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First Fuel-Cell Manned Aircraft

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In February and March 2008 The Boeing Company successfully performed flight tests of the first manned fuel-cell airplane in aviation history. The fuel-cell demonstrator airplane is a modified two-seater motor glider equipped with a hybrid power source powering an electric motor that drives a variable-pitch propeller. The hybrid power source comprises a proton exchange membrane fuel cell, the main power source, and a Li–ion battery that assists the fuel cell only during takeoff and climb, when the maximum power is demanded. The fuel-cell demonstrator airplane successfully completed four test flights. The airplane took off and climbed at 100 km/h, up to 1066.8 m (3500 ft) above sea level, with full power from the Li–ion batteries and the fuel-cell system. Once the cruise altitude was reached, the pilot disconnected the batteries. The altitude profile of the flight mission, logged in an International Civil Aviation Organization certified global positioning system, proved that the airplane maintained altitude. This demonstrated the first manned straight and level flight with only fuel-cell power. The fuel-cell demonstrator airplane generates water vapor as the only exhaust product and seems considerably quieter than the conventional airplane. This paper gives a brief description of the fuel-cell demonstrator aircraft's main subsystems, bench, ground, and flight test results, as well as the main challenges encountered while designing, building, and testing this prototype and the lessons learned for the implementation of fuel cells in aviation.

Introduction

GIVEN the high efficiency and environmental advantages that fuel-cell technology could offer, along with the considerable improvements achieved in the automotive sector in the last 5–10 years, the main airframe manufacturers have started to investigate their potential applications in aviation for both propulsion and onboard auxiliary power generation. In 2008, two important steps toward the implementation of fuel cells in aeronautical applications were met: the flight of the Boeing fuel-cell demonstrator airplane described in this paper and presented in Spain in February 2008[†] and the demonstration of a fuel-cell system generating auxiliary power for the hydraulic and electric systems of an Airbus 320, presented in France in February 2008 [1]. Although these programs will indubitably facilitate the integration of fuel-cell technology in aeronautical applications, there are still many technical challenges to be overcome before these systems can be integrated onboard commercial airplanes. However, fuel-cell technology could have a short-term application (for example) in sport aviation or in specific missions of small manned or unmanned aircraft, in which fuel cells could offer improved mission endurances over those attained with current battery technology. The first challenge relates to increasing the specific energy density, a less serious concern for other industrial sectors but crucial in the aeronautical sector. Moreover, it is imperative to determine their reliability and performance in real flight conditions (for example, at high altitude, at different pitch and roll angles, etc.), since there are many requirements that are exclusive of aeronautical applications and for which no experience has been gained in other industrial sectors. Among these are, for example, variable pressure and temperature ranges and stringent safety requirements.

Although limited in terms of different applications, there is a relatively long experience in the use of fuel-cell systems in the aerospace sector. Despite the fact that recent developments have centered on the automotive industry and in stationary power generation, in the 1960s, NASA (in collaboration with Pratt and Whitney and General Electric) developed fuel-cell systems for the Gemini and Apollo space missions [2]. Nowadays, considerably improved fuel-cell systems are employed onboard the space shuttles to produce water and electricity.

A very innovative program that studied the use of fuel cells in the aeronautical sector was the Helios program, carried out in the United States between 1999 and 2003 [3]. The prototype, developed by AeroVironment, Inc., in collaboration with NASA, was a high-altitude (30,000 m) unmanned air platform with a flying wing configuration powered by electric motors. During the day, the Helios would use the energy provided by the photovoltaic cells for both propulsion and for generating hydrogen (through water electrolysis), and during the night, it would be powered by the fuel cell. Unfortunately, although they achieved an extremely impressive altitude record (30,000 m during 17 h) in 2001, the platform broke in flight in June 2003 and never flew with the fuel cells.

In Arizona, on 26 May 2005, AeroVironment successfully completed the flight tests of one other unmanned platform with a similar aim to that of the Helios program but without using solar energy. It was a scaled prototype of the Global Observer [4]. The fuel-cell-powered unmanned aerial vehicle (UAV) had a distributed electrical architecture in which liquid hydrogen fuel cells provided electricity to electric motors driving eight propellers. The Global Observer program continues with the aim of developing a platform able to stay aloft at high altitude (20,000 m) during at least 1 week, while carrying a 450 kg payload, to perform surveillance, reconnaissance, and frontier monitoring missions.

NASA continues to be interested in high-altitude long-endurance unmanned platform surveillance missions. The Defense Advanced Research Projects Agency recently launched the Vulture program to develop new UAV concepts able to stay aloft at high altitudes during 5 years without interruptions for intelligence, communications, surveillance, and reconnaissance missions over areas of interest.[‡] Currently, the only systems able to cover fixed areas during several years are geosynchronic satellites orbiting at 35,780 km above the earth. The innovative platform would not only need to carry a payload of 454 kg, consuming 5 kW, but it would also need to maintain sufficient speed to withstand the winds at 18,300–27,500 m; that is, it should be able to operate like a satellite but covering larger areas (an almost futuristic challenge). Among other technologies,

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[†]Data available at http://www.boeing.com/news/releases/2008/q2/080403a_nr.html [retrieved April 2008].

[‡]Data available at http://www.boeing.com/news/releases/2008/q2/080421d_pr.html [retrieved April 2008].

solid oxide fuel cells (SOFCs) are being considered within this program.

There have also been a few low-altitude fuel-cell-powered UAV prototypes, including the scaled model of the Global Observer (AeroVironment, Inc., 2005), the Georgia Tech Research Institute fuel-cell-powered UAV (Aerospace Systems Design Laboratory of the Georgia Institute of Technology, and Georgia Tech Research Institute),[§] the Spider–Lion (U.S. Naval Research Labs and Protonex Technology),[¶] the Hyfish (DLR and Horizon Fuel Cell Technology),[**] the SAE Pterosoar (California State University, Oklahoma State University, Horizon Fuel Cell Technology, and Millennium Cell) [5], the Puma (AeroVironment and Adaptive Materials, Inc.) [6] and the Endurance, which recently achieved the current endurance record for fuel-cell-powered UAVs (10 h, 15 min, and 4 s) [7]. The Hyfish , a ducted fan propeller aircraft, seems to be too fast for effective surveillance missions. The rest have also a fixed wing configuration and have been designed for large autonomy. However, they seem to require long runways to take off and land, have low payload capability, and do not seem easy to transport.

A totally different aeronautical application of fuel cells is the onboard generation of auxiliary power. In February 2008, Airbus, Michelin, and the DLR successfully performed the flight tests of an Airbus A320 with a Michelin 20 kW fuel-cell system powering the aircraft's electric motor pump, which was connected to the blue hydraulic circle and successfully moved the aircraft's ailerons, rudder, and other flight-control systems [1]. Within the concept of the more-electric airplane, fuel cells could be used as battery replacement or to substitute the current generators in the auxiliary power unit (APU). In the latter, fuel cells could be used to start the airplane engines or to provide the energy required for the passengers cabin environmental control system (supposedly electrical), or for any other onboard electrical supply (lights, catering, etc.). Current APUs have a very poor efficiency, while a solid oxide fuel-cell/gas turbine hybrid system could achieve up to 70% efficiency, leading to a significant reduction in the fuel consumption and, therefore, to a considerable decrease of the noxious emissions, not only on the ground but also during flight. Moreover, the water produced could be used for antiicing purposes. However, the power requirements of the APU of an aircraft of the Boeing 737 type are between 250–400 kWe, depending on the particular aircraft model. For transport applications, SOFC technology has been developed even less than proton exchange membrane (PEM) technology. Considerable improvements in the specific energy density of the entire system along with desulphurizing and reforming technologies are needed for this application, which seems one of the furthest in the future.

