European Train the Trainer Programme for Responders

Lecture 12

Hydrogen refuelling stations & infrastructure

LEVEL IV

Specialist officer

ALL LEVELS TO BE DETERMINED

The information contained in this lecture is targeted at the level of specialist officer and above.

This lecture is part of a training material package with materials at levels I – IV : Firefighter, crew commander, incident commander and specialist officer. Please see the lecture introduction regarding competence and learning expectations

Disclaimer

Acknowledgments

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Summary

This lecture presents details on gaseous and liquid hydrogen storage based refuelling station (LHRS) and associated infrastructure for hydrogen mobility. The main elements of the liquid hydrogen supply chain, from hydrogen production to end user are incorporated, for good understanding of LHRS operation. Liquid hydrogen challenges and potential risks are described.

Keywords

Liquid and gaseous hydrogen, refuelling station, cryogenic conditions, process, safety features.

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1. Introduction and objectives

The objective of the document is to present gaseous hydrogen refuelling station (GHRS) and liquid hydrogen storage based refuelling station (LHRS) and the associated infrastructure for hydrogen mobility. In this lecture, a comparison is made between GHRS and LHRS, and components of LHRS are described for a good understanding of LHRS operation, challenges and potential risks.

The first question before introducing LHRS could be “why use liquid hydrogen?”. Feedback from HRS showed, the following main pain points:

- expensive supply chain considering gaseous hydrogen for large scale,
- and limited daily capacity.

Given that LH_2 is much denser than GH_2, it is of interest to develop new products in order to increase station capacity and decrease the TCO (total cost of ownership) by using liquid hydrogen as feedstock. Figure 1 shows the different elements of hydrogen – liquid and gas – supply chain, from the production to the use for hydrogen mobility.

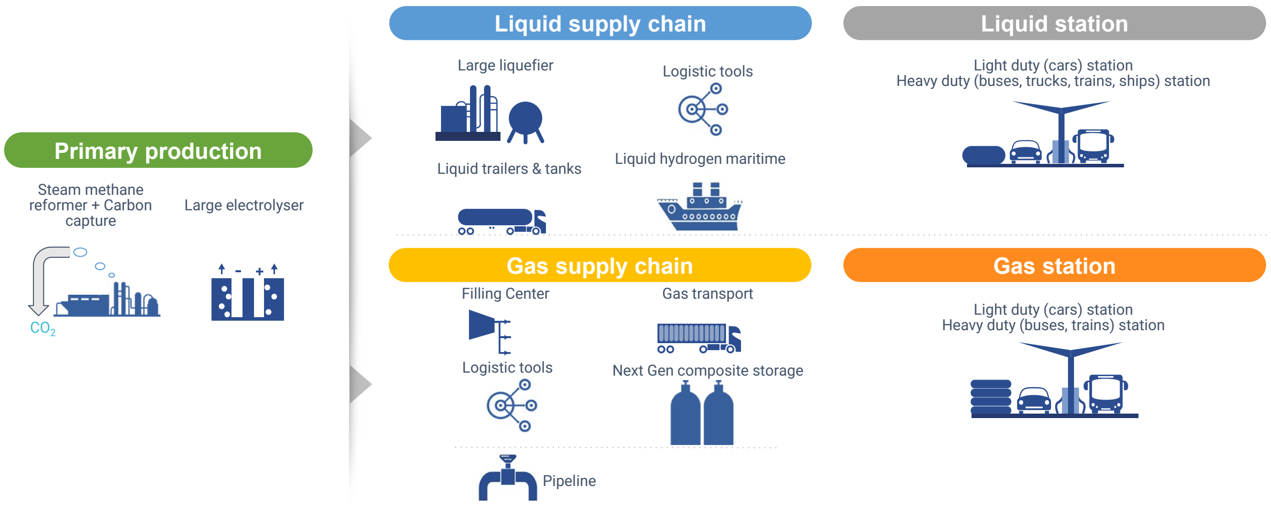


Figure 1. Hydrogen supply chain, from production to use for H_2 mobility.

Figure 2 is a simplified scheme of the liquid hydrogen supply chain, showing that after hydrogen production a liquefier is required to liquefy hydrogen at cryogenic temperature. Then LH_2 trailers (with a capacity up to 4-t H_2) are in charge of hydrogen transportation to the LHRS, where the transfer from trailer to LHRS storage is performed using a small vaporizer. But details of these different steps and required equipment are precisely the topic of this lecture.

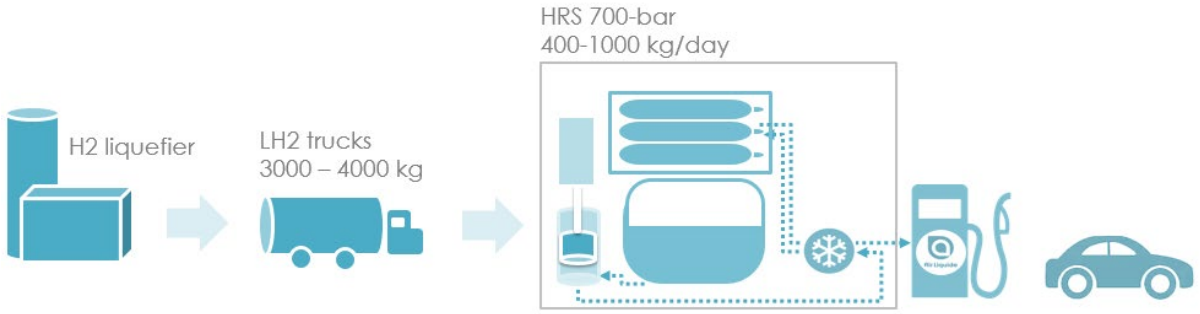


Figure 2. Focus on liquid hydrogen supply for hydrogen refuelling stations

By the end of this lecture Responders/trainers will be aware of:

- hydrogen supply chain – from hydrogen production to use,
- layout and operation of GHRS and LHRS,
- the required equipment of GHRS and LHRS,
- the methods of hydrogen production,
- safety features in GHRS and LHRS and other infrastructures

2. Refuelling station introduction

2.1 Gaseous hydrogen refuelling station (GHRS)

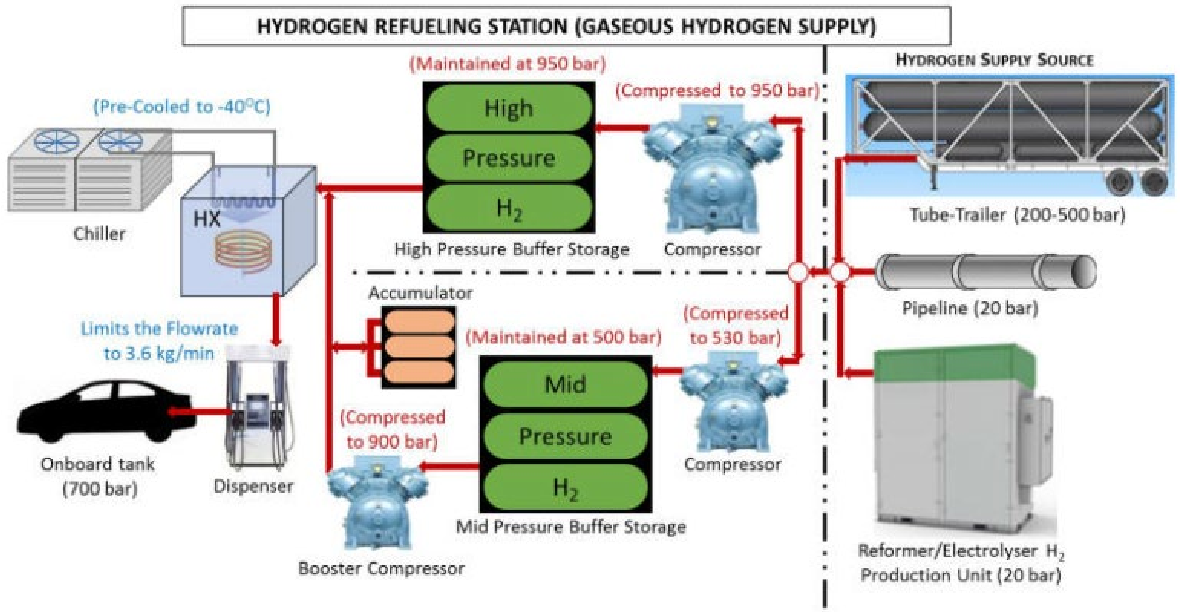
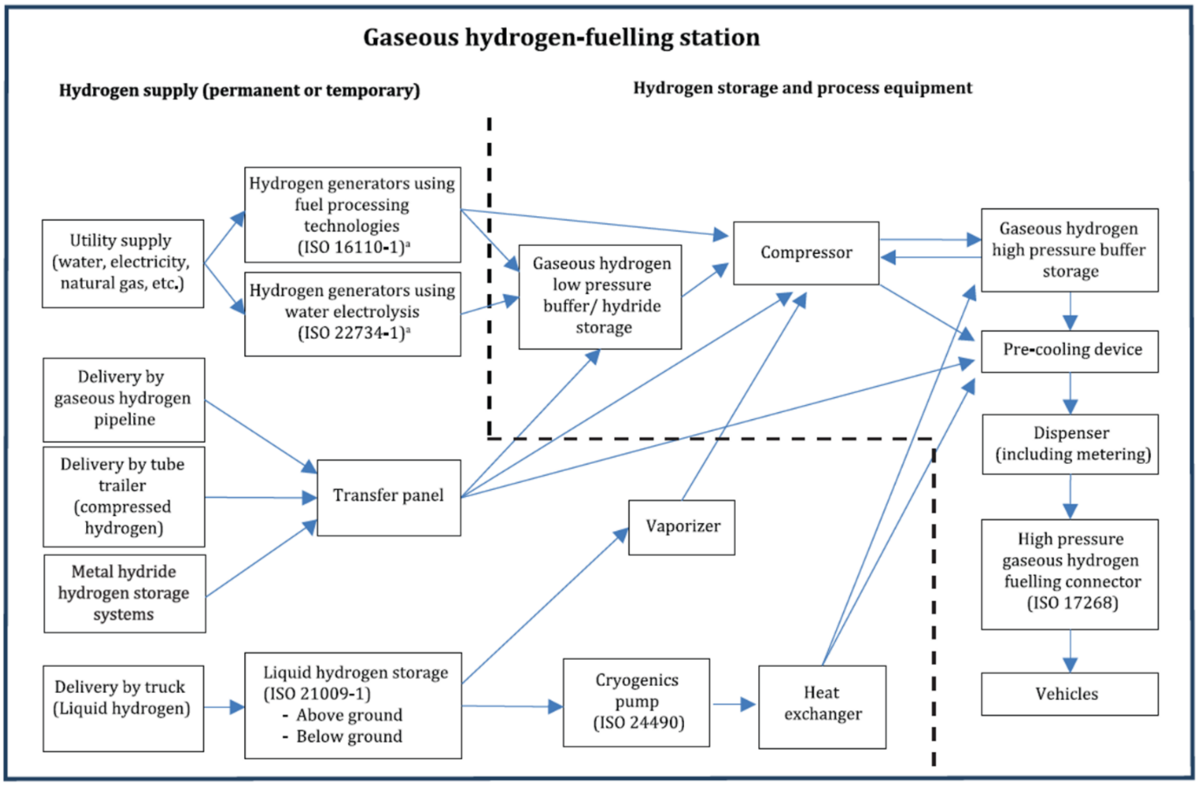


Figure 3. Image of an example gaseous hydrogen refuelling station (GHRS) [1]

Generally, the journey of gaseous hydrogen from supply to onboard tank follows a compression process to either achieve 950 bar in a high pressure buffer storage or 500 bar in a mid pressure buffer storage, then passes a heat exchanger and reaches the dispenser for Fuel Cell Vehicle

(FCV) refuelling. As shown in Figure 3, a typical GHRS includes gaseous hydrogen buffer storage vessels, hydrogen compressors, pre-cooling devices and a hydrogen dispenser. The minimum design, installation, commissioning, operation, inspection and maintenance requirements, for the safety, and, where appropriate, for the performance of public and non-public gaseous hydrogen refuelling stations (GHRS) that dispense gaseous hydrogen to light duty road vehicles (e. g. FCV) have been discussed in ISO 19880-1:200 (E) [2], in which the minimum requirement for GHRS are provided. Many of the generic requirements are applicable to refuelling stations for other hydrogen applications, including but not limited to the following:

- Refuelling stations for motorcycles, fork-lift trucks, trams, trains, fluvial and marine applications;
- Refuelling stations with indoor dispensing;
- Residential applications to fuel land vehicles;
- Mobile fuelling stations; and
- Non-public demonstration refuelling stations.



a - May include a buffer vessel (or accumulator) for dampening or adjusting flow of compressor suction inlet.

