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Operation at the airport of an aircraft powered by a liquid hydrogen fuel cell system and the associated refuelling infrastructure

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Abstract

Infrastructure for hydrogen aircraft refuelling at commercial aerodromes is to be implemented for future operations with hydrogen powered aircraft. Safety hazards for refuelling need to be considered and are more pressing for hydrogen than conventional kerosene refuelling operations. The general procedure on how to approach hydrogen aircraft refuelling on a commercial aerodrome is outlined in this document along with a functional safety assessment. Low minimum ignition energy combined with a wide range of flammability result in risks that need to be mitigated by ensuring adequate ventilation at storage locations along with the implementation of fire preventative measures and personal protective equipment. Positive impacts of the demonstration include the potential for drastic reduction in the emission of greenhouse gases along with raising public awareness for the state of the art in hydrogen technologies and the potential of implementing hydrogen powered aircraft safely in the near future. Other impacts include the fact that aerodromes will have to adjust to the increased safety measures necessary for enabling hydrogen powered air traffic.



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VI. LIST OF ACRONYMS

Acronym	Meaning
AP	Air Products
APU	Auxiliary power unit
ATC	Air traffic control
CG	Centre of Gravity
GA	General Assembly
GH2	Gaseous hydrogen
KOM	Kick Off Meeting
LH2	Liquid hydrogen
MAWP	Maximum allowable working pressure
RTHA	Rotterdam - The Hague Airport
WP	Work Package



1 Executive Summary

The use of hydrogen as an energy carrier for aircraft is one of the main pathways for the aviation industry to lower greenhouse gas emissions. Although many hydrogen technologies have not yet reached maturity it is important to define any limitations that will have to be resolved before these technologies will be put into service. One of these limitations is currently the lack of clarity on the feasibility and safety of storing hydrogen at an airport for aircraft refuelling which this TULIPS demonstration aims to clear up.

This concept of operations describes all the major system components and outlines the general operations for filling a liquid hydrogen storage unit and the subsequent refuelling of an aircraft at Rotterdam-The Hague Airport (RTHA). A functional safety assessment is also included to address any safety concerns linked to hydrogen aircraft refuelling on an active airport. Although there is currently a general lack of comprehensive legislation, there are regulatory bodies that have stipulated requirements for the safe design and use of hydrogen systems which are used in this report to outline the safe operations of liquid hydrogen fuelling at an active airport. By applying the regulatory safety distances to the envisioned hydrogen storage at RTHA it is shown that the safety zones for the designated location will not result in any conflict of interest. Therefore, the location can safely be used for the envisioned operations.

Although the use of liquid hydrogen poses more challenges with regards to handling and safety compared to standard Jet A1 fuel, it can be used safely if the correct safety precautions are taken.

This report aims to prove this claim and provide a comprehensive overview of hydrogen fuelling operations at RTHA while taking all safety considerations into account.



2 Introduction

In Work Package (WP) 2, three innovative demonstrations are performed to support the operational deficiencies that are associated with unattended charging of battery electric aircraft and hydrogen fuelling infrastructure on airports. These are a demo on the development on unattended charging, a modular charging system demo and lastly the airport-facilitated hydrogen flight demo.

This deliverable focusses particularly on the improvement of existing inadequacies related to the operational aspects of the storage and fuelling of liquid hydrogen as this is crucial to achieve the decarbonization of aviation in 2050. The demo focuses on showcasing liquid hydrogen fuelling facilities for hydrogen powered aircraft with participants from Royal Netherlands Aerospace Centre (NLR), Schiphol Nederland B.V (SNBV), and Pipistrel Vertical Solutions (PVS).

To systematically plan the demo and the related operational activities as well as achieve the demo objectives, deliverable 2.4 outlines the initial high-level input. Thus, the Concept of Operations (ConOps) plays a vital role in this key deliverable. A ConOps for a given system is a description of the concept of how human and technical resources within the system solution are to interact to result in the capability outcome. Therefore, a CONOPS is a conceptual description of the operational part of the system solution. The operational part of the system solution is that part of the solution which is intended to meet the requirements on the system which serve an end-use purpose (Halligan, 2022). The structure of deliverable 2.4 is defined as follows.

2.1 Demonstrator description

A comprehensive description of the task 2.4 of Work Package (WP) 2 is discussed in section 3 [Project description](#). Section 4 provides the list of [Reference documents](#) that are applicable to task 2.4, which are used to identify the reference and related standards. The [Description of envisioned system](#) and [Physical environment](#) for the demo are detailed in section 5 and 6, respectively. A short description of the post-deployment plan for the envisioned system is given in Chapter 7: [Support environment](#).

2.2 Assessment of operation

The overall use case, and operational principles are outlined in chapter 8: [Operating principles, system operational scenarios and design reference missions \(DRM\)](#). The positive and negative impacts of the demonstrator are discussed in Chapter 9: [Impact considerations](#). Subsequently, the potential risks and [Functional safety assessment for LH2 handling](#) are given in chapter 10.

Finally, the [Conclusion](#) of the demo is provided in chapter 11.



3 Project description

3.1 Background

The TULIPS project was initiated based on the European green deal which aims to reduce greenhouse gas emissions in the coming decades. The European Union strives to achieve several environmental goals one of which is to achieve net zero emissions of greenhouse gases by 2050 (The European green deal, n.d.). The aviation industry is currently responsible for 2% of global energy related CO₂ emissions and many changes are deemed necessary to achieve the goal of net zero emissions by 2050 (IEA, Aviation, 2023).

In the pursuit of mitigating greenhouse gas emissions within the aviation sector, a multitude of strategies and avenues have been actively under consideration. Among these strategies, a prominent solution entails a fundamental shift towards the utilization of hydrogen as a primary energy source, facilitated by the deployment of hydrogen fuel cells for power generation. This transition not only carries significant implications for the reduction of emissions but also holds potential ramifications for the sustainable evolution of aviation technologies.

3.2 Objective of the TULIPS project

Tulips aims to provide results and perspective for the development of emission reducing technologies for airports and the aviation industry in general. The reduction in emissions will be achieved by a transition to low-carbon mobility and enhance current sustainability actions at airports by developing innovative solutions.

The development is made possible by the funding provided through the European Green Deal and the results are shared publicly to further contribute to the decarbonization of the aviation industry.

Work Package 2 of this project is focussed on the development of two main technologies, these are the unattended charging of battery electric aircraft as well as the fuelling of hydrogen powered aircraft on active airports. This deliverable focuses on the operations at the airport of an aircraft powered by liquid hydrogen fuel cell system and the associated refuelling infrastructure.



3.3 Assumptions and constraints

For this demonstrator several assumptions are made and approved by the work package contributors. These assumptions consist of processes that are currently ongoing but have not yet been completed or equipment that is assumed to be in a certain condition for operations. Additionally, RTHA has requested assessments from the applicable governing bodies such as the Human Environment and Transport Inspectorate (ILT)

3.3.1 Assumptions

Table 1 Demonstrator Assumptions

	Assumption	Description	Explanation
1.	All permits required for handling and storing hydrogen on the airport will be in place by the time the demonstrator is planned	Environmental permit for the storage of H ₂ as well as building permit for the facility	Because there are safety concerns associated with handling LH ₂ , different permits must be acquired from the local municipality for the airport.
2.	NLR's HYDRA 2 drone is in fully working condition by the time the demonstrator is planned.	NLR will operate the HYDRA 2 drone which had previously only flown on GH ₂ . Therefore, the system must be converted to handle LH ₂ . It is assumed that it will be operational by the time of the demonstrator.	Because the LH ₂ needs to undergo a phase transition the onboard system needs to be modified to be able to use LH ₂ for the fuel cells.
3.	LH ₂ Dewar is installed and the LH ₂ facility is fully operational.	The LH ₂ facility is built, equipment is installed, and everything is operational for fuelling the HYDRA 2 drone.	The demonstrator can only be performed if the drone can be fuelled. Which requires an operational LH ₂ storage facility
4.	LH ₂ supply is be guaranteed for the demonstration by Air Products	Small quantity LH ₂ supply by Air Products is assumed to be guaranteed. The LH ₂ will be supplied by LH ₂ trailer and will fill the storage Dewar.	Without LH ₂ the demonstrator cannot take place.
5.	Safety assessment for the installation has been performed and has been approved by the local civil aviation authorities (IL&T)	An assessment on all the planned LH ₂ operations is performed and approved by the local authorities by the time of the demonstrator	A third party is needed to evaluate the safety of the system.
6.	Operations consider flight operations for a flight without any passengers	To cover LH ₂ fuelling operations it is assumed first flights will take place without passengers.	Passenger flights include additional steps in onboarding and off-boarding which are not covered in this ConOps.



3.3.2 Constraints

Table 2 Demonstrator constraints

	Constraint	Description	Explanation
1.	The LH2 Dewar must be filled, and leak tested at least once before the demonstrator.	To validate the Dewar and make sure it is ready for operations the LH2 Dewar must be filled, and leak tested at least once before the demonstrator	Any unvalidated Dewar could show leaks or malfunctions which would only become apparent during the demonstration
2.	The LH2 Dewar should be cooled to dissipate any latent heat left in the Dewar.	The Dewar will have to be pre-cooled with LH2 or Cryogenic GH2	To avoid excessive boil-off losses and prolonged filling times during the demonstration, the Dewar should be pre-cooled. This might take multiple fills to cool the Dewar down sufficiently

3.4 Overview of the envisioned system

This section provides an overview of the envisioned system. A more detailed description will be provided in Section 5.

3.4.1 Overview

In this demonstration the feasibility of hydrogen fuelling operations on an active airport are demonstrated by fuelling and flying a drone powered with liquid hydrogen. The drone, NLR's HYDRA 2, will be fuelled at the location currently designated for hydrogen operations at Rotterdam- The Hague airport after which it will fly a predetermined route at the airport. The drone can fly on hydrogen with its onboard fuel cell technology. The hydrogen is supplied to the fuel cell from the liquid hydrogen storage tank, suspended from the bottom of the drone as seen in the figure below.



Figure 1 Hydra 2 LH2 drone

The hydrogen is supplied to the drone from LH2 storage Dewar that is supplied by Pipistrel an example of which can be seen in Figure 2 Cryoworld 125L LH2 Dewar. The storage capacity of



the Dewar is 125L which equates to approximately 9kg of LH2. This quantity of LH2 will be enough to fuel the drone multiple times over as the drone carries a much smaller fuel tank.

Hydrogen is liquefied to increase the volumetric energy density to roughly 71kg/m³ compared to 0.083kg/m³ for gaseous hydrogen under atmospheric conditions.

The Dewar is a vacuum insulated cryogen storage vessel that can retain the hydrogen for extended periods of time. Like any hydrogen storage Dewar, it suffers from boil off losses. The tank is designed, however, so that boil off losses are kept to a minimum and are estimated by Cryoworld to be 1.5-2.0% per day during normal operation.



Figure 2 Cryoworld 125L LH2 Dewar

To handle the boiloff, which is simply evaporated hydrogen gas, the storage Dewar is connected to a vent stack that will allow any gas to be vented if needed. The vent stack is designed to handle pressures up to 100bar which would only see in case of an explosion. The vent stack itself measures a height of 7 meters and is affixed to the facility to ensure its stability and functional integrity.

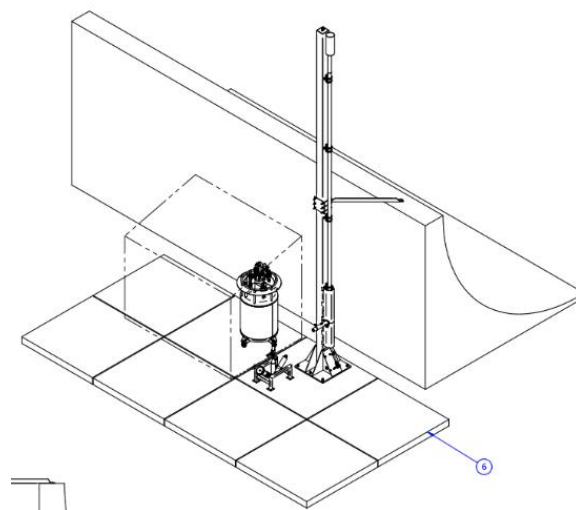


Figure 3 Schematic of LH2 Dewar connected to filling adapter and vent stack

As certain hazards are associated with the use, storage and distribution of hydrogen, a dedicated hydrogen storage facility will be used for the demonstrator.