Regarding the use of fuel-cell systems for propulsion of manned aircraft, besides the fuel-cell demonstrator airplane presented in this paper, only two other projects are currently underway. These are the Environmentally Friendly Inter-City Aircraft Powered by Fuel Cells (ENFICA-FC) project and the Antares DLR-H2 fuel-cell aircraft project. The ENFICA-FC project is a European Union project led by the University of Torino, which is mainly focused on theoretical studies of an intercity aircraft that uses fuel-cell technology for the propulsion system and hydrogen storage.[††] However, the Antares DLR-H2 is a prototype developed by the DLR Institute of Technical Thermodynamics together with Lange Aviation, GmbH. Despite having been presented at Stuttgart Airport on 30 September 2008,[‡‡] the prototype has not flown yet. The Antares DLR-H2 differs from the fuel-cell demonstrator airplane presented in this paper in that the fuel-cell airplane cruised with fuel-cell power but took off and climbed with the aid of an auxiliary Li–ion battery, whereas, if successful, the Antares DLR-H2 would take off and climb only with fuel-cell power.

The objective behind building the Boeing's fuel cell demonstrator prototype was to prove the feasibility of a straight and level manned flight with only the energy delivered by fuel cells and to gain hands-on experience to integrate this novel technology in aerospace applications.

This project was part of The Boeing Company's efforts to develop environmentally friendly technologies for aerospace applications and to reduce airplanes' polluting emissions. Since the 1950s, general aviation has made steady significant progress in protecting the environment by reducing the commercial airplanes' noise footprint by 90% and improving their fuel efficiency by 70%. These efforts continue to reduce weight by using composite materials, to reduce engine emissions and noise, to improve the airplane aerodynamics, to improve the system electrical efficiency by researching less energy-intensive electric systems and reducing pneumatic systems, and to have more efficient operations and air traffic management to consequently reduce fuel use, emissions, and noise. The use of novel propulsion systems that incorporate environmentally friendly technologies can also help to reduce emissions.

Fuel-cell technology has hardly been developed for aeronautical applications. Most of the available systems have targeted applications of other industrial sectors in which the proposed solutions are inherently different or cannot be applied to an aircraft. The most stringent requirements derived from aeronautical applications are weight reduction, safety, and reliability. These pose tremendous challenges for the integration of fuel-cell powerplants in aircraft. Some of them are maintaining the weight and balance of the aircraft, designing the thermal management system, managing the power flows of the hybrid power source when the fuel cell works in parallel with an additional power source, and ensuring a safe operation in a potentially flammable atmosphere.

This prototype tried to preliminarily address the aforementioned challenges and to prove the feasibility of integrating this novel technology in a manner consistent with aviation practices. The result is a safe and reliable prototype with an endurance of approximately 45 min for flights at low altitude and low speed and with operative limitations regarding weather conditions.

Airplane Description

Powerplants based on proton exchange fuel cells are very attractive from the environmental point of view, as they produce no harmful emissions. However, they are still much heavier than the conventional propulsion systems. Therefore, an aircraft that uses a fuel-cell-based propulsion system needs to be extremely efficient from the aerodynamic point of view in order to make up for the weight penalty associated to the fuel cell and auxiliary systems. In addition, it is useful to count with sufficient load capacity to counterbalance all the new systems associated to the fuel-cell power plant. The air platform chosen for the fuel-cell manned aircraft is the Austrian HK36 Superdimona motor glider from Diamond, a two-seater Joint Aviation Requirements 22/European Aviation Safety Agency (EASA) Certification Specification (CS) 22 certified aircraft with a maximum takeoff weight (MTOW) of 770 kg, a wing span of 16.3 m, and a maximum lift-to-drag (L/D) ratio of 27 [11]. This air platform was chosen because of its high L/D ratio and its useful load capacity (210 kg).

The design philosophy was to maintain, as much as possible, the aerodynamic characteristics of the original aircraft. Only minor modifications were performed to the original airframe in order to mount the different components and to improve the ventilation to reduce the risk of having an explosive atmosphere in the unlikely case of having a hydrogen leak. The impact of these modifications on the overall aircraft aerodynamic performance can be considered to be negligible. However, the integration of all the new components resulted in a slightly different weight distribution and an overweight of 100 kg beyond the original aircraft certified MTOW.

[§]Data available at http://www.gtri.gatech.edu/casestudy/flying-hydrogen [retrieved 2006].

[¶]Data available at http://www.designation-systems.net/dusrm/app4/spider-lion.html [retrieved Feb. 2006].

[**]Data available at http://www.horizonfuelcell.com/hyfish.htm [retrieved April 2007].

[††]Data available at http://www.physorg.com/news99921594.html [retrieved June 2007].

[‡‡]Data available at http://www.dlr.de/en/DesktopDefault.aspx/tabid-1/86_read-13650 [retrieved Sept. 2008].

The prototype aerodynamic controls are the original flight controls of the HK36 Superdimona (elevator, rudder, ailerons, and aerodynamic brakes), but modifications made included removing the copilots control lever, spoiler lever, and rudder controls and reassembling the brake system on the pilot's compartment. Further flight controls include the propeller speed control within the propeller pitch controller, the throttle control within the power management and distribution (PMAD) control board, which sends the torque command to the propulsion motor, and the electrical controls within the PMAD control board, which manage the power flow and the electrical protections.

The main new systems are the propulsion system, the electrical system (including the power plant), and the fuel system. Their design was driven by the need of minimizing the weight and maximizing the operational safety. Although the main characteristics of the systems are summarized next, further information can be found in [8–10]. The aircraft layout is shown in Fig. 1. Figures 2–4 show photographs of the engine bay, the cabin, and the fuel compartment interior, respectively. The positions of all the different systems had to maintain the aircraft weight and balance. The extra weight located in the engine bay (mainly due to the fuel-cell system) was counterbalanced with the batteries located in the original fuel compartment.

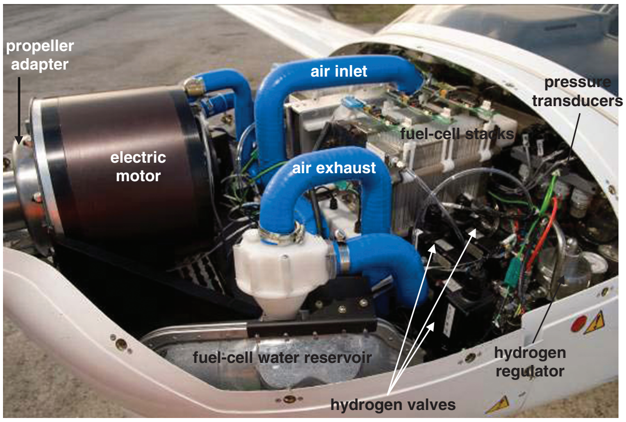

Fig. 2 Engine bay.

Propulsion System

The propulsion system converts the electrical power from the power sources into thrust. The propulsion power is proportional to the torque generated by the motor and the rotational speed set by the propeller. The pilot controls the torque magnitude by means of the throttle lever and the rotational speed by setting it in the propeller pitch controller.

The original propulsion system of the motor glider was replaced by the following components (see Fig. 5): 1) an experimental electric brushless permanent magnet dc motor, from UQM Technologies, with its corresponding driver (inverter and controller); 2) a variable-pitch propeller, coupled to the electric motor; 3) a custom-made propeller adapter to transmit the thrust from the propeller to the engine-mounting structure (rather than to the motor) and to allow the supply of electric power to the propeller pitch change motor through the slip ring by means of some brushes; and 4) the motor thermal management system to provide enough coolant flow to dissipate the 6 kW of heat generated during takeoff and climb and to maintain the motor and the inverter within their operational limits for the entire flight mission. The main components are the motor radiator, the motor radiator cooling pump, and additional auxiliary components.

The preliminary aircraft performance calculations based on the polar of the HK36 Superdimona [8] defined the size of the motor. The UQM PowerPhase 75 was selected because it has an adequate power-to-weight ratio and a performance close to that required for the envisioned flight mission. The specific details on the propulsion system sizing and the brake power requirements for the flight mission are given elsewhere [8]. The original engine mount had to be modified to install the UQM electric motor (see Fig. 6).

