MORE/ALL ELECTRIC AIRCRAFT BASED ON FUEL CELL ENERGY SYSTEM: THE ENFICA-FC EXPERIENCE

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Abstract

*Environmental sustainability should gain a significant role as one of the main drivers in the design of new generation of transport civil aircrafts in order to obtain more/all electric aircrafts powered by greener energy sources as hydrogen fuel cell systems. In this framework, the European Commission has selected ENFICA-FC (**EN**vironmentally **F**riendly **I**nter **C**ity **A**ircraft powered by **F**uel **C**ells), as one of the co-founded projects in the Aeronautics and Space 6th Framework Programme. The goals of the project were the following: 1) A feasibility study in order to provide a preliminary definition of new and innovative power systems based on different fuel cell technologies; 2) The conversion of a modern and conventional two-seat aircraft into an all-electric airplane entirely powered by fuel cell.*

A feasibility study was carried out to provide a preliminary definition of systems (APU, primary electrical generation supply, emergency electrical power supply, landing gear, de-icing system, etc) in which fuel cells (PEM or SOFC) can be exploited. The feasibility study took into account the both present technologies and expected improvements of future generation of fuel-cell systems and thereby showed the differences in aircraft performances that could arise between conventional and more/all electric aircraft for different levels of technology development. In addition, the feasibility of an all-electric propulsion inter-city aircraft (10-15 seat), completely powered by fuel cells, was studied in order to assess the impact that could have a more silent and less polluting aircraft.

The second part of the paper deals with the setting up and test flights of a fuel cell general aviation aircraft fuelled by hydrogen. The all-electrical power system was successfully tested during the experimental flights. A new speed world record of 135 km/h and an endurance of 39 min. were established during several flights conducted for the FAI Sporting Code Category C (airplane). 2.5 hours of effective flight were obtained during these 6 tests for a total path of 237 km. The positive handling qualities and satisfactory engine performances of these six flight tests have led the team to consider these successful flights as a good starting point for further long endurance high speed flights.

1 Introduction

Rapidly emerging hydrogen based technologies, primarily derived from the automotive industry, can be used to launch a new revolution of high reliability and low maintenance electric propulsion systems for general aviation and small commuters aircrafts and electrical system replacement (emergency power, RAT, cabin power, APU, anti-icing system, landing gear retraction, etc.) for larger transport aircrafts. There are several potential advantages of using such a power source, that range from environmental and economic issues to performance and operability aspects.

During the combustion of kerosene in present day engines, CO_2, water and lower amounts of SO_2, CO, NOx and unused hydrocarbons are produced; those gases are directly or indirectly responsible (through further reactions) for greenhouse effect or changes in greenhouse gases methane and ozone. Large emission of

NOx is produced by engines during the airport aircraft operation. The replacement of combustion engines or of APU with fuel cell powered electric motors can guarantee a massive reduction in this kind of pollution, since the only emission produced by a fuel cell is water; however, there is some doubt as to whether water vapour emitted at high altitudes can also produce a long lasting greenhouse effect.

Air pollution is not the only kind of pollution that can be reduced (if not eliminated) through the use of fuel cell driven power systems; noise produced by aircrafts is in fact considered an important form of pollution and it is particularly important for airplanes taking-off and landing at airports located in urban areas or during the night. The possibility to take-off and land within the noise abatement regulations set for small airfields, in urban areas near population centres, will allow the use of these airfields during the late night hours when the noise abatement regulations are even more stringent. In terms of larger aircraft, the use of the Fuel Cell technology for powering the aircraft systems can lead to the replacement of the aircraft today APU allowing for noise reduction (or better removal) for aircraft airfield ground operation.

Another key aspect is represented by the dependency of airline companies on the oil market. Although the problem is still controversial, above all concerning timing, it is generally believed that a peak in oil production has been reached or will have been reached in a few decades, the consequence being a fast increase in oil prices. This price rise (actually 310 cents/gal against 87 cents/gal in 2000) could be detrimental for airline companies if oil is the only available energy source. Hydrogen has the advantage of being obtainable from a variety of sources, and it is therefore less prone to market fluctuations and rises in price. However, it has to be taken in great consideration the fact that other forms of energy must be used to produce the hydrogen which will be used as fuel. Widespread production, distribution and use of hydrogen will require many innovations and investments to be made in efficient and environmentally-acceptable production systems (i.e wind energy, solar power, etc), transportation systems, storage systems and usage devices.

Hydrogen can also offer some advantages in performances; for example, an all-electric or more-electric aircraft is more reliable as the mechanical systems are replaced by electric ones. Mean Time Between Failure of electric motor, inverter and converter, in fact, are in the range of over 50.000 flight hours. Higher reliability also implies lower maintenance costs, and only slight reduction in engine performance due to altitude. Moreover, electric propulsion is much less sensitive to altitude than combustion engines and thus greater altitudes (i.e. smaller power demand) can be reached.

The feasibility of this project is dependent on several key-enabling technologies such as fuel cell stack, fuel cell system, hydrogen fuel storage and a safe airport hydrogen-fuelling infrastructure. Fuel cell systems for airborne applications need to meet safe operational requirements in terms of efficiency, reliability, performance, mass/volume, cost and lifetime under flight conditions at altitude and under high and low ambient temperatures in the air and on the ground. Another important consideration is that it should demonstrate the path to future economic viability. Different studies have been undertaken in recent years on fuel cells in aeronautics transport.

Boeing is currently developing a feasibility study concerning the application of fuel cell technologies to reduce noise and emissions of large transport aircraft; several applications are foreseen in APU and several sub-system applications [1]. Boeing Research and Technology Europe (BR&TE), Spain, developed and succeeded in flying (April 2008, near Madrid) the first electrical powered two-seats fuel cell **motor-glider** [2]. Objective of the project was to demonstrate that a straight level manned flight could be achieved with a fuel cell system as the only source of power in a small motor glider. A two-seat Super Dimona motor-glider with 770 kg of MTOW (850kg by fuel cells) and 16.3 m wingspan was used as the airframe. It was modified by BR&TE to include a PEM fuel cell/lithium-ion battery hybrid system to power a 40 KW electric motor coupled to a conventional propeller. During the flights, the pilot of the experimental airplane climbed to an altitude of 1,000 m using a combination of battery power and power generated by the fuel cells. After reaching the cruise altitude and disconnecting the batteries, the pilot flew straight and level at a cruising speed of 100 km/h for approximately 25 minutes on power solely generated by the fuel cells. A motor-glider was used and is classified in Class D, according to FAI Sporting Code.

Airbus coordinated the European Commission founded project CELINA (Fuel **CEL**l Application **I**n **N**ew Configured **A**ircraft) [3] which had a variety of goals: to define the basic requirements for fuel cell power system integration and to deal with safety, certification, maintenance and installation of such an innovative system; to design an appropriate fuel cell system and the related subsystems; to evaluate fuel cell performances when installed on an aircraft; to integrate fuel cells with existing systems. Airbus and DLR presented the first commercial aircraft powered by fuel cells at the ILA Berlin Air Show 2008. The latest addition to the DLR research fleet is an Airbus A320 which was converted for trials of a fuel cell system. The system trialed is serving as an alternative to the RAM air turbine, which uses an extendable mini-propeller to supply power in the event of an in flight engine failure. No results on flying tests are available.

DLR also flew in July 2009 with the **motor-glider** ANTARES-DLR-H2, which achieved to take off only by fuel cell power [4]. The fuel cell delivers up to 25KW of electrical power, and can maintain level flight on about 10KW. It used **High Temperature PEM FC**. Total efficiency from tank to propeller was about 44% - twice that of a conventional piston engine.

The Boeing Company is developing the hydrogen-powered Phantom Eye UAV, a demonstrator that will stay aloft at 65,000 feet for up to four days [5]. Phantom Eye is powered by two 2.3-liter, four-cylinder engines that provide 150 HP each. It has a 45m wingspan, will cruise at approximately 150 knots and can carry up to a 200kg payload.

AeroVironment was developing the Global Observer UAV to be the first to provide robust, cost-effective and persistent communications and surveillance over any location on the globe, establishing an entirely new category of UAS [6]. Global Observer's unique combination of both extreme flight duration (more than 5 days non-stop) and stratospheric operating altitude was designed to deliver advantages in cost, capacity, coverage, flexibility, and reliability that make it a compelling complement to existing satellite, aerial and terrestrial assets. The Global Observer UAS successfully completed its first flight powered by the aircraft's hydrogen-fuelled propulsion system; GO-1 achieved its first flight on 5 August 2010 powered only by batteries. After completing an initial round of flight tests in Sept.2010, AeroVironment installed the aircraft's long-endurance engine that runs on liquid-hydrogen fuel. The GO-1 Global Observer crashed April 2011 after about 18h flight.

