Co-funded by the Erasmus+ Programme of the European Union

# HySkills KA2 IO2 - Training Course on Hydrogen Transport and Delivery

## **IO2.6** – HYDROGEN TRANSPORT AND DELIVERY

In this training course, students will be able to understand the theory relating to hydrogen's transport and delivery options. Additionally, this module will focus on the types of compressors used to hydrogen in order for it to be transported as well as material selection properties for hydrogen pipelines.

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# 1 Hydrogen Storage Systems

## 1.1 How is Hydrogen Transported?

Domestic and external suppliers of hydrogen currently use roads or pipelines in order to transport hydrogen. This is conventionally done using tube trailers or cryogenic liquid hydrogen tankers. Other forms of less conventional transport options are chemical carriers. This involves the use of Hydrogen rich fuel i.e. chemical compounds that contain a large source of hydrogen atoms like ammonia, methanol, ethanol ($NH_3$, $CH_3OH$, $C_2H_5OH$, respectively) etc. There has also been reports of hydrogen being transported by air barges in special specific cases.

Hydrogen transport via integrated pipelines is the least expensive way to transport vast volumes of hydrogen gas and several lines have been built globally to facilitate this. Recently there has been vast drive and commitment via government to ensure the growth of hydrogen pipelines. Having this infrastructure in place should allow hydrogen to be delivered throughout
Previously lines would have been built near petroleum refineries or chemical plants. However, now there is more of a focus on natural gas and specific hydrogen gas pipelines.

Contrary to this, hydrogen gas can also be compressed and transported via existing road infrastructure using tube trailers. This option is used to move modest amounts of hydrogen at one time over relatively short distance when compared to gas pipelines. Generally, a distance of over 200 miles from point of production makes this option for many companies and suppliers cost-prohibitive.

FIGURE 34

Comparison of hydrogen transport options over various distances

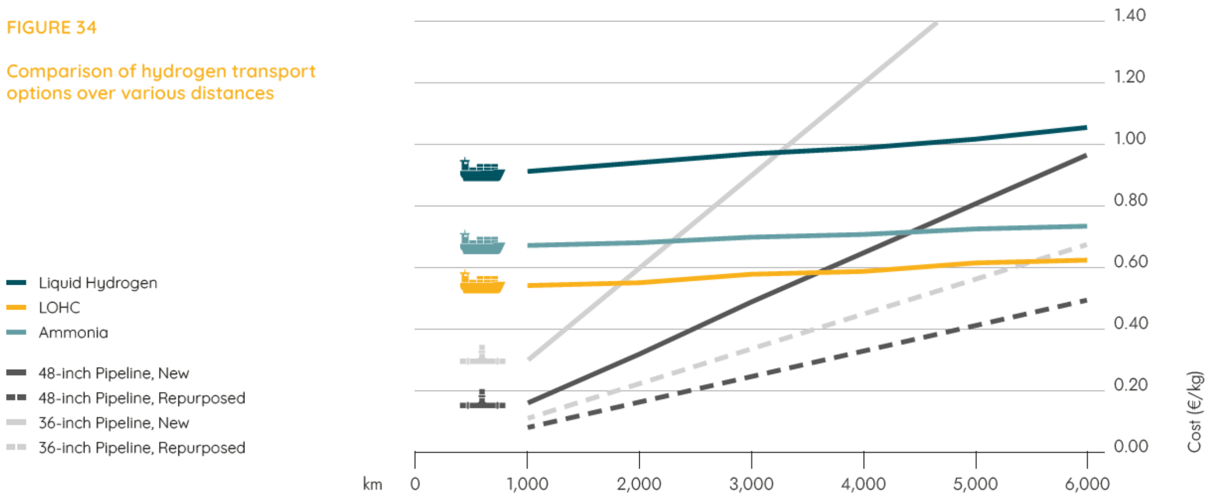



FIGURE 35

Map of example routes to compare shipping and pipelines as hydrogen transport methods

For imports from
(1) North Africa to Northern Europe and
(2) Saudi Arabia to Southeast Europe)