The dc brushless system comprises an inverter and a permanent magnet electric motor. The motor is located in the engine bay (see Figs. 1, 2, 5, and 6). To aid the installation of the motor inverter, the copilot's part of the instrumentation panel was suppressed (see Fig. 3). The motor has a maximum peak power output of 75 kW and a continuous power output of 30 kW. This posed a challenge, because the motor had to comply with the power requirements for takeoff and climb (42 kWe or 36 kW brake during 7 min). The system proved to adequately cope with the takeoff and climb power requirements, but the 7 min could not be exceeded due to the motor internal temperatures being close to their limits [8].

The inverter and the motor are refrigerated by the motor-cooling water pump and the radiator to avoid exceeding the maximum inverter, rotor, and stator temperatures. The inverter's temperature limit (55°C) is the most stringent requirement. The motor radiator was specifically designed to maintain the inverter temperature below its limit throughout the entire flight mission. The main challenges related to the design of the motor radiator were the reduced volume in the engine bay, the existence of two other radiators in the fuel-cell system, and the little knowledge about the real air flow in the engine bay with the new distribution of components [8].

A variable-pitch propeller was chosen since its efficiency could justify its weight penalty with respect to that of a fixed-pitch propeller. The MTV-1-A/175-05 is one of the original models that MT Propeller offers for the HK36 Superdimona, and it includes a propeller pitch controller that electrically regulates the pitch angle to reach the rotational speed set by the pilot and offers a feathering

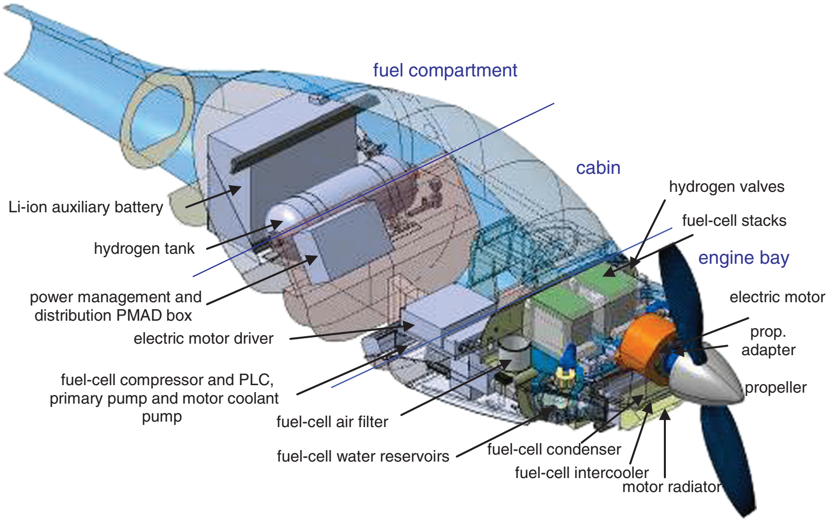

Fig. 1 Fuel-cell demonstrator airplane layout.

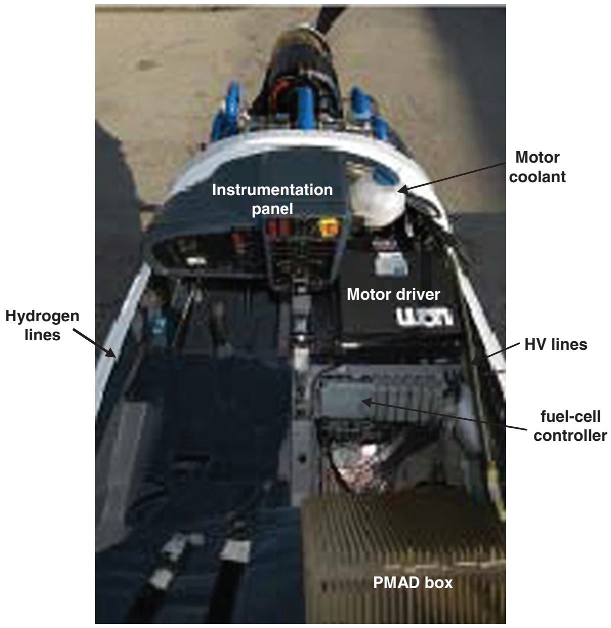

Fig. 3 Cabin (HV denotes high voltage).

Fig. 4 Fuel compartment.

option. The propeller adapter is the mechanical link between the electrical motor and the propeller and transmits the propeller thrust to the airframe structure rather than to the motor, which is not designed to transmit any axial load. The link between the motor and the propeller is through a direct drive; the propeller adapter does not reduce the rotational motor speed to the propeller.

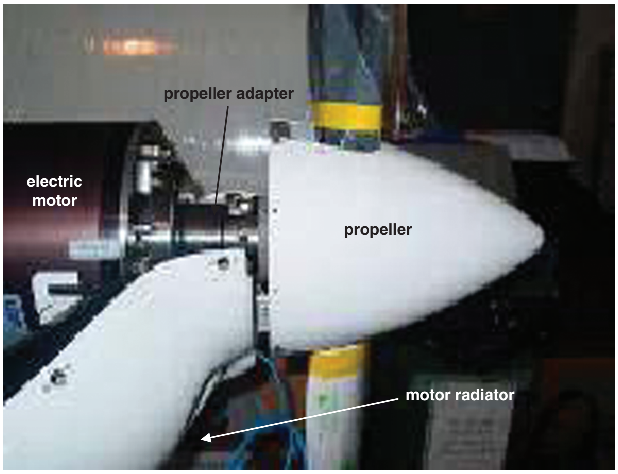

Fig. 5 Propulsion system.

Electrical System

The electrical system distributes the power from all the sources to all the electrical loads, providing different voltage levels according to the type of load. The electrical system in the fuel-cell demonstrator aircraft was built from scratch. The new components are the power sources (fuel cell, Li–ion auxiliary battery, and Ni–Cd backup battery), the loads [mainly the propulsion motor and inverter along with the fuel-cell balance of plant (BOP) and water pumps], and the electrical integrator and links (PMAD box and wiring).

The hybrid power source comprises a PEM fuel-cell system and a pack of Li–ion batteries (auxiliary batteries) to power the electric motor. The fuel-cell system maximum output power is 24 kW gross, and the battery can supply a maximum continuous power in the rage of 50–75 kW.

The fuel-cell system is the main power source of the airplane. It was sized by taking into account the motor efficiency and the consumption of the rest of the electrical equipment, mainly during cruise. However, it also provides the required power during the taxi, approach, and landing. The batteries supply only the additional power for takeoff and climb, and they are only recharged on the ground. This is because, if the batteries were recharged during flight, the fuel cell would need to be larger and, therefore, heavier. The batteries were sized to supply the additional power demanded during a 7 min takeoff and climb up to an altitude of around 1000 m (3500 ft) above sea level (ASL). In addition, in the event of a fuel-cell failure during takeoff and climb, the battery had to be able to supply all the required power demand for at least 5 min, so the airplane could continue ascending up to a safe altitude to proceed with an emergency landing.

The fuel-cell system comprises two pressurized stacks electrically connected in series and the BOP components. These include the air filter, the air compressor (including its motor and drive), the air mass flow meter, thermocouples, current and pressure transducers, the primary heat exchanger (condenser), an air-to-air intercooler, two water reservoirs with level sensors, inlet and outlet water and hydrogen solenoid valves, a scavenge-water pump, and a primary water pump, along with water flow sensors and water filters and an internal control unit [a programmable load controller (PLC)]. The components details and the fuel-cell test results are given in detail elsewhere [8,9].

Most of the fuel-cell components were located in the engine bay (see Figs. 1 and 2), and those components that were neither spark free nor silent were located within an enclosed and ventilated compartment in the cabin, at the copilot's feet (see Fig. 1). A special tray was made to install the stacks in the engine bay (see Fig. 7), and a new lower cowling was made to accommodate the fuel-cell water reservoirs (see Fig. 8). The upper cowling was also slightly modified to have a special air inlet to ventilate any possible hydrogen that might leak from the fuel-cell stack seals during normal operation (see Fig. 9).