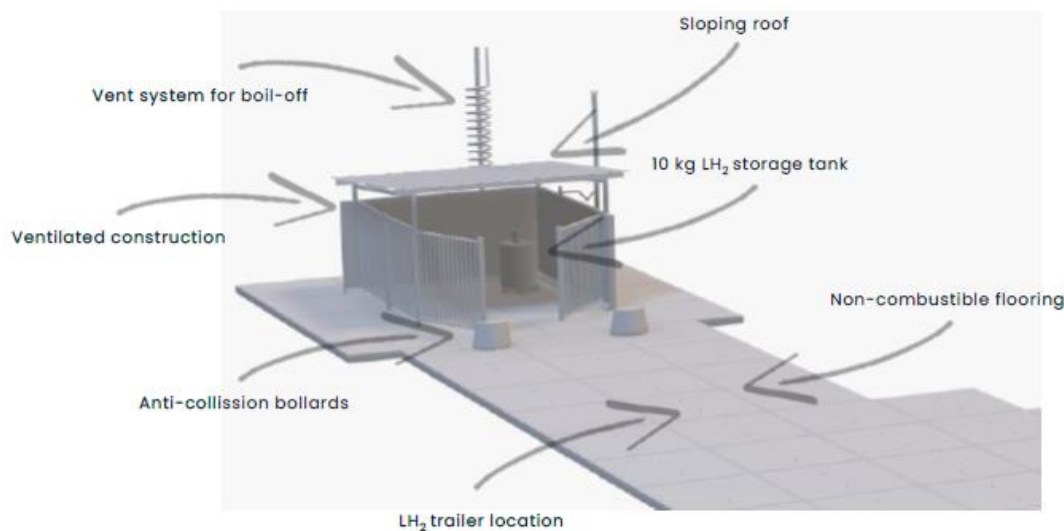


Figure 4 Concept design of RTHA LH2 storage facility

The LH2 storage facility will be built based on the example shown in Figure 4.

This facility will be built adjacent to Platform Lima as seen in the figure below.

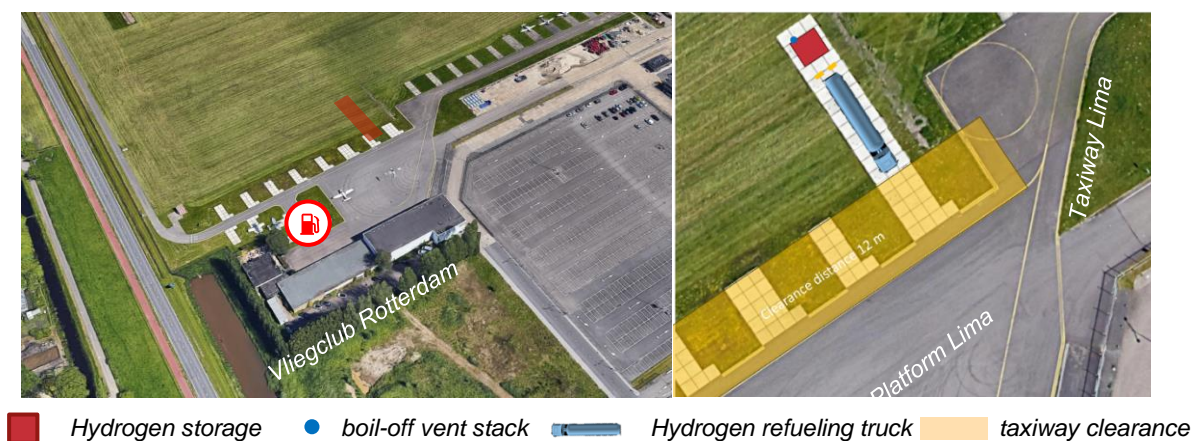


Figure 5 Hydrogen Storage facility lay-out

Platform Lima at RTHA is dedicated to code letter A aircraft with a wingspan of less than 13.5m and has several aircraft stands connected to the platform. The first in this row of aircraft stands will be used for the LH2 storage facility as indicated in red in Figure 5 Hydrogen Storage facility lay-out. The platform will be extended with concrete 2x2m slabs that form the foundation for the facility to be built on. This will also allow the LH2 trailer to reverse onto this platform and supply the LH2 to the storage Dewar. A 12m clearance distance from the platform was defined in which no hydrogen operations will be performed considering that other aircraft can manoeuvre over platform Lima at the same time as LH2 refuelling is taking place.



As the LH2 storage is stationary and will not be moved during demonstrator operations, the drone will be fuelled on the concrete pad in front of the LH2 storage facility.

All fuelling operations will be carried out on a non-combustible surface for safety considerations.

3.4.2 System scope

This Concept of Operations is written for Deliverable 2.4: Operation at the airport of an aircraft powered by a liquid hydrogen fuel cell system and the associated refuelling infrastructure.

The scope of this concept of operations includes the points mentioned below:

3.4.3 In scope of demonstrator

Table 3 In scope of demonstrator

	Item	Description	explanation
1.	Handling LH2 on the airport premises	After the LH2 is transported from the production facility to the airport it is transferred to the Dewar.	The Airport along with Air Products is responsible for the filling operations of the LH2 storage Dewar and will be supported by NLR. Pipistrel has ownership of the Dewar itself and will be supervising as well as providing support during the filling process.
2.	Storage of LH2 on airport premises	LH2 is stored in the Dewar located at platform Lima at RTHA.	The airport is responsible for safe storage conditions and operations around the facility at the airport. Responsibilities involving operating the LH2 Dewar lie with Pipistrel and NLR.
3.	Fuelling aircraft/drone	Fuelling the drone with LH2.	Operations to perform safe and efficient LH2 fuelling of the drone.
4.	LH2 handling during and after refuelling operations	Pressure and temperature monitoring as well as boil-off management.	After the LH2 is fuelled from the storage Dewar to the drone, the cryogenic liquid, and all systems on board the drone need to be managed to stay within the operating temperatures and pressures. Additionally, boil-off needs to be managed.
5.	Aircraft to fuel	The aircraft being moved to the fuel storage.	For this demonstrator the aircraft or drone will always be moved to the LH2 storage.



3.4.4 Not in scope

Table 4 Out of scope of demonstrator

	Item	Description	explanation
1.	Production of hydrogen	Generation of H2 with the use of electrolysis or otherwise.	Air Products will be responsible for the production and liquefaction of the hydrogen.
2.	Transport of LH2 to the airport	Transport of LH2 from production facility to end use.	Air Products will also be responsible for transporting the LH2 from the production facility to the airport.
3.	Fuel to aircraft	Fuel being moved to the aircraft by tanker or otherwise.	For this demonstrator the aircraft or drone will always be moved to the LH2 storage.
4.	Operating the drone	The flight operations of the Hydra 2 drone.	The exact flight operations and manoeuvres performed by the drone are outside the scope of this concept of operations

3.5 Existing systems and operations

Although the use of LH2 in aviation is still a relatively novel technology, there are precedents in this field to base future systems and operations on. Liquid hydrogen has been used for decades in the space industry for rocket propulsion. Consequently, NASA has written comprehensive safety procedures on this topic which will contribute to future safety procedures. In this chapter, the existing systems that have common ground with this demonstrator will be elaborated on.

3.5.1 LH2 infrastructure

The design and operational concept of the LH2 storage facility will be based on the facility currently used by NLR in Marknesse. The facility at RTHA will also utilize the same LH2 storage Dewar that is currently used by NLR. Experience gained by NLR from working in this facility is applied to the demonstrator and safety considerations are incorporated into the overall design.



Figure 6 LH2 storage facility at NLR in Marknesse, Netherlands



3.5.2 LH2 fuelling operations

In September 2023 the first piloted flight using liquid hydrogen powered fuel cells took place under the HEAVEN project (<https://heaven-fch-project.eu/>). A number of successful test flights were performed with the HY4 aircraft in the foothills of the Alps at Maribor airport, Slovenia.



Figure 7 In flight image of the HY4 aircraft powered by a LH2 fuel cell system

This project sets a precedent for LH2 aircraft refuelling operations and can be used as an example for future hydrogen use on airports. During the fuelling and flight tests of the HY4 the airport was not closed off to any air traffic which makes it very representative of the situation to be created at RTHA.



Figure 8 Testing area for the HY4 with all systems connected in Sassenge

The main differences between the HEAVEN and TULIPS fuelling operations are the quantity of LH2 being used in the application.

Beside the differences there are many steps in the process that carry over. In fact, the onboard tank of the HY4 is similar in size when compared to the Cryoworld Dewar.



3.5.3 Aircraft systems and operations

The aircraft to be flown, the HYDRA 2, is an evolution of previous models that also used hydrogen for its fuel cell. However, this drone is modified to carry liquid rather than gaseous hydrogen in the fuel tank.

The main difference with the previous version is therefore the onboard phase conversion from liquid into gaseous hydrogen for use in the fuel cell. As the main components of these systems are placed in or under the fuselage, they do not contribute significantly to a shift in the centre of gravity (CG). The HYDRA 2 has performed flights on gaseous hydrogen already but will fly on liquid hydrogen for the TULIPS demonstrator.

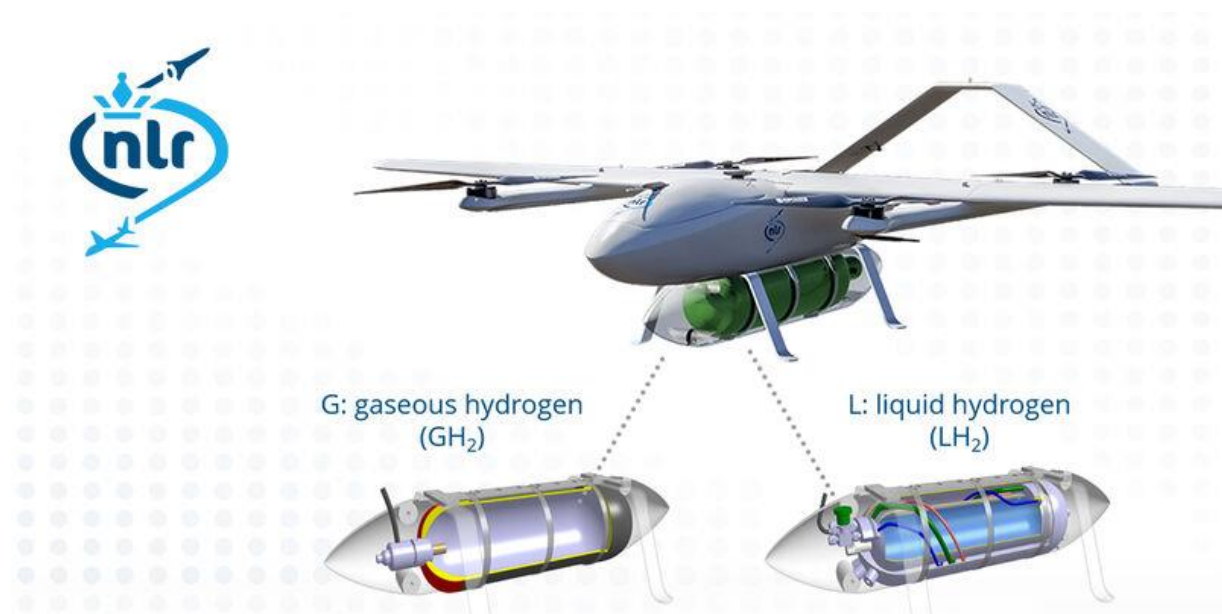


Figure 9 NLR's HYDRA 2



4 Reference documents

Other deliverables in the TULIPS project have contributed to the understanding of possible safety concerns such as TULIPS deliverables 2.1& 2.5. These deliverables have helped shape the context of this concept of operations and are used as a reference. Additionally, the Dewar manufacturer, Cryoworld has provided all the needed documentation for the safe operation of their Dewar.

- D2.1 Feasibility study, airports delivering energy supply for future aircraft.
- D2.5 “conceptual design & safety analysis of hydrogen storage at RTHA”
- Cryoworld - Operating manual LH2 Dewar 125L

4.1 Applicable documents

Although there is little to no government legislation for the safe design and use of liquid hydrogen storage installations, there are, however, different sets of regulations that describe these requirements in more detail. The most comprehensive set of regulations, which will also be used for the design of the LH2 storage facility at RTHA, is the Publicatierreeks gevaarlijke stoffen 35:2015 version 1.0 (PGS 35). For safe operations with LH2, the documents below were also used as reference.

- PGS35:2016 Publication series hazardous substances
- EIGA doc 15/21
- NFPA 55
- NASA Safety standard for hydrogen and hydrogen systems
- PRESLHY; D6.1: Handbook of hydrogen safety: chapter on LH2 safety
- PRESLHY; D6.2: Novel guidelines for safe design and operation of LH2 systems and infrastructure

These documents describe the safe design of both gaseous and liquid hydrogen installations with detailed design requirements as well as more generic cryogenic and LH2 safety requirements.

EIGA doc 15/21 and NFPA 55 specifically were used to define safety distances.

Whereas PGS:35 is currently the most comprehensive set of regulations, the PRESLHY and NASA documents also provide an extensive set of safety precautions and information on liquid hydrogen.



5 Description of envisioned system

This section provides a more detailed description of the envisioned demonstrator and its operation as contained in the following subsections.

5.1 Needs, goals, and objectives of envisioned system

The goal of the demonstrator is not only to showcase it is possible to fly using liquid hydrogen. It is mainly used to play a strong facilitating role for airports by lifting barriers in hydrogen fuelling infrastructure of aircraft by building knowledge and operational experience. Alongside, the necessary safety and operational procedures will be developed for this demonstrator and possibly form the basis for future operational procedures.