Two main fuel cell types are actually under consideration for aircraft applications: PEM (Proton Exchange Membrane) and SOFC (solid oxide fuel cells). Each of these systems offers distinct advantages as well as issues associated with their use in aircraft propulsion applications. PEM fuel cells have many attractive features for transport applications including high power density, rapid start-up and high efficiency. Great improvements have been made in PEM fuel cell development during the last decade mainly for automotive applications: increase of power density and successful testing of many prototypes around the world. However, there still exist some technical obstacles to overcome in order to enhance current performance of PEM fuel cells for transportation applications. The most critical of them are an inadequate water and heat management, the low tolerance to impurities such as CO, the sluggish electrochemical cathode kinetics, and their high cost. Theoretically, those obstacles can be addressed by the use of **high temperature PEM fuel cells** that can be operated in the temperature range between 100 – 200 °C. They offer a number of potential advantages

compared to low temperature (50-80°C) PEM fuel cells which are summarized below:
(1) lower CO adsorption of catalysts leading to lower CO poison of catalysts, thus higher efficiency; (2) lower heat exchange area needed to dissipate excess heat; and (3) the electrochemical reaction product, i.e. water, is easier to be evaporated at higher temperatures, thus easier water management.

The elimination of external humidification implies an important reduction in the complexity of the systems. Additionally, high temperature operation avoids multiphase water, leading to simplifications in the flow field design and in the system components. The high temperature gradient between the PEMFC stack and the environment also helps to reduce the complexity of cooling devices.

Additionally, it is generally agreed that for transportation applications fuel cells should operate at 120ºC with low relative humidity and, for stationary applications, operating conditions are even more demanding and require temperatures higher than 150ºC. Thus there is a critical need for proton conducting membrane able to operate at elevated temperatures and low relative humidity.
Nowadays, the fuel cell stack specific energy, defined as the energy output per unit weight, is the greatest issue concerning fuel cell application to aerospace; actually it is about 700-2000 Wh/kg but it is estimated that specific energy would increase to 10 kWh/kg at middle term (10-15 years) and to 20 kWh/kg at long term (20-30 years) and this performance will enable an all-electric flight of large commercial aircraft. Moreover, even if hydrogen contains an amount of energy per unit mass (120,000kJ/kg) three times higher than kerosene (42,800kJ/kg), (which in turn means that only a third as much fuel has to be carried to cover a certain range) the significantly lower density of hydrogen leads to the necessity to adopt pressurized or cryogenic fuel tanks; either solution means extra weight and volume. Particularly important is the gravimetric storage efficiency of the hydrogen tank; an off-the-shelf value of 3% is already available for compressed hydrogen with possible increase to 10-12% at long term; an off-the-shelf value of 20% is already available for liquid hydrogen with possible increase to 65%.

Hydrogen fuelled propulsion can be exploited trough different routes:

- Fuel cell (which supplies electricity to an electromagnetic motor)
- Internal Combustion Engine H_2ICE
- Turbine
- Hybrid (Internal combustion engines, electromagnetic motor and batteries)

The ENFICA-FC consortium, coordinated by Prof. G. Romeo of Politecnico di Torino, consisted of 9 partners representing the whole value chain with Aircraft manufacturers (IAI, Evektor and Jihlavan Airplanes), Fuel cells Power system producer (Intelligent Energy), Hydrogen distribution (Air Product), Research Institutes (Politecnico di Torino, Université Libre de Bruxelles and University of Pisa) as well as a SME in the field of administrative management (Metec). [7-27]

A feasibility study was carried out to preliminary define the power system that can be obtained by fuel cell technologies, by first identifying few applications for transport aircraft (APU, primary electrical generation supply, emergency electrical power supply, landing gear with electric folding and electric braking, electrical servo actuators, etc). One of the advantages that can be obtained by the application of the Fuel Cell on small business aircraft, without an APU, is the possibility to operate on ground the aircraft systems without running the engines. Opportunity this that can lead to greats advantages in terms of airfield noise and pollution reduction during ground operation.

The main goal, indeed, was to validate the overall reliability of the high performance all electric aircraft system by flight tests and to validate the FC system for several flight envelope conditions. In fact, it was very important to test such load flight conditions since that would produce **some FC system failure;** it happened in one of the six flights of the ENFICA-FC project (two seats aeroplane powered by fuel cells) when the PEM (Proton Exchange Membrane or Polymer Electrolyte

Membrane) fuel cell powering the electric motor had a switch-off because of a vertical acceleration (produced by a normal gust at which the aircraft was subjected).

2 More-electric and all-electric transport aircraft feasibility

The first step to undertake for a More-Electric transport aircraft analysis is to define which non-electric systems can be replaced by an electrical counterpart. This step is crucial because it defines the duty cycle of the fuel cell system and hence its design.

During ENFICA-FC project a wide variety of different aircraft categories and concepts were evaluated and an extensive database of preliminary solutions were produced; since this electrical system conversion has to be made on a single case basis that depends on categories and reference models, a complete description of conclusions can't be made here.

Three different values of fuel cell system power density were considered: off-the-shelf (300 W/kg), intermediate technology, about 5-8 years (500 W/kg), advanced technology, about 12-15 years (800 W/kg). The off-the-shelf fuel cell APU solution is heavier and needs larger space to contain the fuel cell APU. The intermediate technology gives comparable solution in weight and volume if we consider also the elimination of the Accessory Gear Box (AGB) of the jet engines; also the elimination of the generators and the fuel saving because of using electrical ECS (Environmental Control System) instead of using the engine bleed to drive the ECS system, and finally the advantages due to reduced emission and the APU noise on the ground.

The advanced fuel cell technology gives better solution in terms of weight and volume, and also reduces the pollution and the APU noise. At the moment, it seems quite possible to replace all the system (except the turbofan engine) installed on advanced more-electric regional jet aircrafts with electrical ones powered by fuel cells. For each system different solutions were investigated. From the sizing results we can see that with the advanced technology the fuel cell obtain less weight and volume than the conventional APU.

The system that can be replaced and re-designed in a regional jet are:

◊ Wing flaps: they are currently controlled hydraulically. The hydraulic actuator of the flaps control can be simply replaced by an electrical actuator.

◊ The landing gear is retracted by mean of hydraulic struts with possibility of emergency extending. Every landing gear leg is controlled by one hydraulic strut equipped with the mechanical lock in both extreme positions. The main landing gear actuator is double - acting hydraulic cylinder with single piston rod. The extreme positions of the actuator are secured by mechanical segment locks. The locked positions are signalized by electro-block. Further the actuator is equipped with a hydraulic block for gear emergency extending. The hydraulic actuators of nose and main landing gear retracting will be replaced by an electrical actuator. The electrical actuator must allow emergency retracting of the landing gear.

◊ Brakes: the original design provides the use of three-disk six-piston hydraulically controlled brakes. The brake system is optionally equipped with the anti-block system (ABS). The pilot controls hydraulic cylinders by means of levers on the pedals of foot control. Electronic control unit, based on comparison of the relevant main landing gear wheel with the nose landing gear wheel, controls the electro hydraulic element which controls pressure in an appropriate branch of the main landing gear brake system. The hydraulic brake system can be replaced by electro-magnetic brake system.

◊ Steering system: the nose landing gear is controlled by means of the hydro-mechanical cylinder during movement of the aircraft on the ground. The secondary function of the hydraulic cylinder of the nose wheel steering is shimmy damping.

