIDIZER STORAGE OR GENERATION

4.4.1 Introduction

Unlike ground and air vehicle fuel cell systems that only require onboard fuel, UUVs need to operate independently from the atmosphere. The oxygen source must be carried. This reduces the maximum achievable energy density for the fuel cell system significantly. (The heat of combustion of hydrogen is 142 MJ/kg versus the heat of reaction of hydrogen and oxygen to water is only 10.4 MJ/kg.)

The oxygen concentration in the ocean (2 to 8 ppm) is in most cases also insufficient to meet vehicle power requirements, but a UUV based on magnesium oxygen seawater semi-fuel cell has been demonstrated [23]. A concept based on extracting oxygen from seawater has been tried but has not, to our knowledge resulted in a viable system. Thus the generation, storage, and delivery of pure oxygen is consequently of primary concern and poses a number of challenges. The oxygen source must possess a high volumetric and gravimetric O_2 content to fit the weight and volume restrictions of the UUV design. The oxygen source must be readily and rapidly refilled for maximum response time. In the end, the oxygen system must be capable of being operated safely and reliably in an autonomous mode from a diversity of host vessels such as surface ships and submarines. It is therefore relevant to compare methods of storing O_2 or chemically generating oxygen. Oxygen is a permanent gas and its dense storage (relative to typical liquids and solids) is an issue for that reason. Commercially, oxygen is available as compressed gas at pressures up to 300 bar and as Liquid at Normal Pressure (LOX). A combination of low temperature and high pressure may also be used. Some of the relevant physical properties of oxygen and hydrogen are given in the Table 4-3 below.

Table 4-3: Physical Properties of Oxygen and Hydrogen [Fuel Cells Working Group AVT-103, 2006].

Property		Oxygen	Hydrogen
Molecular weight [g/mol]		31.999	2.016
Gas density @ 25°C, 1 atm [kg/m³]		1.308	0.082
Boiling point @ 1 atm [°C]		-183	-252.8
Critical point	Pressure [atm]	49.6	13.0
	Temperature [°C]	-118.4	-240.0
Liquid density @ 1 atm [kg/m³] and boiling point		1140	71
Liquid molar density @ 1 atm [mol/l]		35.7	35.5
Latent heat of vaporisation [kJ/kg]		213.0	446.0

One advantage of operating supercritical is that "sloshing" is of no concern; the centre of gravity of the container is independent of vehicle orientation.

4.5 CHEMICAL GENERATION OF OXYGEN

Oxygen can be stored in pure form or it can be generated on site by chemical decomposition of an oxygen containing substance. In pure form it may be as compressed gas or as a liquid cooled down below the boiling point. Chemical oxygen generation may be based on decomposition of hydrogen peroxide or of alkali metal chlorates and perchlorates in "chlorate candles":

$NaClO_3 \Rightarrow NaCl + 3/2\ O_2$ $\Delta H = -41.2$ kJ/mol $\Delta G = -28.6$ kJ/mol

The oxygen content of sodium chlorate is 45%:

$LiClO_4 \Rightarrow LiCl + 2\ O_2$ $\Delta H = -27.6$ kJ/mol $\Delta G = -19$ kJ/mol

The oxygen content of lithium perchlorate is even higher at 60% by weight.

Even though the reactions are exothermal, in practical systems up to 8% iron powder is added to the chlorates to ensure sufficient high temperature for the decomposition reaction. As the salts melts before they decompose, glass fibers and binders are necessary, making the generated amount of oxygen per weight unit of the compound significantly less than the figures given above. When a candle is ignited it burns to the completion of the reaction. When the oxygen pressure falls below a pre-set level, the next candle is ignited, etc. The advantages of chlorate candles are compact size; they are reliable and have a long storage life. Thus they are used as emergency oxygen supply in airplanes and submarines. Practical systems contain one or more candles, a buffer for oxygen storage and a gas cooler. For AUV use, the complete system should be inside the pressure hull.

Hydrogen Peroxide (HP) is also used as a source of oxygen. One advantage compared to chlorate candles is that it can be stored in plastic bags (like wine in box) outside the pressure hull. Thus the oxygen storage is independent of the design of the AUV. It is pumped by a metering pump into a reactor where it decomposes into steam, water and oxygen according to:

$H_2O_2 \Rightarrow H_2O + ½\ O_2$ $\Delta H = -98$ kJ/mol $\Delta G = -116.7$ kJ/mol

The large free energy of reaction implies that hydrogen peroxide is highly unstable. The decomposition reaction is catalyzed by traces of transition metals, thus extreme cleanliness is mandatory for use of concentrated hydrogen peroxide solutions. As the decomposition liberates heat and heat accelerates the decomposition, thermal runaway may take place in Norway and Sweden have used 85% hydrogen peroxide in torpedoes for many years without any incidents, and lower concentrations are used for bleaching of pulp and paper. Commercially solutions of 50% are used in large volumes by the industry and inhibited solution with up to 70% may be transported according to civilian transport rules.

