HYCARUS

'HYdrogen Cells for AiRborne Usage'

Final Publishable Summary

1. Executive Summary

Launched in May 2013, HYCARUS (HYdrogen Cells for AiRborne Usage) was a European collaborative project partially supported by the Fuel Cell and Hydrogen Joint Undertaking (FCH JU), an initiative of the European Union driven by the joint cooperation of European public research centers and private industries actively engaged in the investigation of the fuel cells usage. The project aimed to demonstrate how promising hydrogen-air Proton Exchange Membrane (PEM) fuel cell system technologies are in non-essential aircraft applications.

The HYCARUS consortium was composed of 10 partners from 5 European countries:

- International high technology group – Safran (Zodiac AET, ZEL, ZGEU, ZCC);
- Fuel cell research organization – CEA;
- World leader aircraft manufacturer – Dassault Aviation;
- World leader in industrial gases – Air Liquide,
- Europe's leading test facility organizations – INTA & JRC and
- Europe leader in collaborative R&D consultancy – ARTTIC.

The main objective of HYCARUS was to develop a Generic Fuel Cell System (GFCS) in order to power non-essential aircraft applications such as a galley in a commercial aircraft or to be used as a secondary power sources on-board business jets. Demonstration of GFCS performances in relevant and representative cabin environment (TRL 6) should be achieved through flight tests on-board a Dassault Falcon aircraft. In addition, HYCARUS aimed to assess how to valorise the by-products (especially heat and Oxygen Depleted Air - ODA) produced by the fuel cell system to increase its global efficiency.

2. Project context and objectives

In order to meet the increasing pressure to reduce fuel consumption and greenhouse gas emissions, airlines are seeking alternative sources to power non-propulsive aircraft systems. The next generation of aircraft is heavily investigating the use of non-fossil fuel to generate electrical power for non-essential applications (NEA).

Hydrogen fuel cells are actively being pursued as the most promising means of providing this power. Fuel cells also have the added benefits of no pollution, better efficiency than conventional systems, silent operating mode and low maintenance. The by-products from the fuel cells (heat, water and oxygen depleted air) will also have a positive impact on the global aircraft efficiency when they are harnessed and reused within the aircraft system.

In this context, the HYCARUS project aimed to design a generic PEM fuel cell system compatible of two NEA, then develop, test and demonstrate it against TRL6. A secondary electrical power generation model for a business executive jet was planned to be run. The application should be tested with the fuel cell system and the storage system under flying conditions.

The HYCARUS project planned to extend the work already completed in the automotive sector, particularly for safety codes and standards, and develop these for use in airborne installation and applications. Improvements in terms of efficiency, reliability, performance, weight /volume ratio, safety, cost and lifetime under flight conditions at altitude and under low ambient temperatures (mainly in the air) were also examined.

The HYCARUS project also aimed to foster a better and stronger cooperation between all the agents of the sector: aeronautics equipment and systems manufacturers, aircraft manufacturers, system integrators and fuel cell technology suppliers.

3. Main scientific and technical project results

The main scientific and technical approaches and achievements of the HYCARUS project are described and presented per Work Package hereafter:

1.1 WP1 – Specifications and Sizing

Leader organisation	DA
Partners involved	ZAET, CEA, ALAT, ZEL, ZGEU-CZ, ZCC

Main objectives of the work package

WP1's main objective was to provide the complete definition of the PEM fuel cell system and related applications. Specifically:

1. Prepare the fuel cell system specifications for its various intended applications

2. Identify a generic application to serve as the basis for hardware testing on the ground and in flight and generate the corresponding detailed sub-system specifications to be used in:

- Developing the generic fuel cell system (GFCS) and corresponding components of WP2, WP3, WP4, WP5 and WP6.

- Steering the modelling activities which will be undertaken within WP7 and used for the generation of the test plans within WP8.

3. Perform a top-down safety analysis of the GFCS to be complemented in the last phase of the project, in WP9, by a bottoms-up evaluation on the basis of the technical results obtained.

The scientific/technical approach, the procedures, methods used

The top-level requirements pertaining to the aircraft and the missions to fulfil were generated based on the engineering know-how and expertise of the airframer.

They were used to derive the fuel cell system specifications for its various intended applications according to a standard engineering approach.

Based on these specifications, the complete definition of a generic system was performed by the system designer, based on its expertise in hydrogen and fuel cell technologies, to serve as the basis for hardware testing on the ground and in flight. Included in this definition are the general test objectives and specifications, to be conveyed to WP8.