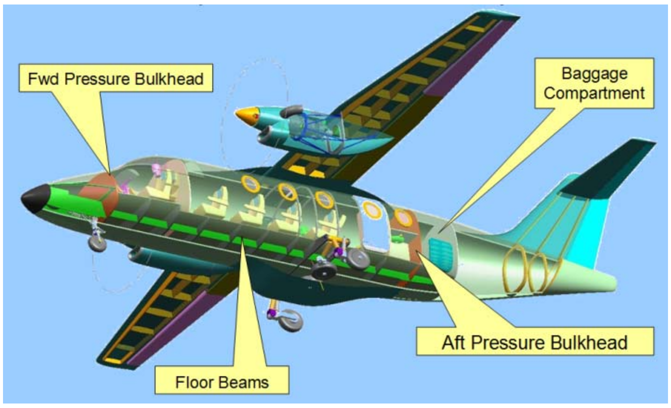
◊ The air conditioning system consists of the heating system and the ventilation and cooling system. The heating system uses bleed air for heating. The ventilation system is made by mean of heating system. The fresh air is led from NACA - inlet through the heating system to the cabin. Optionally the airplane can be equipped by the cooling system. Hot air is used

for heating. Hot air is led from engines via shut-off valves through pipes in the area of the wing leading edge. Cold external air is led to the mixing chamber by means of NACA-inlets. There are several possibilities of heating system solution:
1) The heating system is not changed. Bleed air is the source of hot air. 2) Hot air is taken from fuel cells: it is assumed PEMFC (Proton Exchange Membrane Fuel Cell) system will be used. As a fuel hydrogen is used. The current heating system has to be redesigned. Air is heated with the heat produced by fuel cells. A heat exchanger should be used because exhaust gas is poor in oxygen and rich in nitrogen and should not be used directly for cabin heating. 3) Hot air is taken partially from engines and partially from fuel cells: This system is a combination of the previously mentioned systems 1) and 2). In this system less air can be taken from engines. A part of necessary hot air is to be covered by fuel cells and a part is to be covered by heat from electric heating.
The ventilation system is made by means of the heating system. In the cold environment the fresh air inlet is provided with hot air supply through the heating system. In the warm environment ventilation in the cabin in ensured by the heating system with closed supply of hot air from the compressor. The aircraft can be equipped with the air conditioning cooling unit as an option. This unit is composed of the compressor-condensation unit and two evaporators. The evaporators are equipped with the ventilators which take air from the cabin via inlets in the ceiling section, cooling it down and returning back to the cabin space. Distribution of medium is made by means of the insulated tubing.

◊ Pneumatic boot de-icing system: Currently profiled surfaces are equipped with the pneumatic de-icing system based on the principle of mechanical deformation of a flexible rubber coat surface which is glued on the leading edges of the profiled surfaces. The cooled bleed air is used in the de-icing system for inflating of the rubber coat. A system which can be used for de - icing is the electro-impulse de-icing system. Ice is shattered , de-bonded, and expelled from a surface by a hammer - like blow delivered electro-dynamically. Removal of the ice shard is aided by turbulent airflow; thus, relatively low electrical energy is required. Physically, the system consists of ribbon-wire coils rigidly supported inside the aircraft surface to be de - iced, but separated from the skin surface by a small air gap. A sudden high voltage electric current is discharged through the coil. They must have low resistance and inductance to permit the discharge to be very rapid, typically less than one - half millisecond in duration. A strong electric field forms and collapses, inducting eddy currents in the aircraft skin. The eddy current and coil current fields are mutually repulsive, resulting in a toroidal - shaped pressure on the skin opposite the coil. Actual surface deflection is small, but acceleration is rapid.

At the same time, more theoretical type studies have been carried out on the feasibility of an All-Electric transport aircraft (in collaboration by the Israel Aerospace Industry, Université Libre de Bruxelles and Evektor partners). These will not have an immediate practical application in the initial stages because of the present technological limits, but have the aim of using zero emission propellers in the future to equip aircraft for 10-15 passengers in the intercity sector". Although with slightly smaller performances a preliminary configuration was designed and reported in Fig. 1 [28-29]. An increase of 11.5% in takeoff weight for the intermediate technology readiness (about 5-8 years) and only 2.1% for the advanced technology readiness (about 15-20 years). The all-electric fuel cells Inter-City airplane is not in the same performance category (Range and maximum cruise speed) as the small commuter turbo-prop airplane. The range is decreased from 2300 km to 1500 km and the maximum cruise velocity is decreased from 550 km/hr to 320 km/hr.
Very interesting results have been obtained by Israel Aircraft Industries (IAI) from the preliminary parametric sizing and analysis of a more-electric 32 passengers regional jet aircraft fuelled by liquid hydrogen [28]. The study has led to a better understanding of the practical meaning of transition from kerosene to hydrogen in transportation airplanes. Gas

property changes that occur while burning hydrogen lead to higher efficiency. Therefore, a liquid-hydrogen fuelled engine can operate with a slightly lower turbine entry temperature, and this will result in longer engine life and lower maintenance costs.



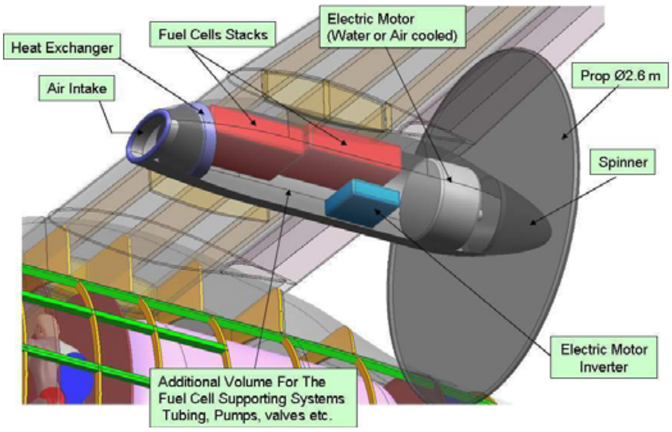


Fig. 1 – All-Electric Intercity Airplane powered by fuel cell fuelled by Hydrogen

During the study some drawback of the hydrogen-converted regional jet were pointed out; for instance the energy consumption increases from 6% to 9% due to the larger wetted surface (more parasitic drag) of the hydrogen fuelled aircraft caused by the huge liquid hydrogen storage volume, moreover the basic empty weight of the hydrogen fuelled airplane would increase from 10% to 17% due to the additional tanks and fuselage weight structures while the MTOW can decrease (from 2% to 6% depending on the aircraft configuration) since the hydrogen fuel weight is 2.8 times lighter than ordinary fuel.

An investigation has been performed to identify the main regulations and normative concerning certification and reliability / safety. Since Fuel cells are not used, so far, in aeronautical applications, the existing certification regulations do not properly address the specific features of this novel technology. Some changes to the existing regulation are required in order to encompass the special features of fuel cells. In addition, some new special conditions need to be formulized. Involvement of certification experts in the early stages of the development is crucial for embedding the required safety features in the evolving FC systems that will provide a level of safety that is equivalent to that provided by the existing technology.

A preliminary safety concept for GA aircraft powered by hydrogen fuel cells was defined. It consists of:

- a short description of novel items included in the GA aircraft,
- a preliminary functional analysis and Functional Hazard Assessment **(FHA)**,
- a subsequent Failure Modes and Effects Analysis/ Failure Modes, Effects and Criticality Analysis **(FMEA/FMECA)** based on data available from open literature or the know-how of the specific partners,
- the definition of a preliminary general risk matrix and a subsequent evaluation through a Fault tree analysis **(FTA)**.

Two maintenance programme suggestions were given for both all-electric propeller driven general aviation airplanes and more-electric regional jet airplanes, including their influence on direct operating costs.

3 Power System of the 2-Seater Airplane powered by Fuel cells

An extensive CFD analysis was performed to define power requested for flight, concerning not only the overall aircraft, but also critical component as the engine cowl [13, 18] that must guarantee a proper cooling of different systems installed in the engine bay and provide a passive safety system for prevention of hydrogen accumulation. Predicted requested powers were found to be about 38 kW for climbing phase and 18-20 kW for cruising phase.

A particular architecture was adopted for the power system in order achieve a safe and flyable aircraft for the prescribed mission. Relying solely on fuel cells for the entire mission, including take-off, leads to an excessive weight due to the required large fuel cell system at high power (40 kW); for this reason a hybrid battery/fuel cell system was chosen. A battery system was added as a secondary power source to increase the rate of climbing during the most power-demanding phases (take-off and climbing to 600m altitude). While fuel cells is always providing up to its maximum power output (20 kW) for normal flight (cruise and descending); the battery was designed to supply 20 kW for 18 minutes. During roll-out tests a fuel cell only take-off was also simulated to demonstrate, from a performance point of view, the capability of a fuel cell only complete mission.

Having two completely separate power source has a strong impact on flight safety, which is the main driver for all decision taken during design; the battery is designed so that it can work as an emergency power source in case of failure of fuel cell, allowing pilot to safely land. Introduction of the second power source requires a more complex electronic control system (Fig. 2); it is necessary indeed that fuel cell is always automatically selected as the main power supplier in order to minimize battery use that is "activated" only when requested power exceed fuel cell maximum one; at the same time the controller needs to be able to instantly draw power from battery to replace fuel cell in case of fuel cell malfunction.