The Li–ion battery is the auxiliary power source for takeoff and climb. To counterbalance the heavy weight of the fuel-cell components in the engine bay and to maintain the airplane balance, the battery was mounted behind the pilot seat, in the original fuel compartment (see Figs. 1 and 4). To do that, the *b* bulkhead of the airplane had to be modified.

The Li–ion battery assembly comprises the cells, electrically connected in series and arranged in modules, and a battery-management unit with its electrical protections. Few electronic boards monitor the individual cell voltages and temperatures, perform the cell balancing, and communicate with the battery-management unit, which receives the battery voltage, current, and temperature measurements. The battery-management unit runs the algorithms controlling the charge, discharge, and state of charge; it commands a power contactor, and it communicates with the user through a serial port and with the pilot through several light-emitting diodes on the instrumentation panel. The battery-

Fig. 6 Engine tray modification.

management unit protects the battery against charge overcurrent, cell overvoltage and undervoltage, and battery over-temperature and undertemperature. Should any of these magnitudes go beyond their threshold, the battery-management unit disconnects the battery by opening the contactor. The battery is protected against discharge overcurrent by means of a fuse. Additional details of the battery are given in [8,9].

The cell modules together with the battery-management unit with its electrical devices are contained within an aluminum case that complies with the loads given in the EASA CS 22 aeronautical standard (9 g forward, 4.5 g upward and downward, and 3 g sideward) [11]. This was necessary because the battery is located behind the pilot; therefore, in case of a crash landing, the battery case might be deformed or deteriorated but is robust enough to maintain

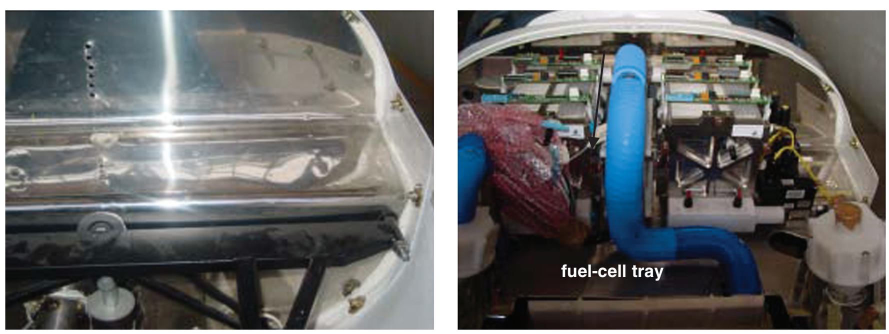

Fig. 7 Fuel-cell tray.

Fig. 8 Lower cowling modification.

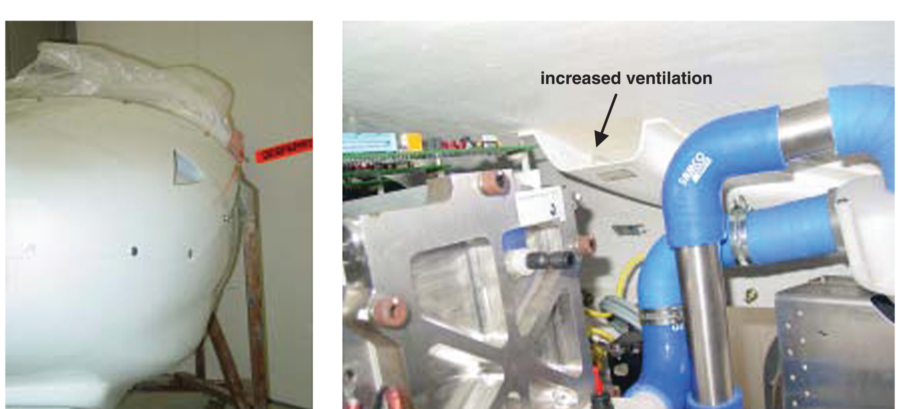

Fig. 9 Upper cowling modification.

the pilot safety by being self contained. The box includes a stainless steel vent port piped to the aircraft exterior to evacuate the exhaust gases, should a cell burst during the unlikely case of a crash landing.

The third power source is a 14 V Ni/Cd backup battery located in the cockpit. This battery is used to start the electrical system and to redundantly power the crucial controllers of the airplane. Should a main power loss occur, this backup battery would enable the crucial controls to command the propeller-feathering position, the interface with the pilot, the continuous monitoring of a possible hydrogen leak, the continuous control of the power flow, and the enabling of the Li–ion battery to allow a main power recovery.

The main loads are the propulsion inverter and motor. Additional loads include the fuel-cell BOP, the propeller pitch controller and motor (on the instrumentation panel), a cooling water pump (in the compressor compartment), the controller of the Li–ion battery (inside the battery box), the PMAD control board (inside the PMAD box), the H_2 in-tank solenoid valve, the H_2 detector, and the components of the instrumentation panel.

The airplane wiring is installed in the opposite side to the fuel lines (see Fig. 3). The PMAD box manages the power flow and controls the electrical protections, comprising the protection of the different components (power supplies and loads), the interface with the pilot through the instrumentation panel, the control of the wake-up/shutdown sequences and the emergency stop, the regulation of the power balance between the fuel cell and the batteries, and the propulsion motor command based on the throttle input and the configuration and state of the electrical system (introducing the coupling between sources and main load). A detailed description of the functionalities of the PMAD box and the airplane electrical architecture is given in [10]. The PMAD was located up front of the copilot seat (see Figs. 1 and 3).

The startup and shutdown sequences are controlled through a state machine that also protects the hybrid power source and the propulsion motor inverter. The low-voltage low-power Ni/Cd battery feeds the controller of the PMAD box and the Li–ion battery-management unit, allowing the PMAD to run the state machine to start the airplane electrical system.

The throttle control receives the throttle lever position, conditions this information, and sends a proportional torque command to the propulsion motor inverter. If the throttle demand implies the propulsion motor power being higher than the power allocated in the sources, the control automatically reduces the torque command to reach a balance between the electrical sources and the electrical loads. Therefore, the throttle conditioning depends on the configuration of the electrical system (one or two power sources) and on the Li–ion battery state of charge. Additionally, the throttle control processes the torque command in order to obtain smooth power-change rates. Since fuel cells have relatively slow dynamics, the throttle control avoids exceeding the maximum allowable rate of power change per unit time.

The PMAD control box also has the capability of regulating the balance between the power supplied by the fuel cell and by the Li–ion battery. This functionality can be enabled or disabled [10]. If the regulation is disabled, there is a natural balance between the sources. If the regulation is enabled, there is a control of the power supplied by each source by means of a serial boost converter connected to the distribution bus in series with the fuel cell. The output voltage of the converter is regulated through a control loop that maximizes the fuel-cell power. Although the unregulated architecture is simpler, more reliable, more efficient, and needs a simpler cooling, the regulated architecture does not discharge the battery as much as the unregulated architecture, allowing the use of smaller batteries, and thus offering a weight reduction possibility; another consequence of the battery energy savings is that the hybrid power source can supply a certain power level for longer without exceeding the fuel-cell power capabilities, maximizing (in this way) the total energy of the hybrid power source. Moreover, the regulated hybrid power source has a more reproducible behavior because it has a lower dependency on the external conditions, such as temperature, aging, or operation. Although both architectures have been simulated, implemented, and thoroughly tested in the fuel-cell demonstrator airplane, the unregulated architecture was more appropriate for the flight tests, mainly because, in this particular application, the battery energy savings, and so the possible weight reduction, was not significant enough. The increase of the takeoff and climb time offered by the regulated architecture was not required either, because 5 min were sufficient to reach the cruise altitude. On the other hand, the safety and reliability of the system were crucial. The unregulated configuration was inherently more reliable due to its simplicity and did not force the fuel cell to operate at its maximum power output, reducing the risk of a fuel-cell tripoff during takeoff and climb and decreasing the amount of water and hydrogen to be carried onboard during the test flights. In addition, a bigger battery could provide the full power for a shorter takeoff and climb in the case of a fuel-cell tripoff, allowing the aircraft to climb up to a safe altitude.

