Dedicated to innovation in aerospace

NLR-TP-2020-041 | February 2020

Hydrogen Drone Research Aircraft

CUSTOMER: Royal Netherlands Aerospace Centre

NLR – Royal Netherlands Aerospace Centre

EXECUTIVE SUMMARY
UNCLASSIFIED

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Hydrogen Drone Research Aircraft

Photo: HYDRA test flight

Problem area

By its high specific energy and zero-emission, hydrogen, in case produced from solar or wind power, is considered as a ideal solution for sustainable aviation. However, a major disadvantage is that hydrogen requires bulky and heavy storage in the form of high-pressure or cryogenic tanks that largely counterbalances the high specific energy advantage. Hydrogen is also extremely reactive and therefore requires appropriate safety measures to eliminate the risk of explosions. Despite these difficulties, hydrogen systems offer significant advantages for electric aircraft compared to batteries as demonstrated by the hydrogen drone project HYDRA (HYdrogen Drone Research Aircraft), see Figure. It was initiated by the Royal Netherlands Aerospace Centre NLR to gain, at a relatively low cost level, practical experience with fuel cell systems for aviation as well as know-how about drone platform optimization, hydrogen infrastructure, test facility for ground performance testing and flight demonstrations.

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AUTHOR(S)
R.C. van Benthem
A.I. de Boer
J. van der Vorst
W.B. van Doorn

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Description of work

One of the objectives of HYDRA, described in this paper, is to demonstrate significantly increased endurance with respect to batteries. The explosion safety analysis and associated hardware modifications are described.

Results and conclusions

An initial flight test with HYDRA-1A, performed in October 2019 at NLR's Drone Test Centre, demonstrated 39 minutes endurance with a small hydrogen tank. With relatively minor modifications, it is expected that 90 minutes endurance is demonstrated early 2020 (HYDRA-1B).

Applicability

For HYDRA-2, planned in 2020, a further extension of the endurance up to several hours will be demonstrated, with a similar hydrogen power system mounted on a Vertical Take Off and Landing (VTOL) fixed-wing drone.

GENERAL NOTE
This report is published as paper no. 43 at the Aerospace Europe Conference, 25-28 February 2020, Bordeaux, France

NLR
Anthony Fokkerweg 2
1059 CM Amsterdam, The Netherlands
p) +31 88 511 3113
e) info@nlr.nl i) www.nlr.nl

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HYDROGEN DRONE RESEARCH AIRCRAFT

R.C. van Benthem(1), A.I. de Boer(2), J. van der Vorst(3), W.B. van Doorn(4)

Royal Netherlands Aerospace Centre, P.O. Box 90502 1006 BM Amsterdam, The Netherlands

(1) Email: Roel.van.Benthem@nlr.nl
(2) Email: Alte.de.Boer@nlr.nl
(3) Email: Jasper.van.der.Vorst@nlr.nl
(4) Email: Jan-Willem.van.Doorn@nlr.nl

KEYWORDS: Hydrogen, Drone, Fuel Cells, Powertrain, Flight Testing.

ABSTRACT:

By its high specific energy and zero-emission, hydrogen, in case produced from solar or wind power, is considered as a ideal solution for sustainable aviation. However, a major disadvantage is that hydrogen requires bulky and heavy storage in the form of high-pressure or cryogenic tanks that largely counterbalances the high specific energy advantage. Hydrogen is also extremely reactive and therefore requires appropriate safety measures to eliminate the risk of explosions. Despite these difficulties, hydrogen systems offer significant advantages for electric aircraft compared to batteries as demonstrated by the hydrogen drone project HYDRA (HYdrogen Drone Research Aircraft), see Figure 1. It was initiated by the Royal Netherlands Aerospace Centre NLR to gain, at a relatively low cost level, practical experience with fuel cell systems for aviation as well as know-how about drone platform optimization, hydrogen infrastructure, test facility for ground performance testing and flight demonstrations. One of the objectives of HYDRA, described in this paper, is to demonstrate significantly increased endurance with respect to batteries. The explosion safety analysis and associated hardware modifications are described. An initial flight test with HYDRA-1A, performed in October 2019 at NLR's Drone Test Centre, demonstrated 39 minutes endurance with a small hydrogen tank. With relatively minor modifications, it is expected that 90 minutes endurance is demonstrated early 2020 (HYDRA-1B). For HYDRA-2, planned in 2020, a further extension of the endurance up to several hours will be demonstrated, with a similar hydrogen power system mounted on a Vertical Take Off and Landing (VTOL) fixed-wing drone.