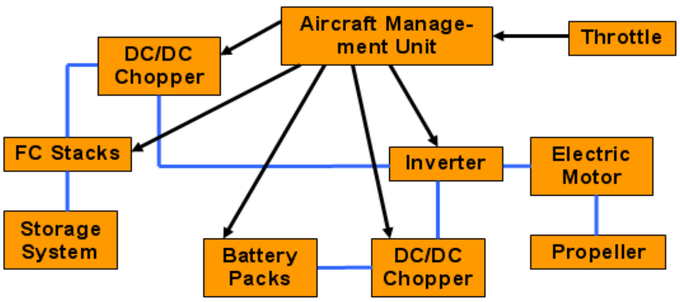


Fig. 2 –Propulsion System Power Electronics

The conventional power system (ICE), is very different from the fuel cell powered airplane both for number of items and for volumes of those items and aircraft balance must be maintained, keeping in mind safety constraints that are particularly important when operating with high pressure hydrogen. Main properties of the Rapid 200-FC aircraft are:

Maximum take-off weight: 5500 N; Maximum level speed: 190 km/h; Cruise Speed: 150-160 km/h. Maximum engine power: 42 kW; Endurance: 1 hr; Wing span: 9.9 m; Wing area: 11.85 m2; Overall length: 7.0 m.

Weight of subsystems are:
Empty Aircraft: 2210N; Fuel Cell System: 1030N; Pressurized Hydrogen Sub System: 510N; Electric Motor: 400N; DC/DC+AC/DC+ vehicle power control Sub-System: 140N; Battery Packs: 510N; Pilot: 740N (limit of one passenger instead of two).

Some structural components were carefully re-designed: engine mount as support for many different subsystems (Fig.3), special lightweight support plate for hydrogen tanks (Fig. 4), etc.

Fig. 3. Engine bay instalments of the fuel cell.

Fig. 4. High pressure hydrogen tank instalment.

As part of the Propulsion System, a new propeller was designed, manufactured and tested, since weight and available power of the converted aircraft strongly differ from the conventional one, to get higher performance for this specific flight tests. A software developed by POLITO was selected to design the optimal propeller. From preliminary calculations, it seemed reasonable to obtain a 90% efficient propeller for cruise condition [12]. The results were validated by ULB by a CFD analysis.

A propeller manufacture (GT Propeller) was contacted by POLITO in order to manufacture the optimized designed propeller. The manufacture requested to slightly modified the design from the technological problems foreseen in the very narrow root section. Almost the same efficiency was obtained for the take-off and climbing phase; however a slight reduction was obtained during the cruise phase (0,86 instead of 0,90). The propeller was initially manufactured in composite material, obtaining a very light propeller (weight = 3.2kg). However, since some small local de-bonding were detected during the non-destructive tests, two new propellers were manufactured in traditional wood.

The propeller was subjected to stationary tests in order to verify the analytical results, obtaining a very good correlation with the experimental results. Good results were also obtained during ground tests carried on the aircraft prototype; also the taxi test had confirmed the excellent thrust obtained by the propeller [12].

4 System Testing

Several experimental test activities have been performed at different levels of growing integration [.

4.1 Individual Sub-System Testing

The fuel cell was carefully tested against endurance at its maximum power output. The system was continuously tested for more than 6 hours with no degradation of performances during the experiment [30]. Few long tests were performed to prove reliability of the FC system.

Tests of battery system regarded mainly the safety of the system during charge and discharge; particular attention was paid to temperatures and minimum voltage during discharge; in fact, for safety reasons, the battery system isn't provided with automatic cut-off, so that the pilot is able to draw all the energy accumulated, eventually damaging battery, in order to safely land during an emergency.

Motor, power electronics and vehicle controller were simultaneously tested, mainly the temperatures that can be reached during a full duty cycle; above all at the very beginning of the mission, when airplane speed, an so fresh air mass flow, is very low. Temperature behaviours of critical components during the tests showed that the maximum temperature reached in the inverter was of 78° C (maximum allowable is 120°C), and in the motor was of 80 °C (maximum allowable is 180°C). Moreover the vehicle controller was tested against its capability of being able to immediately switch from the main to the second power source, and back, without any interruption or unexpected change of motor operation.

Hydrogen storage system (350 bar is the working pressure for this application) was tested against maximum working pressure (438 bar) and burst pressure (984 bar).

4.2 Semi-Integrated System Testing

The whole fuel cell system was completely installed in the final configuration on a fuselage mock-up; the motor/power electronic block was linked to a bench brake; hydrogen was supplied at first by external hydrogen bottles until the system was proven reliable and then by the actual hydrogen system. Main goal of this testing stage was to investigate and tune the communication between systems, above all vehicle controller and fuel cell. Moreover fuel cell system is extremely complex and opportune strategies needed to be defined to pilot it during normal and abnormal operations that may occur during flight; extensive testing was hence devoted to software related issues and tuning.

4.3 Integrated System Testing

The final and most extensive campaign test was the one devoted to the complete aircraft; ground test (Fig. 5) and flight test were performed at Reggio Emilia airport with the goal to validate the design and installation of the complete converted aircraft (Oct 2009- May 2010).

Fig. 5. Preliminary ground tests.

Communication with Italian **CAA –ENAC**- for obtaining the **Permit-to-Flight** and Establishment of requirements, design criteria and safety necessary for the system, through assessment of aviation authority standards and computer modelling. The **Permit-to-Flight as experimental airplane** was finally issued in Feb 2010 giving in this way the possibility to carry all the experimental flight test.

More than 100 tests were carried out in total in order to verify the correct functioning of the electric and fuel cell system. In total, about 28 hours of experimental tests were carried out. Tests were carried out including the Fuel cell and Battery power source. The Fuel cell and battery systems can perfectly supply the power required for the flight in a very prompt response, as can be seen by the many results reported [9-20]. The fuel cells have been working for more than 16 hours; the battery for more than 15 hours; the inverter for about 28 hours. The Brushless Electric Motor, the Inverter and the Vehicle Controller, also including the FCS, have perfectly worked for several time without any minor fault. To be mention the **failure of the Converter Inverter** (CIE) during last ground tests in Reggio Emilia. The most probable cause of the failure might be due to overheating of the CIE, because the cooling system was inadequate during the ground test in Reggio Emilia. In effect the airflow during the flight was much higher than during the tests with the fixed airplane and a better cooling should be obtained during flight. The energy and electrical system was subjected to new ground test on the aircraft for about 9 flight duty cycles. No overheating was recorded during ground tests with the cooling system provided by 4 electric ventilators directed toward the engine cowl front opening [Fig. 6]; a maximum temperature of 77°C was recorded in the inverter [Fig. 7].

Fig. 6. Cooling system for ground tests.

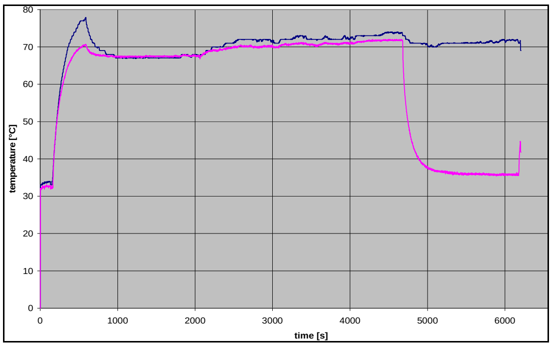


Fig. 7 – Temperature of electronic system on Ground tests (T inverter – T FC_Booster).

An anomalous behaviour of the main power battery was also recorded during the aircraft ground tests. In fact, two cells (n. 13 & n.39) showed a discharge below the secure allowable limits and were substituted.

Indeed an high FC water consumption was recorded during ground tests, although carried not at maximum power. It seemed that water quantity would not be sufficient for a full duty cycle at 20kW of fuel cell power.

The aircraft was equipped GPS data logger FAI certified (LX Navigation Colibrì), which was able to provide a full GPS registration of the test to be correlated with other telemetry data (Fig. 8). The maximum ground speed recorded by the

GPS during this taxi in clean configuration was of about 110km/h.

Fig. 8. Cabin Flight Struments.

This stage mainly investigated the behaviour of output power when connected to the real load (i.e. the propeller), behaviour of propeller, handling of system partial failures, temperatures with the real cooling system (i.e. cooling system exposed to aircraft speed) and finally aircraft performances in take-off and cruise. Great attention was paid to correct handling of the two onboard power sources, testing several scenarios in which different failures were simulated.