The complete oxygen system consists of HP storage (PVC bag outside the pressure hull), a metering pump, a reactor with catalyst, gas cooler and condenser, water separation system and a buffer tank for compressed oxygen. Most systems today are based on 50% or 70% HP giving an oxygen storage density of 0.294 kg/L for 50% and 0.428 kg/L for 70% HP. For comparison compressed oxygen gas at 300 bar has a density of 0.390 kg/L and liquid oxygen 1.140 kg/L, but in those system a much larger weight and volume must be used for the tank material.

4.6 COMPRESSED GAS STORAGE

Commercially, oxygen is available in cylinders of up to 300 Bars. Production and use of pressure vessels for compressed gas is highly regulated and a large safety factor is involved in their construction. Thus lighter designs than discussed below may be possible, depending on application and effort put into their construction and the limitations put to their use (e.g., cycle numbers with respect to fatigue). Gas bottles may be outside the pressure hull. For metal bottles, this is mostly acceptable as they may tolerate external pressure (compression) well. For composite bottles, this may or may not be the case, depending on their coating and the design of the liner.

Some typical examples of commercial cylinders are shown below in Table 4-4.

Table 4-4: Commercial Gas Cylinders.

	Oxygen Content/kg	Volume	Empty Weight	Full Weight/kg	% Oxygen kg/kg	Weight in Water kg (Full)
Linde 3AA2900, Steel	13.9	50 L / 200 bar	73	87	16.0	+26
Linde Gas B50C, Aluminium	16.35	50 L / 250 bar	33.6	50.0	32.7	-14.1
Linde Gas BALU50, Aluminium	13.9	50 L / 200 bar	56.0	69.9	20.0	-2.61
Luxfer L6X, Aluminium	13.9	50 L / 200 bar	56.0	69.9	20.0	-2.61
Luxfer L7X Aluminium	4.18	15 L / 200 bar	13.5	17.7	23.6	-2.82
Luxfer LCX-EL Composite with Al-liner	3.22	9 L / 300 bar	5.9	9.12	35.3	-4.13

From the table above, it is clear that both the B50C and the LCX-EL bottles will have a large positive buoyancy in water, thereby making the design of the AUV easier as most other components are heavier than water.

Oxygen behaves nearly like an ideal gas up to ca 30 MPa. Above 40 MPa the compressibility factor increases rapidly making use of higher pressures less advantageous. Commercial valves and regulators for oxygen at higher pressures than 30 MPa are not easily available, thus compressed gas storage of oxygen will be limited to less than 40 MPa.

These container weight in the above table is significantly higher than the figures given by Haberbusch et al. in They claim to store 50 kg oxygen in a cylinder weighting only 11.6 kg and 35 MPa pressure. The internal volume of that cylinder must be ca 115 L.

4.7 LIQUID OXYGEN (LOX STORAGE)

By cooling the oxygen gas, the pressure decreases and oxygen becomes liquid at -183°C and normal pressure. The boiling point increases with increasing pressure, but above the critical temperature, only gas exist. Thus oxygen may be stored as a liquid below the critical temperature and as a gas at nearly the same high density at the critical temperature and pressure. The advantage of supercritical storage is that sloshing is of no concern; the centre of gravity of the container is independent of the container orientation.

The example shown in Table 4-5 is for commercial units for medical oxygen delivery. In this application, weight reduction does not have a high priority. They also include the weight of valves, displays and physical protection during use and transport. In spite of that, the oxygen weight percentage (65%) is higher than for any of the other systems. Thus it shows the advantages of the cryogenic LOX storage system over the chemical and high-pressure oxygen system. The benefits include:

- Tank mass reduction compared to high pressure GOX storage;
- Tank volume reduction compared to high pressure GOX storage; and
- Oxidizer mass and volume ratio much better than chemical oxygen generation.

Table 4-5: Commercial Medical LOX Storage Systems for Home and Hospital Use.

		Linde HEIMOX Mobil S 44	**Linde HELiOS Stat. Mod. H46**
Tank Material	Units	Double Wall Stainless Steel	Double Wall Stainless Steel
LOX Amount		41 L / 44 kg	46 L / 50 kg
Mass Empty	[kg]	26	27.2
Height	[m]	0.96	0.953
Boil Off	[kg/day]	?	0.54

It should be noted that the advantage of using LOX decreases as the design depth is increased because the weight of the pressure hull for the Dewar increases. Also for smaller systems, the relative volume of the thermal insulation increases. For easy gas delivery, the internal tank should be sufficiently strong to allow an internal pressure of ca 10 atmospheres. The boiling point of LOX is -183°C at atmospheric pressure and increases with higher pressure up to the critical temperature. Materials and components for LOX application are industry standard (TRL 8 – 9). Both hydrogen peroxide and compressed oxygen bottles may be outside the pressure hull, whereas the Dewar must be protected. Also storage is a problem as boil off cannot be avoided. Thus LOX application is best for larger systems.