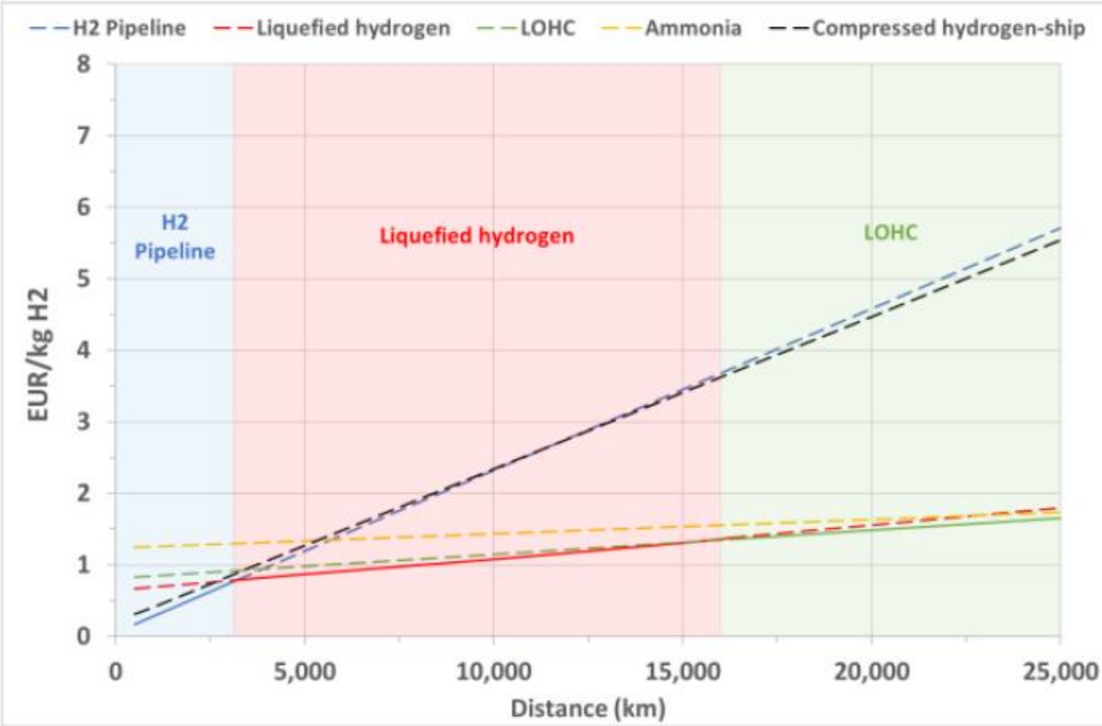



Figure 2 Hydrogen delivery costs for a simple (point to point) transport route, for 1 Mt $H_2$ and low electricity cost scenario.

## 1.2 Types of hydrogen storage systems

When hydrogen is stored as gas on surface, very large storage tanks operated at high pressure up to 300 bars are required. Hydrogen may also be stores underground in caverns, salt domes and depleted oil/gas fields.  Liquid hydrogen requires less volume, but the liquefaction process is costly and is more hazardous to handle due to the exceptionally low temperature required.  Metal hydride-tank-systems are being developed that can store hydrogen at a similar density to liquid hydrogen but are still in development.

By way of illustration, one kilogram of hydrogen has a volume of 12 cubic metres at NTP (Normal Temperature and Pressure or 1 atm, 20°C) and would fill the cargo bay of a large panel van and has the energy equivalent of one gallon of petrol or 33 kWh.

***Figure 1:*** *Large panel van.*

Compressing the hydrogen to 100 Bar reduces the volume to 130 litres equivalent to the size of a standard domestic hot water tank.  At 700 Bar, the operating pressure of a hydrogen vehicle, the volume is reduced to 26 litres.  The Toyota Mirai's two hydrogen tanks are 122 litre combined and have a combined weight of 87.5 kg and 5 kg capacity.

***Figure 2:*** *Water distributor with water cooler bottle pictured on top.*

The liquid volume of 1 kg hydrogen is 15 litres at 1 Bar and -252 °C, the same volume as a typical water cooler bottle.  Storing the same hydrogen in metal hydride requires 17 litres at 33 Bar and 20°C.

### 1.2.1 Transition from Fossil Fuels

There is a need to retrain qualified and experienced personnel from the fossil fuel industries for the hydrogen economy. Furthermore, the public are familiar with fossil fuels and it is useful to begin with the critical differences in properties between natural gas and hydrogen gas, and liquid natural gas LNG and liquefied hydrogen (LH2).