Figure 4. Example of typical elements of a fuelling station including hydrogen supply [2]

This lecture focuses on hydrogen storage and process equipment (on the right side of the dashed line in Figure 4), including gaseous hydrogen low- and high-pressure buffer/hydride storage, compressor, pre-cooling device, dispenser (including metering), high pressure gaseous hydrogen fuelling connector and vehicles. Guidance on high pressure gaseous hydrogen fuelling connector could be found in ISO 17268.

2.2 Liquid hydrogen refuelling station (LHRS)

Before presenting in more details what are the main components of a liquid hydrogen storage-based refuelling station, it is interesting to show an existing and operated station. Figure 5 shows the Linde Liquid hydrogen refuelling station installed at Oakland (US).

Figure 5. Linde LHRS in Oakland.

The layout is presented in Figure 6, in order to assess the footprint of such an installation.

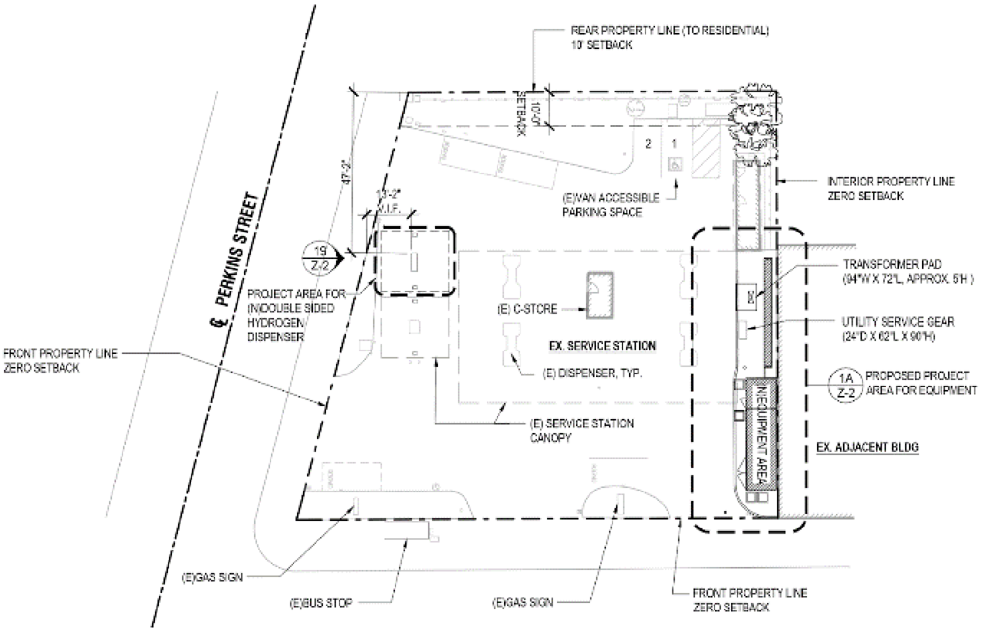


Figure 6. Linde LHRS layout.

2.3 Comparison between liquid and gaseous hydrogen storage based refuelling stations

Basically, a LH_2 storage-based refuelling station consists of:

- a LH_2 tank (around 20 m^3 - 1000 kg-H_2) with a maximal operating pressure of 10.3 bar,

- an insulated process line from the bottom of the storage to the LH_2 pump, driving LH_2 from the storage tank to a vaporizer; this device allows to pump LH_2 up to 1000 bar (100 MPa),
- a heater (named VAP: hot oil, electric in order to heat up hydrogen at 1000 bar (100 MPa)),
- 1000 bar (100 MPa) gaseous buffers (few m^3); these buffers are generally bundles of type I or II (i.e. metallic cylinders or long metallic tube).

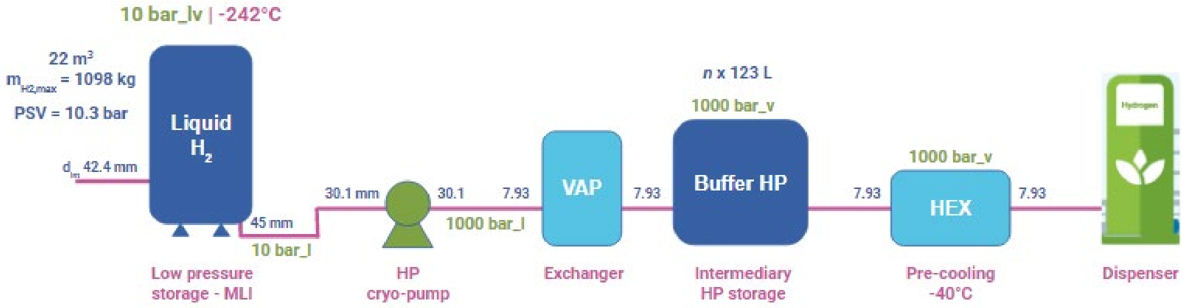


Figure 7. Simplified sketch of a liquid hydrogen refuelling station.

All the other parts (e.g. dispenser, filling hose…) of the refuelling station are similar to classical gaseous refuelling station (see comparison in Figure 8).

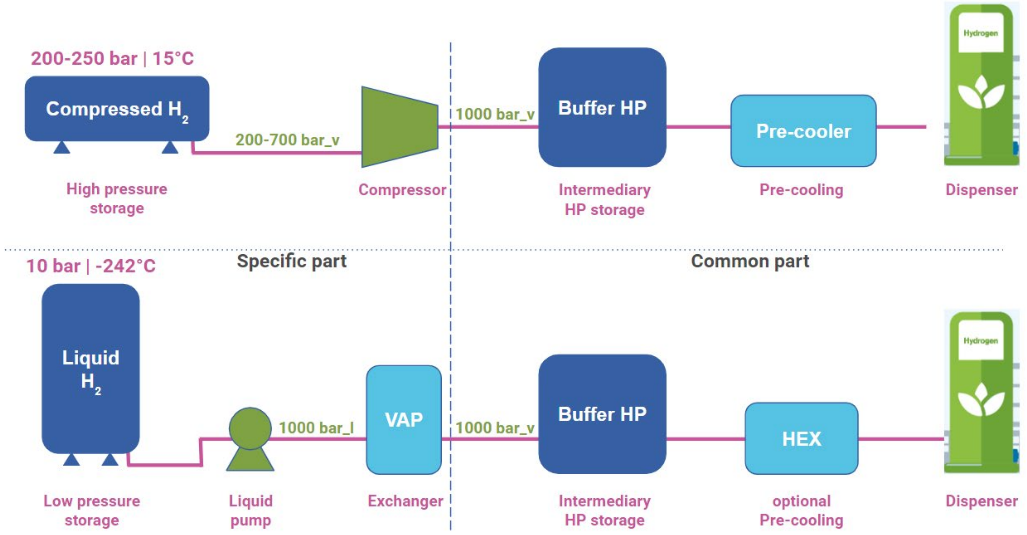


Figure 8. Simplified comparison between gaseous and liquid hydrogen refuelling stations.
Top: gaseous HRS, bottom liquid HRS.

The Table below summarises the main differences between LHRS and HRS.

Table 1. Comparison between LHRS and HRS

Topic	LHRS	HRS
Storage	Liquid hydrogen, cryogenic temperature (-240°C), low pressure (up to 10 bar)	Gaseous hydrogen, ambient temperature, high pressure (from 200 to 500 bar)
Refilling of the station	Transfer of liquid hydrogen from trailer to storage	Mainly swap (= full for empty)
Pressurization of hydrogen	Liquid pump and vaporizer required to deliver gaseous H_2	Compressor

2.4 Gaseous hydrogen storage based refuelling station – Equipment

2.4.1 Gaseous hydrogen buffer storage vessels

The buffer storage vessels, either high pressure or low pressure, are designed for the purpose of storing compressed hydrogen, which can be located between a hydrogen generator and a compressor for an even flow of gas to the compressor or between the compressor and dispensing system for accumulation of pressurised gas supply for vehicle fuelling.

Storage vessels for the storage of hydrogen gas should be manufactured in accordance with a commonly used national/regional standard and designed for the anticipated cycle life. Buffer storage may include hydrogen absorbed in a metal hydride storage system.

If buffer storage vessels of different design pressures are interconnected, they shall be protected in such a way that vessels rated for a low pressure cannot be over-pressurised due to any malfunction.

The design of the buffer storage installation shall include appropriate means to prevent failure in the case of fire when deemed necessary by risk assessment. Suitable prevention methods may include one or more the following:

- Product venting systems, such as TPRDs;
- Thermal shielding or fire barrier;
- Inability for a flammable liquid to pool under the vessel;
- Fixed firewater protection.

It is worthy noticing that the composite storage vessels can require increased protection compared to metallic vessels. The vessels shall be secured to the foundation, with the foundation and supports able to withstand the forces that can be anticipated for the location.

The layout design of the gaseous hydrogen buffer storage vessels and piping shall consider the risk from direct impingement of jet flames from potential leak points or vents onto an adjacent vessel. The station risk assessment shall include mitigation considerations about deflagration to detonation (DDT) in the compressed hydrogen area. Each group of buffer storage vessels that may be isolated with manual or automatic valves, should be equipped with their own set of safety devices.

Note that when hydrogen is delivered in transportable cylinders, tube trailers or multiple-element gas containers (MEGCs)[1], safety relief devices within the cylinder/group of vessels are not always included. However, when transportable cylinders, tube trailers or MEGCs are incorporated into a fuelling station, following appropriate risk assessment that addresses the potentially different design considerations, particularly pressure cycling, any on-site compression system that may compress hydrogen into such a system should include a set of safety devices to protect the storage tubes from over-pressurisation.

2.4.2 Hydrogen compressor

Each compressor shall be equipped with pressure relief devices, or equivalent safety-instrumented systems to prevent overpressure. The compressor and ancillary systems, where applicable, shall be consistent with use in the piping system. Sufficient compensation for potential vibration or movement of the compressor should be provided such that piping systems are not damaged and that leaks do not occur. Compressors should be designed with particular reference to hydrogen service and to minimise the introduction of contaminants. The ingress of air at the inlet to the compressor shall be avoided at all times to prevent the formation of flammable mixtures. Risks associated with installation, maintenance, and operation of compressors shall be assessed, and countermeasures shall be defined and implemented to protect equipment and prevent potentially hazardous events from occurring. Each compressor should be equipped with means to fully depressurise all parts of the system for maintenance purposes. When the risk mitigation review of a compressor system recommends the use of an inert purge, means to purge the compressor with inert gas prior to maintenance operations shall be provided, including a written procedure, to enable effective inerting.

Sufficient compensation for vibration and movement should be provided between interconnected systems at a hydrogen fuelling station and between the hydrogen gas supply piping and compressor suction piping to avoid leaks caused by vibration and movement. Any vibrations that may affect the strength of the piping, fitting and component shall not be transferred to the piping work.

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[1] multimodal assembly of cylinders, tubes or bundles of cylinders which are interconnected by a manifold and assembled within a framework, including service equipment and structural equipment necessary for the transport of gases.

Safety controls shall be installed to ensure temperature and pressure levels do not exceed or fall below set operating levels, for instance for inlet pressure, discharge temperature and pressure, with the control system instigating an alarm and/or shutdown as appropriate, or appropriate alternate measures. In addition to the instruments and controls normally provided for gas compressing systems, the following specific safeguards for hydrogen should be considered.