The storage of LOX raises many safety issues (see below). Cryogenic oxygen storage has been done on an industrial scale, but UUV applications require a higher level of safety and solutions to ice formation and associated problems must be found. One advantage of LOX is that in theory, evaporative heat and oxygen pre-heat can be supplied from the waste heat of the FC system, reducing the system heat losses. Waste heat from the FC has been shown to be a plentiful and effective heat source for vaporizing and pre-heating cryogenically stored liquid oxygen. Seawater is also an available as infinite source of heat.

4.7.1 Loading UUVs with LOX

There are several options of loading an Unmanned Underwater Vehicle with cryogenic O_2 from a host vehicle. Two examples are given in the following:

- The first option is a liquid oxygen transfer from a storage container on the host vessel into the UUV LOX storage system. This option provides a much quicker LOX loading time. The system chill-down gases generated can be used to start the fuel cell and prime the oxygen loop. But a liquid transfer line including a host vehicle LOX Dewar is required for this system. If the host vessel is an AIP submarine, LOX is already present.

- The second option is the direct liquefaction of gaseous oxygen. If the host vessel is a submarine for example, the GOX could be obtained out of the high-pressure GOX system for the breathing air. The host vehicle high-pressure gaseous oxygen is regulated down to a lower pressure. Then a one stage commercially available cryocooler coupled to a heat exchanger can be used to liquefy the GOX directly into the UUV cryogenic LOX storage system Dewar. This is the simplest LOX loading system. The heavy cryocooler compressor can be located on the host vehicle and the relatively light cryocooler cold head and heat exchanger can be positioned on either the host vehicle or the UUV. A host vehicle LOX Dewar is not required. The loading time is relatively long based on a single cryocooler of a reasonable size, but multiple cryocoolers can be utilized in parallel to decrease the loading time as required.

4.7.2 Safety Rules for Clean Oxygen

During operation with clean oxygen, special precautions are required. In the systems and devices working with oxygen and its mixture containing more than 25% oxygen [24] and more than 21% [25] materials and equipment's should have oxygen cleanliness and compatibility. Since not all materials are adapted to contact with oxygen, materials robust to oxygen influence should be used, i.e., materials which cannot undergo self-ignition and do not react with oxygen. The same applies to procedures determining conditions of safe oxygen exploitation. As before, they also should limit probability of self-ignition.

Generally, there are many commercial standards which indicate how the systems and devices working with oxygen should be prepared. Particularly, during operation with clean oxygen, the following rules should be strictly followed:

- Use of constructional and maintenance materials adapted for operation with oxygen;
- Ignition prevention and elimination of sources of ignition;
- Use of non-reactive elements working in conditions of oxygen presence;
- Appropriate ventilation;
- Proper maintenance materials;
- Proper working conditions of systems and devices with clean oxygen;
- Limitation of temperature below ignition value;
- Providing high cleanliness of system's elements and monitoring their condition during exploitation;
- Cleaning oxygen installation by proper degreasing; and
- Packing, marking and storing elements of oxygen systems.

There is some confusion regarding the use of aluminum in oxygen systems. High velocity impact of small aluminum particles are known to result in ignition. On the other hand, aluminum cylinders are in use for oxygen. The report [26] by G.J. Nihart and C.P. Smith on the compatibility of materials with 7500 psi oxygen (500 bar) illustrates this effect of thermal mass on safety. It is possible that an impact of a high velocity projectiles on an aluminum cylinder filled with oxygen may result in energetic combustion of part of the cylinder. For applications where incoming fire is considered likely, this should be experimentally verified or disproved.

4.8 SYSTEM CONSIDERATIONS

4.8.1 Build-Up of Impurities or Inert Gases

Because the system is hermetically sealed, any contaminant in the oxygen or hydrogen supply will build up in the system and must be expelled. As an example, take a 1 kW fuel cell system with an efficiency of 50%. This system consumes 1.45 kg hydrogen and 11.5 kg of oxygen per 24 hours.

Assume also that the oxygen contains 0.1 mol% inert gas (99.9% pure). After 24 hours, that equals 43 L of inert gas compared to a typical cathode system volume of less than 10 L. Thus either a very pure reactant gas must be used or a system for periodic pumping of gases to the outside must be implemented. This adds complexity to the system and for deep diving AUVs requires a significant amount of energy.

Compressed gases are available at high purity (99.999%) as are hydrogen and oxygen from electrolyzersand chemically generated hydrogen or oxygen may also be pure. Reformate gases may be used in SOFC without problems, but traces of CO or CH_4 must be removed from PEM and HTPEM fuel cell systems and CO_2 from the reforming must reaction be disposed of.

Inerts may also diffuse through the membrane from one electrode to the other, leading to increasing levels of inerts in, e.g., anode gas for LOX-based systems using ultrapure hydrogen, making a bleeding the system mandatory.

Industrial LOX quality is 99.5%with the main contaminants being argon and nitrogen. Thus a fuel cell system based on industrial LOX quality must have a way of getting rid of inerts, otherwise they will rapidly build up to intolerable levels. This is easy to do in shallow water, but bleeding of the fuel cell in deep water may be challenging both in terms of energy required for the gas compressor pump and because of the space requirement of the equipment.