The main challenges associated with the design and development of the PMAD box were 1) the design of a state machine controlling the startup and shutdown sequences of the aircraft electrical system and protecting the hybrid power source and the propulsion motor and inverter and 2) balancing the power supplied by the fuel cell and by the battery during takeoff and climb by means of a serial boost converter connected to the distribution bus in series with the fuel cell [8].

Fuel System

The original aviation gas tank was substituted by the hydrogen onboard system, which comprises a high-pressure composite hydrogen tank and the necessary valves and safety devices to provide hydrogen to the fuel-cell system for the entire flight mission. The hydrogen is stored at high pressure (350 bar) in the tank to minimize the system weight. The fuel system stores sufficient hydrogen mass for the entire flight mission at the required purity (greater than 99.992%) and supplies it to the fuel-cell system at its operating flow and pressure. The pressurized gaseous hydrogen tank and the manual valves are located in the original fuel compartment behind the pilot's seat (see Figs. 1 and 4); the piping goes along the cabin on the port side of the aircraft and all the way to the engine bay (see Fig. 3), where the fuel cell is located (see Figs. 1 and 2).

The tank has an integrated solenoid valve on the neck, including pressure and temperature sensors, a pressure relief valve, and an excess flow valve. Downstream, the hydrogen system includes three two-way valves to allow the tank refueling, the external supply, and the onboard supply to the fuel-cell system. The pressure is reduced by three pressure regulators from the tank to the final operational pressure (below 1.7 bar g). Additionally, the fuel system includes other safety devices, such as pressure relief valves and onboard hydrogen detectors.

Since hydrogen is stored and distributed throughout the cabin and the engine bay, these areas become classified or hazardous areas. Guidelines and recommendations from standards have been followed as much as possible to minimize any possible ignition source and to enhance the ventilation. For example, nonsparking electrical equipment and the Explosives Atmospheres Directive (ATEX) certified components, when available, have been used; the piping is routed on the opposite side of the electrical cables and equipment, and all metallic enclosures are grounded to aluminum trays.

Airplane Tests

The airplane correct operation was verified in three stages: 1) component tests before their implementation in the airplane, 2) airplane bench tests (or postintegration functional tests) to debug the electrical and mechanical integration and to check the proper operation of all systems, and 3) airplane ground and flight tests.

Components Testing

The electric motor system, the fuel-cell system, the Li–ion battery, and the electronic boards within the PMAD were tested at the manufacturers' premises to check their compliance with the program requirements.

Propulsion Motor System

Although the UQM motor's peak brake power is 75 kW, the rated continuous brake power is only 30 kW. For takeoff and climb, the motor needed to deliver approximately 36 kW brake power during 7 min. Therefore, the electric motor was tested for compliance with the power requirements of the entire flight mission, including taxi, takeoff, climb, and cruise.

The test setup consisted of a standard dynamometer, with the test motor connected to a torque cell and then to a load motor, running in regenerative operation. The coolant flow was supplied externally at a controlled inlet temperature. The inverter was powered at different voltage levels during the test, within the voltage range of the power supplies of the fuel-cell demonstrator airplane. Stator, rotor, and inverter temperatures were monitored, as well as electrical magnitudes, rotational speed, and motor torque.

The motor system successfully accomplished the planned flight mission power profile [8]. The system variables stayed within the operative limits for every load condition along the entire tests, but the stator and rotor temperatures were near their maximum limit at the end of the tests, indicating that a takeoff and climb duration larger than 7 min at those power levels could damage the motor. The motor efficiencies were between 88 and 89% for the power level corresponding to the cruise and 86% for the power level corresponding to the takeoff and climb. Regarding the backelectromagnetic force, the measurements showed no demagnetization.

Fuel-Cell System

The fuel-cell system was thoroughly tested against the program requirements to assess its performance and the BOP consumptions. The testing comprised steady-state dynamic tests and environmental tests.

The test setup consisted of the fuel-cell system supplied with hydrogen at the required pressure and flow conditions and coupled to a programmable load unit.

The steady-state testing comprised a conventional polarization curve, the reproduction of the flight mission, and the performance verification of the system at its design point (15 kW net) and at its peak power (20 kW net) for continuous steady-state operation during several hours. These tests allowed the characterization of the fuel-cell system, the measurements of the parasitic losses, the electrochemical hydrogen consumption, the water consumption for the flight mission, and the verification of the stable operation, both at its continuous power output and at peak power output. In addition, all parameters of the fuel cell were maintained within the PLC trigger levels during the whole duration of the tests [8,9].

The fuel-cell dynamic tests comprised small signal source impedance tests and load transients. The small signal source impedance tests was carried out by injecting ac onto the dc load setpoint over a range of load setpoints and injection frequencies. These tests allowed the dynamic characterization of the fuel cell, which was modeled to help design the electrical system, including the electromagnetic interference filters within the PMAD box. The load transients were carried out by imposing load steps to the fuel-cell system. The fuel-cell system showed good operation against load steps at low-electrical power levels. However, the fuel-cell system could not cope with large instantaneous steps at high-electrical loadings (from 75 to 100%, for example) and entered in an error mode [8,9]. Therefore, in order to avoid a motor loss due to a fuel-cell failure, the throttle control in the PMAD box was tuned to avoid exceeding the maximum allowable rate of power change per unit time.

Environmental testing included orientation angle tests and electrical environmental tests. The orientation angle tests were done by mounting the fuel-cell system on a custom-made test rig with tilting functionality. The fuel-cell individual components were placed in positions representative of those in the demonstrator airplane. The fuel-cell system showed no cell fluidic balance problems due to operation at the pitch and roll angles that could occur during flight [8,9]. The electrical environmental tests were carried out by introducing voltage spikes on the dc power leads of the fuel-cell PLC. No malfunction of the PLC was observed [8,9], so it behaved immune to those spikes.

Li–Ion Battery

The Li–ion battery was tested against static and dynamic requirements. The static discharge was carried out at the currents expected during normal and abnormal operations to assess how long the battery would last in each case. The dynamic tests consisted of applying current steps to the battery in order to assess whether or not a fuel-cell failure would cause a battery trip.

The battery only worked during the takeoff and climb. When discharging at the normal operating conditions (at 100 A), the battery lasted over 10 min [9], 3 min longer than the 7 min required for takeoff and climb. In abnormal operating conditions (i.e., fuel-cell failure during takeoff and climb), the discharge current would be 200 A. When discharging at 200 A, the battery lasted between 4 and 5 min, depending on the room temperature [9]; this guaranteed that, should a fuel-cell failure occur during takeoff and climb, the battery can provide enough energy to the motor for the airplane to climb up to a safe altitude and perform an emergency landing.

The dynamic test simulated the transient that the battery would suffer should the fuel-cell trip when both sources were powering the electric motor during takeoff and climb at full power. The battery showed a good capability to cope with the imposed transient [9]. Therefore, a fuel-cell trip would not disconnect the battery, and there would be enough power to continue ascending.

Electronic Boards Within the Power Management and Distribution Box

The electronic boards within the PMAD box were tested to check their correct operation before their implementation inside the box. The PMAD box as a whole could only be tested together with the rest of the electrical equipment of the airplane because it is the integrator component.

The tested boards included the PMAD control board, the current and voltage transducer boards, the inverter throttle board, all the converters, and the electromagnetic interference filter boards.

The correct operation of the different sensors, the digital and power circuitry of the PMAD control board, in charge of the overall control of the PMAD of the electrical system was thoroughly checked. The operation of the current and voltage transducers, and that of the inverter throttle board that interfaces the PMAD control board and the propulsion motor inverter, was checked and characterized. In addition, valuable information to calibrate the code in the PMAD control board was obtained. The converters were tested under static conditions to measure the ripple they induced under dynamic load conditions, including step and reference followers. In addition, start and shutdown tests were performed in all of the different limit conditions to prove the converters' reliability. The converters proved to operate correctly in all the tests. To test the electromagnetic interference filter boards, sinusoidal waves were applied at the input of the board, and the output voltage was measured to calculate the attenuation. The boards showed a correct filtering operation.