The objective relevant to this Concept of Operations is defined as follows: 'Showcase LH2 fuelling facilities for hydrogen powered aircraft'.

From this objective we can take the following requirements:

- The facility to be showcased is purpose built for LH2 distribution to aircraft.
- Aircraft to be fuelled at this facility will receive the hydrogen in liquid phase.
- The capability of the facility to fuel hydrogen powered aircraft needs to be demonstrated.

How these requirements are met will be shown in this report.



5.2 Overview of system and key elements

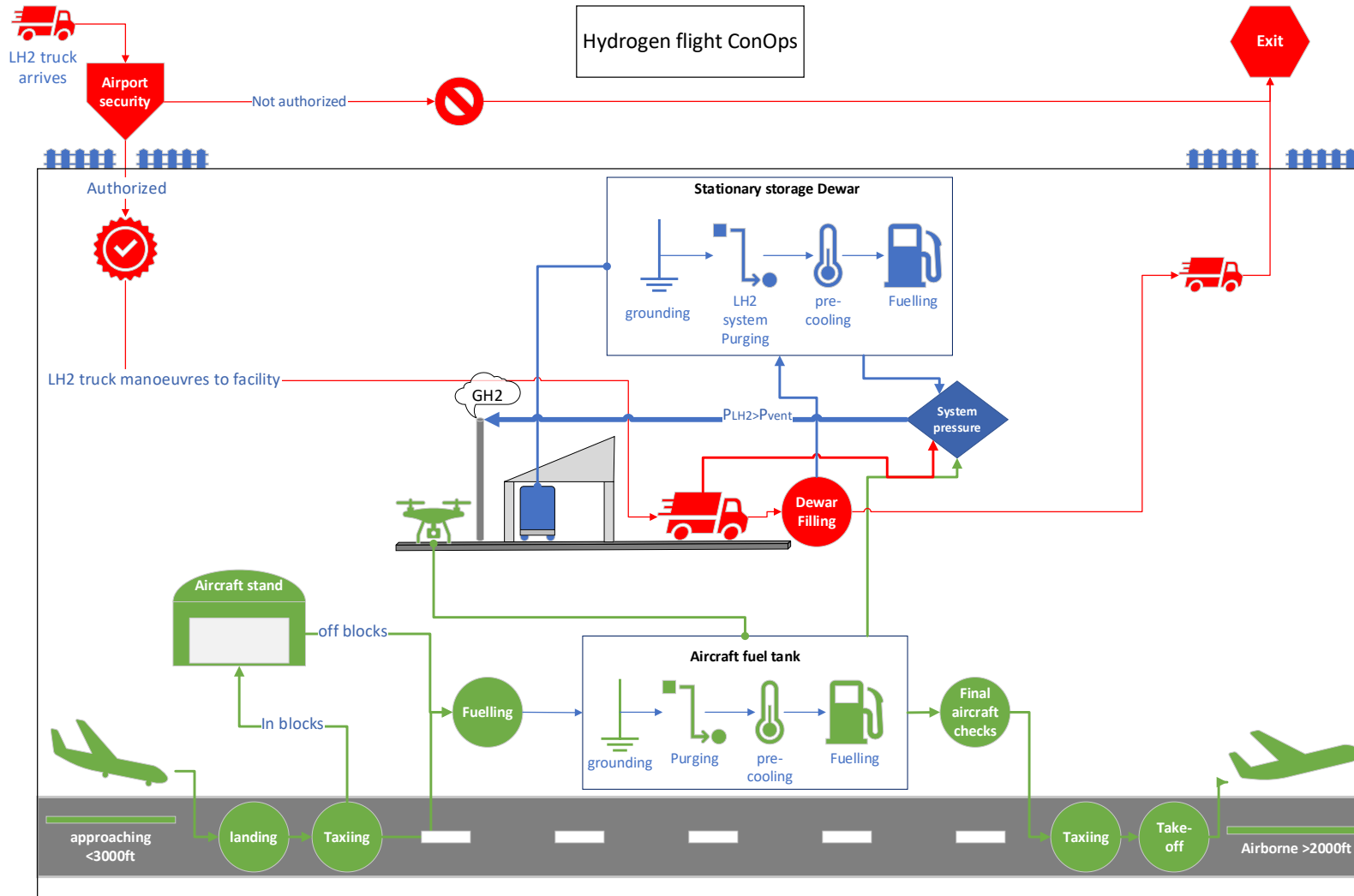


Figure 10 Concept of operations diagram



Operations for fuelling hydrogen powered aircraft can be split into different phases. These are described in the sub-chapters below. All functional elements including users and operators will be discussed in their respective chapters. Above an overview of the operations associated with a hydrogen flight can be seen. For all operations covered in this ConOps, it is assumed there will be no passengers onboard the aircraft.

5.2.1 Dewar filling infrastructure and associated operations

In this chapter the different operations and actors involved in the filling of the LH2 storage Dewar are explained. The processes are split in three phases as can be seen in the following subchapters.

5.2.1.1 Pre-filling phase

The pre-filling phase is defined as the phase from the moment the LH2 trailer enters the airport premise up to the moment the Dewar fuelling phase can commence.

Before proceeding to the filling phase, several preconditions must be met, these include:

- No unauthorised persons near the hydrogen installation.
- The entire hydrogen system is purged and pre-cooled.
- All LH2 filling activities are performed on a non-combustible surface.
- Safety valves, both on the LH2 storage vessel and the drone, have been inspected and are in working condition.
- Equipment is electrically grounded, and connections have been inspected.
- No fuelling takes place during adverse weather conditions such as: heavy rain, hail, snow, or thunderstorms as well as extreme temperatures above 35 ° C or below 0 ° C.
- No handling of the LH2 Dewar is allowed during limited viewing conditions (less than ±20 meters line of sight).
- The maximum filling level is defined and is known to the operator.



LH2 truck approach

Several steps are carried out during this phase starting with the manoeuvring of the Air Products LH2 truck on the airport to the LH2 storage facility. The trailer, as shown below, has a carrying capacity of approximately 3tons of LH2 and is typically used for road transport of LH2. It consists of the large pressure vessel on a trailer featuring a valve box in the rear that allows the operator to perform both filling and purging without any additional equipment. The hydrogen is stored at low pressures up to 12 barg.



Figure 11 Air Products LH2 trailer

The envisioned path that the LH2 truck will travel is shown below (Red = public roads; Yellow = Airside)

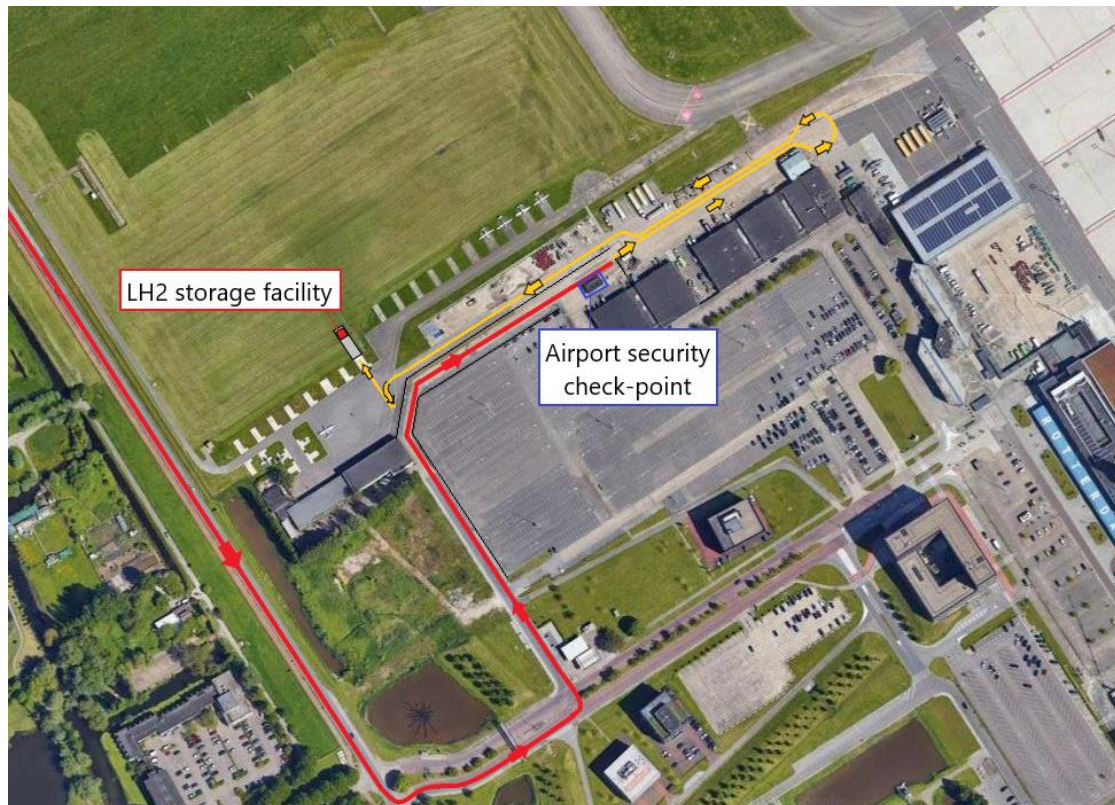


Figure 12 LH2 trailer approach



The truck will drive up to the airport security checkpoint after which a member of the airport staff will guide the driver to the LH2 storage facility. When reaching the LH2 storage facility, the truck reverses onto the concrete pad of the LH2 facility. Reversing is done for 2 reasons, the first and most obvious reason being that all the connections and the valve box are located at the rear of the tanker. Secondly, for safety considerations, the truck will have to be able to drive away from the LH2 facility in case of an accident without having to reverse as specified in PGS 35.

Purging and pre-cooling

Once parked on the concrete pad and the engine of the truck is turned off, the equipment needs to be grounded as to avoid discharging any electro-static charge. Normally the equipment at the facility is always grounded but it is good practice to check these connections before starting the fuelling operation.

The system is then purged to flush out any contaminants like ambient air and oxygen that might be present in the system. This is done to avoid creating an explosive mixture inside the Dewar or flexible hoses as well as avoid the possible freezing of contaminants and subsequent blocking of valves and piping. Typically, nitrogen and helium are used as inert purging gases. Helium is scarce and more expensive than nitrogen which is why nitrogen is commonly used for larger systems. Because the Dewar at RTHA only has an inner volume of 150L, helium gas can be used to avoid any freezing of remaining traces of purging gas.

The following steps are performed by the LH2 truck driver from Air Products in cooperation with the representative from the airport in charge of the LH2 storage facility which in this case would be a qualified NLR or Pipistrel operator.

Purging is done in steps, starting with the supply line. The line is pressurized with gaseous Helium 3-5 times to flush out any contaminants, after which dry gaseous hydrogen is applied at pressure 3-5 times to dilute the purge gas to an acceptable level. After purging the supply line, the same procedure is repeated for the filling adapter, the filling hose and lastly the Dewar itself.

All gases except helium have a higher critical temperature than that of hydrogen which means that at liquid hydrogen temperatures only helium would remain in gaseous state while all other elements would freeze which is why it is important to rigorously purge the entire system before starting to precool the Dewar.

Because the hydrogen needs to remain below 20K at atmospheric pressure, any heat introduced into the liquid will cause it to boil and evaporate. Therefore, it is important to precool all supply lines as well as the Dewar itself. During pre-cooling liquid hydrogen is slowly filled into the Dewar to lower the overall temperature. This may take a relatively large quantity of LH2 depending on the temperature of the storage vessel. This process is done slowly to avoid excessive amount of boil



off gas being generated. Once this step has been completed, the operator can proceed to the next phase.

5.2.1.2 Filling phase

The Filling phase is defined as the phase starting from the moment the last step in the pre-filling phase has been completed up to the moment where all the equipment used for fuelling is decoupled. The fuelling, like the purging is performed by the Air Products truck driver/operator in collaboration with qualified ground personnel from NLR or Pipistrel.



Figure 13 LH2 125L Dewar connected to the filling adapter with the filling hose

Once the Dewar is purged and pre-cooled you can transition to the fuelling procedure. Pressure and flowrates are regulated by pressure regulators on the LH2 trailer and are constantly monitored during fuelling by AP personnel.

Although the vessel is pre-cooled it will still contain some latent heat. This heat will be transferred to the LH2 during fuelling which is partially why an above nominal amount of boil-off can be seen during fuelling. This boil-off can be seen coming out of the vent stack as a white plume of vapour. Once the LH2 has reached the correct fill level all filling valves will be closed manually, and filling can stop. The filling hoses can be detached and left for any remaining hydrogen to evaporate.



5.2.1.3 Post-filling phase

The post filling phase is defined as the phase starting from the moment all the equipment used for fuelling is de-coupled up to the moment the next LH2 trailer arrives for the next fuelling of the Dewar. For the next delivery one of two scenarios will unfold.