4.8.2 Hydrogen Recombination System

All fuel cells leak to some extents. Hydrogen may leak into the atmosphere surrounding the fuel cell stack or contaminate the cathode gas. If the lower explosive limit (4%) is exceeded, the system may explode. Thus it is mandatory that a hydrogen recombination unit is present in systems where an explosive mix may form. (That goes for hydrogen leaking into oxygen/air as well as for oxygen leaking or diffusing into the hydrogen system.) Traditionally a platinum catalyzed recombination unit is used:

$$2\ H_2 + O_2 \Rightarrow 2\ H_2O$$

Water and heat from this reaction must be handled and the hydrogen concentration in oxygen containing compartments should be monitored. Hydrogen recombination catalysts may be poisoned and experimental verification of long term efficiency should be undertaken. For some applications, the fuel cell compartment may be strong enough to tolerate hydrogen/oxygen explosions. As the recombination reaction is identical to the fuel cell reaction, recombination may to some extent take place at the fuel cell electrode surfaces.

4.8.3 Buoyancy and Trim Changes

When using pure reactants such as compressed gas or liquid hydrogen or oxygen, the only requirement for constant buoyancy is to store the water formed in the fuel cell inside the pressure hull and in location(s) so that the center of gravity does not move in the horizontal direction. This requires a void volume at the start of the dive that is sufficiently large. For the 1 kW system mentioned above, a void volume of 13 liter per 24 hours must be available. Thus for a design endurance of 120 hours, the AUV needs to bring 7.25 kg hydrogen, 58 kg oxygen and 65.3 L void volume for water storage.

In an AUV using compressed hydrogen and oxygen generated from hydrogen peroxide that is stored outside the pressure hull part of the water formed during decomposition of HP must be stored as the volume of HP is replaced by seawater (density between 1200 and 1300 kg/m^3 depending on the concentration).

If hydrogen is formed from methanol stored outside the pressure hull, the consumption of methanol makes the AUV heavier, this may partly be compensated the buoyancy change if HP is used as an oxygen source. If in addition, CO_2 is adsorbed on board, the weight increases faster, making CO_2 expulsion a more favorable option.

Similar reasoning should be made for all fuel/oxidant combinations and weighted against other factors such as logistic simplicity and cost when selecting a fuel cell system.

4.8.4 Alternatives to Fuel Cells

With the exception of batteries, most power sources for underwater use are based on the combustion of a fuel with an oxidant. In fuel cells, there is a direct reaction, in heat engines, (Stirling, Rankine and closed cycle diesel) they transfer heat to mechanical energy which is then converted into electricity via a generator. In the thermoelectric generator, TEG, there is a direct transfer of heat into electricity. the underwater application is unique in the availability of an infinite and efficient heat sink, the sea.

In terms of efficiency, the fuel cell is most efficient, but also very choosy in the quality of the fuel. In contrast Rankine and Sterling motors only need a source of heat allowing the use of logistic fuels such as JP-8. This is also the case for the Thermoelectric Generator (TEG). In terms of efficiency, the fuel cell is between 30 and 60% efficient, heat engines between 20 to 35% and thermoelectric generators between 2 and 10%. In spite of its low efficiency, the TEG is able to use low temperature heat and may be used to improve the efficiency of the other systems using the temperature difference between the exhaust gas and the seawater. The TEG is a solid state device, reliable and silent but still under development. An increase in efficiency would make it an ideal candidate for underwater power generation, thus its development should be closely watched. Given a nuclear heat source, the present level of efficiency will be sufficient for long term, highly reliable but politically unacceptable underwater vehicle power sources.

The selection of an air independent power source for an AUV should be made after a detailed study of requirements. Some of these are:

- Hotel loads (what will the AUV be used for);
- Speed, peak and average;
- Endurance (range);
- Noise (electrical – internal), acoustic (internal and external);
- Design depth;
- Size limitations (weight, diameter and length); and
- Logistics.

Generally speaking, small, silent and low power favors batteries whereas large size and shallow water favors fuel cells. As noise requirements are relaxed mechanical power sources such as sterling, rankine and closed cycle diesel generators become more viable.

4.9 EXAMPLES OF FUEL CELL SYSTEMS RELEVANT FOR UUVS

Military use:

- Mine Countermeasure (MCM);

- Oceanography;
- Anti-Submarine Warfare (ASW);
- Intelligence Surveillance Reconnaissance (ISR);
- Inspection/Identification;
- Communication/Navigation Network Node;
- Information Operations; and
- Harbour Protection.

Civilian use:

- Oil Survey;
- Seabed Mapping;
- Pipeline Inspection; and
- Sub-bottom Profiling.

4.10 CONCLUSION

Air-independent applications of fuel cells in underwater vehicles will always have need of the oxidant to be stored along with the fuel. The storage of oxygen and the fuel is a critical issue for UUVs. The weight and size of storage tanks significantly impacts the specific energy and energy density of the fuel cell system. This chapter has indicated that there are a number of ways of storing O_2 and that for achieving the lightest and smallest storage system, LOX is offering the best properties for an underwater vehicle above a minimum size. The total system mass has been shown to be practical for an underwater vehicle and the oxidizer mass ratios have been shown to be significantly greater than alternative oxygen storage techniques such as chemical or high pressure gas.