Ingress of air at the inlet to the compressor shall be avoided at all times to prevent the formation of a flammable mixture. If this condition is no longer guaranteed, the compressor shall be shut down. For example, the inlet pressure should be monitored by a pressure indicator/switch, with the control system instigating an alarm and/or shutdown as appropriate, to avoid a vacuum in the inlet line and consequent ingress of air. This pressure indicator/switch should cause the compressor to shut down before the inlet pressure reaches atmospheric pressure.

If there is a possibility of oxygen contamination under normal operating conditions due to a low inlet pressure, measurement of the oxygen content in the hydrogen can be considered as a mitigation measure during risk assessment. For example, should the oxygen content reach a volume fraction of 1%, the compressor can be automatically shut down. Alternative means can be taken to prevent critical situations.

The temperature after the final stage of compression, or the temperature after the cooler, where fitted, shall be monitored by a temperature indicator/switch with the control system instigating an alarm and/or shutdown as appropriate at a predetermined maximum temperature.

The pressure after the final the final stage of compression shall be monitored by an indicator/swich with the control system instigating an alarm and/or shutdown as appropriate, or initiate alternative actions, such as recycling, at a predetermined maximum pressure which is below that of the over-pressure protection.

The cooling water system should be monitored by an indicator/switch, with the control system instigating an alarm and/or shutdown as appropriate in case of low pressure, flow or high temperature.

Where the motor and auxiliary equipment are purged by an inert gas, or protected by pressurisation with compressed air or an inert gas, low pressure/flow shall be indicated by an alarm, which shall be arranged to shut down the motor and auxiliaries as required by IEC 60079-2.

Where the compressor crankcase is purged by an inert gas or protected by pressurisation with compressed air or an inert gas, low pressure/flow shall be indicated by an alarm, which shall be arranged to shut down the compressor.

2.4.3 Pre-cooling device

Pre-cooling is a process of cooling hydrogen fuel temperature prior to dispensing. The pre-cooling unit cost constitutes about 10% of the total equipment cost of the GHRS [3] and a deeper understanding of its cost component is necessary to achieve the maximum possible GHRS cost reduction. In contrast to the studies of compressor and storage systems, relatively limited information is available on pre-cooling unit. Pre-cooling of the hydrogen fuel before it is dispensed into the vehicle's tank is critical to prevent the tank from overheating. The SAE J2601 fuelling protocol establishes fuelling process limited to ensure safe and rapid filling of FCVs [4].

The SAE J2601 fuelling protocol establishes a hydrogen precooling temperature range for each hydrogen refuelling station type; for example, a T40 station is required to precool the hydrogen to between -33 and -40 °C before dispensing it to the FCVs. Situated between the high-pressure buffer storage unit and the dispenser, the pre-cooling unit precools the gaseous hydrogen to a temperature of at least -33 °C within 30 s of the start of fuelling. It then maintains a temperature in that prescribed range for the entire duration of the fuelling event.

The speed at which FCVs can be refuelled is directly related to the hydrogen precooling temperature, the ambient temperature, and the initial onboard tank pressure [5] among other factors. The higher the ambient temperature is, the longer it will take to fill the tank, and vice versa. However, among these three key factors, precooling has the most significant impact on the refuelling time. Because the refueling time is one of the critical parameters that affects FCV fuelling experience, the precooling system should be designed to deliver the required fuelling rate and capacity under extreme conditions, and at the lowest cost possible.

A typical pre-cooling unit in an GHRS utilises a thermodynamic refrigeration cycle; it circulates a refrigerant through a two-stage compressor, condenser, thermostatic expansion valve, and evaporator heat exchanger (Figure 9). This refrigeration cycle involves a refrigerant sub-cooling to maximize the refrigeration effect at the evaporator by circulating a portion of the refrigerant exiting the condenser through the expansion valve, the sub-cooler heat exchanger, and the compressor's second stage. The dispensed hydrogen is precooled by releasing energy to the low-temperature refrigerant through the evaporator heat exchanger. The evaporator heat exchanger can be designed with a large thermal mass (mainly to act as a buffer and thereby reduce the required refrigeration capacity), or it can have a compact design for packaging purposes.

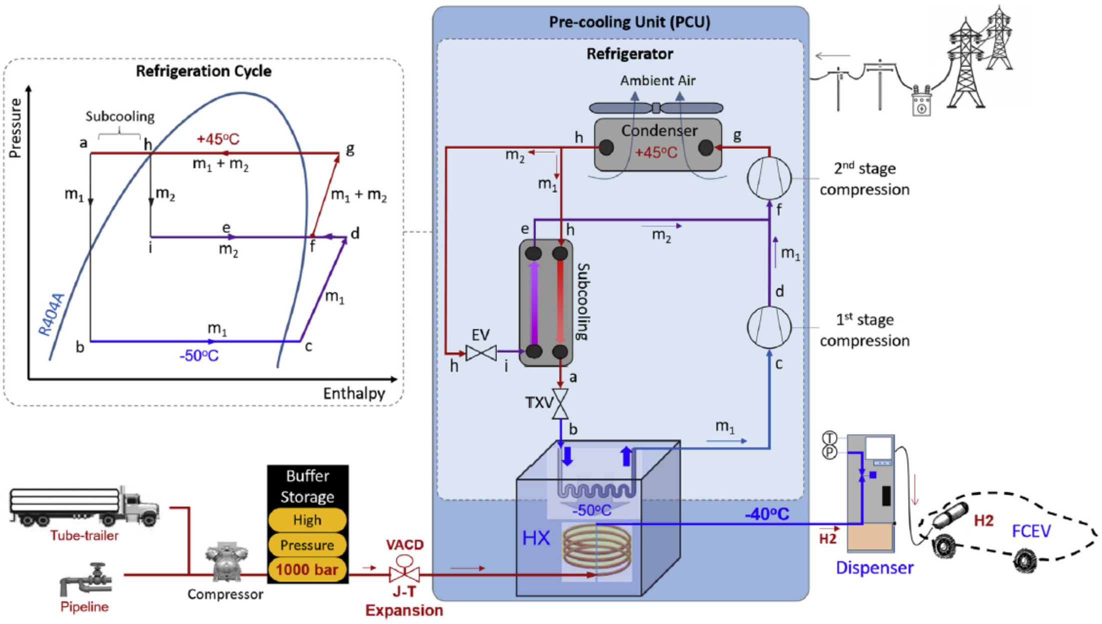


Figure 9. Schematic diagram of the operation of the pre-cooling unit at a GHRS comprised of compressor, high pressure buffer storage, pre-cooling unit and dispenser.

Two major factors affect refrigeration performance and the sizing of the pre-cooling unit: the J-T expansion (Lecture 2) process at the variable area control device (VACD) upstream of the precooling heat exchanger, and the station's requirement to be capable of filling a given number of vehicles back to back (B2B). The J-T effect is related to the inlet temperature of hydrogen fuel flowing into the pre-cooling unit, whereas the B2B filling requirement is associated with peak hourly fueling demand at the dispenser [6].

The J-T effect refers to the temperature change of a gas when it is forced through a valve at constant enthalpy (adiabatic expansion). All gases have an “inversion temperature” below which they experience a drop in temperature during the J-T expansion process. The inversion temperature directly correlates with the critical temperature of the gas. Substances with extremely low critical temperature (e.g., hydrogen, helium, and neon) have inversion temperatures that are well below ambient temperature, and therefore their temperatures increase during isenthalpic expansion above their inversion temperatures (< 224 K for hydrogen). When the high-pressure hydrogen from the buffer storage flows through a VACD, it experiences a pressure drop while expanding. The hydrogen's expansion and pressure drop in the VACD cause the hydrogen gas temperature to increase, because hydrogen has negative JT coefficients at the expansion pressure and temperature (approximately -0.05 K/bar at 900 bar and -0.03 K/bar at 1 bar and 25 °C) [7]. That said, the maximum pressure drop across the VACD could theoretically lead the temperature of hydrogen fuel to increase by 40 °C before it enters the precooling heat exchanger. This significant temperature increase could introduce an additional burden to the pre-cooling unit, such that more cooling power will be needed to compensate for the larger required temperature drop across the heat exchanger. Similarly, an increase in the number of B2B fills that the station is required to satisfy can increase the capacity required of the pre-cooling unit, because the heat exchanger will be sized for peak B2B demand, even if the demand during most of the day is much lower.

The desired number of B2B fills strongly impacts the capacities and costs of refuelling components. In B2B filling, one FCV after another pulls up to the dispenser for refuelling, with a short break of approximately 2 min between fillings [6]. The lack of idle time during a series of B2B fillings provides little time for the GHRS components to recover and recharge. A high number of B2B fillings (e.g., 5) will increase the load on the heat exchanger so that the ability of its thermal mass to keep the hydrogen temperature below -33 °C is jeopardised. In such cases, the refrigeration system may have insufficient time to cool the heat exchanger between fills. Without considering the peak demand associated with B2B refuelling in the design of refuelling components, the pre-cooling unit may be undersized, which puts the refuelling performance and customer satisfaction at risk.

In addition to the J-T effect and B2B refuelling, it is important to consider the trade-off between different pre-cooling unit design concepts. A pre-cooling unit may employ a heat exchanger with a larger thermal mass that is capable of maintaining a small temperature change while cooling the hydrogen flow, thus requiring less cooling power from the refrigeration system. On the other hand, a compact heat exchanger needs to be matched with a refrigeration capacity that meets the instantaneous cooling load (i.e., provides cooling on demand). In addition, because of its smaller buffering effect (due to its smaller thermal mass), the cooling capacity with a compact heat exchanger will be more sensitive to factors that impact its inlet temperature, such as ambient temperature and J-T effect upstream of the heat exchanger.

At higher ambient temperatures, the hydrogen temperature at the inlet of the heat exchanger will increase, so a heat exchanger block with a larger thermal mass may be required to keep its temperature within the design range. However, in a compact heat exchanger system, a higher ambient temperature must be countered by higher on-demand cooling power. One of the thermodynamic disadvantages of having a heat exchanger with a large thermal mass is that it consumes more energy for overhead cooling (to keep the heat exchanger at -40 °C) than its compact heat exchanger counterpart. On the other hand, a compact on-demand heat exchanger cooling configuration needs a more powerful refrigerator but consumes less energy for overhead cooling. In other words, there is a trade-off between the cooling capacity and the heat exchanger thermal mass. In terms of cost, a compact heat exchanger tends to have a more complex structure for on-demand rapid heat transfer, so its manufacturing cost is likely higher than a heat exchanger with a large thermal mass. Nevertheless, the small system size keeps the material, shipping, and installation costs of compact heat exchangers low compared to large thermal mass heat exchangers.

If pre-cooling of the dispensed hydrogen is used, the dispensing system shall be equipped with a means to confirm that the pre-cooled dispenser fuel temperature is correct and that the control meets both the upper and lower temperature limits of the fuelling protocol. If the fuelling protocol uses communication of the tank temperature on the vehicle and experiences a failure of the communication, the protocol should execute a shutdown, or continue to a non-communications fuelling if that is allowed by the protocol.

2.4.4 Hydrogen dispenser

The dispenser system is downstream of the hydrogen supply system comprising all equipment necessary to carry out the vehicle fuelling operating, through which the compressed hydrogen is supplied to the vehicle. The hydrogen dispenser is equipment in the dispensing system which includes the dispenser cabinet and support structure, that is physically located in the fuelling area.