- The Dewar is 'empty' and only contains GH2, the tank will be warm and require precooling for the next fill as described in 5.2.1.1.
- The Dewar still contains some amount of LH2 and is therefore still cold enough to bypass the precooling phase before the next fill.

Depending on the pressure in the 3-ton tank it may have to vent some gaseous hydrogen before continuing to the next destination. Once fuelling is completed, all fuelling equipment can be detached and the LH2 truck will leave the airport premise taking the same route as it came onto the airport.

5.2.2 Aircraft fuelling infrastructure and associated operations



Figure 14 HYDRA-2 Drone

To fuel the drone with LH2, it will have to be moved to the refuelling pad. This is done for two reasons. Firstly, although the 125L Dewar is on wheels, it will not be moved as it needs to remain attached to all the support equipment. Only LH2 fuel trucks would be able to manoeuvre around an airport conveniently for future fuelling operations, however this will pose safety concerns on a busy airport. Secondly, refuelling needs to take place on a non-combustible underground such as concrete. Capacity is expected to increase over time which will necessitate the use of LH2 trucks for smaller airports and fuelling stations closer to aircraft stands for larger airports to eliminate the aircraft having to manoeuvre to the fuelling facility, avoiding congestion at these locations (Aerospace Technology Institute, 2022). In future operations, LH2 fuel tanks are likely to be integral to the airframe, for this demonstrator the fuel tank is detachable, however.

Just like filling the Dewar, fuelling operations can be split into three phases.



5.2.2.1 Pre-fuelling phase

The pre-fuelling phase is similar to the pre-filling phase of the Dewar in the sense that the same grounding and purging procedure is also applicable to the onboard LH2 tank. The fuel tank and any filling lines need to be grounded and purged before fuelling can start. This is, again, done by applying an inert gas like nitrogen or helium to purge any contaminants from the system followed by several flushes of dry hydrogen gas. See Section 5.2.1.1 [Pre-filling phase](#). for the full procedure.

5.2.2.2 Fuelling phase

The exact description of fuelling operations for the HYDRA 2 are yet to be completed. This sub-chapter is therefore a provisional description of these operations.

Before fuelling can start, the same preconditions as described in 5.2.1.1 must be met.

In case all the preconditions are met, the operator can proceed with fuelling operations.

Since all fuelling hoses are already connected for the purging procedure only the flow valves need to be opened to start fuelling.

In general, fuelling can be done either by pressure feeding the LH2 to the application or with the use of LH2 pumps. In both cases it is important that pressures in both the onboard tank and the stationary storage are monitored during fuelling. As for the HYDRA 2, pressure fuelling will be used.

It is important to avoid overfilling the tank at all costs as the LH2 will likely entrain with the GH2 boil-off resulting in excessive evaporation, which the vent stack might not be able to handle. Over filling will also result in an increase in pressure inside the vessel which in turn leads to an increase in evaporation. If not managed well the effects could be detrimental.

Unlike conventional fuelling operations the flow rate of the LH2 needs to be accurately monitored to allow the storage vessel to cool down gradually and limit the losses in LH2.

Once the vessel has reached the maximum fill level all flow valves are closed stopping the flow of LH2. Again, hydrogen left in the filling hose needs to be vented off to avoid overpressure.

5.2.2.3 Post-fuelling phase

After fuelling is concluded and the fuelling hose is disconnected the aircraft is ready to proceed with flight operations. As the LH2 onboard is not actively cooled, it will start heating up gradually resulting in periodic hydrogen venting if pressures rise to a predetermined threshold. Because of this separation distances from the airplane, and especially from the venting location are defined in the chapter: [Safety distances](#).

Hydrogen vapours will, however, rise rapidly due to the buoyancy of hydrogen, mitigating some of the hazard.



5.3 Interfaces

Different interactions will exist on an airport between the LH2 facility, its associated operations and other activities and persons on the airport.

5.3.1 Emergency services

In case of emergency the local airport fire brigade will respond. Minimum reaction times are assured by being located on the airport itself. In case of a fire or injury at the LH2 storage facility, the fire brigade is notified to respond adequately. The fire brigade has followed a hydrogen fire training and possesses knowledge on how to handle dangerous goods. On top of that, the fire brigade has setup a 'hydrogen incident response plan', which is tailored to the LH2 facility at the airport and corresponding operations.

5.3.2 Airport ground personnel

Airport ground personnel will be able to manoeuvre around the airport, including in proximity of the LH2 facility. The LH2 fuelling truck will also be assisted to the LH2 facility by airport personnel. However, only authorized personnel are allowed to engage in operations with the LH2 facility. Airport staff is informed about the presence of the LH2 facility and corresponding hazards.

5.3.3 System interfaces

Interfaces between system components consist of the following:

- LH2 trailer - filling adapter – filling hose - LH2 Dewar – vent hose - vent stack
- LH2 Dewar – filling hose - HYDRA 2 tank – vent hose - vent stack
- LH2 Dewar – vent hose - vent stack

All connections used are rated not only for use with hydrogen but also specifically designed for use with cryogenics.

5.3.3.1 LH2 trailer - filling adapter – filling hose - LH2 Dewar – vent hose - vent stack

When filling the LH2 Dewar, five component interfaces exist. Firstly, the connection between the LH2 trailer and the filling adapter. The purpose of the filling adapter is to ensure the correct flow direction as well as act as a pressure relief valve. The adapter allows for two different size connections to be connected to one another. The two systems are connected with a flexible LH2 transfer hose fitted with a Linde bayonet connection as seen below.

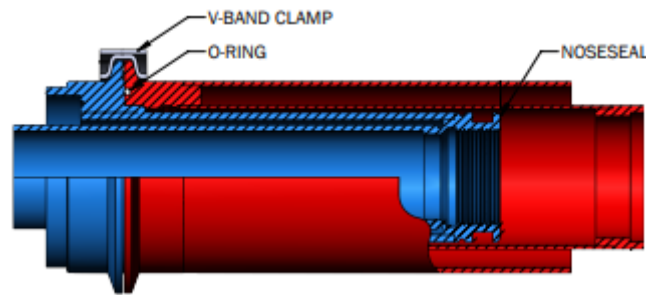


Figure 15 Bayonet connection

The receiving end on the filling adapter features an Air Force 2" Female bayonet fitting. Whereas the other end is fitted with a Cryoworld DN8 female LH2 bayonet to receive a flexible LH2 transfer hose that is connected to the LH2 Dewar. These connections may vary in other systems.

Both the Dewar and the LH2 trailer are in turn connected to the vent stack with a vent hose during Dewar filling. This allows both systems to vent off any boil-off gases to the vent stack independently.

In case of the Cryoworld Dewar a KENOL fitting is used to ensure a proper seal between the gas connection on the Dewar and the transfer hose connected to the vent stack. This connection uses a metal seal to avoid cracking or failure under cryogenic temperatures.

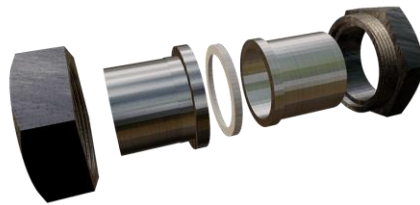


Figure 16 Kenol joint

5.3.3.2 LH2 Dewar – filling hose - HYDRA 2 tank – vent hose - vent stack

During fuelling of the HYDRA 2 drone four different interfaces exist. These are the connection between the LH2 Dewar and filling hose, the filling hose to the drone tank, the drone tank to the vent hose and lastly the connection from the vent hose to the vent stack.

The Dewar is connected by a flexible LH2 transfer hose to the drone tank. Both systems are also connected with their own vent hose to the facility's vent stack during fuelling to vent gaseous hydrogen.



5.3.3.3 LH2 Dewar – vent hose - vent stack

The Dewar is continuously connected to the vent stack to allow for any boil off to be released as to prevent excessive pressure build up in the Dewar. The Dewar is connected with a flexible vent hose to the vent stack. An example of a vent stack, currently used by NLR, is shown in Figure 17. The spiral vent stack is 5m in height to provide additional heat exchange before the cryogenic gas is released.



Figure 17 Close up of vent stack at NLR Marknesse

It should be noted that the vent stack at RTHA, which can be seen in Figure 18, will feature a different form factor and is designed by Cryoworld. The vent stack to be installed at RTHA will reach a total height of approximately seven meters.

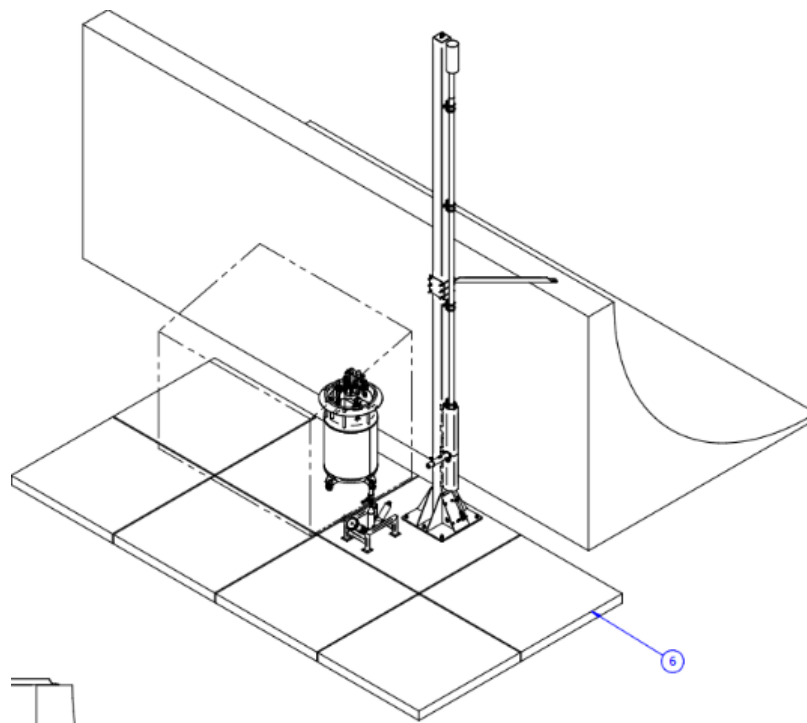


Figure 18 7m vent stack to be used at RTHA



5.4 Modes of operations

Different modes of operation are expected to occur for the LH2 storage facility, these are:

- LH2 filling
- LH2 storage
- LH2 withdrawal
- Taking out of service of Dewar

5.4.1 LH2 filling

When the Dewar has depleted almost all its LH2 it is ready to be filled again, the filling process is explained in chapter 5.2.1. The pre-filling procedure is included in this mode of operation which includes the approach of the LH2 truck. Under normal conditions some percentage of the total volume in LH2 is left in the tank to maintain low temperatures until the next fill of the Dewar. If the Dewar is still cold and filled with hydrogen, only the filling lines will need purging for the next fill.

5.4.2 LH2 storage

During this period the LH2 is stored, and pressures are maintained below the MAWP. Because the Dewar is not actively cooled, the LH2 will slowly heat up over time. When pressures rise above the MAWP due to the boil-off, the GH2 is vented through the vent stack.

5.4.3 LH2 withdrawal

Fuelling consists of the transfer of LH2 from the storage Dewar to another vessel used for storing LH2 as a fuel. For the demonstrator the HYDRA 2 drone is fuelled. The fuelling process is described in chapter 5.2.2.

5.4.4 Taking the Dewar out of service

The Dewar can be taken out of service due to malfunction, for maintenance, long term shut down or for transport. To do this safely the hydrogen needs to be removed from the vessel and the vessel needs to be heated back to ambient temperature. This can be done by letting the hydrogen boil off naturally or by introducing warm helium or hydrogen gas into the system to speed up the evaporation of any hydrogen that is left in the Dewar. When all LH2 is evaporated, the pressure is released, and the vessel is purged with either nitrogen or helium gas. This process is repeated until the hydrogen and oxygen level in the Dewar have reached an acceptable level. For transport or long-term storage, the Dewar is filled with Nitrogen at a slight overpressure to avoid any ingress of air into the system.



6 Physical environment

This chapter aims to provide context on the operating environment of the demonstrator covered by deliverable 2.4.

6.1 Rotterdam-The Hague Airport

The hydrogen demonstrator will be carried out at a representative (EASA aerodrome) airport. This airport was chosen to be Rotterdam-The Hague Airport in the Netherlands. The airport is adjacent to an urban area with highways bordering the airport on both northwest and southwest sides and part of the Royal Schiphol Group.

The airport handles around 2.1 million passengers annually and has around 60.000 flight movements (2022). Roughly 25% of these movements are commercial narrowbody operations. The airport is also home to a large amount of general aviation including recreational general aviation.

RTHA is fully committed to making air mobility more sustainable and is investing in the development of a liquid hydrogen installation at the airport. This ambition is aided by the proximity of the hydrogen production sites in the Rotterdam harbour area and will help the transition to hydrogen-based energy storage and deployment for the airport.