This activity yielded the elaboration, by the system designer based on its expertise in aeronautical systems, of the corresponding detailed sub-system specifications to be used in the component design activities of WP2, WP3, WP4, WP5 and WP6.

This system definition work also formed the basis for the modelling activities to be undertaken within WP7 and for the generation of the test plans within WP8.

In parallel and in conjunction with these design activities, a top-down safety analysis of the generic fuel cell system was performed. According to the standard rules of aeronautics, a Preliminary System Safety Assessment (PSSA) was performed to evaluate the various risk events and their possibility of occurrence. As the definition of the system was later completed and actual values of failure rates were identified, the safety analysis was finalized in the form of a System Safety Assessment (SSA).

Summary of the main steps of the work

WP1 consisted of six major tasks which were completed sequentially: 1) starting with the top-level requirements coming from the airframer (aircraft related specifications), 2-4) the detailed specifications of the systems addressing the various applications (galley & lavatory, crew rest compartment; secondary power and generic) are defined. 5) These system specifications are then exploited to design the detailed specifications of the GFCS (sub-system). 6) In parallel, a safety analysis is conducted to assess the GFCS.

Main results

The complete set of specifications pertaining to the aircraft and the missions to fulfil for the various intended applications (Galley & Lavatory + Crew Rest, Secondary Power, Generic). The complete set of specifications of the PEM fuel cell systems for the various applications. The definition of the general test objectives and their related specifications. The complete set of specifications of the sub-systems and their components for the generic application. The complete safety analysis of the generic fuel cell system.

1.2 WP2 – Fuel Cell sub-system development

Leader organisation	CEA
Partners involved	AET, ZCC, JRC

Main objectives of the work package

The main objectives of WP2 were to: 1) Design and develop the different sub-systems (Oxidant Management Sub-system, Thermal Management Sub-system, Hydrogen Low Pressure Sub-system, Water Management Sub-system, Fuel Cell Stack and Monitoring and Control Sub-system) based on the specifications made in WP1. The remaining sub-systems described in WP1 will be developed in WP3 (Electrical Power Management Sub-system), WP4 (battery system) and WP5 (Hydrogen High Pressure Sub-system). 2) Design and develop a new high performance MEA. 3) Perform life testing at stack level (durability test representative of the load profile of the application).

The scientific/technical approach, the procedures, methods used

The development of the different fuel cell sub-systems (hydrogen low pressure sub-system, oxidant management sub-system, thermal management sub-system, water management sub-system and monitoring and control sub-system, was performed according to WP1 requirements. In particular, the safety, reliability and environmental constraints (DO160) had been taken into account. The first period of the project was dedicated to the sizing and the design of the different sub-systems using AMESim modelling activities. The second period focused on their manufacturing and testing. Off-the-shelf components were mainly supplied but key components (compressor or main heat exchanger for example) were specifically developed. Once all tests at component level (including performances validation and environmental tests to mitigate some risks) were completed, each sub-system was subsequently assembled and tested successfully (performance validation and control and monitoring strategy and algorithms fine tuning. The design of MEA (Membrane Electrode Assembly) for aircraft requirements was realized. 750 MEAs were produced at CEA pilot line, for two stack designs. The MEA development was based on the selection of the best components (catalysts, membranes and diffusion layers), with adapted ink formulation and deposition on the diffusion layer. All the components were assembled at CEA and tested in dedicated mini-stacks (including durability test coupled with modelling) before launching the production of the MEAs. Three fuel cell stacks were developed and assembled. The first stack was based on CEA technology. The second and third stacks, based on the new design, were assembled in the third period of the project. The stacks fulfilled the constraints and specification of WP1, airframe standard and codes and the risk reduction according aircraft DO160 norms. The new stack design was based on ZAET and CEA bilateral collaboration. The developed fuel cell stack is dedicated to aerospace application with a specific objective on power density (1.65 kW/kg and 2 kW/L).

Summary of the main steps of the work

The main steps of WP2 were: 1) Development of MEAs (selection of the best catalysts, membranes and diffusion layers, manufacturing and tests) for three stacks (in total 750 MEAs); 2) Development of a stack (Design, manufacturing and tests) for aircraft application with D0160 requirements and 3) Development of the different FC sub-systems (specification, definition of the architecture, sizing and design of all components, manufacturing and tests verification).