Figure 1 NLR's Hydrogen Drone HYDRA-1A, Size: Ø120 x 60 cm

1. INTRODUCTION

Hydrogen is the lightest and most abundant element in the universe constituting 75% of all Baryonic mass. The chemical symbol of hydrogen is H with atomic number 1 and atomic weight of 1.008. A hydrogen atom has a proton and electron [1].

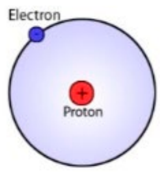


Figure 2 The hydrogen atom

Usually, when talking about hydrogen, the two-atoms (gaseous) hydrogen molecule H_2 is meant. Industrial production of 'grey' hydrogen is done by steam reforming of natural gas (a byproduct of which is CO_2) or with more energy-intensive methods such as the electrolysis of water (Eq 1).

$$2H_2O(l) \rightarrow O_2(g) + H_2(g) \qquad (1)$$

The efficiency of electrolysis on industrial scale is about 70% [2]. In a reversed chemical reaction of Eq. 1, combustion of hydrogen with oxygen in air produces water vapour. In case hydrogen is produced from a green energy source such as solar or wind power, no carbon dioxide is emitted in the process. However, in case hydrogen is used as a fuel for a combustion engine or gas turbine, NO_x is produced from the 80% nitrogen in air, due to the high temperatures of 1200-2500°C inside the combustion chamber. In a Low-Temperature Proton Exchange Membrane Fuel Cell (LT-PEM), hydrogen and oxygen react to water at a temperature of around 80-90°C without producing NO_x. Green hydrogen processed with a LT-PEM is therefore considered as a sustainable fuel.

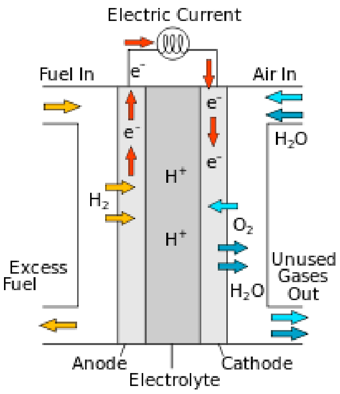


Figure 3 Operation of a PEM fuel cell [2]

The operation of a fuel cell (FC) is based on a Proton Exchange Membrane (PEM) placed in between a hydrogen and oxygen supply. See Figure 3. The negative charged electrons are directed via an external circuit, producing useful electrical power with an efficiency of 50-60% at nominal output power.

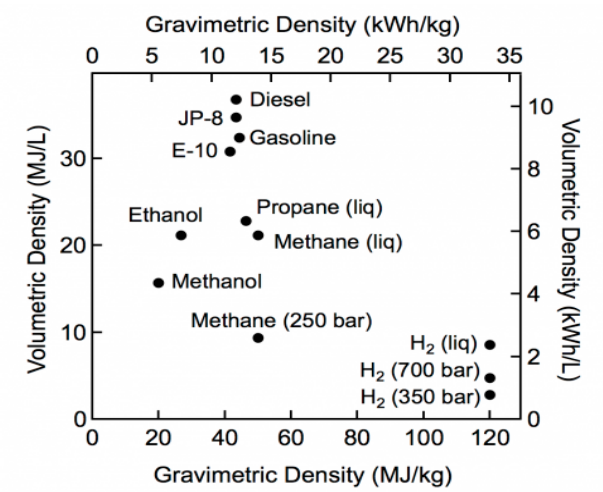


Figure 4 Energy density of fuels [5]

In terms of energy efficiency, the storage of hydrogen by pressurization or liquefaction is 86% (at 550 bar) and 79% respectively [3]. The overall efficiency for production of electrical power with a FC using green hydrogen is therefore 28-36%, including electrolysis, storage and FC efficiency. See Figure *5*.

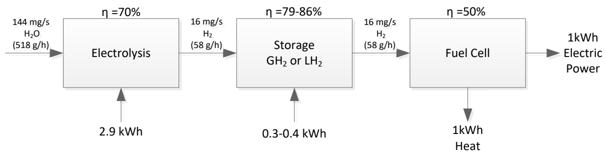


Figure 5 3.3 kWh of electric power is needed to produce 1 kWh with a Fuel Cell

For 1 kWh output power generated with a FC, 3.3 kWh of green electrical energy is needed, for electrolysis, hydrogen storage and FC efficiency. With the production cost by offshore wind farms of 0.017-0.028 €/kWh [3] the 'energy' cost of green electric power 'up in the air' is 0.05-0.08 €/kWh, neglecting transportation and depreciation costs. The service life of the electrolysis device, the compressor and the FC will largely determine the additional costs. The energy costs for a hydrogen FC is in the price range as useful shaft power for (untaxed) kerosene at 0.10-0.11 €/kWh. *(Price = 0.4 €/L (2015), ED jet fuel = 10 kWh/L (figure 4), combustion engine efficiency = 37-40% [8])*