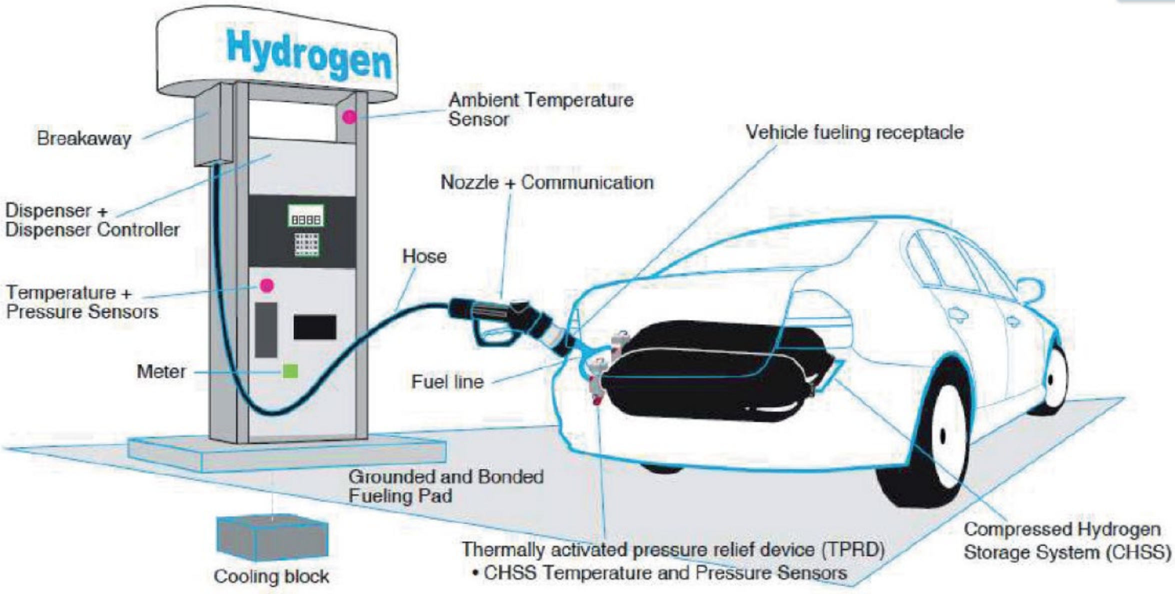


Figure 10 Example of the key components of the fuelling station dispensing system [2]

Figure 10 illustrates an example of the key components of the fuelling station dispensing system including the FCV high pressure hydrogen system, comprising, amongst others, the receptacle and compressed hydrogen storage system (CHSS) with sensors as well as pressure relief devices. The CHSS has a thermally activated pressure relief devices to protect against overpressure due to a fire. On the station side, there is an automated dispensing system control system (e.g. through a programmable logic controller (PLC)) for performing the fuelling, as well as fault detection and management procedures. The station also has an over pressure protection device such as a pressure relief device or equivalent to protect against over pressurisation of the dispensing system and the vehicle.

The dispenser at a public fuelling station for light duty vehicles is typically designed with separate nozzles to fuel vehicles to 35 MPa and/or 70 MPa nominal working pressures. The station fuelling nozzle may contain a communications receiver and the vehicle may contain a communications transmitter (e.g. SAE J2799). The vehicle infrared data association (IrDA) communications system may use the SAE J2799 protocol to transmit the measured temperature and pressure of the compressed hydrogen storage system on the vehicle to the hydrogen dispenser. The dispensing system control system may use this data for the control system to manage the fuelling process.

In order to achieve the maximum operating pressure (MOP) needed to fuel the CHSS of the hydrogen vehicle under the full range of operating conditions, the recommended minimum component pressure ratings needed for the hydrogen dispensing system relative to the dispenser hydrogen service level (HSL), the pressure class (as defined in ISO 17268), and the dispensing system maximum allowable working pressure (MAWP) are shown in Table 2.

Table 2 Dispensing system pressure levels and recommended component minimum pressure ratings

Hydrogen service level (HSL)	Pressure class	Maximum operating pressure (MOP)	Dispensing system maximum allowable working pressure (MAWP)
Equal to NWP of vehicle being fuelled		1.25 × HSL Highest pressure during normal fuelling	1.375 × HSL Highest permissible setpoint for dispensing system pressure protection
25 MPa	H25	31.25 MPa	34.375 MPa
35 MPa	H35	43.75 MPa	48.125 MPa
50 MPa	H50	62.5 MPa	68.75 MPa
70 MPa	H70	87.5 MPa	96.25 MPa

If components are used that are below the pressure rating in Table 2, then the MAWP of the dispensing system shall be lowered according to the component with the lowest pressure rating. The dispensing system shall be also protected against over-pressurisation.

In addition to the pressure rating, the components in the hydrogen dispensing system should meeting the following requirements:

- an ambient temperature range of -40 °C to +50 °C, unless local conditions permit or require other temperature limits;
- compatibility of materials normally in contact with hydrogen;
- a specified cycle life before maintenance or replacement.

Target cycle life should be 100,000 cycles for the fuelling assembly, but, whether this target is met or not, the cycle life should be defined and stated so that planned maintenance activities can pre-empt a failure.

High pressure hydrogen dispensing system components shall be marked with the pressure class only if components are designed and verified to meet or exceed the pressure, temperature, material compatibility, and service life requirements as defined above. High pressure components shall be mounted in strict compliance with the supplier's instructions, following a well-defined assembly procedure. The manufacture shall ensure that the pressure drop between the dispenser fuel pressure sensor monitoring the vehicle pressure and the nozzle does not exceed the value defined in the fuelling protocol during the hydrogen flow to the vehicle.

2.5 Liquid hydrogen storage based refuelling station – Equipment

LHRS is typically integrated with LH2 storage, consisting of LHRS skid, LH2 tank, interconnecting lines, hydrogen dispenser and test device as the main parts (see Figure 11).

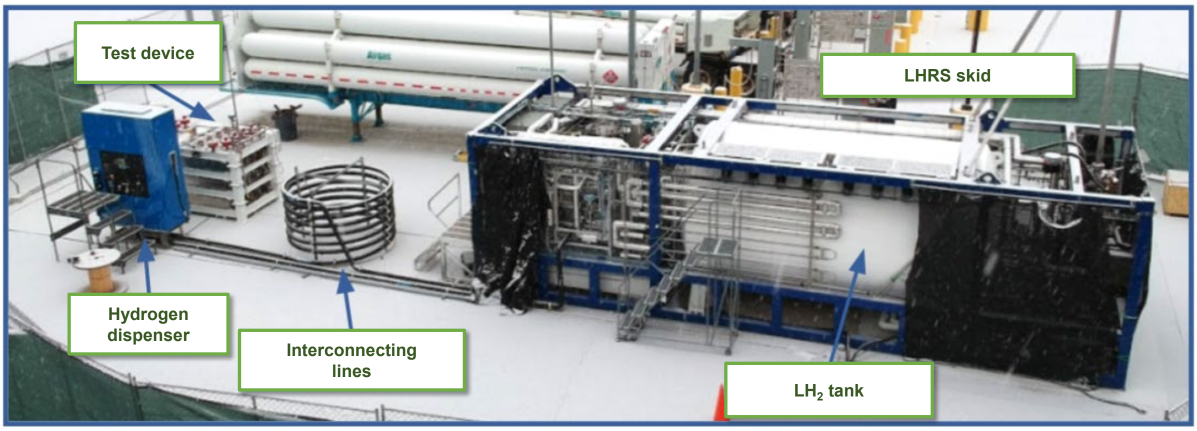


Figure 11. Overview of the main parts of a type of LHRS with integrated LH$_2$ storage.

The general liquid hydrogen refuelling station process flow diagram is presented in Figure 12.

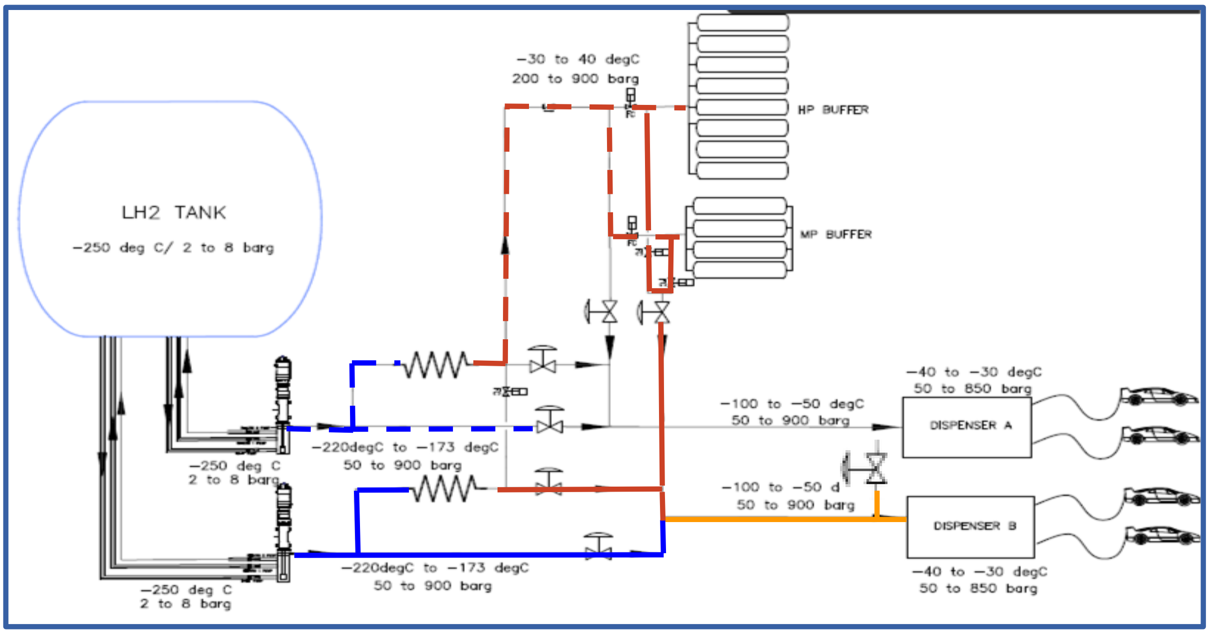


Figure 12. Process flow of a LH$_2$-based refuelling station.

The main equipment of the LHRS are:

- the LH_2 tank,
- the cryogenic pump,
- the vaporizer,
- the valve panel,
- the buffers,
- the connection to dispenser,
- the dispenser.

A type of LHRS main skid is shown in the following picture with identification of the main functional equipment:

- in Figure 13, for the "cryogenic" side,
- in Figure 14, for the "warm" side.

Equipment will be described with more details and functionalities in the following dedicated sub-sections.

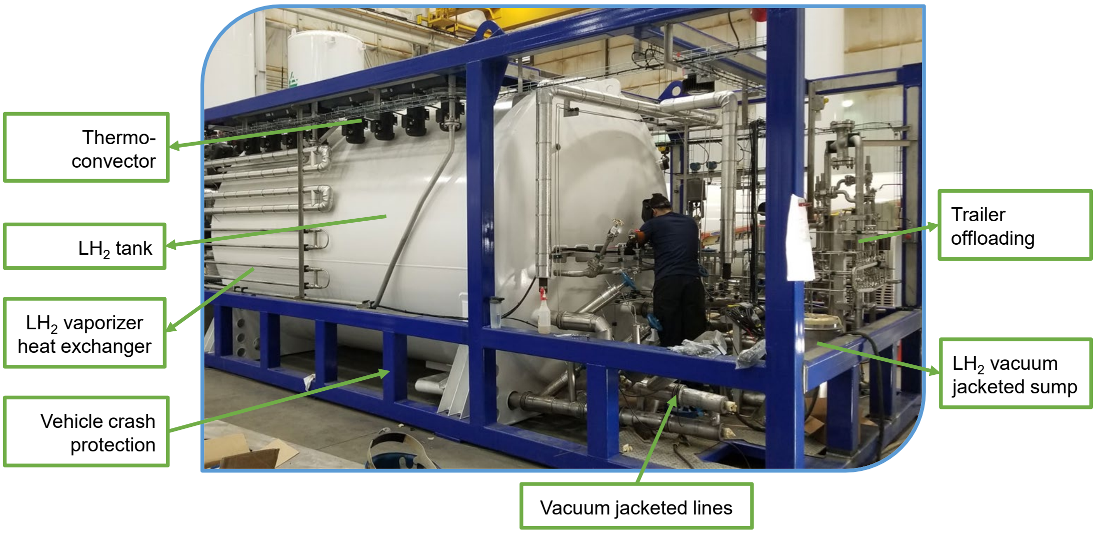


Figure 13. LHRS skid overview – "Cryogenic" side.

Figure 3. LHRS skid overview – "Warm" side.

2.5.1 Liquid hydrogen storage

Regarding LHRS, the liquid hydrogen tank can be integrated inside a skid as it is represented in this document and as shown on Linde LHRS in Oakland. Nevertheless, LH_2 storage can be a stand-alone vessel, vertically or horizontally set up.

For LHRS as shown in Figure 15, LH_2 storage volume is around 20 m^3 providing a capacity of 1-t H_2. The temperature of storage is around -250°C, and the storage pressure is from 2 to 8 bar.