Main results

The manufacturing of 750 MEAs for three stacks with two different designs. The durability was tested with 2000 hours durability tests with mini stack and extrapolated by modelling. Adaptation of CEA in-house stack for aircraft application, and stack new design (specifically for aircraft application co-designed by AET and CEA in a bilateral collaboration) that require the environmental specification for aircraft application in the cabin environment. The development of the different sub-systems (hydrogen low pressure sub-system, oxidant management sub-system, thermal management sub-system, water management sub-system and monitoring and control sub-system) was completed.

1.3 WP3 – Electrical Power Management Subsystem development

Leader organisation	ZEL
Partners involved	CEA

Main objectives of the work package

The main objective of WP3 was to develop and test the Electrical Power Management Subsystem (EPMS) demonstrator prior to its integration into the complete fuel cell demonstrator within WP8.

The scientific/technical approach, the procedures, methods used

The approach chosen for WP3 started from the high-level requirement specification for the Electrical Power Management Sub-system from WP1. Due to strong functional relationship between all the GFCS sub-systems, WP2 (fuel cell subsystem), WP4 (battery subsystem), WP5 (HHPS) and WP6 (system integration) were expected to provide subsystem characteristics and performance. Once the Electrical Power Management Sub-system was developed and tested within WP3, two shipsets were provided to WP8 (system demonstration) to test the whole Generic Fuel Cell System in the flight test configuration (one for the environmental tests and one for the flight test campaign). Environmental tests results were also provided to WP8 where the complete GFCS will be submitted to qualification testing.

Summary of the main steps of the work

The activities consisted in the following steps: 1) Equipment specification, 2) Preliminary and detailed design, 3) EPMS demonstrators manufacturing, 4) EPMS Functional testing and 5) EPMS components qualification risk mitigation activities.

Main results

The delivery of 2 tested EPMS demonstrator shipsets to WP8 (system demonstration) to test the whole Generic Fuel Cell System in the flight test configuration (one for the environmental tests and one for the flight test campaign).

1.4 WP4 – Battery System Adaptation

Leader organisation	CEA
Partners involved	ZEL

Main objectives of the work package

The main objectives of WP4 were to:

1) Specify the battery system to be used in the Fuel cell system

2) Adapt technical solutions to fulfill the technical specifications based on existing battery modules (from commercial modules or CEA in-house modules)

3) Adapt the pack battery to fulfill the technical specifications

4) Validate the performance of the battery system, in particular for test on an electronic test bench, durability test

5) Define and qualify the most relevant tests for battery system (vibrations, temperature, fire…)

6) Support the integration of the battery system in the Generic Fuel Cell System, with validation of the communication bus linking to the battery pack and the system, and validation of all interfaces of the system (mechanical, electrical, thermal…)

The scientific/technical approach, the procedures, methods used

Based on the system specification, a battery module was chosen, tested, and adapted for the application. In particular, a state of charge algorithm was developed for the NiCd battery, to have an accurate estimation as in input of the energy management algorithm developed in WP7.

Summary of the main steps of the work

The main steps of WP4 were: 1) Technical specifications, 2) Battery system adaptation, 3) Assembly of the battery system, 4) Functional and performance tests and 5) Definition of a state of charge algorithms.

Main results

Selection of a battery pack

Development and validation of the electronic interface board

Validation of the battery system in climatic chamber

Development and validation of a state of charge algorithm

1.5 WP5 – Hydrogen High Pressure Sub-system Development

Leader organisation	ALAT

Main objectives of the work package

The main objectives of WP5 were to:

1) Develop an airborne Hydrogen High Pressure Sub-system capable of storing about 2,4 kg of H_2 at pressure between 350 to 700 bars with a common pressure regulator (Outlet pressure around 10-15 bar) all accommodated into a highly integrated packaging structure. The Sub-system shall work in a possibly unpressurized and non-thermalized environment at temperature ranging from -40°C to +70°C.

2) Achieve mass reduction (being a key objective): materials like Aluminium instead of Stainless Steel shall be used for the pressure regulator, requiring thorough analyses and tests for checking its compatibility with H_2 (risk of embrittlement for instance) and safety regulations.

3) Perform tests at Hydrogen High Pressure sub-system (HHPS) level regarding performance and tightness.

4) Develop a protocol to refill the on-board pressure vessel.

5) Provide a hydrogen charging system (bases on a transportable high-pressure bundle and the adequate interface skid) to allow HHPS refilling during the flight tests.

The scientific/technical approach, the procedures, methods used

Development process

The development of this storage device was managed by ALAT. The design process complied to a V&V cycle, which means that a traceability and the verification and validation of the design was performed step by step from specification to design to manufacturing of prototypes, and then to tests.