Hydrogen is attractive for aviation due to its high gravimetric energy density of 120 MJ/kg which is about 3.8 times higher than conventional jet fuels such as JP-8 or kerosene, containing roughly 42 MJ/kg (Figure 4) of energy. Note that when a jet fuel is combusted in a gas turbine about 37-40% is available as useful trust and de rest (60-63%) is lost as heat.

Disadvantage of hydrogen compared with conventional fuels having volumetric densities of about 33 MJ/L, hydrogen has a roughly 3 times poorer volumetric density (<9MJ/L), even in case pressurized to 700 bar or liquefied at 20K.

A major disadvantage related to the storage of hydrogen is that the high-pressure or cryogenic storage tanks are relatively heavy, compared with the light-weight tanks for storing liquid fuels at atmospheric pressure. Unless hydrogen storage technologies are significantly improved, liquid fuels provide more efficient energy storage for long-distance travel.

Another disadvantage of Fuel Cell Systems is that "balance of plant" equipment is required to provide the hydrogen feed, air supply, humidification and cooling. Despite this, hydrogen offers advantages for electrical aircraft compared to the limitations imposed by batteries. Modern Li-ion batteries claim to achieve energy densities on cell level of 0.38 kWh/kg [6] but for practical systems this 30% lower on package lever which is closer to 0.2 kWh/kg [7]. Extending flight duration, by adding batteries, is restricted by the Maximum Take-off Weight (MTOW) of an aircraft.

In Figure 6 a logarithmic scaled comparison is made between the power density [kW/kg] and energy density [kWh/kg] of batteries, hydrogen and jet fuels indicating that hydrogen applications fit in-between the two extremes. The component and system level performance of HYDRA-1 is indicated. The indicated values are calculated below in Table 1.

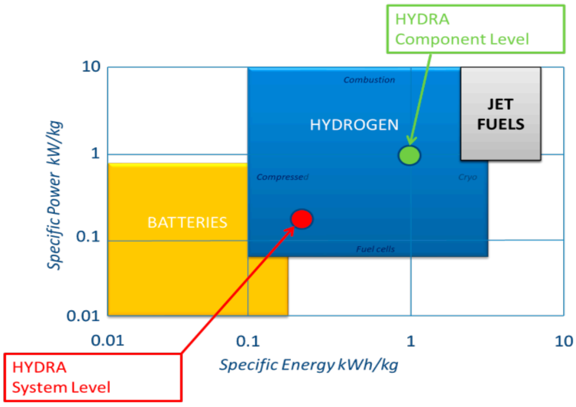


Figure 6 Power and Energy Densities of batteries, hydrogen and fuels indicating the component and system level performance of HYDRA

For the design of power systems the power density and the energy density are usually decoupled except for batteries. The power density is related to the power unit performance such as a fuel cell, electric motor or a combustion engine and the energy density to the fuel tank or battery characteristics. For HYDRA-1 (Table 1) a comparison is made between component and system level power density and energy density. The system level energy density includes a 50% efficiency of the fuel cell for transferring the chemical energy of hydrogen into electric output power.

Table 1 Component and system level power and energy density for HYDRA - 1A and -1B

HYDRA-1A	*Weight*	*Power Density*	*Energy Density*
***1 FC stack* (850 W, 2L @ 300 bar)**	*kg*	*kW/kg*	*kWh/kg*
Fuel Cell	0.96	*0.89*	
Pressure Tank	1.35		*0.98*
Hydrogen	0.04		
Pressure Regulator	0.29		
Residual (mounting, batteries)	0.40		
System Level	**3.03**	**0.28**	**0.22***

HYDRA-1B	*Weight*	*Power Density*	*Energy Density*
2 FC stacks (1700 W, 7.2L @ 300 bar)	*kg*	*kW/kg*	*kWh/kg*
Fuel Cell	1.91	*0.89*	
Pressure Tank	3.75		*1.32*
Hydrogen	0.15		
Pressure Regulator	0.28		
Residual (mounting, batteries)	0.70		
System Level	**6.79**	**0.25**	**0.36***

**System level energy density is based on a 50% Fuel Cell efficiency.*

For HYDRA-1B an energy density between 0.22 - 0.36 kWh/kg will be achieved, which is in the range or better than possible with commercial batteries (~0.2kWh/kg) and with a significant potential for improvement. With larger tanks, higher pressures or cryogenic storage, the energy and power density of hydrogen systems can be further increased, indicating the potential of hydrogen power systems to extend endurance for aviation.