Airplane Bench Tests

Following the individual component testing and the subsystem onboard installation, the airplane was thoroughly tested in a laboratory bench. This allowed debugging of the subsystem's mechanical and electrical integration and assessed the system acceptance before any ground and flight tests.

In the test bench configuration, a controllable hydraulic brake, capable of handling the motor power levels, replaced the propeller. A bench station was built and programmed to acquire the electrical and motor data, as well as controlling the hydraulic brake. The coolant air flow was simulated by means of a vacuum fan ducted with the airplane air inlet. The hydrogen for the fuel-cell operation was supplied externally rather than from the onboard fuel system. Apart from this, a laboratory power supply was used for the first tests to simulate the fuel cell or the Li–ion battery.

The test campaign mainly concentrated on validating the correct electrical and mechanical implementation of the different systems, verifying the correct operation of the electrical protections, assessing the behavior of the hybrid power source when one of the sources tripped, and simulating normal flight and emergency flight profiles, the latter to assess the response of the propulsion system to a fuel-cell system trip.

The correct operation of the electrical system, the fuel-cell system, the Li–ion battery, the control system, and the instrumentation system was thoroughly checked. The electrical system worked properly with the level of electromagnetic perturbations induced by the propulsion inverter and motor. The battery withstood the transient caused by a fuel-cell trip at full power during takeoff and climb; that is, a fuel-cell trip did not cause a battery trip. However, the fuel cell could not withstand the transient caused by a battery trip; that is, a battery trip would cause a fuel-cell trip and, subsequently, a total loss of power. The main cause of the fuel-cell trip in the event of a battery error was air stagnation at the cathode. The compressor control was not fast enough to supply the required air to the cathode, resulting in a fuel-cell voltage drop and the subsequent fuel-cell trip.

Regarding the simulated flight mission, the electrical parameters, system temperatures, power management, energy availability, and hydrogen consumption were measured and analyzed. Special attention was given to the motor and electronics' temperatures, which remained below the thermal limits during the entire mission [9].

In the event of a fuel-cell failure during takeoff and climb, apart from withstanding the transient, the battery proved to supply the entire required power for at least 5 min; this would allow the pilot to continue climbing to reach a safe altitude (approximately 400 m) to land safely.

Ground and Flight Tests

The wings and the propeller were assembled, and the airplane was weighted. In addition, the airplane thrust with both the takeoff and cruise power levels was measured to validate the performance calculations. The validation was done by flight testing the original Superdimona with the conventional engine at those thrust levels and with the overweight of the fuel-cell demonstrator. Indeed, 15 kW brakes were sufficient to maintain a leveled flight, and 36 kW brakes were sufficient for takeoff and climb.

The fuel-cell demonstrator airplane ground and flight test campaign took place at the Ocaña airfield (Toledo, Spain), which has an altitude of 733 m. The concrete runway has a 1200 m length by a 30 m width.

Ground Tests

The aim of the ground tests was to determine the fuel-cell demonstrator airplane behavior in motion and its acceptance before any experimental flight tests. The onboard fuel system and the propeller were tested for the first time. The tests were first done with the airplane brakes on. Once the systems proved correct operation, the pilot carried out the low- and high-speed taxi tests. During the ground test campaign, the parameters of the motor, battery, and fuel-cell system were monitored by their respective software programs. The fuel-cell and the PMAD data were logged in their internal memory cards for a posttest analysis.

The gas tightness of the onboard fuel system was verified before refueling the tank. While refueling, the system pressures, the tank temperature, and the filling durations were monitored.

The airplane electrical protections and controls reproduced the correct operation observed during the bench tests. Moreover, the throttle control was finely tuned, taking into account the dynamics imposed by the propeller. This ensured that the fuel-cell power is not exceeded while feeding the motor coupled to the propeller.

The air-coolant flow induced by the propeller within the engine bay, through the radiators and through the cabin, was enough to keep all system temperatures below their limits. The fuel-cell demonstrator aircraft was operated successfully in a temperature range from 3 °C to over 25 °C. In addition, the ventilation avoided any small hydrogen leakage from the stacks accumulating in the engine bay. On the other hand, the ventilation through the fuel-cell compressor compartment at the copilot's feet was also sufficient to dissipate the compressor lubricant vapor.

The effect of vibration in the system installation was checked during the high-speed taxi tests that were carried out on rough terrain at an unpaved runway. The vibration level induced by the electric motor was far lower than that of a conventional combustion engine. Neither vibration nor resonance issues were detected for the propeller. All the electrical and mechanical connections and fittings remained tight after the vibration tests.

The fuel-cell demonstrator airplane behavior in motion and its maneuverability were appropriate, despite the new weight distribution and the overweight. The airplane's original brakes and flight controls also operated properly. The high-speed taxi test allowed checking of the proper operation of the propulsion system at full throttle, and therefore at full power. In addition, the adequacy of the aircraft center of gravity and the takeoff trim settings for takeoff were determined. The takeoff roll distance measured during the high-speed taxi tests was approximately 400 m at a takeoff speed exceeding 70 km/h.

Flight Tests

The flight tests strictly followed the protocols and the airworthiness limitations approved by the Spanish civil aviation authorities for the airplane experimental certification. The electrical and fuel-cell data were logged in memory cards within the PMAD and the fuel-cell system, respectively. In addition, for the last flight, the airplane was equipped by an International Civil Aviation Organization (ICAO)/Fédération Aéronautique Internationale (FAI) certified global positioning system (GPS) logger (Filser Electronics, GmbH, model LX-20) that recorded the flight profile data, such as rate of climb, rate of descent, altitude, and ground speed. The GPS conformed to FAI rules and regulations. The accuracy of the altitude measurements logged in the GPS system was approximately ± 10 m. The ambient temperature was between 10 and 20 °C, the accuracy of the temperature measurements being ± 1°C.

In the maiden flight (2 July 2008), the aircraft rotated at approximately 70 km/h; it took off and climbed with full power from the Li–ion batteries and the fuel-cell system to perform a short cruise without disconnecting the batteries, for safety reasons. Then it landed back at the runway on only fuel-cell power. The aircraft maneuverability was appropriate despite the overweight.

Three flight missions (two on 26 February 2008 and one on 8 March 2008) were completed to obtain all the required data and to check the reproducibility of the results. In all flight tests, the airplane rotated at approximately 70 km/h; the airplane took off and climbed up to approximately 1000 m (3500 ft) ASL at a rate of climb of 1.5–2 m/s (300–400 ft/ min) with full power from the Li–ion batteries and the fuel-cell system. The takeoff and climb lasted approximately 5 min. The input motor power measurements were between 40 and 42 kW, which corresponds to approximately 35 kW brake power, and the rotational speed of the propeller was set to 2000 rpm.

Once the cruise altitude was reached, the pilot reduced the motor torque (and the motor power) by throttle down and disconnected the batteries. Afterward, he adjusted the rotational speed to 1500 rpm and readjusted the motor torque to maintain altitude. The input motor cruise power was approximately 17 kW, which corresponds to approximately 15 kW brake power. During cruise, the fuel-cell supplied all the airplane power: approximately 20 kW gross. Depending on the specific flight, the input motor power varied from 16 to 20 kW and the fuel-cell power from 18 to 22.5 kW. The airplane ground speed was approximately 100–110 km/h.

On average, the flight missions lasted from 26 to 28 min. At the end of the missions, the fuel-cell demonstrator airplane still had around 100 bar of hydrogen in the tank and an average of at least 35% of the Li–ion battery capacity. The theoretical maximum duration of a flight with the total amount of hydrogen and battery charge was of the order of 60 min.

Figure 10 shows the recorded input motor, fuel-cell, and battery powers within the PMAD box for the second flight mission, which took place on 26 February 2008.