Development Plan Strategy

A development plan and a qualification plan were implemented in order to optimize and secure the development of the HHPS.

Two complete sets of equipment were produced: one for the qualification tests, and one for the flight tests. The purpose of this sharing was to keep the flight test model in the best conditions possible for the safety of flight.

Some risk mitigation tests were performed at component level when there was an uncertainty of compliance with the specified tests (vibration tests on the multifunctional valve’s former design for instance).

A vibration test was also performed on an intermediary configuration in order to verify the design of critical safety related aspects before launching the final assembly of the prototypes.

Both prototypes were assembled and tested sequentially in order to benefit from the return on experience on the first one before assembling the second one.

This specific strategy allowed to use an efficient development process and to avoid any heavy non-compliance which would have resulted into a major development risk in the project.

Specific tools

Specific tools were used for process simulation (a dimension tool), for heat release and shockwaves pressure surge to evaluate the impact of the ignition of a hydrogen flow at the output of a vent line on the aircraft fuselage.

Applicable rules

The aerospace certification frame does not yet cover the hydrogen storage devices, especially in composite material. Therefore, in order to be able to demonstrate the safety of the design we merged the requirements from:

- The CS25/FAR25 requirements (civil commercial aircrafts certification)
- The SAE/Eurocae guideline and preliminary standards applied to airborne fuel cell systems safety
- The Air Liquide background on hydrogen safety for ground devices
- The American DOT (Department of Transport) certification for composite vessels, because a few DOT vessels are able to be transported in aircraft.

Summary of the main steps of the work

The work consisted in the following steps:

1) Functional analysis

During the specification process, the functional analysis helped ensuring all functions and constraints were well considered.

2) Conceptual study

The first step consisted in developing several concepts using one or several existing vessels, at 350 bar or 700 bar.

The goal of this conceptual step was to investigate different possible configurations which comply with the main requirements of payload, weight and space allocation and determine what are the pros and cons of each configuration.

At the end of this process we had to decide between a 2-vessel and a 1-vessel configuration, at 350 bar.

The 1-vessel option was selected, associated with a remote multifunctional device allowing a full quick connect/disconnect of the HHPS.

The other key features designed are the following:

- An innovative hydrogen level measurement system
- The pressure release functions using the most relevant technologies considering the failure case and the integration in the cabin of the aircraft
- A manual fast hydrogen dumping function
- A mechanical installation mechanism
- A mechanical system to manage the vessel's dilatation/retraction issue

3) Preliminary design

The preliminary design allowed to demonstrate that no blocking point required to reconsider the specifications. Some mitigation tests were performed on some critical components, mainly mechanical tests on existing configuration before launching the modification to comply with the project specifications.

4) Detailed design

This phase's outcome is the definition dossier, and the manufacturing and supplier specifications to launch the manufacturing and the supply of the parts and plan the assembly.

5) Manufacturing

Two HHPS prototypes were manufactured sequentially in order not to risk failing twice with the same process! This manufacturing process was very long and complex, because the pressurized components had to be pressurized step by step, so the assembly sequence was divided into multiple steps of assembly and pressurization tests.

Some partial configurations were made before the final assembly in order to test specific critical points such as:

- The mechanical fixation concept to install and secure the HHPS on its brackets
- The compliance to vibrations of the high-pressure parts