To summarize:

For aviation, hydrogen electric power systems have the potential to go beyond the weight versus energy density limitations imposed by batteries.

Advantages

- Hydrogen is the lightest element in the universe with a high energy density of 120 MJ/kg making it very suitable for aviation.
- Processing of hydrogen using a low-temperature fuel cell to generate electric power, emits water vapour, without CO_2 or NO_x, with an efficiency of 50-60%.
- For hydrogen powertrain components there is a significant potential for improvement of the system level energy density compared to the projected developments of batteries.

Disadvantages

- The volumetric density of hydrogen is poor, even if compressed or liquefied, requiring large and heavy tanks.
- Next to the storage tank, a “Balance of Plant” is required for Fuel Cell Systems to produce electric power with hydrogen. This includes an air compressor, humidifier, DC/DC convertor and cooling loop with a radiator, lowering the power density and energy density of the power system.

2. THE HYDRA PROJECT

The HYDRA project was initiated by NLR to build up experience with hydrogen electric systems and to research hydrogen as a fuel for aviation. The HYDRA project was supported by a new ground test facility THETA (Testing of Hydrogen Electric Technologies for Aviation) for ground testing of hydrogen electric systems up to 5kW. NLR's drone test centre supports the project with flight testing of experimental drones. The objective of the HYDRA-1 project was to develop a flight demonstrator of a hydrogen-electric-powered drone, with a targeted endurance between 0.5-2.5 hours and payloads between 0.5-1.0 kg using commercially available hardware. The HYDRA project followed a gradual approach with laboratory and flight tests with increasing power, payload weight and endurance. Apart from flight tests, system modelling and laboratory tests were done to evaluate the performance of the powertrain components.

The HYDRA-1 project was divided in two main phases (Table 2). The first phase (HYDRA-1A) focuses on the realisation of a test platform with limited flight performance based on one FC (Fuel Cell) system. HYDRA-1A has been flight tested successfully in October 2019. In the second phase, HYDRA-1B with improved flight performance will be demonstrated early 2020. For HYDRA-2 an extended endurance will be demonstrated, up to a few hours, with a similar hydrogen power system mounted on a VTOL fixed wing drone.

Table 2 HYDRA phasing and objectives to improve endurance, payload weight and manoeuvrability

HYDRA	Description	Endurance hr	Payload kg
1A	Laboratory ground and flight test of basic system	0.5-1	-
1B	Lab laboratory ground and flight test of improved system, close to operationally usable system	1 - 1.5	0.5-1
2	Flight demonstration fixed wing drone	> 3 hr	>1

3. The HYDRA-1 drone

The HYDRA-1 drone is a modified Hexacopter *TAROT T960* with an air cooled Fuel Cell System (FCS) of *Intelligent Energy*. See Table *3* for the component specifications. For HYDRA-1A one 800W FC stack is used and for HYDRA-1B two FC stacks are connected in parallel (1600W). The FCS is mounted at the lower end of the drone with a horizontal inlet and outlet for ventilated air for cooling and oxygen supply. See Figure 7 for a schematic layout and a photograph of the drone hardware in Figure 8.

Table 3 Drone components HYDRA-1

	HYDRA-1A	HYDRA-1B
Autopilot	Pixhawk 4	
Autopilot firmware	Arducopter 3.6.5	
Motor	T-Motor MN501-S 300KV	
Propeller	T-Motor Carbon Prop 18"X6.1"	
ESC	Hobbywing XRotor 40A-OPTO	
Power sensor	Mauch 200A	
Fuel cell system	Intelligent Energy 1 x 800W (air cooled)	Intelligent Energy 2 x 800W (air cooled)
IFC battery (connected to Fuel cell system)	6S 1800mAh	2 x 6S 1800mAh
Back-up battery	6S 5000mAh	6S 5000mAh