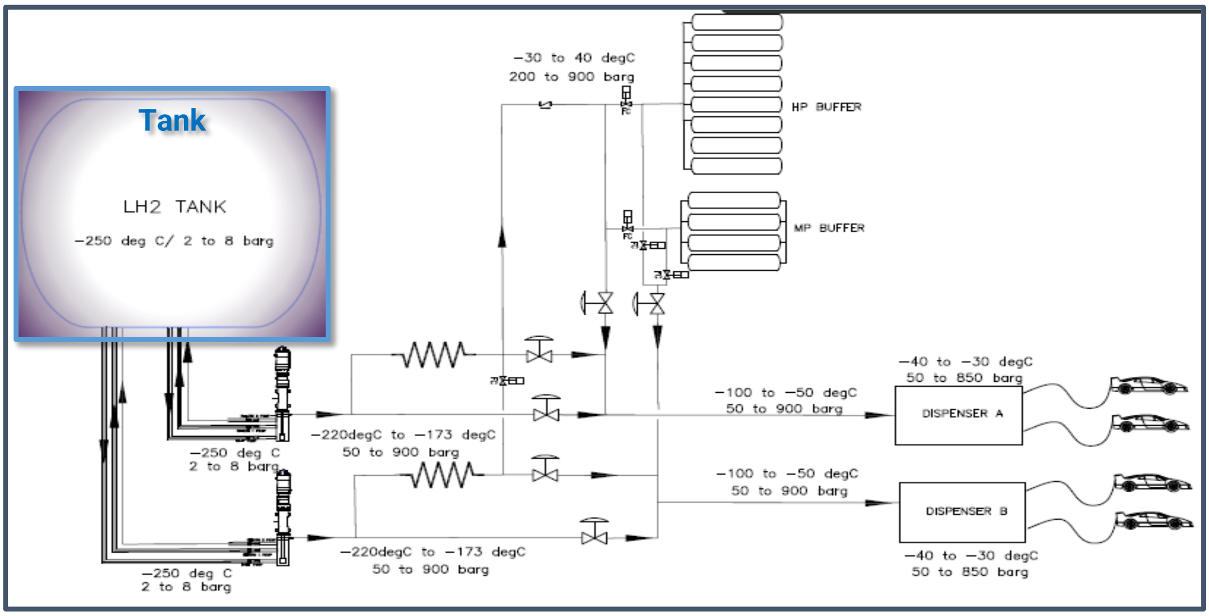


Figure 4. Process flow of a LH_2-based refuelling station – LH_2 storage tank

The main parameters on this part of the LHRS are:

- Insulation chosen is a multi-layer insulation (MLI) with vacuum in order to maintain cryogenic temperature (see Figure 16),
- Tank is horizontal to be integrated inside a skid and match with permitting requirement (other configurations are possible, with stand-alone tank of higher capacity for instance),
- All interfaces are on one side of the tank,
    - Feeding and return lines for each pump (+ a third one to control level in the LH_2 pump sump)
    - Either conventional mode or Thermosiphon mode
    - Safety, vent lines
    - Filling lines (bottom and top)
- Crash protection is integrated on the frame (see Figure 17).

Figure 5. MLI insulation.

Figure 6. Crash protection (in blue) at the bottom.

The LH_2 tank is delivered by a LH_2 truck. This LH_2 truck is composed of a 40 m^3 horizontal tank operating between 1 and 12 bar (inventory: 4 t-H_2). The connection between the storage and the truck is done by a flexible transfer line. The transfer is performed without a pump. A small vaporizer is present on the trailer to produce a pressure build-up in the truck tank and allow the transfer of liquid hydrogen in the stationary vertical storage.

2.5.2 Cryogenic pump

The cryogenic pumps installed in LHRS are shown in Figure 19.

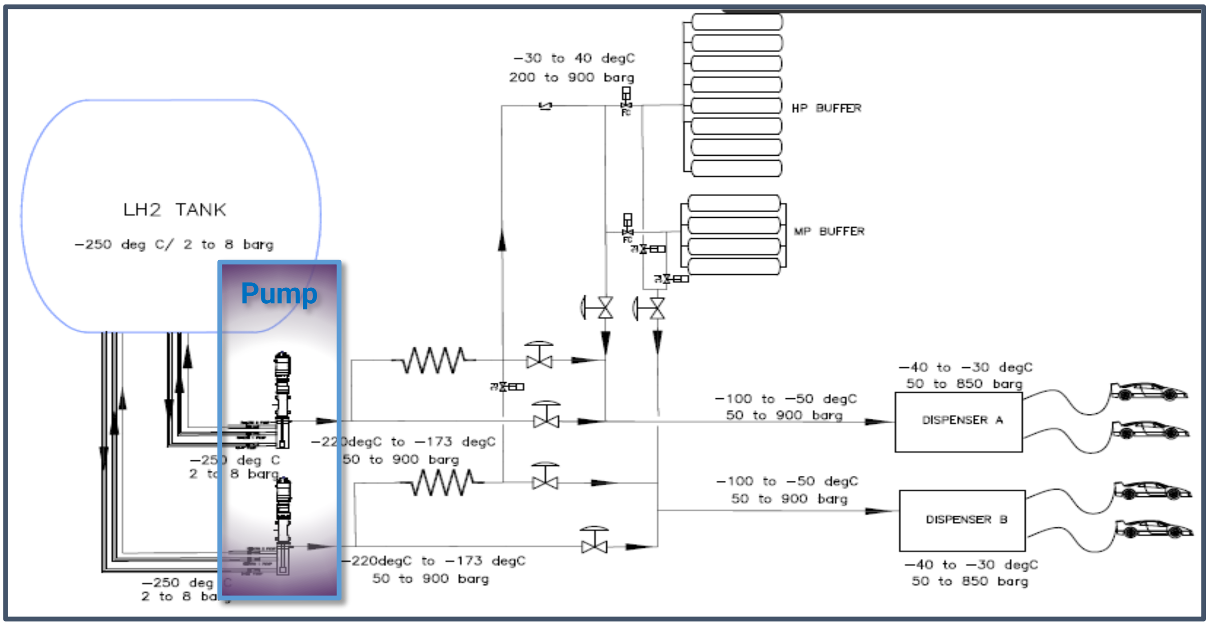


Figure 7. Process flow of a LH_2-based refuelling station – LH_2 pump.

The cryogenic pump, as shown in Figure 19, allows to transfer liquid from storage tank to heat exchanger. Pressure of liquid hydrogen is slightly increased between storage and heat exchanger.

Figure 8. Cryogenic pump.

Pump is submerged in a vacuum jacketed sump as illustrated in Figure 20.

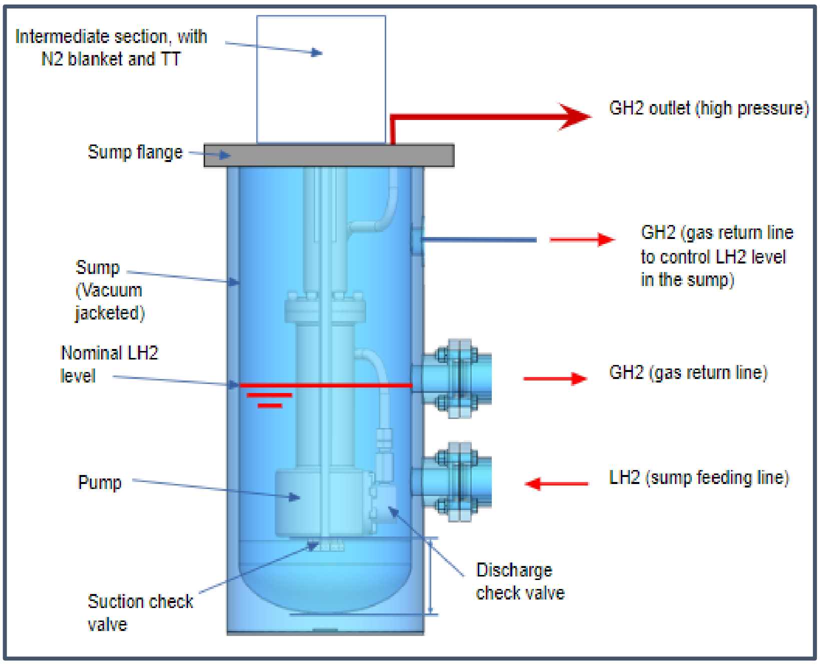


Figure 20. Pump in vacuum jacketed sump.

2.5.3 LH_2 vaporizer

The vaporizer in LHRS is shown in Figure 21.

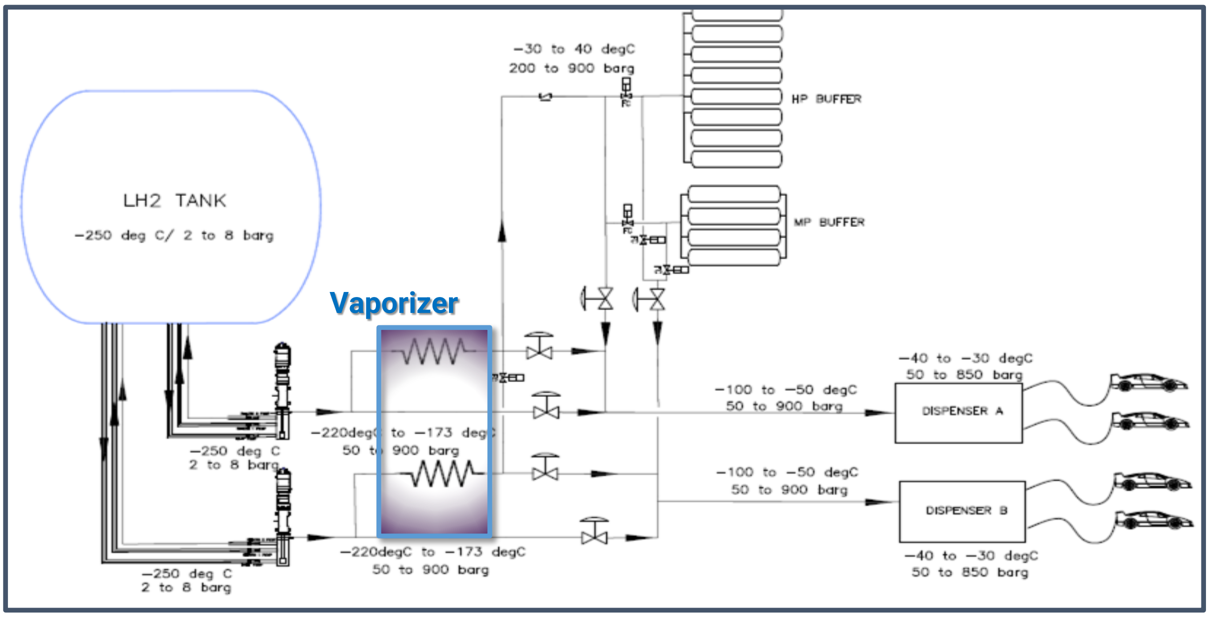


Figure 21. Process flow of a LH_2-based refuelling station – Vaporizer.

The aim of the vaporizer is to increase pressure of the gaseous hydrogen which will be stored in intermediary buffers at a pressure up to 900 bar. Temperature of hydrogen is increased as well from -220 to -30°C.