The airport is involved in multiple hydrogen-related projects and developments, amongst others the realization of a hydrogen fuel station and hydrogen taxi tests with code letter A and B aircraft.



6.1.1 Airport lay-out



Figure 19 Satellite image of RTHA airport

RTHA airport is located north of Rotterdam along the A13 highway. It features a single runway positioned in a northwest to southeast orientation with the approach from the northwest. The different service buildings are located south of the runway. The terminal with the existing remote platforms is positioned on the southwest side of the airport with the fire brigade commanding a more central location.



6.1.2 Demonstrator location

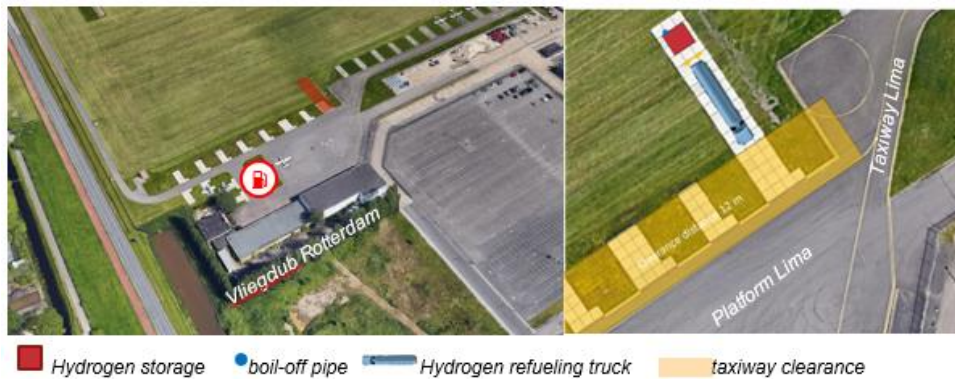


Figure 20 LH2 fuelling demonstrator location

The fuelling of the hydrogen drone will be demonstrated at platform Lima, which is used by Vliegclub Rotterdam and recreational general aviation, on the far west side of the airport. This location borders the code letter A aircraft stands at platform Lima but no other major infrastructure. For this reason, there is space available to apply the proper safety distances that will allow for safe operations. The approach for the LH2 trailer is also in relatively proximity to the LH2 storage facility, therefore the LH2 trailer will only have to traverse a small part of the airport to reach the facility. Next to that, the location is within an operational environment at the airport including air traffic.



6.1.3 Environmental conditions

Since the RTHA is in the Netherlands, it is subjected to a temperate oceanic climate. This means that temperatures extremes, below 0° C and above 35°C, are a relatively rare occurrence and precipitation is generally abundant. However, with climate change asserting a more dominant presence over time, more extreme temperatures and increased risk of flooding are expected to occur in the future (World Bank Group, n.d.). Below, the average monthly temperature and precipitation in the Netherlands from the past 30 years are shown.

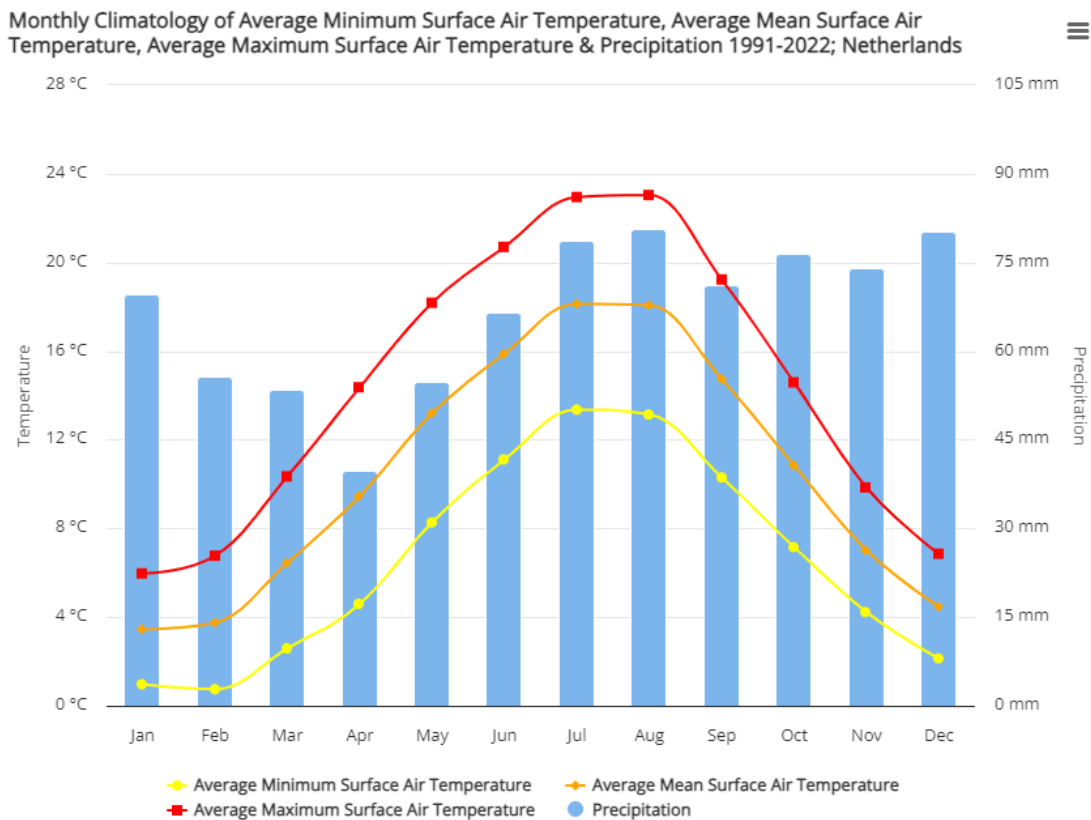


Figure 21 Monthly climatology between 1991-2022 in the Netherlands

As the airport is located 4m below sea level, flooding cannot be excluded from possible consequences of a change in climate. The closest large body of water that could cause significant flooding is the Nieuwe Maas which, at its closest point, is located just over 5km from the airport. Therefore, the chance that the airport will flood, although not impossible, is still unlikely. Extreme weather conditions might however limit the number of days suitable for operations. Although the system is not expected to be operational during extreme weather conditions, it is expected to sustain these conditions and be operable as soon as conditions return to normal.



7 Support environment

This section describes how the envisioned system will be supported after being fielded.

7.1 Maintenance and repairs

Regular checks of the system are required to ensure everything is in working order and no leaks exist in any part of the system. This maintenance is pre-scheduled and is performed by trained personnel, which is typically done by the equipment manufacturer but can also be done by other trained operators.

For maintenance on the LH2 fuelling system it first needs to be taken out of service as described in chapter 5.4.4.

There are several areas where maintenance could be necessary, these are: vacuum insulated piping, cryogenic valves, LH2 Dewar, vent stack, and safety devices. The most visually noticeable indicator that maintenance is necessary is the formation of ice or condensation on any vacuum insulated equipment. Ice formation indicates a loss of vacuum which will need to be reinstated before operations can resume. These visual inspections will be carried out by the airports Location Concierge that inspects airport assets.

During the taking out of service the safety devices should also be inspected. In case of any malfunctioning of the system only trained personnel should perform any repairs, this might mean the manufacturer is contacted to perform maintenance.

7.2 Decommissioning

Once the system has either reached its end of life or is deemed necessary to be decommissioned, steps are taken to decommission the LH2 system. These steps involve the same approach as the taking out of service as previously described to safely transport the LH2 Dewar.



8 Operating principles, system operational scenarios and design reference missions (DRM)

8.1 Nominal conditions

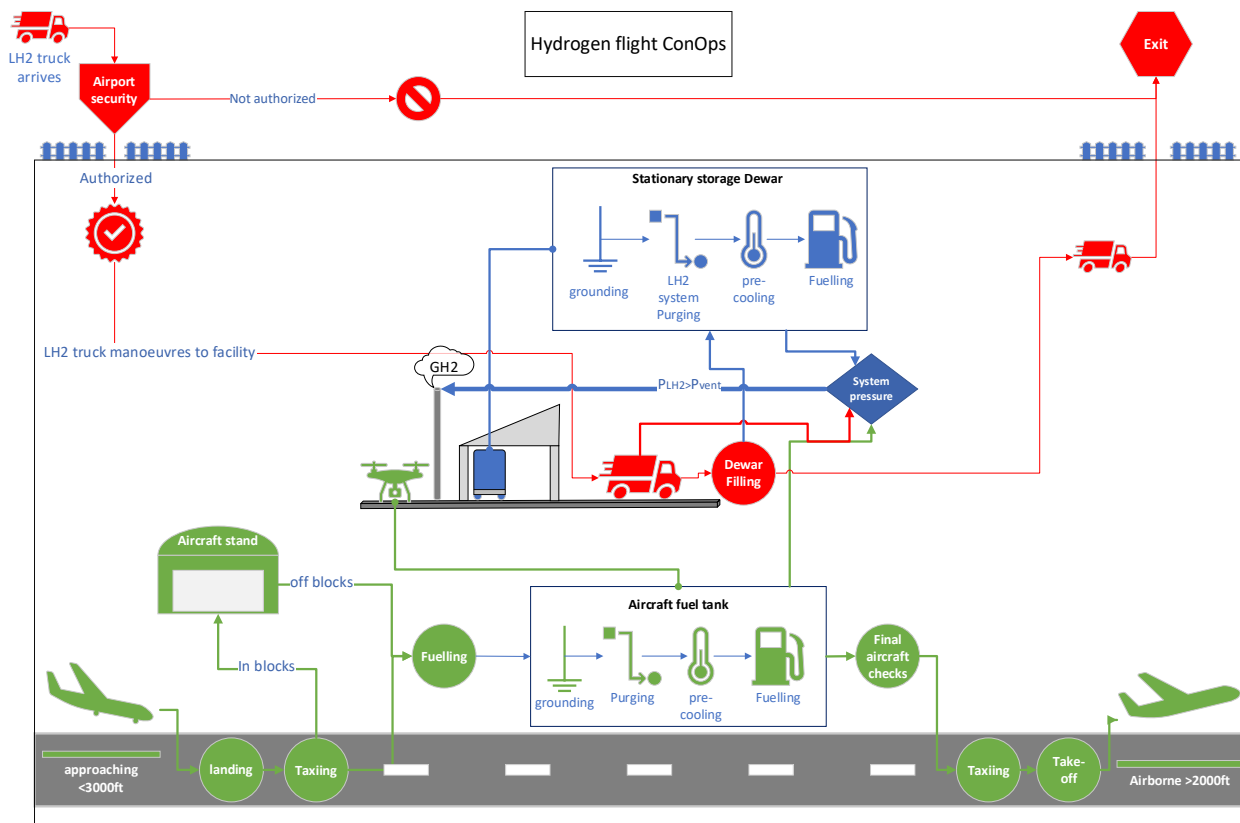


Figure 22 Concept of operations diagram

For the DRM of aircraft refuelling, it is assumed that the airport LH2 storage is sufficiently full to fill the aircraft fuel tank completely. It is also assumed that the aircraft just landed with some quantity of LH2 still left in the fuel tank, the tank is therefore still cold. For this DRM any passengers or cargo are not considered.

**Turnaround flight DRM:**

1. An aircraft approaches the runway at <3000ft and is in contact with ATC, the control tower is aware of the incoming aircraft and operations on the airport continue as per usual.
2. The aircraft performs a successful landing.
3. The aircraft needs to be fuelled after landing; it will taxi to the airport LH2 storage facility where it can park for fuelling.
4. Once parked any systems bar the safety systems are shut off.
5. The Aircraft is grounded to avoid electrostatic discharge.
6. fuelling can start.
7. The fuel tank is still cool and only contains hydrogen, therefore the fuel tank itself will not have to be purged. The LH2 supply lines do, however, as they have been disconnected and will contain some concentration of ambient air or oxygen.
8. After purging, the supply lines are cooled and any boil-off is vented.
9. The fuel tank is now filled to the desired fill level, supply lines are safely disconnected, and the aircraft is ready to continue its mission.
10. Final aircraft checks are performed before taxiing.
11. Once checks are complete the aircraft can taxi to the runway where it will take off.

One way flight DRM:

1. An aircraft is parked for some period and is preparing for flight.
2. The aircraft needs to be fuelled for take-off and will taxi to the airport LH2 storage facility where it can park for fuelling. As the main fuel tank is likely depleted after prolonged dormancy the aircraft will need other means of reaching the LH2 fuelling pad. This can be done with assistance of the APU or by being towed by an aircraft tractor.
3. Once parked any systems bar the safety systems are shut off.
4. The Aircraft is grounded to avoid electrostatic discharge.
5. fuelling can start.
6. The fuel tank is no longer cool but should still contain hydrogen gas, therefore the fuel tank itself will only have to be precooled before fuelling. As an extra safety measure the purging procedure can also be performed before fuelling. The LH2 supply lines must be purged regardless as they have been disconnected and will likely contain some concentration of ambient air or oxygen.
7. After purging, the supply lines are cooled and any boil-off is vented.
8. The fuel tank is now pre-cooled and filled to the desired fill level, supply lines are safely disconnected, and the aircraft is ready to continue its mission.
9. Final aircraft checks are performed before taxiing.
10. Once checks are complete the aircraft can taxi to the runway where it will take off.