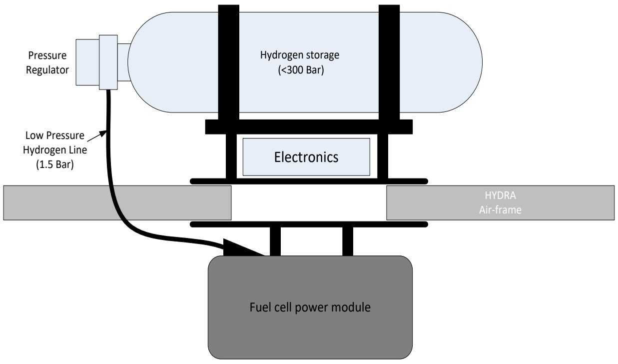


Figure 7 Hydrogen system of HYDRA-1

A composite (type 4) hydrogen tank (*2L, 300 Bar, Intelligent Energy*) is mounted with two brackets on top of the drone. The tank has a light-weight pressure regulator *(PressureTech, LW351)* that is developed for drones and is used to reduce the tank pressure to 1.5 ± 0.25 bar(a) to feed the Fuel Cell.

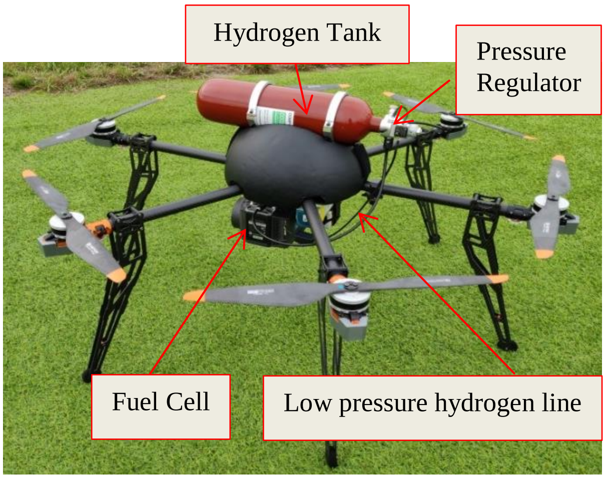
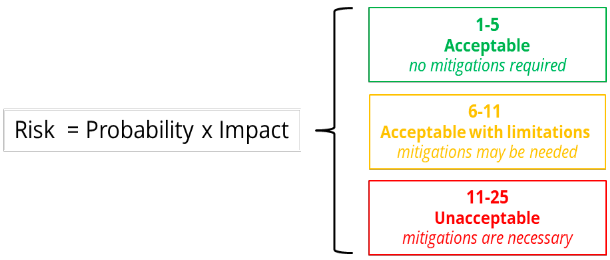


Figure 8 Picture of the HYDRA-1A drone with the hydrogen tank and fuel cell installed.

4. SAFETY APPROACH

Although hydrogen-electric drones can nowadays be bought from several manufacturers, there are no clear aviation safety regulations for hydrogen drones. Commercial use of these systems is therefore limited. The highly explosive nature of hydrogen is not helping in this respect. The Lower Explosion Limit (LEL) of hydrogen is 4.2% in ambient air. However, in open air hydrogen is no more dangerous than any other fuel when taking appropriate precautions. Hydrogen is extremely buoyant and rises fast in case of a leak. For an outdoor drone, a hydrogen leak is quickly diluted in air below its Lower Explosion Limit basically elimination the explosion risks.

In the Netherlands several regulations apply. On one hand, under the national Dutch regulations for drone operations, NLR's drone operations organisation is licenced to conduct flight tests with experimental and commercial drones. For experimental flights an experimental technical assessment of the drone is required, following the Dutch regulations for drone technical requirements. Additionally, a flight test plan and a risk analysis are required. On the other hand, the European regulations (ATEX 153/144) require that in case of explosive materials, any company should protect its employees by writing an Explosion Safety Document (ESD). For the HYDRA-I project NLR followed both the drone and the explosion safety regulations.



***Probability**: 1 = Extremely Improbable, 2 = Improbable, 3 = Remote, 4 = Occasional, 5 = Frequent*

***Impact:** 1 = Negligible, 2 = Minor, 3 = Major, 4 = Hazardous, 5 = Catastrophic*

Figure 9 Risk Evaluation Method

The explosion safety analysis evaluates the risks related to the use of hydrogen and identifies the mitigating measures. The applied risk assessment is based on NLR's Safety Management System for drone operations. Focus of this method is to identify the risks for drone operations and implement effective mitigations to reduce these risks to an acceptable level. The method (Figure 9) is based on an assessment of both the *Probability* and *Impact* of a hazard before and after taking mitigating measures. The risk level is calculated by multiplying the *Probability* and the *Impact* of a failure with a number between 1-5 for both factors. Drone specific risks (not including the use of the hydrogen system) are already covered in the Operations Manual. The focus of the safety analysis was on hazards related to of the hydrogen system, such as malfunctions.