A drawback of using LOX is that strict conditions must be met for its safe handling and storage. Safety relief valves are required and must exhaust into the outside water, but not freeze shut. Storage tanks outside the pressure hull must be able to withstand a pressure greater than the external pressure at the submerged depth. The system design must include a strategy to recombine or dispose of any leaking gases.

The waste heat from the fuel cell can be a plentiful and effective heat source for vaporizing and pre-heating cryogenically stored liquid oxygen. Seawater may also be used as a free available source of heat. Helium gas may be used as an efficient heat transfer medium.

Chapter 5 – UNMANNED SURFACE VEHICLES (USVs)

5.1 INTRODUCTION

In recent years, Unmanned Surface Vehicle (USV) technology has been intensively developed not only in US but also in European countries. USVs can be characterized by different levels of autonomy:

- Manual – They are remotely operated mainly by radio communication link;
- Semi-autonomous – They can operate autonomously only in selected operations, e.g., to reach desired waypoint, but they have to also be supervised by operator; and
- Fully-autonomous – They take and carried out decisions to achieve desired goal from launch point to recovery point.

USVs are in most cases driven by diesel engines coupled with screw propellers.

Historically, USVs were constructed for patrolling and reconnaissance purposes. Nowadays, they are destined for following missions [12]:

- Mine Countermeasures (MCMs);
- Anti-Submarine Warfare (ASW);
- Maritime Security (MS);
- Surface Warfare (SUW);
- Special Operations Forces (SOF) Support;
- Electronic Warfare (EW); and
- Maritime Interdiction Operations (MIO) Support.

USVs may be classified based on classification used in US Navy [Figure 5-1]:

- The “X-Class” is a small, non-standard class of systems capable of supporting SOF requirements and MIO missions. It provides a “low-end” Intelligence, Surveillance, Reconnaissance (ISR) capability to support manned operations and is launched from small manned craft such as the 11 m Rigid Inflatable Boat (RIB) or the Combat Rubber Raiding Craft (CRRC).
- The “Harbor Class” is based on the Navy Standard 7 m RIB and is focused on the MS Mission, with a robust ISR capability and a mix of lethal and non-lethal armament.
- The “Snorkeler Class” is a ~7 m Semi-Submersible Vehicle (SSV) which supports MCM towing (search) missions, ASW (Maritime Shield) and is also capable of supporting special missions that can take advantage of its relatively stealthy profile.
- The “Fleet Class” is a purpose-built USV, consistent with the handling equipment and weight limitations of the current 11 m RIB.

USV MP Priority	Joint Capability Area (JCA)	Seapower Pillar	USV Mission	X-Class (small)	Harbor Class (7M)	Snorkeler Class (7M SS)	Fleet Class (11M)
1	Battle Space Awareness (BSA) / Access/ Littoral Control	Sea Shield	Mine Countermeasures (MCM)		MCM Delivery, Search / Neutralization	MCM Search, Towed, Delivery, Neutralization	MCM Sweep, Delivery, Neutralization
2	BSA / Access/ Littoral Control	Sea Shield	Anti-Submarine Warfare (ASW)			Maritime Shield	Protected Passage and Maritime Shield
3	BSA, HLD, Non-Trad Ops, 7 Others	FORCEnet	Maritime Security		ISR/ Gun Payloads		7M Payloads
4	BSA / Access/ Littoral Control	Sea Shield	Surface Warfare (SUW)		SUW, Gun	SUW (Torpedo), Option	SUW, Gun & Torpedo
5	BSA / Access/ Littoral Control/ Non-Trad Ops	Sea Strike	Special Operation Forces (SOF) Support	SOF Support	SOF Support		Other Delivery Missions (SOF)
6	BSA, C&C, Net Ops, IO, Non-Trad Ops, Access, Littoral Control	Sea Strike	Electronic Warfare		Other IO	High Power EW	High Power EW
7	BSA, Stability, Non-Trad Ops, Littoral Control	Sea Shield	Maritime Interdiction Operations (MIO) Support	MIO USV for 11M L&R	ISR/ Gun Payloads		

Primary Missions supported by
X-Class | Harbor Class | Snorkeler Class | Fleet Class
Secondary Missions of each class that are possible

Figure 5-1: Classification of USVs According to "The Navy Unmanned Surface Vehicle (USV) Master Plan".

Results of the analysis of USV technology existing on USA market are included in "The Navy Unmanned Surface Vehicle (USV) Master Plan" (see Figure 5-1). No similar publication concerning the EU market was found. Therefore, independent analysis of European USV technology was carried out by the Polish Naval Academy. The analysis was based on 23 USV platforms built included in Table 5-1 below. In the report, the most important results of the analysis were presented.

Table 5-1: Analyzed Constructions of European Unmanned Surface Vehicles.