For the demonstrator the same steps as above apply except for the landing and take-off procedure. Above operations are likely to be performed in the upcoming years by parties like AeroDelft, NLR, Pipistrel and the TU Delft by using the LH2 facility at the airport.

8.2 Off-nominal conditions

As LH2 cannot be contained indefinitely, there will be situations that will compromise the DRM's described above.

These situations are a result of off-nominal conditions and are described below.

8.2.1 Adverse weather conditions

Unexpected extreme weather conditions might jeopardise the fuelling procedure in case of extreme temperatures, extreme precipitation, and thunderstorms. This includes heavy rain, hail, and snow fall. Under these conditions fuelling cannot take place. If fuelling has already started it will be at the discretion of the operator to either abort fuelling, temporarily halt operations or continue.

8.2.2 Delays

Delays due to external factors might also result in extended periods on the tarmac. Depending on the fuel tank fill level and the dormancy time until venting, this could result in insufficient fill levels by the time the aircraft is due to take-off. When this situation occurs, the aircraft will have to return to the fuelling station to fill the fuel tank to a sufficient level.

8.2.3 Hazardous situations and emergencies

Due to external factors or faulty onboard equipment, hazardous situations can occur. These situations, although hard to predict, should have their own safety mitigation plans. When an external hazard occurs, the airport will have a set of procedures to follow. These procedures might result in an aborted flight, or a delay as described in 8.1.1.2. In case of an aborted flight, the state of the LH2 fuel tank will need to be continuously monitored as the LH2 inside the tank will heat up and slowly evaporate without the fuel cells being able to use the GH2. For this reason, aircraft fuelled with LH2 cannot park inside a hangar unless proper ventilation is installed to vent out any boil-off gas.



9 Impact considerations

Compared to the kerosene-powered ICE (Internal Combustion Engine), a hydrogen powered propulsion system emits no CO₂ (carbon dioxide) and other toxic chemicals during the operation. Although, due to the early adaptation and challenges, the operation of hydrogen causes several impacts. On the opposite end of the spectrum, as aviation is expected to grow, the utilization of hydrogen will contribute to the overall GDP (Gross Domestic Product) growth taking a share of the trillions in current economic activity (Adler & Martins, 2023). Furthermore, the emerging technology supports job creation in many sectors by creating a competitive eco-system. These aspects together with the scientific and technical impacts have positive effects with minimum impact on the environment. Therefore, both positive and negative potential impacts on the environment and other areas such as, production and distribution, transportation, handling, and storage together with impacts on aircraft operations are discussed briefly in this chapter. Focussing particularly on liquid hydrogen.

9.1 Environmental impacts

Liquid hydrogen paves the way to a sustainable aviation in an environmentally responsible manner. During the operation as an energy carrier, hydrogen generates no CO₂. In addition, it reduces the emission of soot and the formation of sulphate and NO_x. Therefore, the use of hydrogen as aviation fuel would negate aviation's impact on the environment. Meanwhile, the carbon footprint associated with hydrogen depends heavily on the production method. Steam methane reforming (SMR) for example, while being the most used and cost-effective method of hydrogen production, generates significant CO₂ and CO emissions. On the other hand, if hydrogen is produced by electrolysis from renewable energy, there is no carbon penalty as this method does not produce any greenhouse gases. The downside of electrolysis is the large amount of energy it takes to generate hydrogen.

Due to hydrogen's low volumetric energy density at standard atmospheric conditions, the hydrogen needs to be preconditioned with higher pressure or cryogenically cooled to liquid state. For example, If the energy that a Boeing 777-200ER carries in kerosene were stored in ambient pressure and temperature hydrogen, the required volume would correspond to about 500 fuselages of this aircraft (Adler & Martins, 2023). Therefore, both production and storage methods have their own challenges in various aspects that impact the environment.

Contrail formation is primarily associated with regional and commercial airliners. These aircraft, operating at high altitudes, can leave behind contrails. At a high enough air humidity, impurities in the engines exhaust, particularly sulphur and soot particles, can act as nucleation points that can cause water vapour to freeze, essentially leaving a trail of ice crystal clouds. The significance of these contrails lies in their potential to create a layer in the atmosphere that can reflect long wave thermal radiation from the earth, resulting in a net warming effect and contributing to the



greenhouse effect (Kärcher, 2011). The impact of contrails on the environment, therefore, extends beyond their immediate visual presence in the sky, as they play a notable role in influencing the Earth's heat balance. Aircraft that fly at lower altitudes contribute much less to the contrail formation and subsequent greenhouse effect

Although hydrogen (-electric) aircraft do not emit soot or sulphur particles they do emit water. These water emissions can raise the local air humidity. If the air is locally saturated, some of the water will remain as small water droplets that can freeze at high altitudes. Because it is unclear what the impact will be exactly it will have to be closely studied to avoid any unforeseen negative consequences.

9.2 Organizational impacts

Apart from the environmental impacts, the integration of hydrogen technology requires substantial changes in the development and production process as well as changes in safety and regulatory requirements. Organisations need to be prepared for necessary changes in infrastructure and safety standards.

Safety training is required for ground personnel as improper handling of hydrogen can cause safety hazards such as fires or explosions. To prevent such hazards, precautions need to be implemented for hydrogen handling. As LH2 is a cryogenic liquid, special attention is required to ensure proper handling of the hydrogen by the operators.

The need for change in airport infrastructure will lead to the exploration and application of new approaches in managing supply chains, as well as aircraft operations and maintenance. However, if airports decide to locally produce hydrogen with the use of electrolysis and subsequently liquefaction, it could lead to increased energy demands which can be costly.

Security is critically important in hydrogen facilities due to the inherent risks associated with hydrogen, such as its high flammability and cryogenic storage. These factors, combined with the possibility of large-scale impacts or malicious attacks, make hydrogen facilities attractive targets for sabotage. The economic and strategic importance of hydrogen as a clean energy source further underscores the need for robust security measures. These should include physical and cyber-security defences, continuous monitoring, and comprehensive emergency response plans to ensure the safety of the facility, its workers, the surrounding community, and the environment.

When the first hydrogen aircraft come into service there will still be a fleet of conventional kerosene burning airplanes operational. Although it is likely that more sustainable alternatives will replace this fleet over time, these two propulsion methods will coexist for some time. To accommodate this change in operations the infrastructure also needs to be suitably adjusted. This might mean that fuelling operations for hydrogen aircraft will not take place at the same locations as jet fuel refuelling if safety requirements cannot be met. It is also to be seen how refuelling infrastructure will change



over time as the demand for LH2 increases. Initially, it is likely that mobile refuelling trucks will be the most logical refuelling option. For future operations, automated refuelling arms are already being considered to increase safety (Aerospace Technology Institute, 2022).

For the supply of LH2 to airports two main routes are being considered, these are gaseous supply through pipeline and liquid supply by transport trucks. Both options have their own advantages and disadvantages but both options will likely be tailored to different size airports depending on the demand of LH2. As demand will increase over time a transition from LH2 supply trucks to hydrogen pipelines is likely to happen.

9.3 Scientific/Technical impacts

Hydrogen operations also impose a technological and scientific impact due to its challenges that must be overcome for this technology to be effective.

Such technological deficiencies are improved by investing more in academic research. Moreover, performing a gap analysis will increase the likelihood of achieving more sustainable production of hydrogen.

Electric power in a fuel cell is generated directly by converting the chemical energy to electrical energy. The electrical energy can be utilized with an electric motor efficiently. Moreover, the generated energy can be partially combined with a propulsion battery system to have a hybrid propulsion system that contributes to the overall adaptation of a sustainable aviation. The SAF (Sustainable Aviation Fuel) and the hybrid propulsion system can also be combined to elevate the early adoption of the hydrogen technologies.

Modelling of the embrittlement and wall characteristics need to be further investigated which results in further studies in chemicals and other aspects of material science. Therefore, the studies in the section of embrittlement have direct implications for the safety of handling hydrogen and the longevity of the equipment. This affects the material selection, design, and other aspects of the technological advancements.

Overall, the demo offers educational benefits, enhance safety training, validate new technologies, increase public awareness and acceptance, and stimulate investment and innovation in sustainable energy. These demos play a crucial role in advancing and promoting hydrogen as a viable clean energy source.



10 Functional safety assessment for LH2 handling

In this chapter an assessment is made on the safe and appropriate handling of liquid hydrogen as an energy source and all liquid hydrogen systems related to the hydrogen flight demo. Furthermore, different stages of operations are analysed and mitigations for possible hazards and contingencies that can be expected during ground handling and flight are proposed.

There are several properties associated with hydrogen that, if not handled properly, could result in a safety hazard. For that reason, these characteristics are elaborated on along with the description of the resulting hazards and the appropriate mitigations.

10.1 Legislation and regulation on hydrogen storage and fuelling

The legislation that applies to the LH2 storage depends on the country or region where LH2 fuelling is performed. The correct authorities should therefore always be consulted before starting operations.

Although minimal legislation is currently in place for hydrogen fuelling, there are sets of regulations that describe the safe use and set up of hydrogen installations. One such set of comprehensive regulations is the “Publication Hazardous Substances series 35” (PGS35:2015).

Other credible documents on the safe use of LH2 include the following:

- EIGA doc 15/21: Gaseous hydrogen installations
- NASA safety standard for hydrogen and hydrogen systems
- Pre-normative Research for Safe use of Liquid Hydrogen (PRESLHY); handbook of hydrogen safety: chapter on LH2 safety
- Pre-normative Research for Safe use of Liquid Hydrogen (PRESLHY); Novel guidelines for safe design and operation of LH2 systems and infrastructure
- ISO 13984:1999 Liquid hydrogen-land vehicle fuelling system interface.
- National Fire Protection Agency: NFPA 55 compressed gases and cryogenic fluids code

10.2 Hazards inherent to hydrogen as an energy source

There are certain characteristics that are inherent to H2 that can cause hazardous situations if not handled properly. This is down to three main factors, these are:

- Low minimum ignition energy
- Wide range of flammability
- Extremely low critical temperature of LH2

Gaseous hydrogen has a very wide range of flammability from as low as 4% up to 75% (Linde, n.d.) concentration in air. Additionally, the minimum ignition energy of only 0.02mJ (Hydrogen compared with other fuels, n.d.) making it extremely flammable.

To store hydrogen in liquid form, the H₂ must be cooled to approximately 20K. These temperatures present an inherent and noteworthy safety concern, namely the occurrence of cold burns, which emerge as a tangible and substantial hazard at such low temperatures.

10.2.1 Fire and explosive hazards

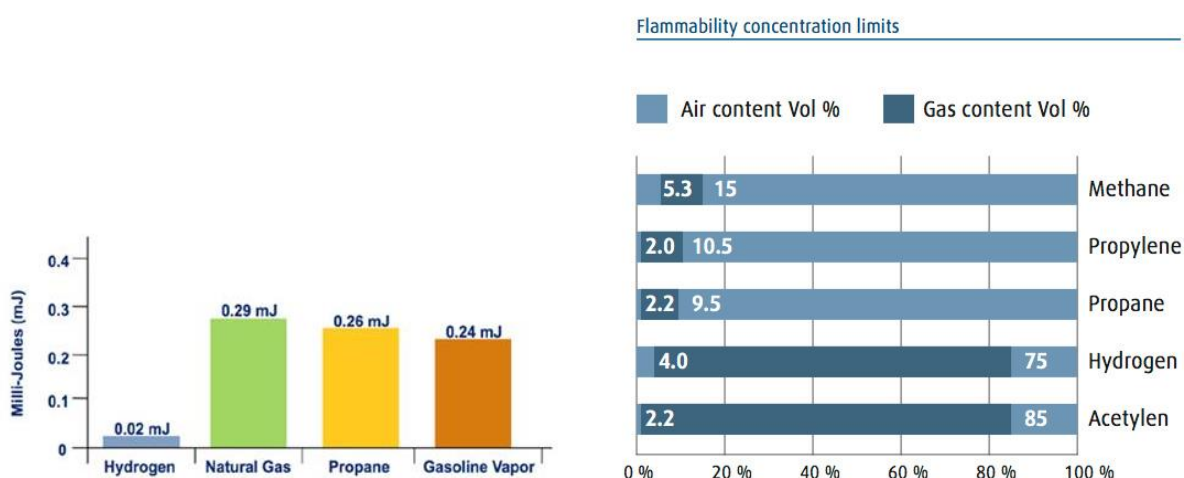


Figure 23 Minimum ignition energy (left); Flammability concentration limits (right)

As previously mentioned, hydrogen is extremely flammable which has its benefits when used in a situation where combustion is required like in a gas turbine. However, in a hydrogen fuel cell the H₂ is used to generate electricity rather than combusted to generate heat. In fact, combustion should be prevented at all costs. The same is true for the storage of hydrogen. Pure hydrogen will burn almost colourless making hydrogen fire detection difficult. Additionally, although hydrogen can burn at over 2000°C, it radiates very little heat. The combination of these two factors can make unknowingly approaching a hydrogen fire very dangerous.