The choice of storage materials is different from natural gas. In hydrogen systems there is the potential for embrittlement of materials, hydrogen permeation, extreme low temperatures, and the possibility of electrostatic build-up and discharge. The higher pressures that hydrogen is stored at means the velocity of any hydrogen flow is large and the resulting impact and friction can create electrostatic build up on non-grounded or insulated materials. Such “charge collectors” may discharge and provide a source of ignition for hydrogen [1].

The safety-related hydrogen properties for hydrogen storage include its low density, low ignition energy, wide flammability range, and potential explosiveness. Table 1 summarizes safety critical hydrogen properties and compares them with those for methane and the impact on safety is highlighted.

*Table 1: Comparison of safety-related properties for hydrogen and methane* [2].

| Property | Hydrogen | Methane | Consequences for hydrogen safety |
|---|---|---|---|
| **Gas density at NTP** | 0.0827 kg/m³ | 0.659 kg/m³ | Can be positive for outdoor dispersion due to buoyancy, but only for passive clouds. High-pressure jet dispersion is dominated by momentum not buoyancy. Also negative because LFL may extend further for hydrogen jet than for methane. |
| **Flammability range (25 °C, 101.3 kPa)** | 4-75 vol% | 5-17 vol% | Negative, causing larger flammable cloud volume. LFL = 4% only for upward propagating $H_2$ flames, 8% is the lean limit of hydrogen combustion for practical applications. |
| **Autoignition temperature** | 585 °C | 537 °C | Neutral. |
| **Minimum ignition energy** | 0.017 mJ | 0.27 mJ | Negative. The ignition energy varies significantly with gas concentration (see Figure 4.1). For hydrogen concentrations up to 60%, the ignition energy is less than that of methane, with the absolute minimum being more than an order of magnitude less. |
| **Boiling point** | -253 °C | -161 °C | More challenging than $CH_4$. $LH_2$ can condense oxygen in air and cause unknown effects due to concentrated oxygen. Cryogenic effects different from LNG. |
| **Amount of energy, heat of combustion (lower heating value)** | 120 kJ/g | 50 kJ/g | For high-pressure gas releases at the same pressure and through the same hole size, the energy released for hydrogen is about 85% of that for methane. |
| **Maximum burning velocity in NTP air (cm/s)** | 265-325 | 37-45 | Negative. Results in much greater flame acceleration in congested areas and higher pressures in confined spaces due to the greater difficulty in venting the explosion fast enough. Rapid flame acceleration will give high explosion pressures in small clouds. |
| **Detonability measured in minimum mass of tetryl (Bull, 1979)** | 0.8 g | 16 000 g | Negative. Given greater flame acceleration with hydrogen (see above), DDT is a realistic if unlikely possibility. This is not the case for methane. A hydrogen detonation can propagate through the full cloud and increase the explosion severity significantly. |
| **Laminar diffusion coefficient at NTP (cm2/s)** | 0.61 | 0.16 | Negligible effect on dispersion which is dominated by turbulent diffusion. Other effects are more important, such as flow speed and low density causing longer momentum jets. |
| **Speed of sound at NTP (m/s)** | 1 294 | 446 | Negative, contributes to larger volumetric flowrates from leaks. Hydrogen has higher speed of sound and lower density. These cancel eachother out, resulting in similar jet momentum for releases with the same pressure and hole size. |
| **Compressibility factor Z average 0 to 300 barg** | 01. Jan | 0.9 | Minor effect of non-ideal gas. Causes a reduced mass leak rate for $H_2$ compared to using ideal gas law. For higher pressure, real gas effects are larger. |
| **Joule-Thomson effect when pressure is relieved** | Causes a small temperature increase | Causes a temperature decrease | Negligible since the temperature increase effect on hydrogen is only a few Kelvins. Requirement to limit $CH_2$ temperature in storage tanks restricts filling rates (relevant for $CH_2$ bunkering). |
| **Adiabatic flame temperature** | 2 045 °C | 1 875 °C | Hydrogen flames can be hotter. |
| **Heat radiated from flame to surroundings** | 17-25% | 23-33% | These ranges are indicative and vary with release rate. Smaller hydrogen flames are invisible. At large release rates, a hydrogen fire can have the same radiation level as methane. There is very limited large-scale hydrogen data. |

Comments give positive or negative safety effects for hydrogen compared with methane or natural gas systems. (NTP = Normal Temperature and Pressure, 20 °C and 101.3 kPa.)