Having the complete system installed on board allowed checking the real efficiency of cooling systems. In order to investigate this, temperatures were observed during high speed roll-outs which were performed for testing theoretical data about taking-off distances and speeds; cooling systems presented a very satisfactory behaviour keeping temperatures below admissible limits.

The Reggio Emilia airport (LIDE) flight route was chosen such to always permit a total power loss return to base procedure, with a glide profile flown at best glide speed, leading to safe landing on runway 29 in Reggio Emilia. Flights was executed in radio contact (voice & data) with test control (telemetry) and ATC – Reggio Emilia AFIS. Meteorological conditions for flight tests were suitable for VFR, pilot had always to be able to keep visual contact with ground and with the airfield. Furthermore the air had to be calm and without any meteorological precipitation. Flight test area is plotted in Figure 9. Flight path was chosen so that the aircraft was always able to land at the airport or at a close airfield, gliding with no available power.

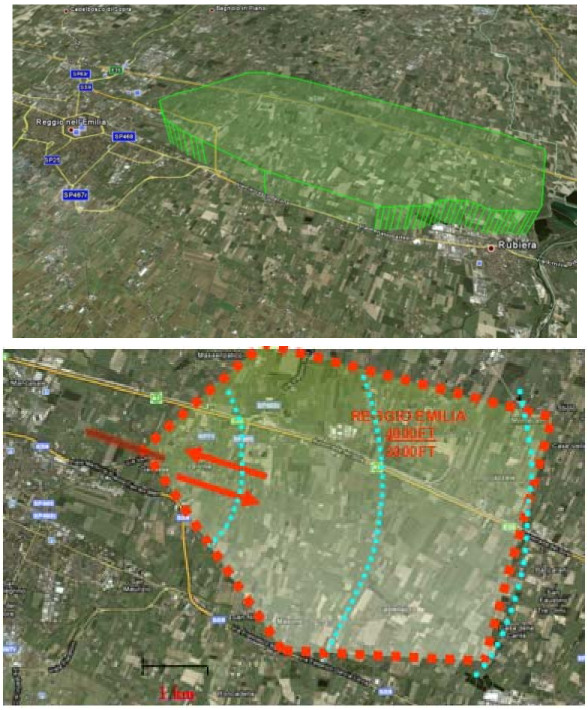


Fig. 9: Reggio E. airport, flight test area: ...

Every blue arc represents a 1000ft altitude eng. out glide range (above Field Elevation), when flown at V Best Glide. Range calculated at Vmax efficiency (best glide) 105 km/h u/c extended and flap t/o (Vvi 482 ft/min = 2,45 m/s) (3927m on ground for each 1000ft/ 330m of altitude exchanged). Range calculated at Vmax efficiency (best glide) 130 km/h u/c and flap retracted (Vvi 460 ft/min = 2,34 m/s) (5000 m on ground for each 1000ft/ 330m of altitude exchanged). Two emergency landing airfields were planned in Reggio Emilia (LIDE 29) and Castellazzo (CAST02) (UL grass airfield). Use of runway **11** for take off, and **29** for landing to avoid populated areas over-fly (Fig. 10).

Fig. 10.

Risk Assessment for Flight Test Operations

Among many others, the following issues were considered:

1) Ground Fire fighting procedures and technical intervention on powered up engine. Engine loss of control.

2) Taxi, braking, manoeuvrability on ground at low and high speed will take place in radio contact with telemetry and Reggio Emilia FSS (Flight Service Station) without any air or personnel traffic in the same airspace.

3) Failure before V1/Vr, crash landing.

4) Flight profile is studied such as from any point it is possible to reach Reggio E. runway 29 in a safe glide performed at V max efficiency (135 km/h clean conf, 105 km/h landing conf).

5) Approach and landing procedures will be exclusively executed in VMC conditions.

6) In case of engine failure (partial or complete) any applicable emergency procedure must be adopted on the field to grant a safe recovery of landing aircraft, inside and outside of the airfield boundary.

7) In case of failure of telemetry radio com channel, if no alternative way of communication exists, the flight will be interrupted, advising the crew through ATC radio system.

8) In case any malfunction inhibits throttle signals to inverter control unit, the engine will automatically be brought to a medium power setting. This setting may be useful to assist the RTB (Run-to-Base) manoeuvre. Once on ground engine hardware shut off will permit to safely bring the aircraft to stop.

9) High pressure Hydrogen tanks and low pressure connections are certified to be crash resistant. All internal compartments of test aircraft are properly ventilated so as to avoid any possible stagnation of Hydrogen in case of leak. Tank compartment is ventilated upwards and backwards.

Analytical Performances

Expected performances stated here are valid for the version with retractable landing gear.
Performances correspond to ISA sea level.
TAS = IAS ± 8 km/h. MTOW: 5500 N.

Cruising speeds

Cruising speed (2000 RPM)	150 km/h

Stalling speeds

Flaps up speed V_{S1}	79 km/h
Flaps extended (landing position) speed $\mathbf{V_{S0}}$	65km/h
Flaps extended (take-off position) speed $\mathbf{Vs_2}$	72 km/h

Note: The airspeeds stated above are valid for idle engine speed.

Take-off and landing distance

Take-off

Concrete RWY	
Total distance of take-off (till reaching 50 ft)	580 m
Calculated Rolling distance	320 m

Note: Take-off distances for grass RWY depend on the surface condition.

Landing

Concrete RWY	
Total distance of landing (from 50 ft)	200 m
Run out distance	100 m

Climbing

Using take-off power (Max 40kW).

Climbing in ft/min (m/s) at 38.5 kW	492 (2.5)
At airspeed [km/h]	120

Gliding

Gliding velocities when engine idling.

Optimal airspeed of gliding [km/h]	110
Sink rate [ft/min] (m/s)	354 (1.8)

Gliding speed with engine stopped.
Flaps take-off position, undercarriage extended.

Optimal airspeed of gliding [km/h]	100
Sink rate [ft/min] (m/s)	413 (2.1)

Ceiling **1000 m**

5 Flight Tests

After this extensive test campaign, the aircraft finally flew at Reggio Emilia airport (Fig. 11). Experimental Test Pilot: Commander **Marco Locatelli.**

Fig. 11. Rapid 200FC during flight test (flight movie in ref. 7) (Copyright G. Romeo)

Six flights were performed, starting from a first 2 minutes maiden flight and ending with speed world record attempt for electric aircraft powered by fuel cells according to "FAI Sporting Code Section 14 – Electrically-powered Aeroplanes. Class CE. Edition 2010 – Draft". The objective of this record task was to achieve the greatest average speed over a 3,000 meter course.

a. All the following requirements shall be met:
-the course shall be minimum 3,000 m. in length;
-the course shall have defined start and finish straight corridors of at least 1,000 m. in length,
-the course and its corridors shall have a maximum width of 200 m.

b. The flight performance shall be flown as two consecutive runs over the course, in opposite directions.

c. The flight performance begins at start and ends at finish point.

d. The aeroplane shall not descend more than 100 m. and not climb more than 100 m. between the start and the finish point.

e. The flight performance shall be completed within 30 minutes.

f. The achieved speed shall be the average speed of the two individual runs.

g. The speed measurement shall be accomplished by timing each run using synchronized timing devices to determine start and finish times. The course length shall be divided by the elapsed time to determine the speed for each run.

The airplane was equipped with the IE removable start-up battery pack in order to get the voltage for Aircraft Display Unit and Telemetry.

A four-seat Cessna 270 was used as Chase Plane to monitor the Rapid 200-FC during its flight, and eventually detect any anomalous behaviour; also to follow the test plane in an eventual emergency landing (Fig. 12).

Fig. 12. Rapid 200FC & Cessna 270 chase plane

5.1 Maiden Flight (Flight N. 1)

First flight aim was to demonstrate a/c capability to perform a safe take off and landing in fixed flap and gear configuration. Engine behaviour and aircraft flight controls mechanical efficiency were test objectives and were investigated in this preliminary in-flight envelope. Engine air-cooling capability and efficiency at maximum power was to be tested in flight. Secondarily, radio-telemetry data acquisition and main and backup radio com system performance had to be checked.

Refuelling was made with the hydrogen pack (16 bottles) at 200 bar (Fig. 13). Aircraft H2 tanks were filled up to 148bar by direct connection of H2 pack to H2 tanks onboard. During all tests the high sensitivity APL H2 detector was used into the cockpit and placed near the firewall to eventually detect any possible H2 leak. The APL sensor detected as low as less than 5 ppm of H2 concentration.