There are notable differences between hydrogen fires and hydrogen explosions both in their nature and in their consequences. Depending on the pressure and the concentration of hydrogen both scenarios can have very different effects, these are explained in the following subsections.



10.2.1.1 Hydrogen jet fire

Hydrogen jet fires can occur when a high-pressure discharge from a leaking component or connection is ignited. This is particularly dangerous to ground handling personnel as gaseous hydrogen is hard to detect without the use of sensors or detectors as the gas is colourless, odourless, and tasteless. Hydrogen fire can also be colourless increasing the risk of dealing with hydrogen fires.



Figure 24 Hydrogen jet fire experiment (Maraner, Stolen, & Li, 2019)

10.2.1.2 Hydrogen deflagration

Deflagration is an explosion where the flame propagation speed is lower than the speed of sound for a given media. Hydrogen deflagration can occur when a flammable concentration of H₂ is ignited. Because the minimum ignition energy of hydrogen is only 0.02mJ (hydrogen compared with other fuels, n.d.) an explosive hydrogen/air mixture can easily ignite. Deflagration tends to happen at atmospheric pressures in a mixture of hydrogen with air.



Figure 25 Hydrogen deflagration (WHA international INC., 2023)

10.2.1.3 Hydrogen combustion

Hydrogen can also combust when pressurized which is generally more dangerous than deflagration as a detonation or combustion explosion creates a shockwave propagating faster than the speed of sound and has the potential to cause serious damage to nearby building or people.

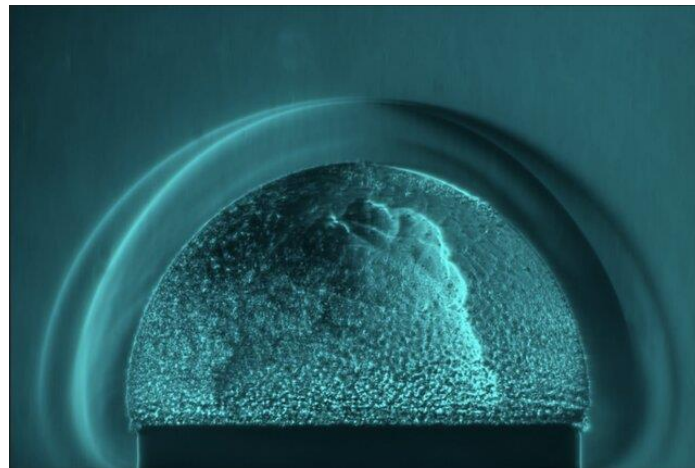


Figure 26 Schlieren photography of an explosion of H₂ - O₂ gas inside a bubble detonated with an electrical spark (Gai, 2020)

Shock waves can be seen propagating from the point of ignition in Figure 26 Schlieren photography of an explosion of H₂ - O₂ gas inside a bubble detonated with an electrical spark. Explosions can happen due to over pressurizing storage vessels.

10.2.2 Cold burns

Along with the combustibility of hydrogen, there are risks associated with the handling of LH₂ due to the extremely low temperature of the energy carrier. At -253°C the effects of LH₂ on the human body are severe and are in fact very similar to the effect of hot temperatures. Exposure to the cryogenic liquid or gas can result in cold burns which have to be treated appropriately.

10.2.3 Asphyxiation

While it is well-established that hydrogen (H₂) is not intrinsically toxic to humans, it is vital to underscore that it has the potential to inadvertently cause asphyxiation because of oxygen displacement. This phenomenon is more relevant within inadequately ventilated, confined environments. Given the property of hydrogen being lighter than air, any leakage can induce the displacement of the ambient atmosphere, thus diminishing the oxygen concentration within the enclosure, consequently culminating in a deficiency of breathable oxygen for individuals occupying that specific space.

10.3 Potential hazards resulting from LH₂ fuelling operations

Any hazards that can be encountered during LH₂ fuelling operations are a result of the three inherent hazards mentioned in 10.1.

The volatility of hydrogen combined with the flammability makes it extremely important to implement the right hazard mitigations, these will be addressed in section 10.4. The main hazards during LH₂



fuelling are described below. For the description of the hazards the mitigation measures are deliberately not considered but rather addressed in chapter 10.4.

10.3.1 Improper preconditioning

Improper preconditioning of supply lines and storage vessels can cause several issues. When a hydrogen system is improperly purged there is the possibility of air, and therefore oxygen, to remain in the system which can result in the formation of an explosive atmosphere inside the system. Because of the incredibly low ignition energy this explosive mixture can easily be ignited. Secondly, improper precooling of the supply lines or the storage vessel will lead to large quantities of boil-off gas being generated during filling. This hydrogen gas must be vented off to prevent over pressurizing the system. If the filling is done too rapidly and the vessel is not properly precooled, large quantities of hydrogen will be lost. Additionally, after both the pressure relieve valves have been activated and the pressure continues to rise, the burst disk should brake, resulting in hydrogen being released into the area where an operator might be standing. This can be hazardous to the operator not only because of the risk of cold burns but also because of a possible ignition.

10.3.2 Leaking fuelling equipment

Any interface between hydrogen carrying components can be a location for hydrogen to leak if the interface is not properly sealed. Leaks inside enclosed spaces can lead to asphyxiation as described in 10.1.3. Leaks in a properly ventilated area are less problematic but can still lead to fire hazards when exposed to ignition sources. Direct contact of hydrogen with the aircraft fuselage can over time lead to hydrogen embrittlement and structural degradation of the material. For that reason, the location of the fuelling port needs careful consideration.

10.4 Hazards applicable LH2 aircraft operations

10.4.1 Leaking onboard LH2 equipment

Because hydrogen on an aircraft is contained within the fuselage, any leaks, or fires result in a much larger hazard than for outdoor storage.

A hydrogen leak inside the aircraft is not naturally vented which can cause several issues including asphyxiation of those onboard but also fire and explosive hazards. Cold burns are less likely as the hydrogen system will be separated from the rest of the airplane by a bulkhead. Most airplanes do have some form of air conditioning system, however, if this system is also saturated with hydrogen or hydrogen makes its way into any compressor, it can also result in deflagration or ignition of the hydrogen. A hydrogen fire onboard the airplane is also much more hazardous for the occupants as there are limited emergency exits and the fire could be hard to detect. Additionally, passengers and personnel will have to be carefully instructed where to exit the aircraft as hydrogen venting locations



could compromise the safety of certain exits. For these reasons, LH2 onboard tank design as well as safety measures must consider the hazards associated with hydrogen inside the airframe.

10.4.2 Loss of insulating vacuum

If for some reason the vacuum in the insulative jacket around the LH2 tank were to degrade during flight, the insulative properties of the tank will also be significantly affected. This will result in a significant increase in heat inleak, increasing the amount of boil-off. Rapid boil-off will trigger the pressure relief valves or in the worst case rupture the burst disks. This will result in rapid losses of hydrogen which will have detrimental effects on the remaining range of the aircraft.

10.5 General hazard precautions

To allow for the safe use of LH2 for fuelling aircraft the mentioned hazards need mitigation measures. These safety measures are mentioned below.

10.5.1 Ventilation

There are three main safety measures that will ensure a safe work environment when handling LH2, the first of which is ventilation. LH2 refuelling should be done in the open air where possible, however due to adverse weather conditions it might be preferable to do this under cover. During fuelling, a small amount of hydrogen might leak from the dispenser when connecting or disconnecting a transfer line to a fuel tank. There is also a potential for a leak to occur in a hydrogen system. If any closed off or covered space is not properly ventilated naturally or artificially, there is a potential for hydrogen build up which could result in an explosive mixture of air or an asphyxiating atmosphere. To prevent such concentrations from occurring, ventilation should be in place to displace enough volume so that an explosive mixture can never occur. This is true both for ground and onboard systems but will have the most impact on any enclosed space such as an aircraft fuselage.

This ventilation could be triggered by hydrogen concentration sensors when a high enough concentration is measured. Procedures will have to be developed on how to handle high hydrogen concentration onboard aircraft. These procedures might even be activated automatically when high hydrogen concentrations are detected by ventilating compartments in the airframe for example or triggering a warning for the operator at a ground storage facility.



10.5.2 Prevention of ignition sources

In case of an explosive mixture of hydrogen occurring in an atmosphere, the second most important hazard mitigation is to prevent any ignition source from igniting said mixture. Because of the extremely low minimum ignition energy it is important to keep away any open flames, heat sources and objects that may spark. For ground operations this means grounding all equipment to prevent a static discharge. On most aircraft static wicks are installed on the trailing edge of the wings or empennage to prevent the build-up of static electricity during flight. To be absolutely sure that no electrostatic discharge will happen between components or fuelling equipment and the aircraft, the potential of the equipment needs to be equal. This must be done before fuelling can start.

10.5.3 Prevention of leaks

In addition to the previous point, preventing any leaks is another important hazard mitigation.

A leak can occur in a pressurized part of a hydrogen system, or it can occur in the vacuum insulation of a storage tank or transfer hose.

As for the pressurized sections of the hydrogen system it is important to prevent any hydrogen from leaking out and create an explosive atmosphere. Leaks can be prevented by only using suitable materials such as 316L stainless steel piping and connections with regular inspection and maintenance. Helium leak testing can be performed prior to entry into service or after maintenance.

A leak in the vacuum insulation of a storage Dewar also has major implications on the storability of the LH2 inside the Dewar as the vacuum space provides the insulation for the cryogenic liquid to remain cold. Without the insulation the liquid rapidly starts heating up resulting in a significant amount of boil off gas that will need to be vented to prevent over pressurisation of the system.

Preventing both scenarios from occurring allows for safe operation of an LH2 system. If a leak does occur operations should be halted if possible until the leak is resolved and, if applicable, the vacuum is reinstated. A hydrogen system should always be leak checked with Helium before putting into service.

10.5.4 Personal Protective equipment (PPE)

Along with the hazard mitigations mentioned above, PPE should always be worn as a preventative measure by the LH2 fuelling operator.

To prevent exposure to extreme temperatures, due to either a hydrogen fire or contact with cryogenic gas or liquid, the operator should always wear protective equipment such as gloves, a face shield, and ATEX rated clothing. ATEX rated clothing prevents any build-up of static electricity while the clothing also acts as a protective barrier.



10.5.5 Detection of hydrogen

H2 sensors

Because hydrogen gas is colourless, odourless, and tasteless it is almost impossible to detect without the use of sensors. For that reason, sensors are placed both on ground storage and dispensing installations as well as inside aircraft to detect any concentration of hydrogen. When hydrogen concentrations are detected at 10% of the lower explosive limit (LEL) the responsible entity will be notified. At 20% LEL the hydrogen supply will be stopped as to prevent any further leakage of hydrogen.

H2 flame detectors

In addition to hydrogen sensors, hydrogen flame detecting equipment should be used in stationary installations. Hydrogen fires are very hard to detect with the naked eye for the reasons given in 10.2.1. Hydrogen fires can be detected with IR and UV sensors, however. Hydrogen fires emit little IR radiation compared to hydrocarbon fires, hydrogen does emit UV radiation, however. It is therefore recommended to use a combination of IR and UV detectors to monitor for hydrogen fires. These systems can be coupled to an automatic shut off device to prevent the propagation of the hydrogen fire. Detection of a fire should also trigger dedicated operational emergency procedures.

10.5.6 Safety distances

To ensure the safe operation of hydrogen fuelling and other operations performed in and around a hydrogen storage location, there are safety distances defined by the European Industrial Gas Association (EIGA) as shown below. Other standards exist such as the NFPA 55 with similar safety distances.

Table 5 Safety distances

standard Items	EIGA Doc 15/21 Distance[m]
'90 min fire resistive walls'	2.5
'Technical and unoccupied buildings'	10
'Occupied buildings'	20
Air compressor intakes, air conditioning	20
Any combustible liquids	10
Any combustible solids	10
Other LH2 fixed storage	1.5
Other LH2 tanker	3
Liquid oxygen storage	6
Flammable gas storage	8
Open flame, smoking, welding	10
'Place of public assembly'	20
Public establishments	60
Railroads, roads, property boundaries	10
Overhead power lines	10



These safety distances are important to be implemented where possible. Situations that do not allow for these distances to be implemented should feature additional safety features and hazard mitigation measures.