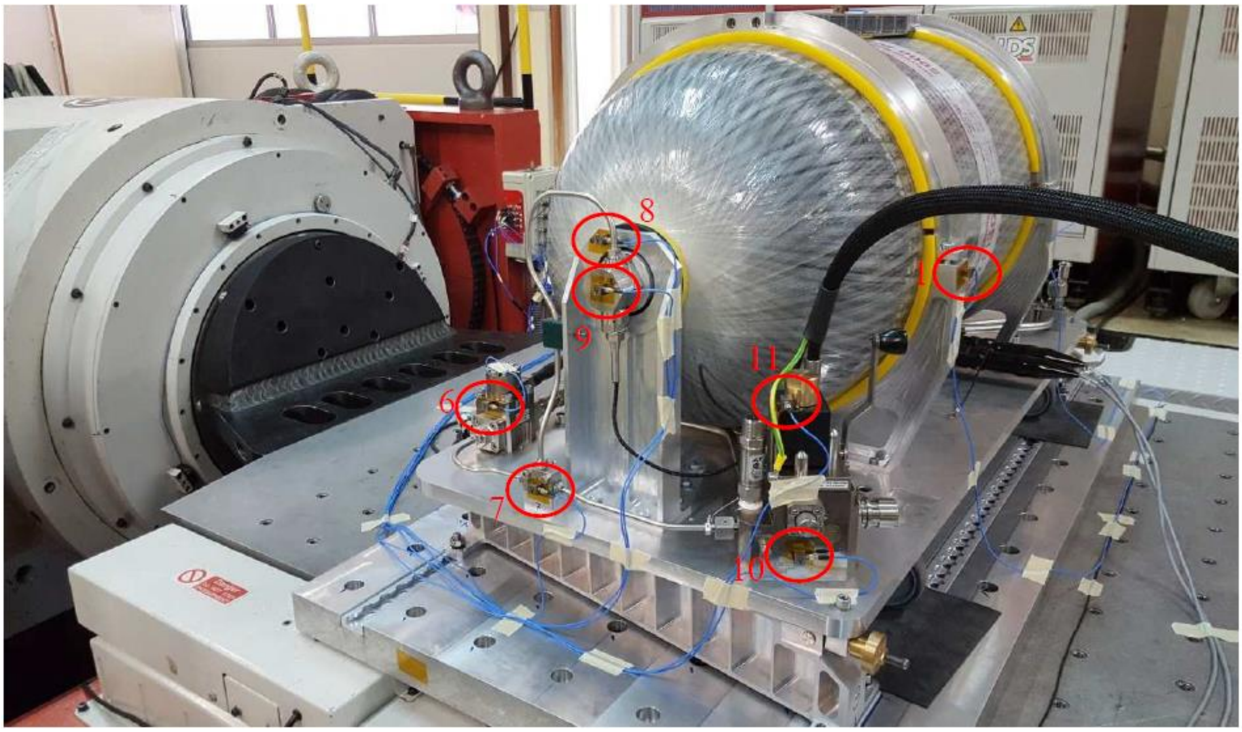

Figure 1: HHPS vibration test

6) Functional and performance testing

Intensive functional testing was then performed on both prototypes. The filling protocol was defined through tests. The dynamic performances of the hydrogen supply function were assessed. The measurement accuracy was demonstration.

7) Environmental qualification testing

Certain tests were performed at HHPS level, mainly vibrations to mitigate the risk of failure during the system tests. Then the HHPS was tested against a lot of environmental requirements inside of the system at INTA.

The next steps were the delivery of the flight test model to AET for system tests and then installation in the aircraft.

Main results

The development of the HHPS was successful. Two prototypes were produced. The first one was used for fuel cell system environmental tests (WP8). The second one was integrated into the flight test system.

The environmental qualification was successful and only a few issues (components failure in vibration, dismounting after vibrations) happened and were addressed successfully by a few modifications and retest.

1.6 WP6 – System integration

Leader organisation	ZGEU-CZ
Partners involved	AET, CEA, DA, ZCC

Main objectives of the work package

The main objectives of WP6 were to:

1) Integrate the Generic Fuel Cell Sub-systems (except the HHPS) into a dedicated frame for the flight test configuration

2) Integrate the GFCS into a Galley: the chosen monument for integration was a Single Aisle Galley

3) Assess the re-use of the fuel Cell by-products (ODA and Heat) for aircraft applications

4) Assess that the health, safety and comfort of the crew and passengers is not jeopardized.

Successful integration of the GFCS into the test aircraft involves careful layout of the GFCS components. Clearances, interfaces and accessibility were also considered.

Additionally, a secure human machine interface was developed to ensure safe operation by flight test operators at all times.

The scientific/technical approach, the procedures, methods used

As within this WP, ZGEU worked only as an integrator of GFCS into the galley, no specific scientific/technical approach has been applied only standard development process with the only change that due to the fact that GFCS due to its design maturity was more sensitive to design changes, more design iterations were required for the integration.

The standard development process consists in the following steps:

- Define product requirements
- Propose conceptual design
- Verify conceptual design
- Perform detail design
- Built a representative unit
- Check the functionality
- Update the design in line with production findings

Due to changing requirements and changes of interfaces, there were various design iterations in the whole process.

In order to install the Generic Fuel Cell Systems (GFCS) on-board a Falcon aircraft, a study was carried-out by AET to define the lay-out of the GFCS (except the HHPS) into a dedicated frame. Starting from different concepts, a complete mechanical design was conducted for the frame and the different mechanical interfaces (brackets for example) using several mechanical simulation and calculation iterations in order to demonstrate (risk assessment) the frame design compliance against mechanical constraints and requirements from the DO160. This mechanical integration was also completed by an electric integration. When the design was completed, the manufacturing of the frame and the different mechanical parts and harnesses was carried-out and all the components of the system were assembled successfully into the frame.