	Country	Name of USVs	No. of Constructions
1.	Austria	Roboat	1
2.	France	Rodeur, Inspektor, Basil	3
3.	Greece	Krissalos	1
4.	Germany	STIPS II, Seawiesel I, Seawiesel III	3
5.	Norway	Viknes, Mariner	2
6.	Portugal	Delfim, Caravela	2
7.	Sweden	Piraya, SAM 3	2
8.	Great Britain	Springer, C-Target, C-Sweep, C-Hunter, C-Cat, MIMIR EV1, Sentry	7
9.	Italy	Charlie, Alanis	2
		Total	**23**

Not all of the platforms constructed have been included since their technical specifications were not accessible, e.g., German MMSV or French Argonaute. Moreover, objects of the analysis are both commercial products and prototypes of USVs.

The first criteria of the analysis is connected with size of European USV. The main parameter describing size is a length of a hull. In Figure 5-2 below, distribution of a hull length for analyzed European USVs is presented. Based on this distribution, the most of European USVs have a hull length in the range of 4 to 5 m. Only one of the constructions can be classified as a Fleet Class, four of them as a Harbour Class and fifteen of them as the smallest units X-Class. Moreover, three USVs belong to Snorkeler Class. This is illustrated in Figure 5-2 below.

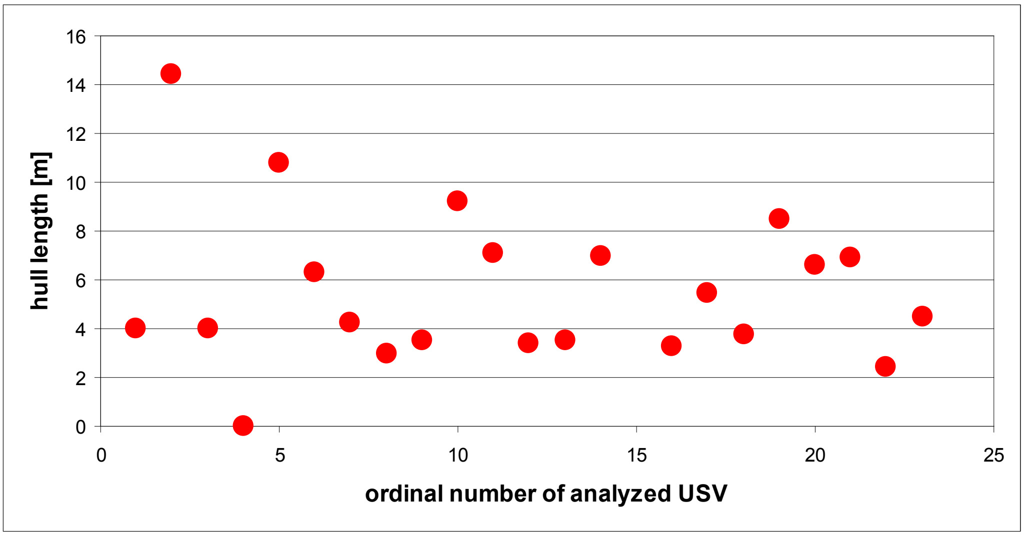


Figure 5-2: Distribution of Hull Length for Analyzed European USVs.

The next parameters describing size but also transport capabilities are a mass in air and a payload. Distribution of these parameters for following USVs is illustrated in Figure 5-3 below.

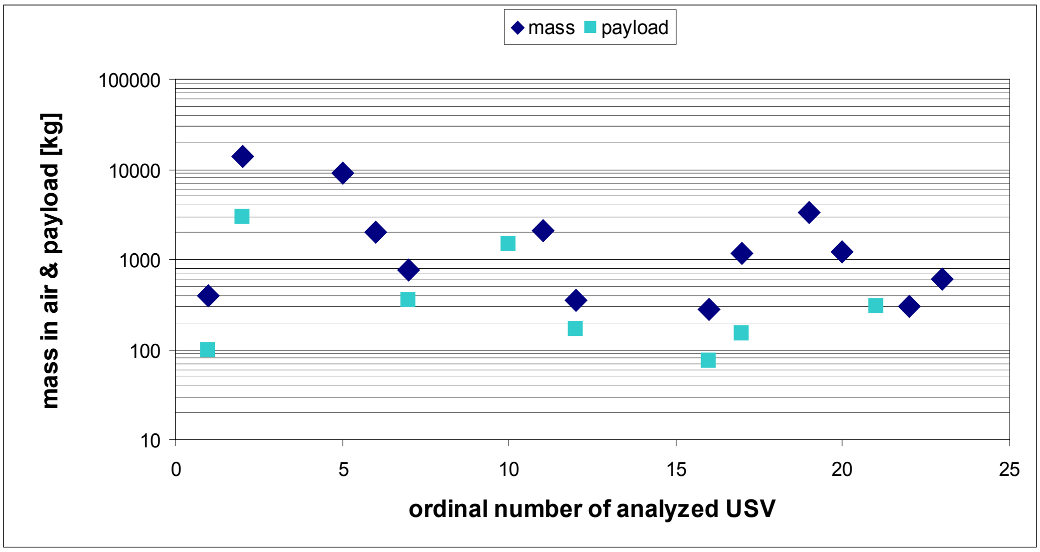


Figure 5-3: Distribution of Masses in Air and Payloads for Analyzed European USVs.