Figure 11 shows the altitude profile of the flight mission logged in the GPS system during the last flight, proving that the fuel-cell demonstrator maintained altitude and, thus, flew level only with the

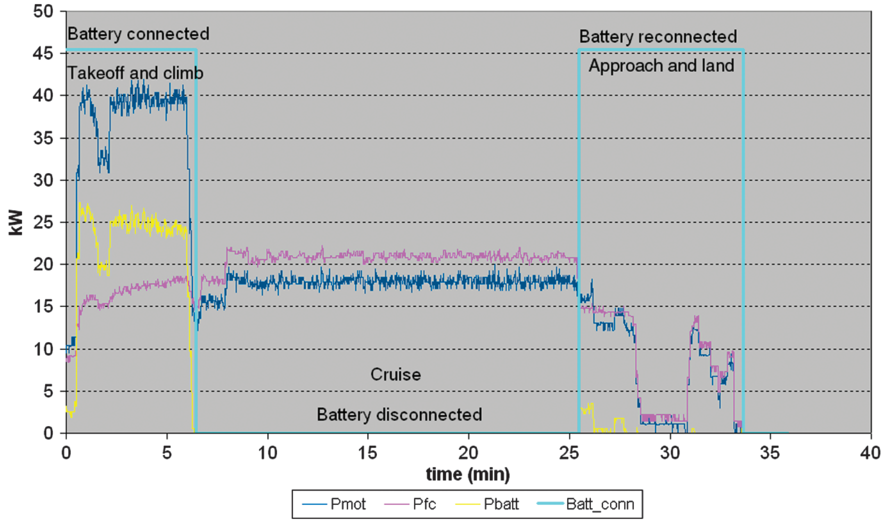

Fig. 10 Power data recorded by the PMAD during third flight mission.

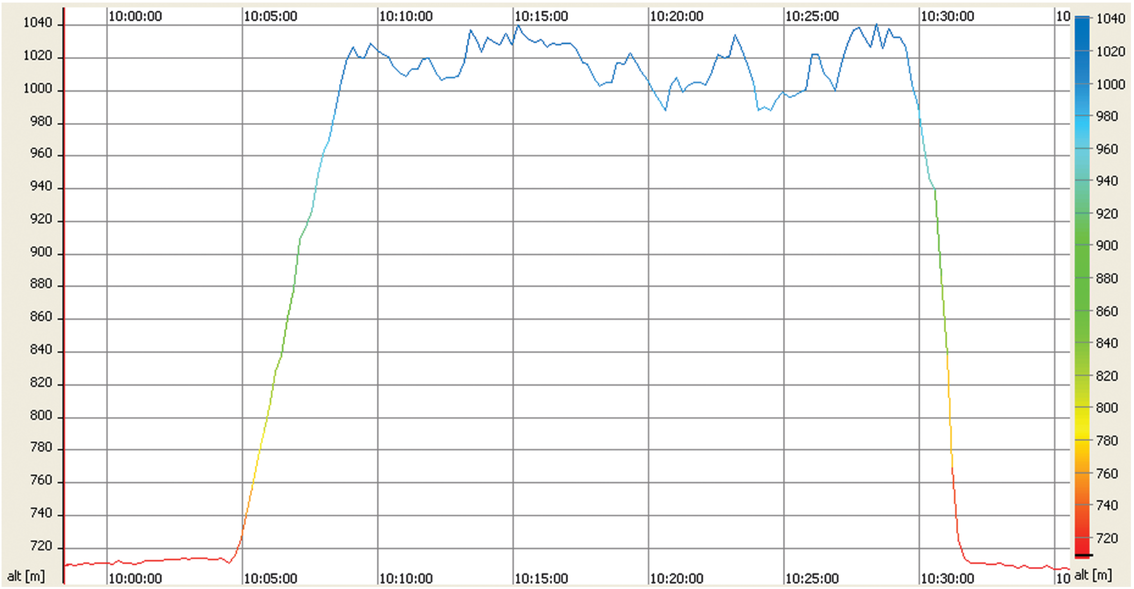

Fig. 11 Third flight mission altitude profile.

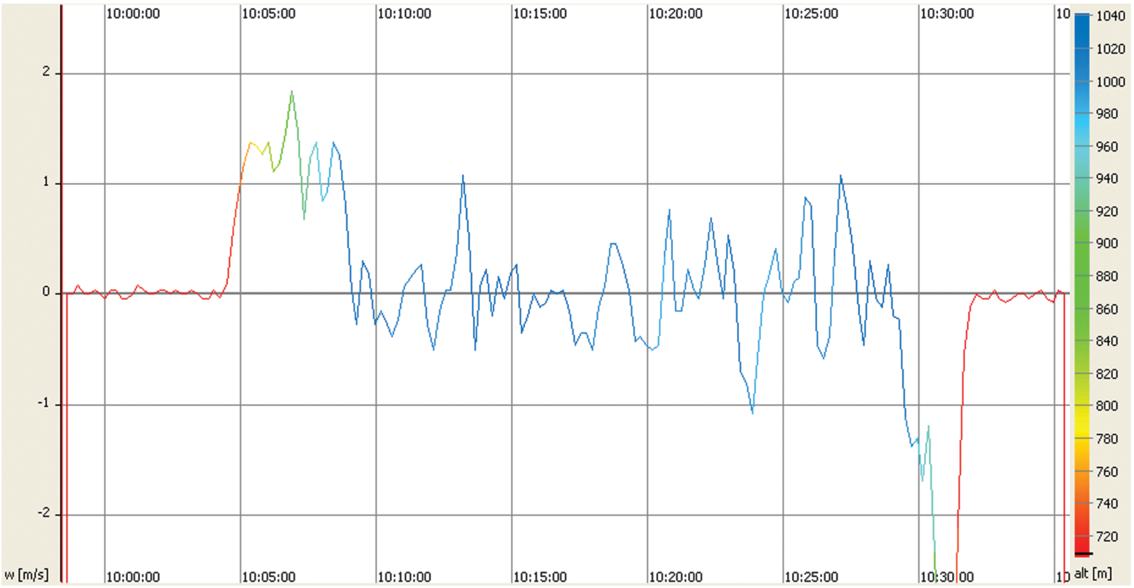

Fig. 12 Third flight mission vertical speed profile.

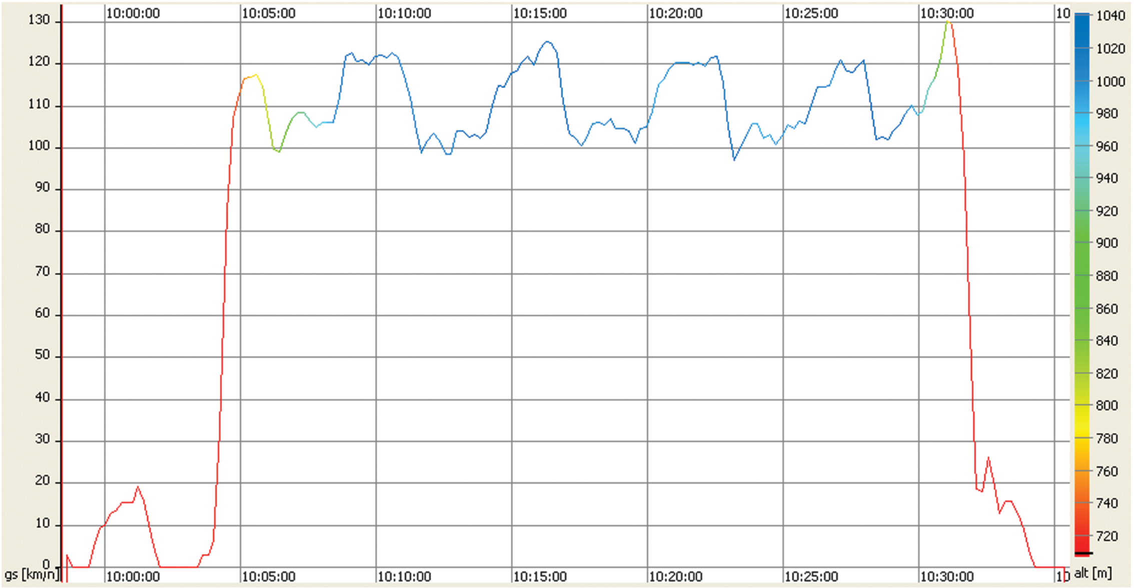

Fig. 13 Third flight mission ground speed profile.

fuel-cell power. During the entire cruise, the fuel-cell demonstrator aircraft maintained an altitude higher than 1000 m (3500 ft) ASL. The observed minor altitude losses were due to the 90° coordinated turns and the atmospheric instabilities. On the straight flight segments, the aircraft was not only capable of maintaining the altitude but, in some cases, it climbed slightly.