Summary of the main steps of the work

<u>For the integration of the GFCS into a galley, the following activities were carried out:</u>

1) Initial system architecture and preliminary system safety assessment & GAIN (Electrical Galley Insert) equipment selection, Galley monument selection and space allocation.

The system architecture was translated into spacious areas, concentrating on specific behaviour/ technology (Hydrogen, high power electrics, cooling, etc.). All these “space envelopes” were used to identify how much volume is free, and which areas are allowed for specific technology/ system parts.

2) The mission profile together with the assumed power management and GAIN selection was created and multiple times iterated to a standard, which was used to identify the electrical load analyses ELA. Known GFCS (Generic Fuel Cell System) components were integrated into the selected monument and iterated after updates of the components and after architecture changes (both fuel cell and electric related).

3) The ELA (Electrical load analysis) was created, updated and finalised; this was the first major milestone for ZGEU.

The ICD (Interface control document/drawing) data of the majority of the GFCS main components became available and some valuable integration progress was made by placing these components into the 3D model taking into account all component boundary conditions. This allowed for a more detailed concept and reduced the number of iterations required afterwards.

4) The galley itself became more and more mature and therefore standard used completion kit selection and configuration was used to identify and define the HYCARUS monument. Still GFCS components changed e.g. the fuel cell stack, resulting in a major redesign of the GFCS component installation. The thermal knowledge and components also started to be integrated and caused more design iterations to be executed, mainly driven by the thermal fluid behaviour and boundaries (drain slopes, tube bend radii etc.)

5) The integrated GFCS into a galley becomes a fact, it looks complex and a lot of new technologies, system topologies and architecture of different domains are integrated within the 3D model. All connections of the components were made except the complete electrical routing. Almost no changes occurred anymore onto GFCS components keeping the 3D design intact. Electrical routing and the electrical control box integration was the main topic. As the galley has a different configuration than the flight test unit, a new/ re-design of the E-box is required. The internal electronics had so far been mainly AET expertise and required a significant amount of study and a knowledge step for ZGEU to be able to do the redesign.

6) Electronic box was integrated and 3D model design was finished, several design areas of the GFCS (TMS, OMS, FMS, etc.) were drawn on 2D and drawing packages were released for purchasing/ ordering.

The maintenance study and documentation were created and executed.

<u>For the Generic Fuel Cell Sub-systems (except the HHPS) integration for flight test configuration, the following activities were carried out:</u>

1) Concept definition phase. Different concepts were investigated starting from aircraft constraints (space envelop for example).

2) Preliminary design phase on the concept selected. Several mechanical simulation and calculation iterations were required in order to demonstrate (risk assessment before the real environmental tests on the whole system the frame design compliance against mechanical constraints and requirements from the DO160.

3) Detailed design phase in order to issue part lists, interface drawing of all parts.

4) Manufacturing of the different parts (interfaces + frame)

5) Assembly of the whole components of the Fuel Cell system into the frame

6) First article inspection.

Main results

1) Delivery of two fuel cell systems in their final representative integration. The first one was used for the environment Fuel Cell system tests and the second one was delivered to Dassault for the flight tests campaign.

Figure 2: HYCARUS Fuel Cell System

2) Electrical Load Analysis performed. The purpose of this activity was to define the power profiles (user profile) for the different applications, to find a generic fuel cell system architecture and sizing for the HYCARUS project. This was done for three scenarios; two for a galley and lavatory and one for a LDMCR. The secondary power supply will be covered by these two profiles. The two profiles have been based upon a three-hour normal flight profile and a nine-hour flight profile specifically for the lower deck mobile crew rest compartment application.

The power profile was optimized – after implementing the selected GAIN, a new power profile was generated. This power profile has a lower peak power input and also a lower mean power. The peak power dropped from 25.6 kVA to 17.0 kVA and the mean power dropped from 5.71 kVA to 3.97 kVA. Also the over al energy usage dropped from 17.1 kWh to 11.9 kWh.

3) Galley demonstrator: integration study into a Galley was completed.