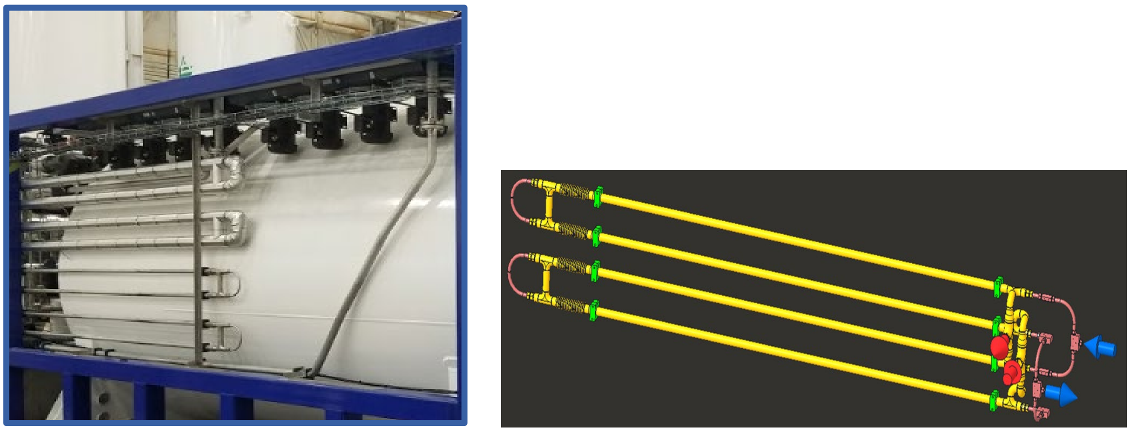
Several technologies are available for this heat exchanger. The main are:

- atmospheric vaporizer,

- and tube-in-tube vaporizer.

Tube-in-tube vaporizer, as shown in Figure 22, is preferred for refuelling stations for the reasons below:

- simple and easy to manufacture,
- compact solution compared to atmospheric vaporizer,
- no creation of enriched O_2 zone,
- low power consumption compared to electrical heater (8 times less).



(A) (B)

Figure 22. (A) Tube-in-tube heat exchanger set up in LHRS skid, (B) Vaporization of LH_2 principle (blue arrows).

2.5.4 Valve panel

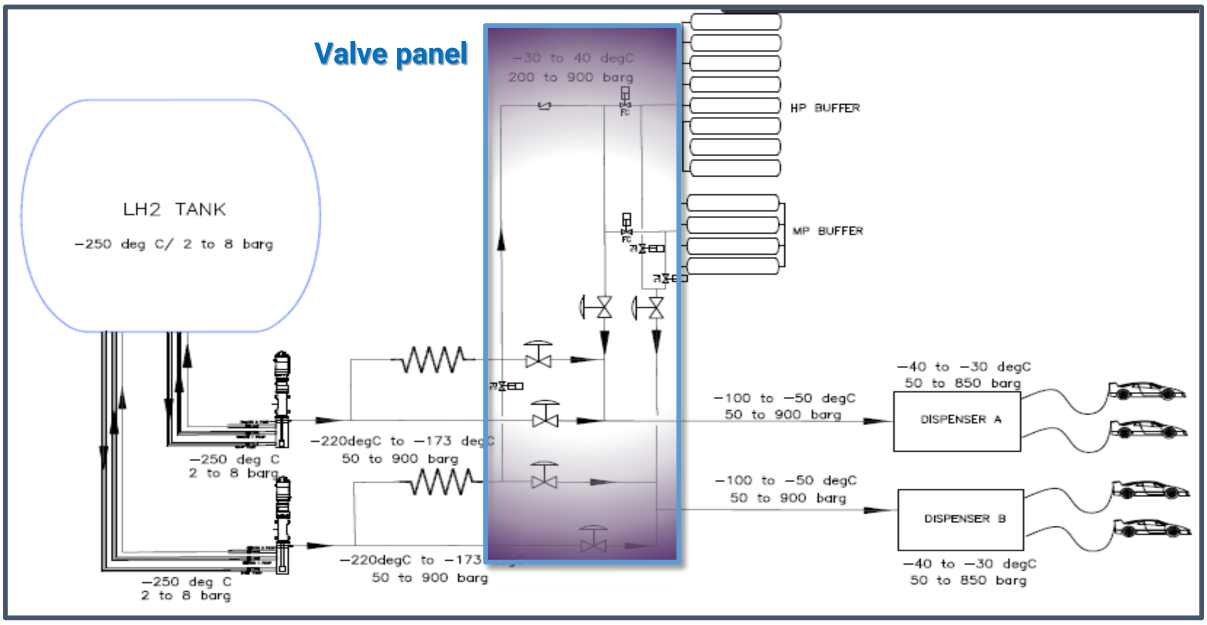


Figure 23. Process flow of a LH_2-based refuelling station – Valve panel.

The valve panel in LHRS is shown in Figure 23.

A view of valve panel is shown in Figure 24. This part of the process is quite simple, but it is a potential source of gaseous hydrogen leakages due to the high number of connections for valves, pressure transmitters and other required equipment for station operation.

Figure 24. Valve panel.

At this stage, hydrogen is gaseous, and the maximum pressure reach 900 bar.

2.5.5 Gaseous buffers

The gaseous buffers in LHRS are shown in Figure 25.

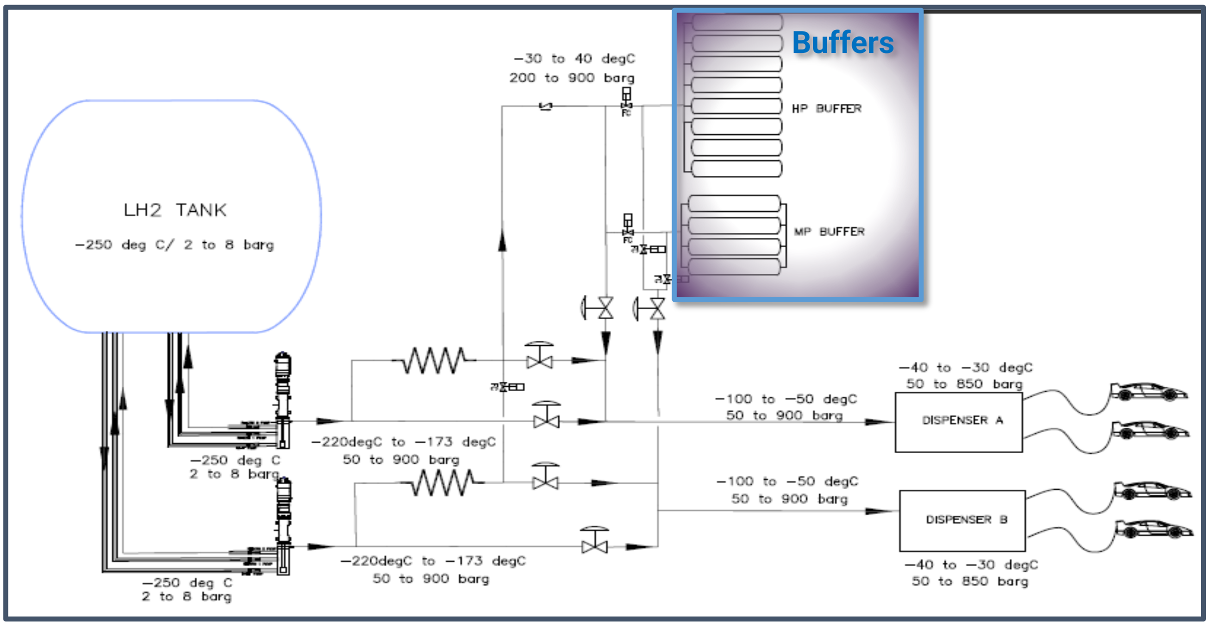
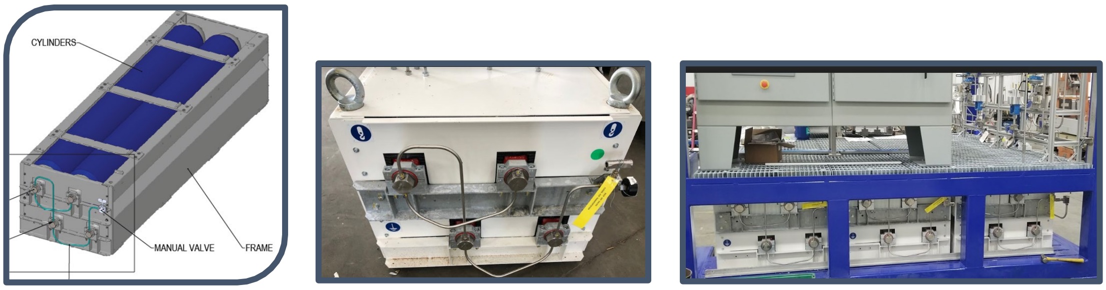


Figure 9. Process flow of a LH2-based refuelling station – Gaseous buffers.

The maximum allowable working pressure (MAWP) of the buffers is 1000 bar (100 MPa). Type-II cylinders in steel and carbon wrapped to reinforce mechanical strength of the cylinders are used. In the presented station configuration, selected cylinders have a volume of 123 L. These cylinders are packed by 4 in 3 bundles as shown in Figure 26, and integrated in the mainframe.



(A) (B) (C)

Figure 10. High pressure buffers. (A) 4 type-II buffers in a bundle, (B) Interconnections at buffer heads, (C) Integration of bundles in the LHRS skid.

Each bundle has a weight of 3 t. Buffers are fire protected thanks to a specific insulation.

2.5.6 Connection to dispenser

The connection to dispenser in LHRS is shown in Figure 27.

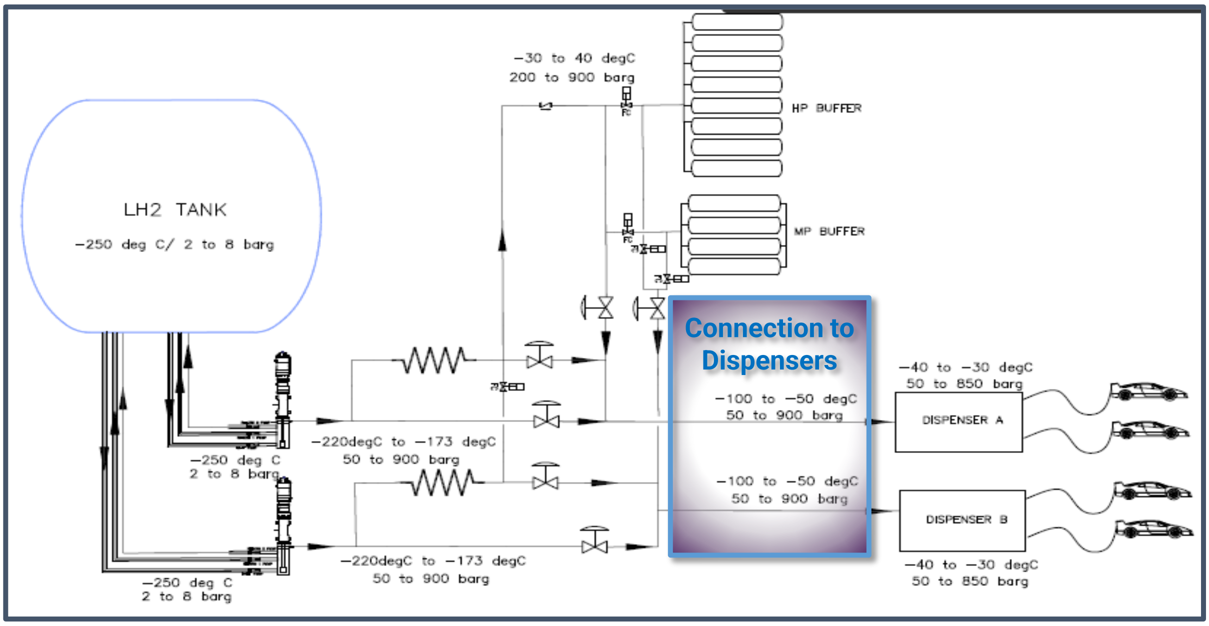
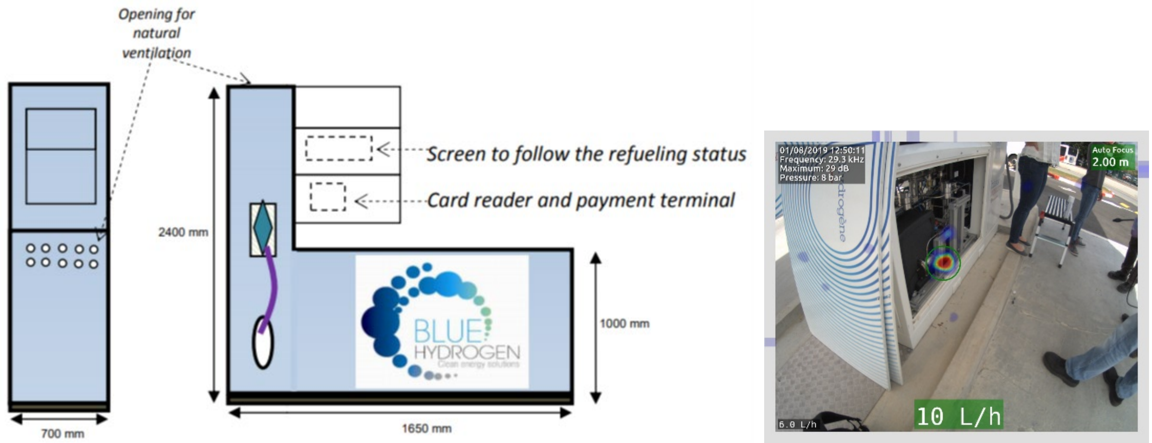


Figure 11. Process flow of a LH_2-based refuelling station – Connection to dispenser(s).