Starting, idling and increased power setting were regularly performed. Engine was predictable, responding and replicating usual behaviour as shown during ground test phase. Maximum power and idle power can be attained respectively in 6 and 7 seconds from opposite throttle setting positions, regardless of throttle speed (when lower of 6 and 7 seconds).

Figure 13.

Runway 29 high speed taxi. On runway 29, with maximum power set, 18” were required to reach 110 km/h in about 280 m. Aircraft taxi, steering and braking behaviour was satisfactory. 1980 rpm were reached as maximum propeller speed at fixed position (brakes held) and 2040 at maximum speed (110km/h). An estimated 200 m. of ground roll were calculated to reach Vr = 84 km/h. Just a light propeller couple compensation was required at low speed. As speed built up to 50 km/h rudder became more and more efficient, allowing pilot to release right pedal effort.

Runway 11 take-off run. (Fig. 14) Similar positive engine behaviour was seen on take off run on runway 11. Less runway distance was nevertheless necessary to attain 84 km/h: 180 m and 12”. Rotation was possible with a neutral trim setting and a moderate backward (est. 900 g) effort on stick.

Climb to pattern altitude. A positive trend on indicated airspeed and vertical speed was possible with a 3-4° pitch up attitude. Same pitch angle was kept until 110 km/h, half runway, where a light right turn was initiated, while still climbing at constant speed. When turn was stopped all excess power was used for climb, stabilizing 350 ft/min. Engine indication then read 2100 rpm and 212 Amp with 34,5 kW, full forward throttle. Flight controls looked smooth and precise both on pitch and roll. Rudder looked to be efficient and smooth, a prompt dihedral effect transformed lateral inputs in pro-verse roll reaction. At 350 ft over airport boundary the climb was stopped and IAS 120 km/h attained with landing gear and flap still extracted (takeoff position), engine at full power

Figure 14.

Left base. A left base turn was then initiated slightly retarding engine power to 15 kW to keep speed at 120 km/h maximum. Left base was commenced in level flight. (Fig. 15)

Figure 15.

Landing. Cleared to land, at 100 ft above rwy end, throttle was slowly retarded and speed reduced to 90 km/h. Touch down was possible in the first 100 m of runway length after a 3° nose up flare and engine idle. Very light ground effect was felt, and a gentle touch down on main gear was possible with about 5° nose up at 80km/h ca. No brake application was required to vacate runway at last intersection. IAS was lower than 50 km/h in less than 200 m.

Rapid 200 FC maiden flight time was 2 minutes, block time 10 minutes, engine working time 20 minutes. Flight path followed by the airplane in its Maiden Flight is plotted in Fig. 16.

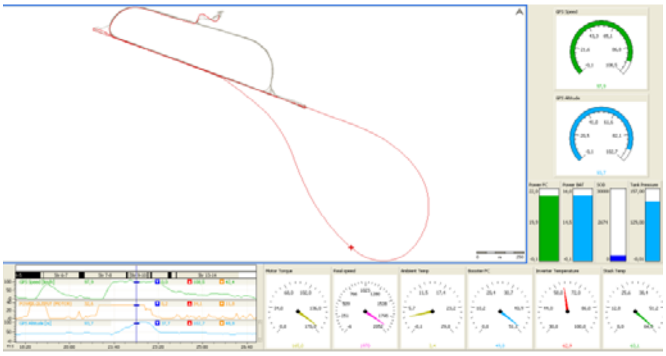


Figure 16.

The power (max 36 kW) was supplied either by the Fuel cells (max 20 kW) and by the Main Battery System installed onboard.

The perfect functioning of the Telemetry system all along the taxi and flight tests was confirmed within these tests, allowing POLITO to obtain the main important results and response of the electric propulsion system.

5.2 Flight N. 2

Flight aim was to demonstrate a/c capability to perform safe take off and landing and flap and landing gear manoeuvres. Engine behaviour and aircraft flight controls mechanical efficiency were also test objectives as well as flying qualities after first flight lateral balance issues. Engine air-cooling capability and efficiency at maximum power were also to be tested during a longer flight time. Secondarily, radio-telemetry data acquisition and main and backup radio com system performance had to be checked at greater distance. Aircraft H2 tanks were filled up to 122bar by direct connection of H2 pack to H2 tanks onboard.

At higher ambient temperature higher runway distance was required to attain Vr 84 km/h: about 250 m and 12”. Vertical speed was stabilized at 350 ft/min with a 3-4° pitch up attitude at 110 km/h, engine at full power, 34,5 kW (Fig. 17). Engine indication read 2010 rpm and about 211 Amp with 34,9 kW, full forward throttle. After two turns, 750 ft of altitude were attained over airport. At level flight 110 km/h IAS was stabilized with less than 16 kW, flap t/o and gear in extended. Engine indication then read 1750 rpm and about 130 Amp with 17 kW, about half forward throttle. Radio com was efficient and clear both in tx and rx modes on 127,15 kHz at the maximum distance from tower (about 2 km). On the same freq also TM and test coordinator came loud and clear.

Figure 17.

Handling. Landing gear retraction takes place in less than 10 seconds at 110 km/h (from lever up to lights off). An aural warning is audible since flap are left in t/o position, with gear up. Reduced drag allows to retard throttle to less than 14 kW in order to keep 110 km/h constant speed. No pitch angles or tendencies were seen during gear transition. Gear extension requires about 10 sec. Gear retraction was uneventful, speed attained at 13 kW was 130 km/h. Flap retraction induces a higher pitch angle of about 2-3° and a slight pitch up trim to keep level flight. At 130 km/h better roll performances were found and only 12,8 kW were required to stabilize speed in level flight. Throttle idle stabilizes propeller speed of 1000 rpm at 120 km/h (vertical velocity about 400fpm). This could be the condition when gliding the aircraft in case of total engine failure (propeller free).

Landing. Descent to landing pattern was then performed at 95 km/h flap land, engine set at around 20 kW (Fig. 18). At 100 ft above rwy end, throttle was very slowly retarded to idle and speed reduced to 90 km/h. Aircraft pitch up capability was then sufficient to flare and touch-down with controlled Vvi. Ground effect may be helpful since a 3-4° pitch up was then attained at around 80 km/h when main gear wheels touched rwy concrete.

The flight path followed by the airplane in its 2nd Flight is plotted in Fig. 19.

Figure 18.

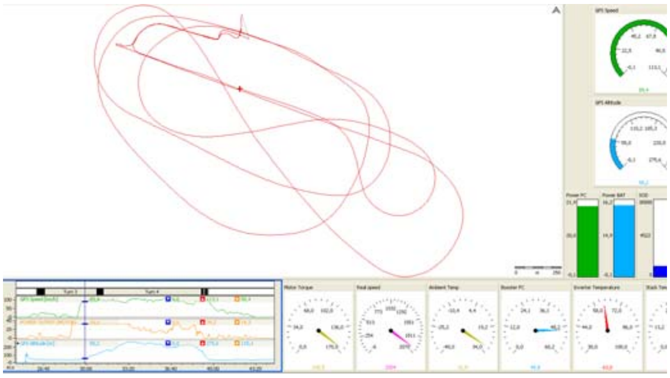


Fig. 19 – Flight Path of Test n. 2

The power (max 36.2 kW) was supplied either by the Fuel cells (max 20 kW) and by the Main Battery System installed onboard. Rapid 200 FC 2nd flight time was 11 minutes, block time 17 minutes, engine working time 24 minutes.

5.3 Flight N. 3

Flight n. 3 main aim was to demonstrate a/c capability to perform long endurance flight and at maximum speed. The S100 hydrogen refuelling system at 350 bar was installed in the Reggio Emilia airfield for these tests. An overall view of the system is given in Fig. 20.

The complete system is composed by:

- an Hydrogen pack (16 bottles at 200 bar)
- an air compressor to increase, (by a membrane) the H2 pressure up to 420 bar into the refuelling station
- a safety system (flame detection + H2 leakage + automatically stop)
- the refuelling station S100

Fig. 20 – APL S100 Refuelling System

Three cylinders are installed inside the fuelling station S100 to gradually increase the pressure up to 420 bar. More than 8 hours were necessary to complete the procedure.

Three Fire Brigade trucks and one first aid ambulance were available close to the test area. Two trucks and the ambulance were located at Castellazzo emergency airfield. The third truck was located in the Reggio Emilia airfield. Fire fighting and first aid personnel received specific information on the test aircraft safety features and procedures (Fig. 21).

Figure 21.

The flight path followed by the airplane in its 3rd Flight is plotted in figure 22. Also the GPS data logger results are plotted.