The density of hydrogen gas at 0.083 kg/m$^3$ is an order of magnitude lighter than air 1.204 kg/m$^3$. Hydrogen's high buoyancy can be both an advantage and a hazard, and it needs to be considered in designing hydrogen systems. Due to the lower density of hydrogen, an outdoor hydrogen gas release will disperse quickly. However, for a high momentum jet with a release rate above a certain value, the gas is driven by its momentum, not buoyancy - under these conditions it can build a large gas cloud in a similar manner to a natural gas leak. This momentum effect is also relevant inside enclosed rooms, where a gas cloud can build up at all locations before it moves upwards to the ceiling.

A stoichiometric mixture is one where the amount of fuel is matched with the exact quantity of oxygen required for complete combustion with the maximum combustion energy being released. A stoichiometric mixture of hydrogen in air contains 29.5 (vol)% hydrogen, whereas for natural gas, it's 10 (vol)%. Although hydrogen thus requires a larger leak rate that natural gas, the higher pressure that hydrogen is stored ready provides high leak rates. Furthermore, an equal hole size gives hydrogen about three times the volumetric flow of natural gas in a like-for-like situation due to hydrogen's low viscosity and small molecule size. Due to the wide flammability range of hydrogen, it can build a larger flammable cloud compared with methane.

The autoignition temperatures for hydrogen and methane are comparable; hence, there are similar ignition probabilities from hot surfaces. While the minimum (spark) ignition energy for hydrogen concentrations below 15% is similar to methane, for higher hydrogen concentrations, the ignition energy is an order of magnitude lower. Therefore, richer hydrogen clouds have a far greater risk of ignition by electrical discharge than methane clouds.

When hydrogen burns, the only combustion product is water vapour. Clean hydrogen/air mixtures burn with a non-luminous, almost invisible, pale-blue hot flame liberating the chemically bound energy as heat (gross heat of combustion). The theoretical maximum flame temperature of a premixed stoichiometric mixture of hydrogen in air is as high as 2130 °C. Hydrogen flames can reach higher temperatures than other gases, but at the same time the radiation heat transfer out from the flame is normally lower. When the size of the fire increases, the radiation level also increases. For a large hydrogen fire, the radiation levels are comparable with those from hydrocarbon fires, and the flame becomes more visible. A hydrogen explosion could be a serious consequence from a hydrogen storage leak (and ignition) in an enclosed or semi-open space, and this scenario might for certain conditions lead to high explosion overpressures. Estimation of hydrogen explosion risk is therefore a key element in hydrogen risk analyses.

## 1.3 Liquid Hydrogen ($LH_2$)

Hydrogen in liquid (cryogenic) form is more energy intensive to store as a liquid compared with methane, due to hydrogen's extremely low boiling point (-253 °C). Since hydrogen has a narrow 20ºC temperature range for its liquid-phase it is more demanding to maintain hydrogen in the cryogenic liquid phase and to minimize boil-off compared with natural gas.

The potential cryogenic effects of a $LH_2$ release need to be considered. Air is composed of oxygen and nitrogen which liquefy or even solidify in contact with $LH_2$. As the boiling point of nitrogen (77.36 K) is lower than that of oxygen (90.19 K), liquid oxygen is concentrated when air is in contact with liquid hydrogen or LH piping, increasing the probability of ignition and serious explosion events.