Lines can be more than 60 m long (200 ft). It requires to maintain them cold to perform successful refuelling. In order to cope with warming, a crossover solution was found and specific smart filling processes were established according to the variations of the load of the station during the day.

2.5.7 Dispenser



(A) (B)

Figure 12. (A) Dispenser main elements and indicative dimensions, (B) valve skid.

The dispenser enables a fast, easy, and safe connection between the station and the vehicle to process the fuelling. The configuration of a typical dispenser is shown in Figure 28.

The dispenser is composed of sub-assemblies:

- Distribution: Mast and valves panel with automatic filling valve, nozzle and breakaway,
- Control: HMI - Filling automatic control – Electrical panel – Access control.

As shown in Figure 29, within all the technical characteristics of the dispenser, the following features can be highlighted:

- Fuelling is automatic and requires minimum customer manipulations (nozzle + start push button),
- The vehicle connector or nozzle will be easy to use and approved as per SAE J2600 standard,
- A breakaway coupling ensures a mechanical interruption of the fuelling in case the vehicle drive away from the dispenser without removing the nozzle,
- IR nozzle (compliant with SAE J2799) for 700 bar line.


(A) (B)

Figure 13. (A) View of dual dispenser, (B) nozzle for refuelling.

The station is capable of dispensing hydrogen through two fuelling positions simultaneously into light duty vehicles (2-10 kg) with the dual dispenser.

Pressures of delivery according to the kind of dispenser are:

- 350 bar for car with range extender,
- 700 bar for fuel cell car,
- 350 bar for buses and trucks.

Maximal flowrates are:

- 60 g.s-1 for car refuelling,
- and 120 g.s-1 for bus and truck 350-bar refuelling.

Temperature of delivery is from -30°C to +40°C (fuelling protocol: SAE J2601 H70 T40).

In terms of safety, very close to the dispenser or inside, are:

- H_2 detector inside the dispenser,
- Natural ventilation of the dispenser,
- Flame detector close to the dispenser,
- Emergency shut-off buttons.

3. Production

3.1 Steam methane reforming

The steam methane reforming (SMR) process uses steam and a catalyst to make hydrogen from a light hydrocarbon such as methane or propane (see Figure 30 and Figure 31). The process basically strips the hydrogen from the hydrocarbon and from the water necessary to convert all the resulting carbon and oxygen to CO_2.

Figure 30. Air Liquide SMR plant.

The two main steps of the conversion are as follows:

$CH_4 + H_2O \rightarrow 3H_2 + CO$ - SMR

- Endothermic reaction: $\Delta H^o = + 206$ kJ.mol^{-1}
- Catalytic reaction: Ni/Al_2O_3
- 20 - 30 bar, 900 – 1000°C, few minutes

$CO + H_2O \rightarrow CO_2 + H_2$ - water gas shift

- Slightly exothermic reaction
- Catalytic reaction: CuO ; Fe_2O_3; Cr_2O_3
- 20 - 30 bar, 400°C (high temperature) / 200°C (low temperature)

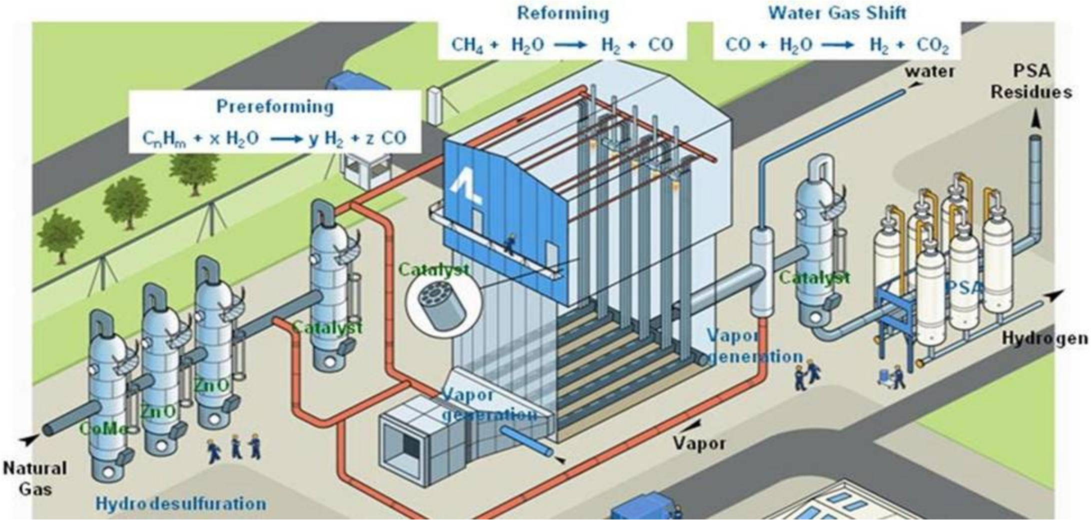


Figure 31. Sketch of a steam methane reforming plant.

3.2 Electrolyser

Water electrolysis comprises the splitting of water molecules into their constituent parts (H_2 and O_2) by passage of an electrical current (see Figure 32).

Figure 32. Principle of electrolysis process.

Figure 33 gives the following sketch of the process. Water is split by electricity to generate hydrogen and oxygen. The purity of the generation hydrogen is extremely high.

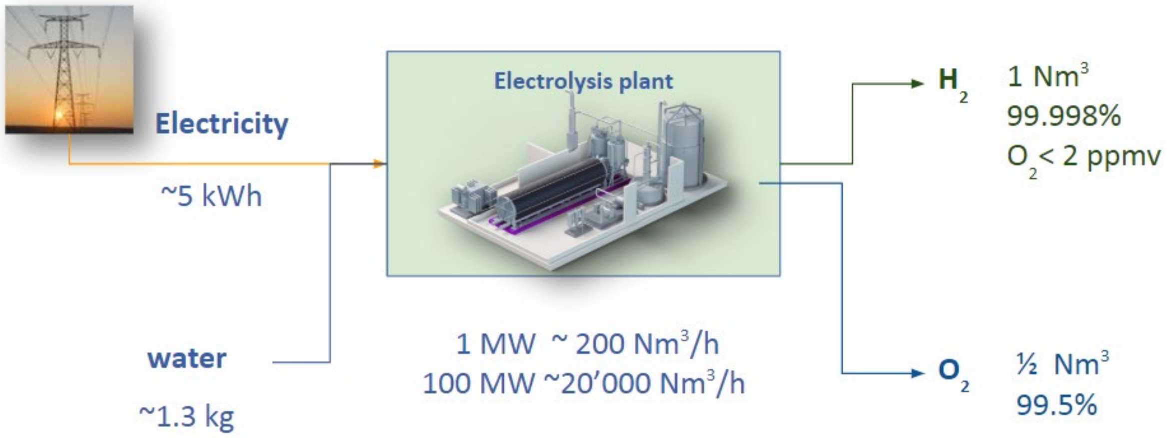
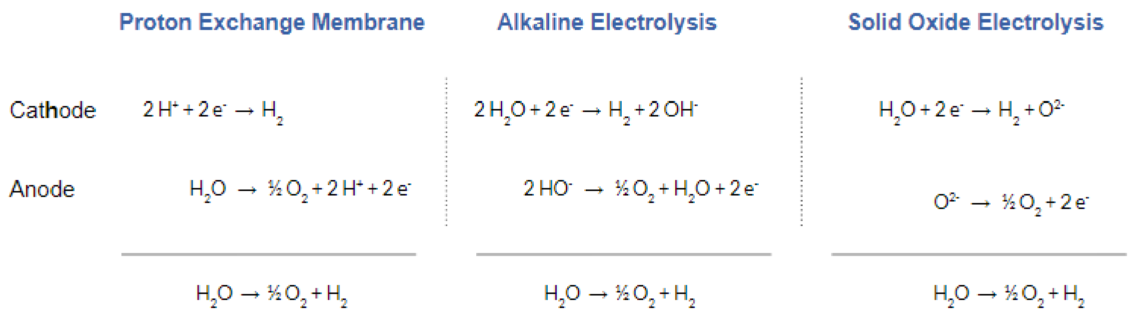


Figure 33. Electrolysis system.

There are several electrolysis existing technologies with different maturity levels (also named as technology readiness level (TRL)):

- Proton exchange membrane (PEM) electrolyser – TRL 8
- Alkaline electrolyser – TRL 9
- Solid oxide electrolyser – TRL 6

But the main electrolyser technologies are alkaline, which contain liquid electrolytes (potassium or sodium hydroxide), and solid polymer electrolyte, e. g. PEM, electrolysers. The main reactions of different electrolysers are shown in Figure 34.



	Proton Exchange Membrane	Alkaline Electrolysis	Solid Oxide Electrolysis
Cathode	$2H^+ + 2e^- \rightarrow H_2$	$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$	$H_2O + 2e^- \rightarrow H_2 + O^{2-}$
Anode	$H_2O \rightarrow ½O_2 + 2H^+ + 2e^-$	$2HO^- \rightarrow ½O_2 + H_2O + 2e^-$	$O^{2-} \rightarrow ½O_2 + 2e^-$
	$H_2O \rightarrow ½O_2 + H_2$	$H_2O \rightarrow ½O_2 + H_2$	$H_2O \rightarrow ½O_2 + H_2$

Figure 14. Main reactions according to electrolysis technologies.

The main differences between these technologies are:

- The separator: diaphragm or membrane.
- The electrolyte: liquid, solid, acid or basic.

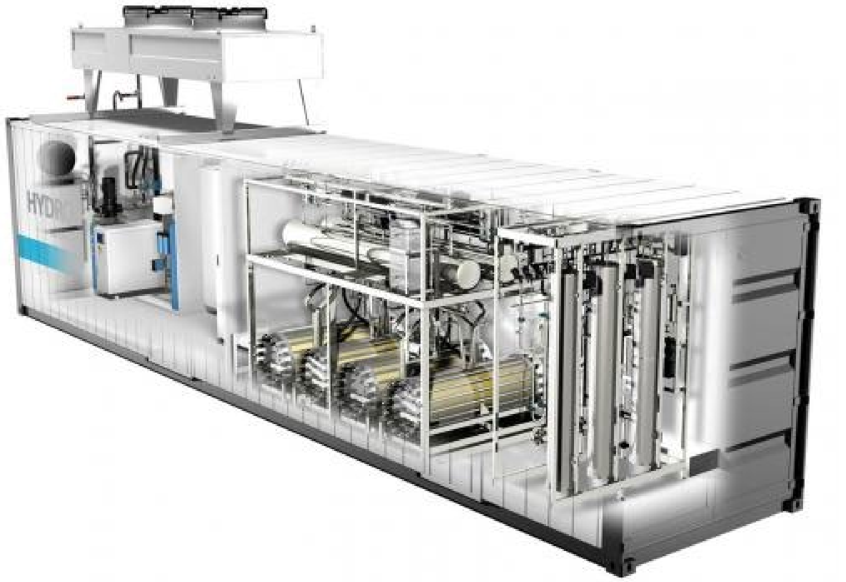


Figure 15. Sketch of Hydrogenics electrolyzer skid.

Besides the electrolyser unit, an on-site station generating hydrogen by electrolysis requires water purification systems and a hydrogen purification and drier unit to treat the hydrogen produced. Many electrolysers generate hydrogen at relatively low pressure, e.g. 10 to 25 bar, so further compression is required to elevate the pressure to storage pressures.