In Table 4 the identified risks are listed. The major effort was that for all risks, a significant number of component level failures, needed to be evaluated.

Table 4 Identified Risks for HYDRA-1

Type	**Identified Risk**
Mechanical failures	1.1 Drone Crash 1.2 H2 tank rupture 1.3 Large mechanical forces on H2 tank 1.4 Cut-off/loosening/blocking of hydrogen feed 1.5 Damage of tank head (PR) during a crash 1.6 Reduction of FC output power 1.7 Power line disconnection 1.8 Damage of FC by overpressure 1.9 Loose hydrogen tank 1.10 Tank separates from drone
Thermal failures	2.1 FC overheating 2.2 FC Tank overheating by fire 2.3 FC high environmental temperatures 2.4 FC low environmental temperatures 2.5 Battery malfunction & fires
Leakages and flames	3.1 High pressure hydrogen leaks and flames 3.2 Low pressure hydrogen leaks & flames
Electrical failures	4.1 FC failures by in flight discharges, EMC 4.2 Static electricity discharges during landing 4.3 Static electricity discharges during FCS installation
Explosions	5.1 Explosion by flying through a vapour cloud 5.2 Explosion during landing 5.3 Explosion on ground 5.4 Explosion during take off 5.5 Explosion by an uncontrolled drone flying into a building 5.6 Explosion after a crash

In Table 5 a summary of the identified safety measures is listed for Equipment and Procedures in arbitrary order. The main risk (R1.1) is a drone crash severely damaging the fuel cell system components such as the tank. In an extremely unlikely case that the pressure regulator breaks off during a crash (R1.5) the drone or tank may be propelled towards people. This risk is mitigated for HYDRA-1A by limiting the flying height to 2-3 meters (M12) and a safety zone of 7 meters after crash (M15). For the second phase (HYDRA-1B) an *Excess Flow Valve* (EFV) will be installed (M3) inside the tank limiting the momentum forces of the released hydrogen in case of regulator would break-off during a crash. Regular visual inspection of the bracket design (M17) is critical to prevent that the tank is separated from the drone during flight (R1.9-R1.10). A backup battery (M1) is also essential to mitigate for several power failure modes of the fuel cell such as a disruption of the hydrogen flow or connector failures (R1.4, R1.6, R1.7, R1.8). The following risks are covered by manufacturer of the fuel cell system: R2.2, R2.3, R2.4 and R4.1. Most of the explosion risks (R5.1-R5.6) are discarded while considered *extremely improbable* in open air and by regular leak testing and inspection (M8) of the hydrogen tubing (M18).

Table 5 Safety measures taken for the HYDRA-1 to mitigate or prevent Risks

	Mitigation or prevention	Risk
E q u i p m e n t		
M1	Back-up batteries	1.4 1.6 1.7 1.8
M2	Remote switch to block hydrogen flow	1.4
M3	Tank Bracket Design	1.9
M4	Down Link (D/L) FC power (battery voltage) alarm @ 24V	3.2
M5	D/L Tank pressure (alarm at @ 20 Bar)	3.1 3.2
M6	Excess Flow Valve (HYDRA 1B)	1.5
P r o c e d u r e s		
M7	Procedures for tank filling, transportation, installation and storage, torque & inspection PR	3.1 3.2
M8	Leak testing low pressure line after installation tank, activating and deactivation FCS including FCS outlet	3.1 3.2 5.4
M9	Wear antistatic cloths during FCS start-up	4.2
M10	Humidity above 40%	4.2 4.3
M11	Hydrogen tank installation: last in first out.	5.3
M12	Flying height of 2-3 m (only for HYDRA-1A)	1.5
M13	Reduction of tank pressure to 150 Bar (initial tests only, HYDRA-1A -> 300 bar)	1.2
M14	Safety zone drone installation and landing site (4 m)	4.3
M15	Safety zone crash location (7 m) and waiting time (1h) before approaching drone	5.6
M16	Safety zone between buildings and people during flight (10 m)	1.1 2.5 5.5
M17	Regular Inspection tank bracket	1.9 1.10
M18	Regular visual inspection of the low pressure tubing and connectors	3.2
M19	Regular visual inspection of the electrical wiring and connectors	1.7
M20	Regular Battery inspection and replacement.	2.5
M21	Replacement of tank after drop, crash or hard landing	1.2

Regular inspections (M17, M18, M19, M20) of the mechanical and electrical parts is highly important for prevention of risks. Remote monitoring is implemented such a as downlink for battery voltage (M4) and tank pressure (M5). Procedures (M7) have been prepared to maintain safety zones such that the test engineers and drone pilot know in advance how to act during flight (M16) take-off and landing (M14) and for emergencies such as drone crash (M15). Although the risk of ignition of hydrogen is extremely improbable in open air it is additionally reduced by leak prevention (M8, M18) antistatic measures (M9) and air humidity above 40% (M13) and with a remotely controlled solenoid valve to close-off the hydrogen feed (M2).