The figure inserted above show that masses of the most of the USVs are in the range of 300 to 2000 kg and their payloads are contained in the range 100 to 400 kg. Unfortunately, values of these parameters for some of constructions are not accessible. The payloads mentioned above is sufficient for installing most of the ISR equipment and even light armament and small underwater vehicle. The payloads can be insufficient for transfer of heavier weapon like torpedos, rockets, etc.

The next analyzed parameter is a range of mission. In Figure 5-4 below, distribution of ranges for analyzed constructions of USVs. Unfortunately, precise values of the range was not achieved for all considered USVs.

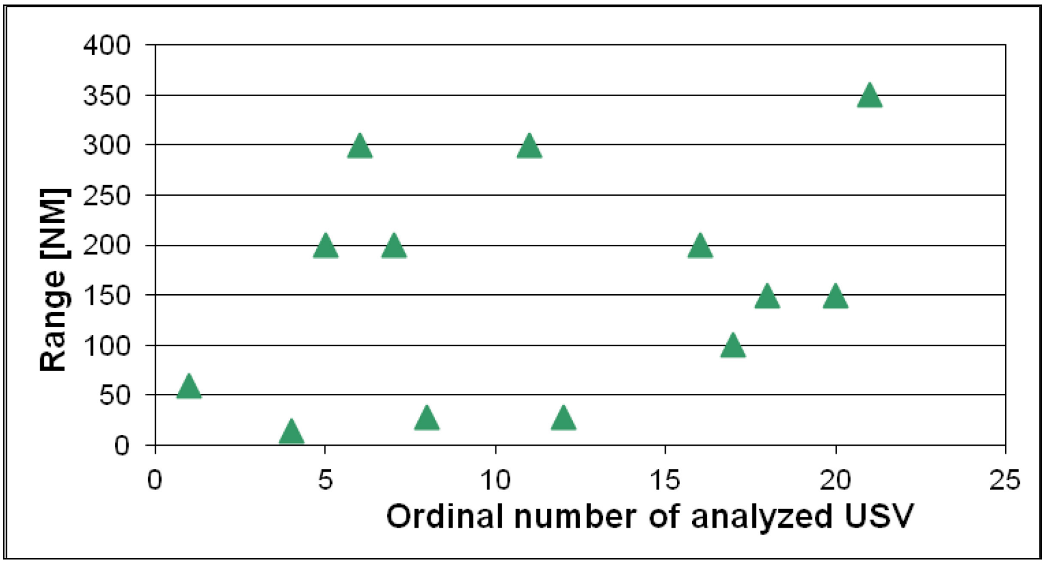


Figure 5-4: Distribution of Ranges of Mission for Analyzed European USVs.

Most of the commercial USVs have range of mission from 100 to even 300 NM. These values of ranges allow them to perform mission during one day, what seems to be enough especially in the case that they belong to smaller USVs X-Class or Harbour Class. Therefore, their area of operation is not as large as for larger USVs and usually it is limited to littoral water and it is connected with performing tasks of ISR and MCM.

After analysis of 23 European USVs constructions [1], following conclusions should be distinguished:

- Most of European constructions are X-Class USVs (1 Fleet Class, 3 Snorkeler Class, 4 Harbour Class, 15 X-Class);
- Most of European USVs has payload 100 – 400 kg (mainly ISR equipment and sensors, small ROV and underwater sensors); and
- Most of European USVs has range of mission 100 – 200 NM (with average velocity 10 knots).

5.2 USV APPLICATIONS RELEVANT FOR FC SYSTEMS

Based on presented above conclusions, X-Class and Snorkeler Class USVs seem to be most suitable for using FC systems instead of classical diesel engines.

X-Class are small USVs using mainly for ISR purposes among others by Special Forces. Therefore, more efficient energetic and silent source of energy will be useful and valuable for mentioned above missions.

Snorkeler Class are semi-submersible vehicles mainly used for MCM and ASW missions. In these kinds of operations, FC also has more advantages than classical diesel engine. Using of FC in Snorkeler Class will be even more efficient than in UUVs, because oxygen can be obtained from atmosphere.

5.3 CHOICE OF OPERATIONAL SCENARIOS

Selected scenarios have following requirements:

- Long endurance; and
- Stealth technology (difficult to detect).

Therefore, electric drive is proposed to use in scenarios presented below.

No information about using fuel cell systems in USVs was found. Using of fuel cell as a power supply of USVs should result in achieving more silent platform in comparison with diesel powered USVs and more efficient platform in comparison with USVs powered by rechargeable batteries. Therefore, some analytical examples of using fuel cell in USVs are shown below.

5.3.1 Scenario 1 – MCM and ASW

Speed: 10 knots

Duration: 24 h

Size: Snorkeler Class

The fuel cell system for the Snorkeler Class USV will be similar to the fuel cell system used in UUV with similar dimensions. One difference between the vehicles will be no need of oxygen storage on board of USV. In this case the oxygen will be delivered from atmosphere.