4) A heat evaluation study was made in order to assess the possibility of using heat from a Fuel Cell system. An identification of the thermal needs for an aircraft galley was made first and an iterative approach was carried-out after to identify how to re-use the "waste heat" of a fuel cell system using existing Galley inserts. One of them was identified and modified to make some preliminary tests in order to validate some assumptions. The interest for an optimized thermal circuit should be also assessed thanks to quantitative parameters (integration, reliability, ease to handle heat in comparison to bring more weight aboard…). These criteria request to have a very good knowledge of the whole aircraft (especially interfaces with heat disposal equipments/systems onboard the A/C) but no commercial A/C manufacturer was involved in this study.

5) ODA (Oxygen Depleted Air) Evaluation: in the frame of the HYCARUS project, FC-ODA was characterized (quality and quantity) and relevant requirements on the ODA quality were determined in order to allow the FC-ODA fuel tanks inerting. A first set of calculations was made and showed an interest to use Fuel Cell

ODA to insure fuel tanks inerting function. A state-of-the-art review of the most relevant equipment for the ODAPS (Oxygen Depleted Air Preparation System) was prepared and allowed AET to propose a first preliminary architecture for the ODAPS. This ODAPS architecture was also compared with actual standard membrane-based FTIS architecture. As explained, this comparison is only qualitative. Additional investigations and studies would be necessary to compare FTIS and FC-ODA inerting system at A/C level, with a quantitative point of view. At last, the maturity of the drying equipment has also to be improved to be installed on board an aircraft.

1.7 WP7 – System Modelling and Extrapolation

Leader organisation	CEA
Partners involved	AET, DA

Main objectives of the work package

The main objectives of WP7 were to: Develop tools to optimize the sub-system parameters that depend of different constraints Validate through simulation the performance of the generic system through a dynamic model and the performance of the whole system Define the real time energy control management to be implemented in the generic system supervisor Define and validate the other scenarios defined in WP1 (secondary power application)

The scientific/technical approach, the procedures, methods used

Extrapolation by modelling of the optimal sizing of the fuel cell system for the real applications of DA partner. In particular, the main objective was to optimize (function of different criteria) and to perform a sensitivity study, on a fuel cell system for a Falcon aircraft. The choices of the power hybridization and the operating conditions of the fuel cell system were optimized to minimize a criterion under constraints (use of Dynamic Programming algorithm). Adaptation of set of tools for modelling and energy management strategy of the hybrid fuel cell system developed in HYCARUS project. In particular, the entire fuel cell system and architecture were modelled to validate the energy management strategy of the fuel cell hybrid system.

Summary of the main steps of the work

The main steps of WP7 were: 1) Fuel cell system model development (based on CEA libraries) and validation 2) Energy management strategy definition and validation 3) Extrapolation and optimal sizing of other aircraft application

Main results

Validation by simulation of the system architecture, by using a multi-physics fuel cell model, to calculate the effects on fuel cell local conditions to the system architecture and control. Optimal sizing of a real use case application (EVASAN use case, medical Falcon aircraft).

1.8 WP8 – System Demonstration

Leader organisation	DA
Partners involved	DA, AET, CEA, ALAT, INTA, ZEL, ZGEU-CZ

Main objectives of the work package

The two main objectives of WP8 were to:

1) Perform GFCS system flight testing (flight test configuration) on board an aircraft and demonstrate proper operation in a representative aircraft environment. This objective covers in particular the following activities:

- Perform the functional tests of the GFCS
- Demonstrate GFCS compatibility with aircraft on board application by proving the safe for flight feature of the system
- Guarantee performance along time
- Verify system efficiency

2) Perform a Maintainability and accessibility study of the GFCS components for a Galley configuration.

The scientific/technical approach, the procedures, methods used

The realization of flight tests implies a rigorous set of procedure-based validation activities, organized around a sequential approach. These validation activities have mostly consisted in tests on actual hardware and analyses. Three major sets of tests were foreseen:

1. Verification tests (including development tests at system level) (AET)
2. Environmental tests (INTA)
3. Flight test demonstration (DA)

- Verification tests have consisted in demonstrating that the system delivers sufficient power to operate the generic application with a functional view and that the electrical power supplied is compatible with the existing aircraft electrical network characteristics.

- The environmental tests were performed according to a dedicated document dictating the specific purpose of each test, along with how it shall be conducted: the "Safety of Flight Qualification Program Plan (QPP)". This QPP describes the qualification requirements and means of compliance to be used in order to substantiate a sufficient level of safety to undertake flight tests. The environmental requirements and the qualification and test methodology are based on the standard procedure RTCA DO-160, version G.