The conclusion of the safety analysis was that taking into account the above measures, the safety risks while performing experimental test flights on NLR's premises Marknesse in The Netherlands with NLR's hydrogen drone HYDRA were acceptable.

5. FLIGHT TEST PREPARATIONS AND INITIAL TESTS

The HYDRA-1 drone is built by NLR using commercial off-the-shelf components. The first flights with the HYDRA-1 drone were performed using batteries only. These flights were used to tune the autopilot, open the flight envelope, and measure power required at different weights to predict flight time with the hydrogen system. Take-Off weights between 6kg and 12kg were tested. Data analysis showed that the tested performance of the selected motor and propeller deviated from the manufacturer's specification. To increase performance, a batch of different propellers and motors were tested on a static test rig as shown below in Figure 10.

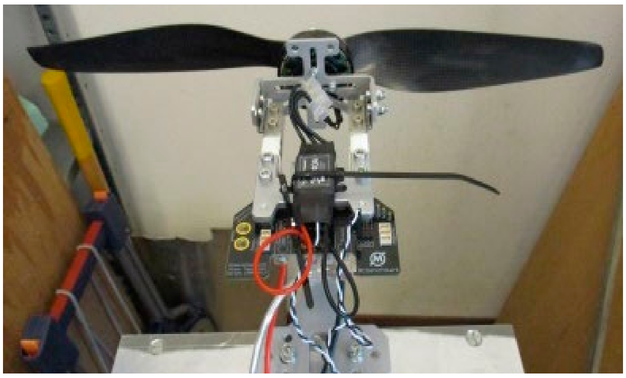


Figure 10 Propeller Test Bench at NLR

From this test the best motor and propeller were selected. Using this new drive train a thrust increase of 20% with the same power consumption was achieved. With the above improvement the power required at 8.3kg (weight of HYDRA-IA) for hover was approximately equal to the maximum continuous power of one FC stack. Therefore, a flight on a single FC stack was now possible.

From the safety analysis (section 4) it was decided to use a back-up battery in parallel to the FCS.

Using a separate data link, the FCS status was monitored and logged. This data contained among others: tank pressure, output voltage, backup battery voltage and error messages. To operate the normally closed solenoid inside the pressure regulator in case of an emergency, a remotely controlled relay was installed.

Ground performance testing of the fuel cell system was done with a newly built test facility at NLR called THETA. The facility (Figure 11) allows for safe performance testing of fuel cell systems up to 5 kW in an air-ventilated cabinet. Representative loads are simulated with a programmable load bank and the results were compared with model predictions.

Figure 11 THETA Test Bench at NLR

6. FLIGHT TEST RESULTS

The first HYDRA-1A flights have been performed at NLR's Drone Test Centre in Marknesse, The Netherlands in September and October 2019.

Figure 12 NLR drone Test Centre © NLR 2020

Table 6 below shows the results of HYDRA-1A flight tests and the expected performance of the HYDRA-1B configuration.

Table 6 HYDRA Flight test results

	HYDRA-1A *(demonstrated in 2019)*	**HYDRA-1B** *(demonstration in 2020)*
Fuel	40 g H_2	120-150 g H_2
Tank	2L @ 300 bar	2x3L- 7.2L @300 bar
Endurance	38 minutes*	60-95 minutes**
Flying height	2-3 meter (limited for safety)	>3 meter (installation of safety measures)
FC output power	ca 900W (1 FC stack)	ca 1800 W (2 FC stacks)
Payload weight	NA**	0.5 – 1 kg**
Back-up & FCS batteries	1.1 kg	1.4 kg
Drone weight	8.3 kg	ca 12 kg

**Projected endurance with a 3L tank and corresponding mass saving is over 60 minutes.*
*** Within these specifications, mass saving is required when increasing payload weight or endurance*

The demonstrated endurance with HYDRA-1A was 38 minutes. The endurance was tested with a tank pressure starting at 300 bar(a) down to 10 bar(a) at landing which left approximately 1 gram of unused H_2 in the tank. Using the back-up batteries could extend endurance with 5-7 minutes – this was not done in the 38-minute flight test. The average FC output power is ca 900W which was about 12% higher than the specified 800W power. Ca 50-75W is consumed by the internal fans for air supply, cooling and recharging the FCS batteries. Mass saving up to 1 kg is possible by means of optimizing structures, reducing back-up batteries and miniaturization of safety systems. With the above reduction, a 3L hydrogen tank could be used containing 60g of H_2 resulting in an expected flight time of over 60 minutes.