Main Results obtained (Fig.23): Rapid 200 FC 3rd flight time was 39 minutes, block time 50 minutes, engine working time 55 minutes.

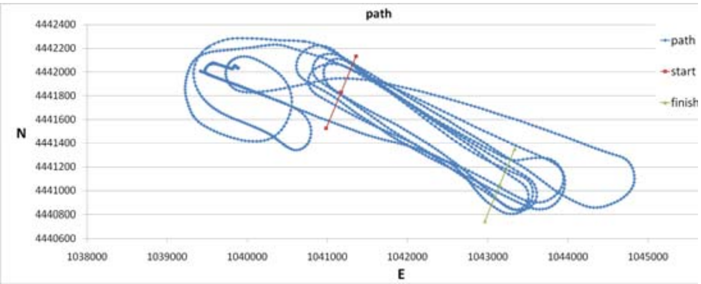
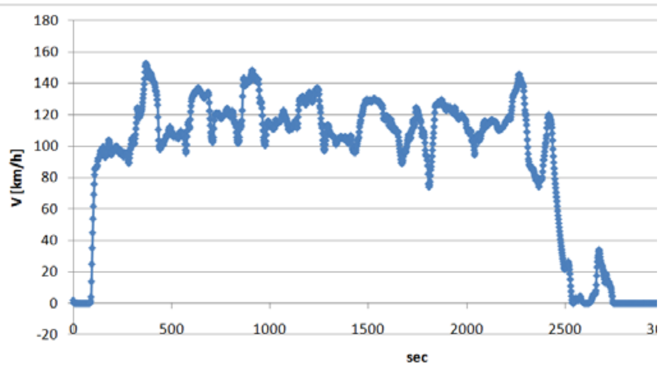
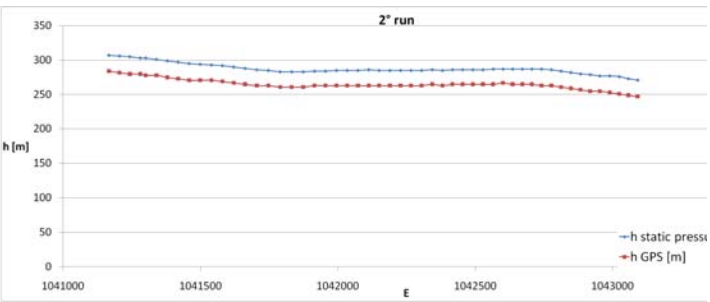


Fig. 22- Third Flight path



Ground Velocity



Flight GPS altitude throw 2 planned lines

Figure 23.

The maximum endurance of 39 minutes was recorded during the flight.
The maximum speed of 131 km/h was recorded during runs 4-5.
The maximum speed greater than 150 km/h was reached during a free flight.
The minimum pressure of 70 bar was measured in the H2 tank at end of flight. 5.9 bar/min were approximately consumed during flight; more 11 minutes were than possible increasing flight endurance up to 50 minutes.
Water level minimum value of about 10% was indeed reached.
Total GPS Horizontal Path Length (Taxi + roll out + climb + hor. Flight + landing): 76,5 km.

5.4 Flight N. 4

Flight n. 4 aim was to repeat and confirm a/c capability to perform long endurance flight and at maximum speed. The 15km flight path was planned between Calatrava bridges – CALA1K – and Rubera – RUB15K. Secondarily, radio-telemetry data acquisition and main and backup radio com system performance had to be checked at longer distance. As in Flight 3, the same equipments and refuelling system were used. The flight path followed by the airplane in its 4th Flight is plotted in figure 24. Recorded path is plotted in red.

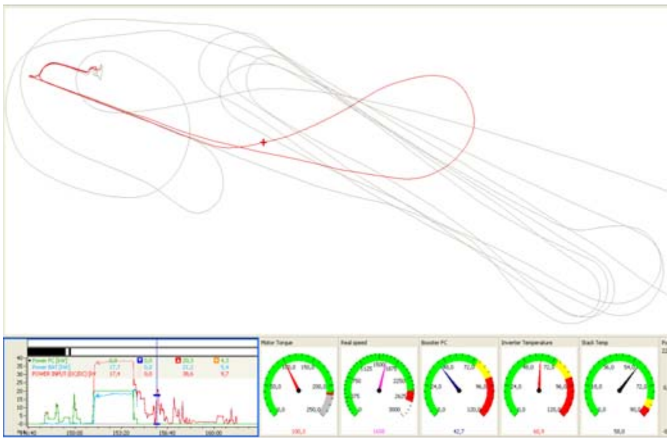


Fig. 24- Fourth Flight path

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Take-off happened, with 37,5 kW power, at a speed of 98 km/h in 365m and 33 sec. A positive trend on IAS and vertical speed was possible with a 3-4° pitch up attitude. Same pitch angle was kept until 110 km/h, half runway, where a light left turn was initiated, while still climbing at constant speed. All power was used for climb, stabilizing 350 ft/min. Engine indication then read 2200 rpm and 210 Amp with 37,5 kW, full forward throttle. Flight controls looked smooth and precise both on pitch and roll.

At 635ft during climb and left turn, engine at full power and GPS speed of 105 km/h, maybe because flying in a light turbulence, aircraft was subjected to a negative g. As consequence the fuel cell had a fault and FC power revealed an abrupt decrease to 3kW for about 14 sec before completely switched-off. The battery continued to supply power to the motor with its maximum power (20.8 kW) and the airplane continued to climb to the maximum altitude of 760ft and speed of 97km/h. Since fuel cells didn't re-start again their functioning, it was decided to abort flight and to safely land to the base (Fig. 25).

The left base turn was then completed just with battery power at 20 kW to keep speed at 90-100 km/h maximum. Base turn was then initiated, slight descent, engine power at 15 kW, to acquire runway 29 final alignment. Cleared to land, at 100 ft above rwy end, throttle was slowly retarded and speed reduced to 85-90 km/h. Touch down was possible in the first 100 m of runway length after a 3° nose up flare and engine idle. Very light ground effect was felt, and a gentle touch down on main gear was possible with about 5°nose up at 80km/h when main gear wheels touched rwy concrete.

Figure 25.

It was always stated in many reports and discussion by Project Coordinator to have a back-up power auxiliary system in order to provide the safe power necessary for the flight; in fact, the FCS was not able to restart as a failure happen during flight duty cycle. In all these cases, the battery will supply the power necessary for a safe landing to the airfield.

5.5 Flight N. 5

Flight n. 5 aim was to repeat and confirm a/c capability to perform long endurance flight and at maximum speed. As in Flight 3, the same equipments and refuelling system were used. The flight path followed by the airplane in its 5th Flight is plotted in figure 26. Take-off happened, with 38 kW power, at a speed of 88 km/h in less than 300m. All power was used for climb, stabilizing 350 ft/min. Engine indication then read 2240 rpm and 212 Amp with 38,9 kW, full forward throttle. Flight controls looked smooth and precise both on pitch and roll. 8 turns were then started to attain some speed records (Fig. 27).

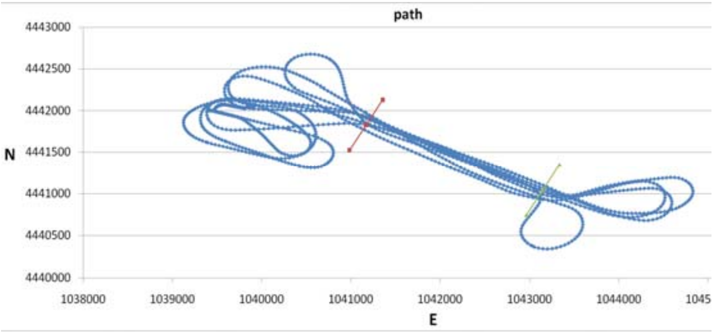
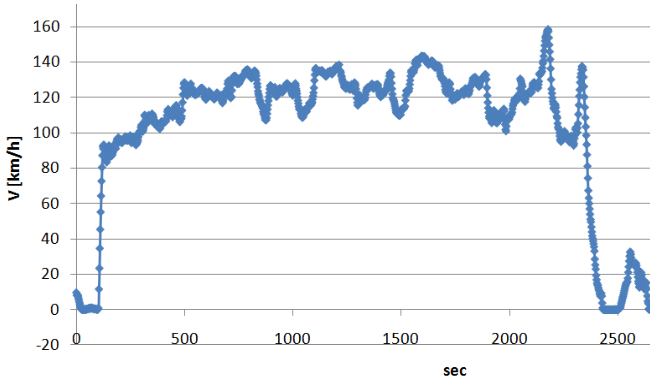
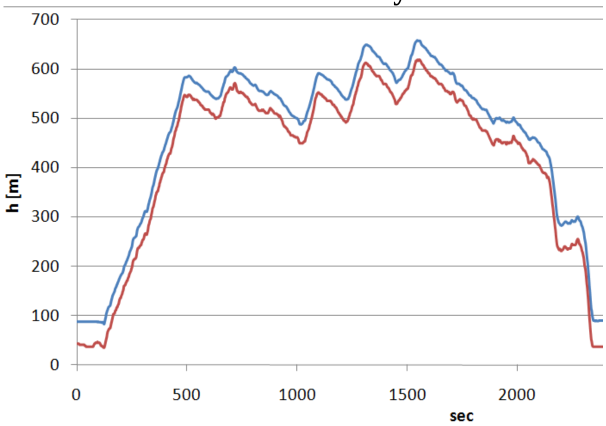


Fig. 26 – Flight Path of Test n. 5



Ground Velocity



Barometric and GPS Altitude

Figure 27.