The vertical speed profile of the last flight is shown in Fig. 12. The mean rate of ascent recorded during climb was approximately 1.3 m/s, with a peak climb speed of 1.8 m/s. The average ascent and descent speeds during cruise remained within ± 0.5 m/s.

In terms of ground speed, the average speed for the flight mission was approximately 110 km/h for this flight mission. Figure 13 shows the headwind and tailwind sections, which differ at approximately 15–20 km/h.

The aircraft maneuverability was appropriate despite the overweight and the slightly different weight distribution with respect to that of the original aircraft. Qualitatively, the vibration level seemed far lower than with a conventional engine, although no vibration measurements were specifically performed. Even if the autonomy and the range were lowered with respect to the original aircraft performance (see Table 1), the only exhaust product generated by the demonstrator was water vapor. The prototype also seemed considerably quieter than the conventional Diamond HK36 airplane equipped with the original Rotax engine, with the propeller being the main noise source. When the propeller was working at low revolutions per minute, the noise came mainly from the fuel-cell compressor.

Conclusions

Early in 2008, the Boeing fuel-cell demonstrator aircraft demonstrated, for the very first time in aviation history, a straight level manned flight with a fuel-cell system as the only source of power. The prototype was a modified two-seater motor glider

Table 1 Performance comparison (HK36 Superdimona [12] vs the fuel-cell demonstrator airplane)[a]

	HK 36 Superdimona		
	TC 100 model	TTC115 model	Fuel-cell demonstrator
	Powerplant		
Motor	Rotax 912 S3 (100 hp)	Rotax 914 F3 (115 hp)	PowerPhase 75 electric brushless dc motor from UQM Technologies, Inc. (45 kWe peak)
Propeller	MT propeller MTV-21-A-C-F/ CF 175-05 2-blade hydraulic constant-speed propeller with hydropneumatic feathered pitch	MT propeller MTV-21-A-C-F/ CF 175-05 2-blade hydraulic constant-speed propeller with hydropneumatic feathered pitch	MTV-1-A/175-05 variable-pitch propeller, feathered pitch
	Performance		
Takeoff distance (ground roll), m	190	182	400 approx.
Takeoff distance (50 ft obstacle), m	299	274	600 approx.
ROC ASL MTOW, m/s	4.9	5.4	(1.3–1.8 at 700 m above mean sea level)
Maximum cruise speed, km/h	261 IAS	261 IAS	110 GS
Maneuvering speed, km/h	215 IAS	220 IAS	158 (max.)
Glide ratio	1:27	1:27	1:27
	Specifications/Weights		
Seats	2	2	1
Empty weight, kg	560	568	789
Payload, kg	210	202	71 (pilot and fuel)
MTOW, kg	770	770	860
Fuel capacity	80l	80l	1 kg H_2 (34 L at 350 bar)
Fuel grade	Unleaded 95 100 LL/Mogas	Unleaded 95 100 LL/ Mogas	H_2 Alphagaz[b] (purity > 99.9999%).

[a]ROC: rate of climb; Mogas: motor gas (in contrast to Avgas: aviation gasoline); GS: groundspeed; IAS: indicated air speed.
[b]Commercial grade of hydrogen.

equipped with a hybrid power source powering an electric motor that drove a variable-pitch propeller. The hybrid power source comprised a PEM fuel cell, the main power source, and a Li–ion battery, that assisted the fuel cell only during takeoff and climb, when the maximum power was demanded. Once the cruise altitude was attained, the battery was disconnected, and the airplane maintained straight and level flight with only the fuel-cell power.

The fuel-cell demonstrator airplane completed four test flights, strictly following the protocols and the airworthiness limitations approved by the Spanish civil aviation authorities for airplane experimental certification. The airplane rotated at approximately 70 km/h, took off and climbed at 100 km/h, during approximately 5 min, up to approximately 1000 m (3500 ft ASL) with full power from the Li–ion batteries and the fuel-cell system. Once the cruise altitude was reached, the pilot disconnected the batteries. The altitude profile of the flight mission logged in the ICAO/FAI certified GPS system during the last flight proved that the airplane maintained altitude and, thus, flew level with only fuel-cell power.

The aircraft maneuverability was appropriate despite the overweight. Even if the autonomy and the range were lowered with respect to the original aircraft performance, the only exhaust product generated by the demonstrator was water vapor.

Among challenges faced during this project, the weight increase related to the low specific energy density of the new power system, along with the challenges related to hydrogen storage and the integration of the components both electrically and mechanically within a restricted volume, count as the most important technical barriers toward the implementation of this novel and promising technology in aerospace systems.

In the fuel-cell demonstrator airplane, the overall weight increase due to the substitution of the internal combustion engine by the hybrid power system was of the order of 150 kg. In general, this weight increase was unavoidable because most of the fuel-cell BOP components were not optimized for aerospace applications. However, in certain power levels (below 3 kWe and around 75 kWe), there are few commercially available fuel-cell systems that have been developed for other industrial sectors with energy densities in the 0.5–1 kW/kg range. Such systems could already offer competitive advantages with respect to conventional technologies for certain applications.

Because of the low specific energy density of fuel-cell-based power plants, the aircraft needs to be extremely efficient from the aerodynamics point of view. Moreover, it seems logical to design a very efficient air platform from scratch, having in mind many of the requirements associated with this type of powerplant at the early design stages.

In general, the cooling requirements of a fuel-cell-powered aircraft are much higher than those of a conventional aircraft. In contrast to internal combustion engines, electric motors do not dissipate any heat through the exhaust gases; thus, the airplane thermal management system has to dissipate the heat generated by both the motor and the fuel-cell system. Fuel cells operate at theoretical efficiencies close to 50%. The rest of the power is dissipated in the form of heat.

Hydrogen is an energy carrier with similar characteristics to the fossil fuels currently used. Using appropriate design and operating procedures, hydrogen could be even safer than working with many fuels commonly used today. In the fuel-cell demonstrator airplane, the operational risks associated to pressurized hydrogen were mitigated through redundancies in the design, which of course have the penalty of adding weight to the overall system, minimizing the existence of any possible hydrogen leak in the system, maximizing the ventilation and using ATEX certified components or at least spark-free components. However, the poor availability of ATEX certified components that suit the specific technical requirements for mobile applications and, in this case, aerospace applications still represents a big challenge. Moreover, while hydrogen is a valid answer for not only the demonstrator airplane but also for broader applications to commercial aviation, the possibility of using an onboard reformer to convert a hydrocarbon-based fuel such as kerosene into hydrogen should obviate the need of storing and handling hydrogen in its gaseous (or liquid) form. The use of reformers is envisioned for some applications because of the advantage of storing much more energy per unit volume in fuels such as kerosene or gasoline as compared with the energy per unit volume stored in hydrogen. But the challenge is to achieve a proper integration between the fuel-cell system and the reformer so that fast responses to load demand are achieved. Needless to say, the weight of such devices needs to be considerably reduced before they can be considered for aerospace applications.

Although there is still a long way to go before the fuel-cell technology could be applied to commercial aerospace applications, this project sets the first footprint on the way to a more environmentally friendly aviation. This type of powerplant could have a short-term application in sport aviation and/or in small manned and unmanned air vehicles for which this technology may demonstrate its advantages in specific missions: for example, if the flight autonomy was enhanced with respect to that of electric propulsion systems powered by batteries. Being the first fuel-cell demonstrator airplane worldwide, there is considerable room for performance improvement. However, the fast progress of not only fuel-cell technology but also additional technologies, such as those present in this project, in terms of weight, safety, and reliability are starting to draw the baseline for a promising future with greener aviation.

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