3.3 Liquefier

The liquefaction of H_2 is a highly energy intensive process. The minimum work required for the liquefaction of hydrogen (at ortho-para equilibrium) is 3.92 kWh of electricity /kg of H_2 or 0.12 kWh /kWh of H_2. Typical values for the whole process, however, are in the range of 8 - 14 kWh/kg for relatively large liquefaction units. Reducing the energy consumption of liquefiers is an active subject of development for the LH_2 industry (see IDEALHy FCH JU project for instance(https://www.idealhy.eu/).

Most plants (11) are located in North America. In Europe, plants (3) in France (see Figure 36), Netherlands, and Germany are operated with a total capacity of 19 $t.day^{-1}$. The largest plant size is currently 68 t/d (New Orleans, USA). The latest (2017) start-up liquefier (10 $t.day^{-1}$) is owned by Airgas (now Air Liquide) in Calvert City.

Figure 16. Air Liquide LH_2 filling stations
(left: Little Town, USA; right: Becancour, Canada).

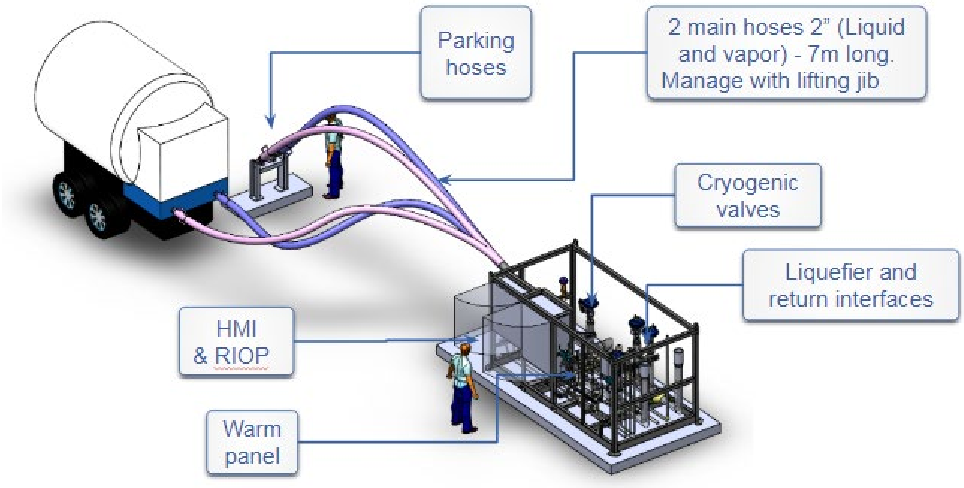


Figure 17. Generic loading bay ergonomy for LH_2 trailer filling.

Figure 37 shows the ergonomy of LH2 trailer filling. For transferring LH_2 from a storage to another (for instance from a large storage to a truck or from a trailer to a storage at use site), there are two methods:

- pressure build up (natural pressure build up or voluntary vaporization of LH_2 via a small external heat exchanger). Hence, the pressure in the “mother storage” becomes more than the pressure in the “daughter storage” and LH_2 transfer is easy. The main drawbacks of this method are a long operating time and an increase of the pressure of the “mother” storage leading sometime to the need of a pressure venting;

- pumping in the "mother storage" using an appropriate transfer centrifugal cryogenic pump. The main drawbacks of this method are the cost of the pump and the need of frequent maintenance of the pump mostly due to cavitation (low available NPSH - Net Positive Suction Head: difference between liquid pressure and saturation vapour pressure of the considered compound - due to low density of LH_2).

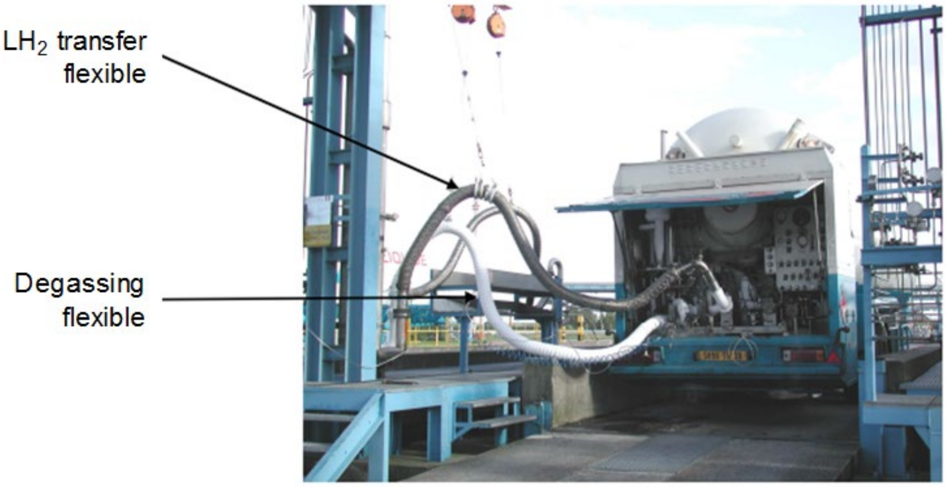
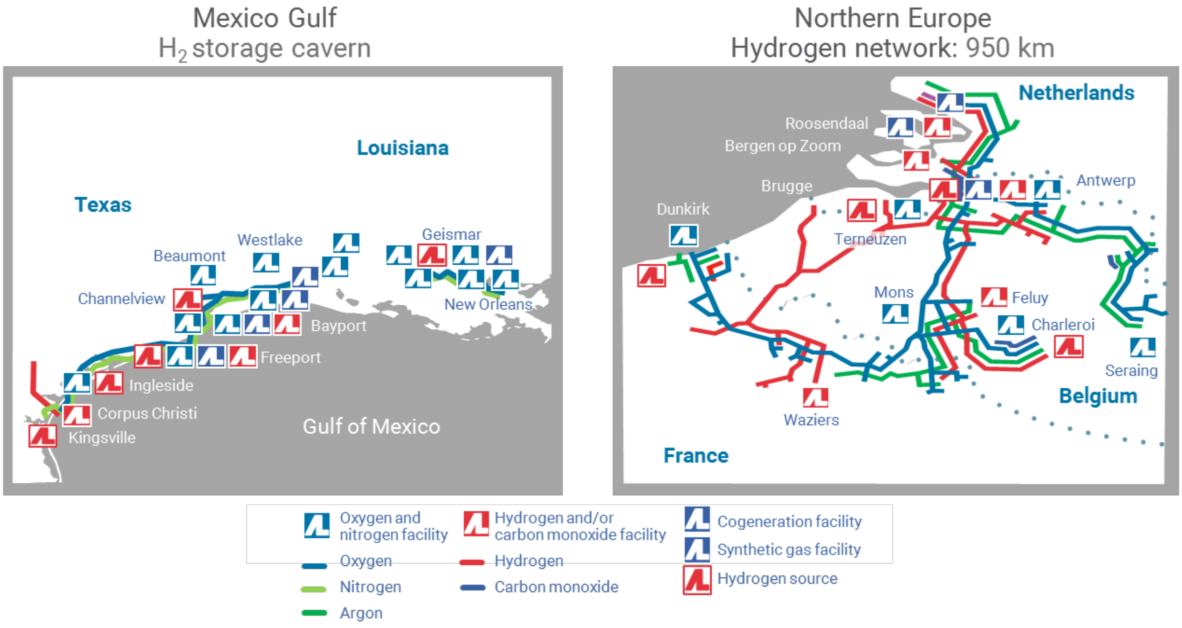


Figure 18. LH_2 trailer during transfer.

4. Pipelines


Mexico Gulf
H_2 storage cavern

Northern Europe
Hydrogen network: 950 km

Figure 19. Air Liquide hydrogen sources and network.

Pipelines are used in order to transport gaseous compounds in large amounts. According to the properties of the carried gas and the requirements of the customers the pressure in the pipelines can vary. For hydrogen transportation, the pressure inside pipelines can reach 100 bar. Figure

39 shows Air Liquide pipeline network and production plants for hydrogen, syngas and other gases in USA and northern Europe.

As illustrated in Figure 39, these pipelines are installed relatively close to the production plants. On pipeline network, according to the distance between the production plant and the customer, pressurization stations can be required in order to maintain the targeted pressure in the pipeline. It is important to note that only very stations are directly connected by pipelines. Trailers are the main mean. For some cases, on-site production can be interesting.

5. Safety features in HRS and other infrastructures

(what/where/for what/normal and abnormal (emergency) operation/ to do – to avoid during intervention)

Table 3. Safety features for electrolyser.

What	Where	For what
Process monitoring (pressure, temperature)	General	Detect leak and dysfunction
ATEX certified equipment	In the skid which is a confined space where leaks can occur	Avoid ignition sources
H_2 detection	Inside the skid	Activate warning, and shut-off valves if required in case of accidental leakage
Flame (UV/IR) detector	Outside the skid	Activate warning, and shut-off valves if required in case of accidental ignited release

Table 4. Safety features for gaseous hydrogen trailer.

What	Where	For what
Isolation valves	Cylinders	According to ADR, during transportation all storage are isolated by a valve
TPRD	Specifically on trailers with type-IV cylinders Located on the roof of the trailer, and upward directed	Avoid the pressurization and the burst of the cylinder in case of fire NB: not mandatory but set-up on some high capacity trailers with type-IV cylinders
Leak tightness test	Trailer storage	Avoid major leaks after trailer refuelling

Table 5. Safety features for high pressure hydrogen pipelines.

What	Where	For what
Pressure monitoring	Pipeline	Detect major leaks on network
Periodic inspection	Pipeline	Detect coating defects and avoid major leaks
Cathodic protection	Pipeline	Avoid pipeline corrosion

Table 6. Safety features for gaseous HRS.

What	Where	For what
Qualified and validated hose and fittings	Process and dispenser	Avoid accidental leakages
Periodic replacement of the hose	Dispenser	Avoid accidental leakages
H_2 detection	Inside the process container Inside the dispenser	Activate warning, and shut-off valves if required in case of accidental leakage
Flame (UV/IR) detector	In the process container Outside, close to the dispenser	Activate warning, and shut-off valves if required in case of accidental ignited release
Automatic shut-off valve	Several between H_2 storage and dispenser	Limit H_2 inventory in case of accidental release
Process pressure monitoring	General	Detect abnormal pressure drop due to leak or piping rupture
Naturally ventilated confined spaces	Process container Dispenser	Avoid to reach flammable limits of H_2-air mixture in case of accidental release
Forced ventilation	Process container for some models	Avoid to reach flammable limits of H_2-air mixture in case of accidental release if natural ventilation not possible or not efficient enough
ATEX certified equipment	In confined spaces where leaks can occur (i.e. skids and dispenser)	Avoid ignition sources
Hose grounded	Dispenser	Prevent sparks caused by static electricity during refuelling
Automatic leak test before filling	General	Avoid accidental leakages
Flow restrictors	General	Limit flowrate in case of release or piping rupture
Automatic closing time	General	Close H_2 feeding valves in case of hose rupture or leak

Hose break-away device	Dispenser	Avoid major leak by closing feeding flexible in case of tearing by forgetting to disconnect the vehicle
Shock protection (bollard)	Dispenser	Protect the dispenser from major mechanical aggression by vehicle accidental stamping and avoid catastrophic leak
Emergency punch stop	Few meters from the dispenser	Close H_2 feeding valves in case of emergency
Conductive (grounded) concrete slab	Dispenser	Prevent sparks caused by static electricity during refuelling

Table 7. Safety features for liquid hydrogen trailers.

What	Where	For what
Two safety valves with at least one pneumatics	Tank	According to ADR, during transportation all storage are isolated by a valve
Road safety valve	Tank	Evacuate overpressure
Rupture disc	Tank	Avoid burst of the storage in case of pressure increase
PRD	Tank	Limit the risk of boil-off

Table 8. Safety features for liquid hydrogen storages.

What	Where	For what
Pressure and temperature monitoring	Tank	Detect insulation default
Level monitoring	Tank	Avoid overfilling
Rupture disc	Tank	Avoid burst of the storage in case of pressure increase
PRD	Tank	Limit the risk of boil-off

Acknowledgement

The HyResponse project is acknowledged as the materials presented here are extended based on the original HyResponse lectures.

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