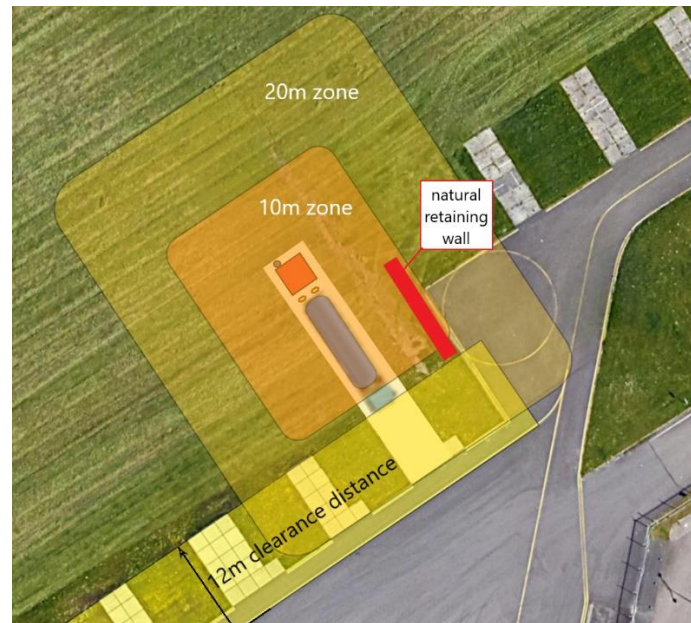


Figure 27 Preliminary Safety zones for LH2 storage at RTHA

An example of how these safety distances would be implemented is shown in Figure 27 Preliminary Safety zones for LH2 storage at RTHA. The 20m zone overlaps with the taxi way, however. This will not create any issues as the only items that are not allowed in this zone are occupied buildings, air compressors intakes and air conditioning, places of public assembly and public establishments. None of which are present within the 20m zone at RTHA. Additionally, a natural retaining wall will be placed between the taxi way and the LH2 storage. The closest public establishment is the flying club building which is located approximately 80 meters from the LH2 storage.

10.6 Response to emergency situations

In case anything was to happen to the hydrogen system that could endanger any personnel or equipment, a mitigation plan needs to be in place. The following subchapters elaborate on the emergency responses for certain situations.



10.6.1 Hydrogen fire or explosion

Because the consequences and the procedures of dealing with explosions and sustained fires are different, they will be addressed separately.

A hydrogen fire is characterized as a sustained burning of gaseous hydrogen whereas an explosion is the sudden and rapid release of energy that can produce potentially damaging pressures.

A hydrogen fire can either start due to the ignition of a hydrogen leak or be the result of a residual fire due to an explosion. Inversely, a fire can also create the right conditions for a hydrogen explosion.

If all the precautions mentioned in section 10.5 are followed, a fire should not occur. However, in the case that it does due to external circumstances the best procedure is to create a safe distance between any persons and flammable substances in the vicinity and the fire. The best procedure is to wait until the hydrogen supply is depleted and has stopped burning. If possible, any supply valves should be closed from a remote location. Water should only be used to extinguish any secondary fires, not the hydrogen fire itself.

In case any boil-off gases from the vent stack were to catch fire, it should never be extinguished with water. As the vent stack is still cold from the cryogenic gas being vented, the water will freeze and block the vent stack. This removes any potential of pressure release from the system which can cause the hydrogen storage vessel to explode due to overpressure.

Hydrogen explosions can be caused, as described in 10.2.1.2 and 10.2.1.3, by ignition or overpressurization. In case of a fire near to the LH2 storage vessel, the pressure inside the vessel will start to rise. If this pressure cannot properly be released an explosion due to overpressurization can occur. Similar to the hydrogen fire a safe distance should be kept to the source of hydrogen. Apart from following the mitigating measures described in section 10.5 and keeping a safe distance, there are no mitigating factors to an explosion. An explosion could start secondary fires which can in turn be extinguished with water.

10.6.2 LH2 spills

A hydrogen spill can be described as a large amount of liquid hydrogen that escaped from any part of the system. Pool formation generally only occurs when very large quantities of LH2 are released at once. If a more gradual spill takes place, the hydrogen will simply evaporate instantly. Contact with liquid hydrogen should always be avoided as to prevent cold burns. In case of a spill the LH2 supply should be cut off to stop the flow of LH2.



10.7 Explosive hazard areas

Explosive areas or ATEX zones are defined by the likelihood and duration of an explosive atmosphere occurring. The level of an ATEX zone determines what safety precautions would be applicable. Any LH2 storage vessel is designated as Zone 0 while a zone 1 is in the direct vicinity of the fuelling point as these locations are most likely to occasionally see a small amount of hydrogen. An ATEX zone 2 is defined as an area where explosive atmospheres are not likely to occur during normal operation and only persist for a short period if they occur. Therefore, this constitutes the area covered by the LH2 fuelling facility. An example of these three ATEX zones is shown in Figure 28 Diagram of ATEX zones.

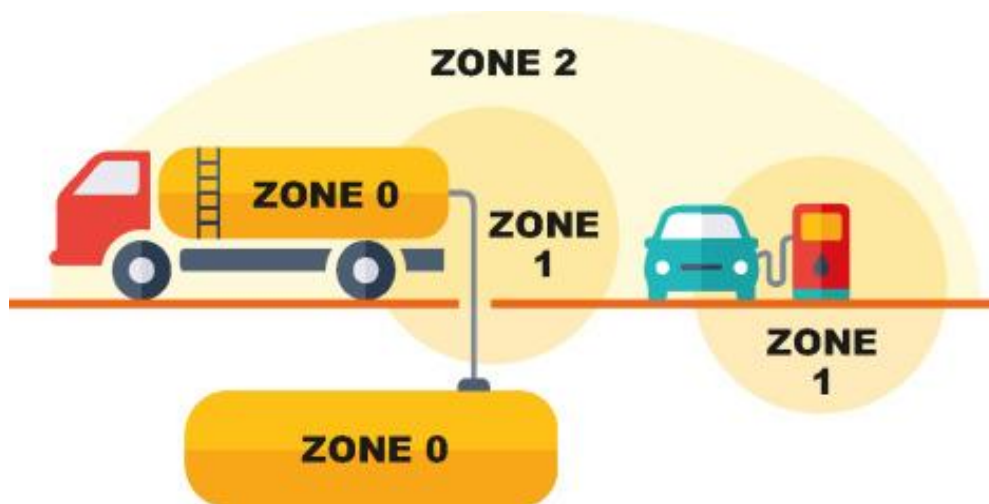


Figure 28 Diagram of ATEX zones (World Pumps, 2019)



Safety zones are also defined for conventional aircraft as can be seen in Figure 29 Hazardous zones on conventional aircraft.

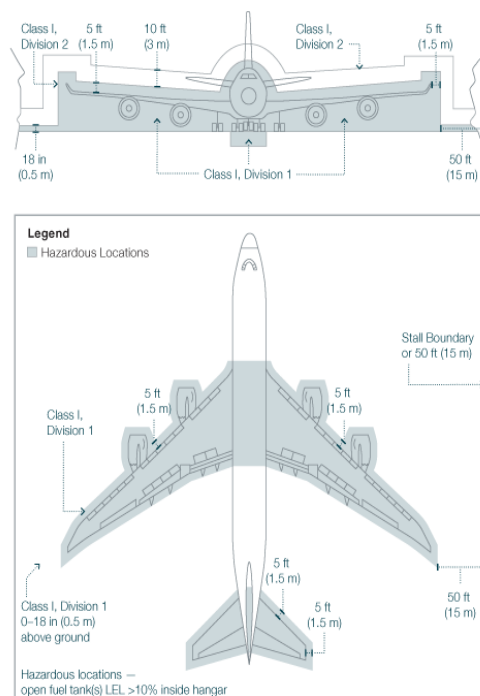


Figure 29 Hazardous zones on conventional aircraft (Jones, M.D., 2011)

Hydrogen fuel tanks will by all expectations be integrated into the fuselage rather than into the wings. Therefore, these zones will be defined accordingly, as seen in Figure 30 Safety zone for hydrogen aircraft concept. The safety zones are also larger as hydrogen is more flammable than Jet A1 fuel.

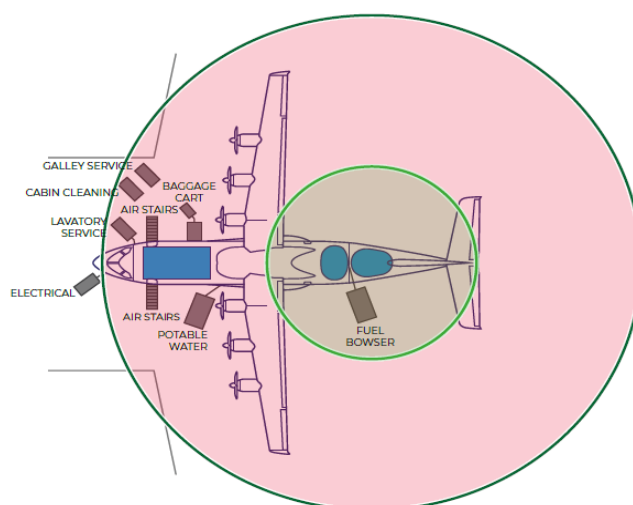


Figure 30 Safety zone for hydrogen aircraft concept (Aerospace Technology Institute, 2022)



In Figure 31 Preliminary ATEX zones for RTHA hydrogen storage the ATEX zones are indicated. ATEX zone 2 is indicated as the area under the awning where the LH2 Dewar is located. When the Dewar is being filled this zone should be extended to cover any connections with the LH2 supply trailer as there is always a potential for leaks. ATEX zones are not defined as distances but rather with the likely hood and severity of an explosive atmosphere occurring. As the zones indicated in Figure 31 Preliminary ATEX zones for RTHA hydrogen storage, do not coincide with any other utilities, hydrogen can safely be stored in this area.

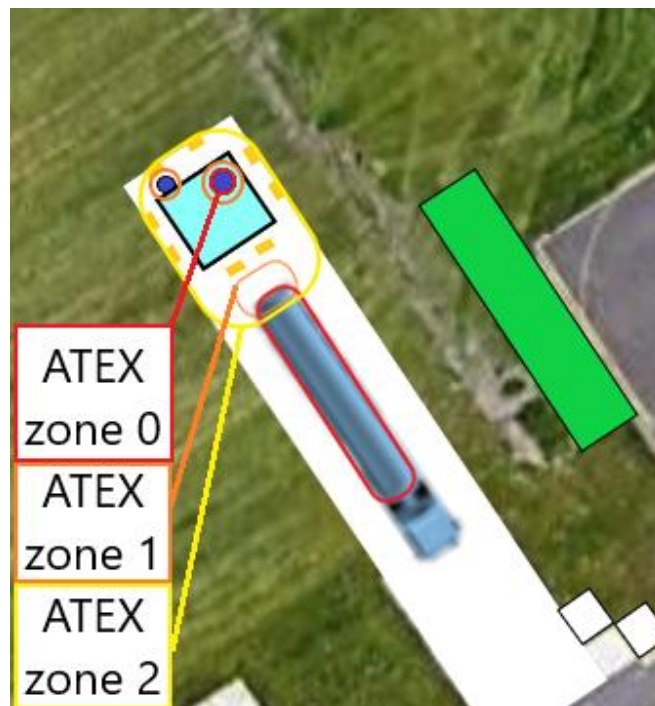


Figure 31 Preliminary ATEX zones for RTHA hydrogen storage



11 Conclusion

Based on existing systems, projects, and operations performed by other institutions, a concept of operations was constructed and presented in this report.

The demonstrator consists of fuelling and flying the HYDRA 2 drone with liquid hydrogen which will be stored at the designated fuelling location for which the safety requirements stipulated by regulations will be incorporated.

The main steps of the Dewar filling procedure consist of purging and precooling followed by filling the Dewar with LH2 where it is important to minimize the total amount of boil-off generated. These steps can also be applied to the fuelling operations of the drone, and in the future to larger aircraft.

Reference projects include the European HEAVEN project (<https://heaven-fch-project.eu/>) with successful test flights on both gaseous and liquid hydrogen and LH2 infrastructure and operations at NLR in Marknesse. Other reference documents include design and safety regulations for gaseous and liquid hydrogen installations such as PGS35 and EIGA Doc 15/21 among others.

Nominal hydrogen aircraft operations do not significantly differ from conventional operations with the exception of the fuelling procedures and the added safety precautions.

The impact of the hydrogen demonstration generally has positive environmental effects by eliminating the carbon emissions from combustion. There are effects, however, such as increased water emissions, that need to be investigated further as they could negatively impact the environment. Upscaling hydrogen fuelling on airports will require adaptation of airport infrastructure as a separate line of logistics will be required for the supply of large quantities of LH2.

Due to the flammable nature of hydrogen safety precautions such as hydrogen detection, ventilation and the elimination of ignition sources will be implemented into the storage facility and in the future as onboard systems.

The operations of the hydrogen supply on the airport including the filling of the Dewar are described in section 5. Additionally, provisional fuelling operations of the drone have been addressed as well.

Preliminary safety zones have been defined as shown in section 10.5 & 10.6 and are shown to not cause any safety concerns and allow both the Dewar and the drone to be filled safely at the designated location.

All in all, the hydrogen demonstrator at RTHA can safely be executed with the right planning and safety precautions in place.



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