Based on the comparison tests of AUV Urashima with length 9.7 m (Figure 5-5 driven by electric motor (main 1.5 kW, horizontal 2 x 0.5 kW, side thruster 0.5 kW) and supplied by lithium-ion rechargeable battery or fuel cell system (4 kW Solid Polymer Electrolyte FC) following ranges were obtained [4]:

1) For classical lithium-ion battery – 100 km; and
2) For fuel cell system – 300 km.

Figure 5-5: AUV Urashima Powered by Fuel Cell System.

Therefore, using fuel cells instead of the battery resulted with three-times longer mission. In the case of USV, additional profit will be achieved connected with no need of oxygen storage and using pressure vessels for fuel cell and hydrogen tank.

5.3.2 Scenario 2 – ISR and SOF Support

Speed: 20 knots

Duration: 8 h

Size: X-Class

Scenario of using electric drive for USV was analyzed based on technology demonstrator of the surface vehicle called Edredon.

Presented in Figure 5-6, USV called Edredon is the first Polish Unmanned Surface Vehicle. It is based on almost 7 m length RIB. It was built within the framework of development project by consortium whose the leader was the Polish Naval Academy. The vehicle can be remotely operated from Mobile Command Centre or controlled by a steersman from its board. The USV is driven by a single screw propeller integrated with a rudder. Nowadays, the vehicle is being equipped with algorithms for increasing its 'intelligence' to be able to operate in an autonomous mode.

(a)

(b)

Figure 5-6: System of Unmanned Surface Vehicle Called Edredon: (a) the Vehicle; (b) the Mobile Command Centre [3].

After analysis of existing solutions of electric drives of USVs, 25 kW electric motor was accepted instead of diesel engine with the maximal power 180 km.

To ensure approximate 8 hours operation activities (the maximum speed is used only periodically) for asynchronous motor with a power of 25 kW at a rated voltage of 96 V is needed about 100 kWh of energy. In the case of using lithium-ion battery with 200 Wh/kg energy density, battery weight would be about 500 kg.

When using a fuel cell with a power 25 kW, weight of all system would be about 90 kg. To produce 100 kWh, this stack needs a hydrogen with average flow of 240 Nl/min, making a total of about 57,600 Nl (5.17 kg) of hydrogen. The hydrogen tank weight and volume depends primarily on the technology of its storage. A metal hydride reservoir of 60,000 Nl of hydrogen weighs about 540 kg. The large mass is a consequence of using together with the metal hydrides tank heating tubes and heat exchangers. A total mass of the energy storage system is about 630 kg which is more than using batteries.

More efficient method of hydrogen storage, considering total mass of the system, is gaseous hydrogen. Using composite tank with 700 bar the weight of tank is about 90 kg. In this case total mass of the fuel cell system and hydrogen storage is 180 kg. Total mass is almost three times smaller than the mass of batteries.

The similar efficiency method for hydrogen storage seems to be chemical hydride. Protonex Company claims that they achieved solutions where hydrogen is 7 – 8 % of mass of hydrogen generator. In this case a mass of hydrogen generator would be about 75 kg.

5.4 CONCLUSION

Based on the scenarios presented above, fuel cell technology used for supplying USVs driven by electric motor offers higher energy density than rechargeable lithium-ion batteries.

Using fuel cell technology to electric supply of USVs especially the smaller ones and submersible ones seems to be promising due to larger range.

FC system installed in USVs will be simpler than in UUVs, because the former don't need to store oxygen onboard.

Chapter 6 – CONCLUSION FOR UNMANNED VEHICLES

Fuel cells for unmanned systems have the potential for significant increase of energy density, and consequently endurance, compared to batteries and lower signature compared to ICE-systems. The potential increase of energy density is highly dependent on the mission scenario and the unmanned system, and needs to be calculated for each case. In general, fuel cell systems will be more favourable in systems with high energy demand and low average power. The report includes results of analysis of using fuel cells in different unmanned vehicles in different scenarios. Conclusions from these analyses are presented under each section.

All unmanned vehicles need a storage system for the fuel, and UUVs (and in some extent UAVs) also for the oxidant. The design of the storage system will very much decide the energy density of the power system in the vehicle. There is a trade-off between different storage methods regarding volume and weight. By converting an existing battery or ICE vehicle into a fuel cell vehicle, ineffective compromises must be made, especially with bulky energy storage systems. In order to achieve maximum benefit from changing to a fuel cell system, the vehicle should be design from scratch.

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14. Abstract

Current unmanned systems rely on either rechargeable batteries, an internal combustion engine or a combination of the two, depending on the size of the system, to provide power for propulsion and the various sensor systems mounted on the platform. The major problem related to both of the solutions is lack of time on station/mission endurance. Reducing the weight or increasing the energy density of the energy source frees up payload that can be applied to other systems or a lighter system that has longer mission times. A major effort for reducing this weight is the replacement of these systems with a fuel cell. This report identifies the state-of-the-art of fuel cell technologies as they can be applied to various unmanned vehicles, aerial, ground, above and below water systems.

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