7. CONCLUSION & RECOMMENDATIONS

Hydrogen is attractive for carbon-neutral aviation, both for combustion or production of electrical power in fuel cells. It has a high specific energy of 120MJ/kg and no CO_2-emission and in case of a LT-PEM Fuel Cell also no NO_x emission. Disadvantage is that for a compact storage of pressurized or liquefied hydrogen heavy tanks are required. Also, for a hydrogen electric powertrain, "balance of plant" equipment is required for air supply, humidification and cooling, lowering the power and energy density of these systems. Despite this, the power and energy density of commercially available Fuel Cell Systems are improving beyond the limitations of batteries as demonstrated with NLR's hydrogen drone HYDRA.
An experimental flight test was done by NLR at the Drone Test Centre in Marknesse, The Netherlands.

The flight test was conducted under NLR's authorization for experimental drone operations under national regulations. Additionally, explosion safety was ensured by implementing mitigating measures from an explosion safety analysis. A large part of the effort in this project consisted of the safety analysis assessing the risks associated with hydrogen. This resulted in implementation of several safety measures, ranging from prevention, hardware & software adaptations and test procedures. The HYDRA drone and power system was built using commercially available components which were modified for improved performance and safety. A successful 38 minute flight was demonstrated with HYDRA-1A (Figure 13), at a limited flying height of 3 meters for safety. This can be extended up to 60 minutes with a slightly larger 3L tank and mass reduction.

For HYDRA-1B operational performance, a payload up to 1 kg and endurance up to 90 minutes are expected to be demonstrated early 2020. Future research activities are foreseen in 2020 by installation of a similar hydrogen powertrain in a VTOL fixed-wing drone. This will enable NLR to design and flight test hydrogen power systems for drones and to prepare for the development of a hydrogen range extender for its manned electrical aircraft the Pipistrel Alpha Electro within a couple of years.

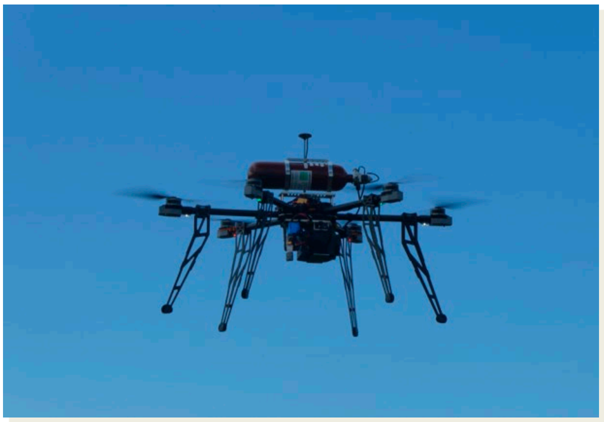


Figure 13 Test Flight with HYDRA-1A

8. ABBREVIATIONS AND ACRONYMS

ATEX	*ATmosphères EXplosibles*
ED	*Energy Density [kW/kg]*
EFV	*Excess Flow Valve*
ESD	*Explosion Safety Document*
FC	*Fuel Cell*
FCS	*Fuel Cell System*
HYDRA	*Hydrogen Drone Research Aircraft*
LEL	*Lower Explosion Limit*
LT-PEM	*Low temperature PEM*
NLR	*Royal Netherlands Aerospace Centre*
PD	*Power Density [kWh/kg]*
PEM	*Proton Exchange Membrane*
PR	*Pressure Regulator*
MTOW	*Maximum take-off weight*
THETA	*Testing of Hydrogen Electric Technologies for Aviation*
VMS	*Safety Management System*
VTOL	*Vertical Take Off and Landing*

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Postal address
PO Box 90502
1006 BM Amsterdam, The Netherlands
e) info@nlr.nl **i)** www.nlr.org

NLR Amsterdam
Anthony Fokkerweg 2
1059 CM Amsterdam, The Netherlands
p) +31 88 511 3113

NLR Marknesse
Voorsterweg 31
8316 PR Marknesse, The Netherlands
p) +31 88 511 4444