Qualification tests were only performed at the system level. Environmental test compliance of subsystems or components was required before the actual system qualification test campaign could start. The INTA facilities, where the qualification campaign was performed, were adjusted so that the system could safely be operated and tested with hydrogen. For that purpose, dedicated hazard analyses and safety action protocols were**Error! Reference source not found.** developed and applied throughout the entire test campaign.

The qualification tests were divided into three main groups according to their nature:

- EMC and RF tests (DO-160 Sections 18, 19, 20, 21 & 25)
- Climatic tests (DO-160 Sections 4, 5 & 6)
- Mechanical tests (DO-160 Sections 7 & 8)

- Finally, a flight test demonstration was planned to demonstrate that the system developed, once its performances and safe operation being proven, can endure real flight conditions within a Falcon aircraft.

A flight test protocol, jointly defined by DA and relevant partners, was to guide the realization of three test flights: the first one to validate safe and proper operation of the system under real flight conditions;

the second and third ones to assess the influence of system and flight operating parameters on the system performance and behaviour.

In parallel, the items of analysis required for the elaboration of a Permit to Fly were compiled along with their associated justifications. These consisted in:
- a risk and safety analysis of all the sub-systems
- a justification of the structural coherence of all the sub-systems
- a zonal analysis;
- an aircraft modification file
- a cabin inspection analysis
- a safety analysis at aircraft level
- a description of the flight limitations

As part of this Work Package, the maintainability evaluation of the most critical HYCARUS Fuel Cell subsystems and subsystem components installed on a galley configuration has been performed with the purpose to provide recommendations to improve the maintainability of the critical Fuel Cell subsystem components with an MTBF value of less than 60,000 FH. Regulatory as well as internal requirements for the maintainability aspects have been defined. By using 3D model the accessibility of critical items have been checked and described. As a result of the work, a final report has been created.

Summary of the main steps of the work

In order to achieve the first objective, a validation sequence was established prior to going in flight. It consisted in the following steps, which have been the core part of the entire project activities:

- Functional validation of components (at lab level)
- Environmental tests on the key critical components (dedicated risk mitigation tests on the others)
- Functional validation of the complete system in laboratory environment (at AET); this includes performance and safety validation tests
- Environmental validation of the complete system (same definition as the system to be installed into the test aircraft) (at INTA)
- Engine run tests (ERT) on the aircraft to validate proper operation (performance and safety) upon system installation on-board the aircraft

Unfortunately, in spite of all the efforts done by the ALAT, DA and AET teams, it was not possible in the timeframe of HYCARUS to meet all requirements related to the management of pressurized hydrogen gas on the ground and on-board the aircraft.

DA's Flight Test Director therefore stated that neither the flight tests nor the ground tests (including the ERT) could be performed with a sufficient level of guaranteed safety. It was then decided to end the activities at that point.

As a consequence, the objective of testing the system with hydrogen on-board the aircraft could not be accomplished, neither on ground nor in flight.

In order to achieve the second objective for the Galley configuration, the main steps were:

- Identification of the subjected GFCS components
- 3D investigation study for the accessibility linked to WP6
- Spatial study on the Galley including the aircraft environment
- Write the final report on spatial study.

Main results

Noticeable outcomes resulting from this work include:

- Completion of the qualification test campaign at INTA's facilities
- Completion of the performance test campaign at ZAET's facilities
- Modifications of the test aircraft to accommodate the installation of the system
- Proper installation of both parts of the system (empty of hydrogen) on-board the aircraft

- Deployment of the hydrogen refilling station within the premises of the flight test center
- Completion of the maintainability and accessibility study for the Galley configuration.

4. Potential impact and use of project results

The main project results are:

- Demonstration of GFCS performances in relevant and representative cabin environment (TRL 6)
- Ability of the consortium to define, implement and validate a Fuel Cell system design process in compliance with aerospace standards and certification requirements
- Demonstration of feasibility of using Fuel cell as an alternative source to power non-propulsive aircraft systems
- Contribution to the development of guidelines for Hydrogen Fuel Cell Systems for airborne applications
- Contribution to change in public perceptions and acceptance of hydrogen on board an aircraft.

The GFCS is a demonstrator which will serve as a precursor for an independent power source for business jet aircraft cabin or for a commercial aircraft to supply, for example, galleys. These applications / technologies will also contribute to reduce fuel consumption and greenhouse gas emissions and offer innovative alternative sources to aircraft manufacturer, airliners and business jet operators to power non-propulsive aircraft systems.