The left base turn was then completed just with fuel cell power less than 20 kW; the maximum speed of 158 km/h was reached on a slight descend of 150 m. Base turn was then initiated, slight descent, engine power at 15 kW, to keep speed at 90-100 km/h maximum and to acquire runway 29 final alignment.

Main Results obtained: Rapid 200 FC 5th flight time was 38 minutes, block time 48 minutes, engine working time 55 minutes.

The maximum endurance of 38 minutes was recorded during fifth flight.

The maximum GPS speed of 135 km/h was recorded during runs 6-7.

The maximum GPS speed of 158 km/h was reached during a free flight.

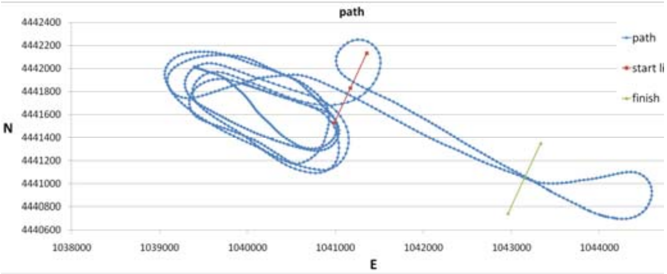
The minimum pressure of 70 bar was measured in the H2 tank at end of flight. 5.8 bar/min were approximately consumed during flight; about more 10 minutes were than possible increasing flight endurance up to 48 minutes.

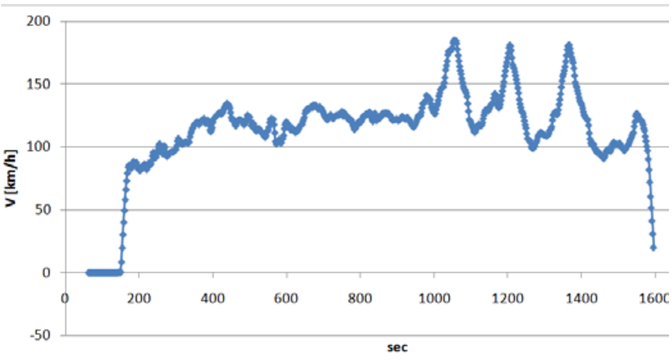
Water level minimum value of about 20% was indeed reached.

Total GPS Horizontal Path Length (Taxi + roll out + climb + hor. Flight + landing): 76,5 km

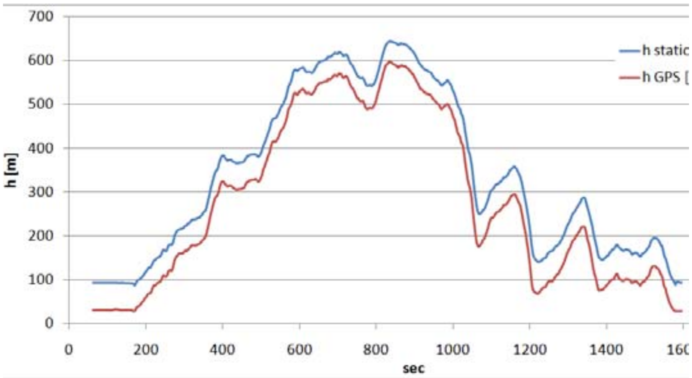
5.6 Flight N. 6

Flight n. 6 aim was to repeat and confirm a/c capability to perform long endurance flight and at maximum speed. A further aim was also to verify the manoeuvrability of the airplane in several light dives followed by light pull up. As in Flight 3, the same equipments and refuelling system were used. The flight path followed by the airplane and main results in its 6th Flight are plotted in figure 28. 2 turns were then started to attain some speed records. Three manoeuvres of slight dive and pull-up were then tested to verify the good manoeuvres capacity of the airplane also powered only by fuel cells. The maximum speed of 180 km/h were reached during the slight descend of 300 m.





Ground Velocity



Barometric and GPS Altitude

Fig. 28 – Flight Path and main results of Test n. 6

Main Results obtained: Rapid 200 FC 6th flight time was 24 minutes, block time 29 minutes, engine working time 35 minutes.
The maximum endurance of 24 minutes was recorded during sixth flight.
The maximum GPS speed of 127 km/h was recorded during runs 1-2.
The maximum GPS speed of 180 km/h was reached during a free flight.
The minimum pressure of 177 bar was measured in the H_2 tank at end of flight.
Water level minimum value of about 50% was reached.
Total GPS Horizontal Path Length (Taxi + roll out + climb + hor. Flight + landing): 48 km

6 Conclusions

Six flight tests were successfully carried out in total by POLITO on the ENFICA-FC aircraft RAPID200-FC at Reggio Emilia airport. The extensive experimental campaign carried out, as well as the theoretical estimations, have proved that fuel cell technologies represent a promising innovation in aeronautics as a key-enabling technology for all-electric, zero emission, low noise aircraft.

The main results obtained [7-22] were: (see flight movie in ref. 7)

- The completely electrical power system was successfully tested during the experimental flights.
- The rotation speed of 84 km/h was obtained within 184 m of taxi at power of 35 kW.

- A maximum endurance of about 39 minutes, being the limiting factor the water consumption used for the stack humidification; the water tank capacity was undersized and needs to be reconsidered in future development; hydrogen measured pressure was 100 bar at the end of that particular flight in which a drop of 5.9 bar was recorded for each minute of flight; further 16min flight would be possible.
- A maximum average speed (according to FAI definition) of 135 km/h was recorded during the best world record attempt; the speed was measured during two continuous 3km long runs and with an altitude variation of less than 100m between the start and the finish points; The new speed world record and endurance was established during several flights for Category C (airplane) of the FAI Sporting Code
- A maximum speed of 158 km/h was reached during level flight; with a top speed of 180 km/h, which was measured during several diving and pull-up manoeuvre tests.
- 2.8 hours of block time and 2 hours of effective flight were performed during these 6 tests for a total path of 237 km (Taxi + roll out + climb + horizontal flight + landing).
- Fuel Cell system did not showed to be fully reliable; few simple changes has to be introduced to obtain the required reliability.

Fig. 29– Enfica-FC partners and EC Project Off.

Furthermore, some interesting results have been obtained for an inter-city aircraft from the preliminary parametric sizing. It has in particular been shown that future developments in FC technology and storage tank efficiency could drastically improve the aircraft performances to a point where very light FC powered aircraft could be a viable alternative to conventional combustion onesThe real strength of the “all-electric aircraft” concept doesn’t lay only in an improvement of the performances, but in the environmentally friendly use of the aircraft itself (among the other also the noise pollution and low emissions particularly important for commuter airplanes that usually takeoff and land from urban areas). The possibility to takeoff and land within the noise abatement regulations set for small airfields, in urban areas and near population centres, will allow the use of these airfields during the late night hours when the noise abatement regulations are even more stringent. Other advantages of this commuter all electric aircrafts are: high reliability, low maintenance and only slight reduction in engine performance due to altitude.

The experience positive handling qualities and satisfactory engine performances led the team to consider these successful flights as a good starting point for further long endurance high speed flights. At the moment, for general aviation aircraft, fuel cells and the related technologies seem to need improvement from the gravimetric efficiency point of view; the actual one does not allow the same performances to be achieved as the original aircraft; a mid-range technology development would be sufficient to obtain acceptable performances.

The results obtained during the projects can be considered as a further step in the European and World Aeronautics Science field towards introducing zero emission flight.

Acknowledgments

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