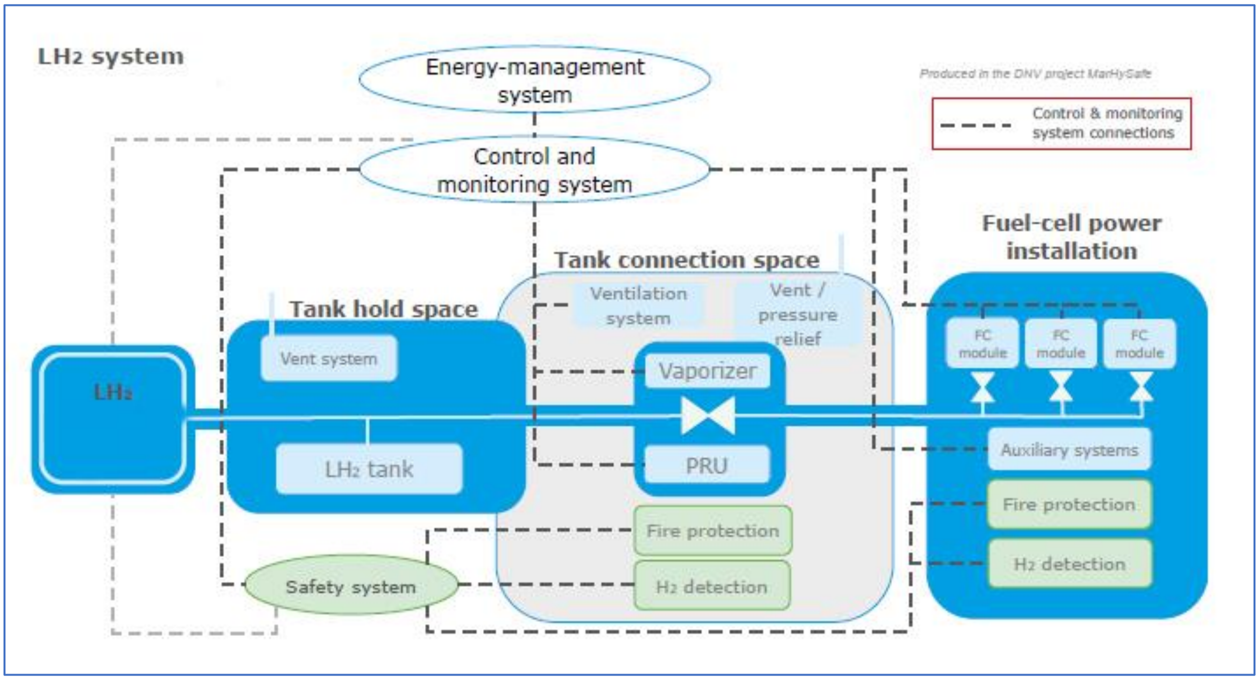



***Figure 3:*** *Liquid Hydrogen Storage System* [2].

As hydrogen at 461 kJ/kg has a lower latent heat of vaporisation than natural gas (510 kJ/kg), it needs less energy to evaporate than LNG, and therefore a similar size $LH_2$ spray will vaporize more easily and result in less cooling of the surrounding environment (e.g. steel) than a comparable LNG spray. Although a pool from spill of $LH_2$ is colder than a similar LNG pool, the $LH_2$ evaporates quicker. Fast evaporation of leaking $LH_2$ may lead to fast pressure build-up in confined spaces if venting is insufficient or ineffective. This needs to be considered in the dimensioning of $LH_2$ storage-tank hold space enclosures and related vent systems.

## 1.4 Cryogenic tanks for liquid Hydrogen ($LH_2$)

Cryogenic hydrogen is often referred to as liquid hydrogen ($LH_2$) and has a density of 70.8 kg/m$^3$ at its normal boiling point of -20K. Some other characteristics of LH2 are as follows:

- Critical pressure: 13 bar
- Critical temperature: 33K

The theoretical gravimetric density of LH2 is 100%. However, **only 20 wt.% $H_2$** can be achieved in practical hydrogen systems as of today. On a volumetric basis, the respective values are 80 and 30 kg/$m^3$, respectively. This ultimately means that $LH_2$ has a much better energy density than that of its counter-part compressed hydrogen; which is outlined below.

Some advantages and disadvantages of using cryogenic liquid hydrogen storage are as follows:

*Table 2: Advantages and Disadvantages of using cryogenic liquid hydrogen storage.*

| **Advantages** | **Disadvantages** |
|---|---|
| The high energy storage density can be reached at relatively low pressures. | There is a significant energy penalty, where approximately 30-40% of the energy is lost when $LH_2$ is produced. |
| Liquid hydrogen has been demonstrated in conventional commercial vehicles (i.e. BMW) | Another disadvantage with $LH_2$ is the boil-off during dormant periods, plus the fact that super-insulated cryogenic containers are required. |
| Subsequently, in the future it could be utilized as an aviation fuel source, as it provides the best weight advantage of any Hydrogen storage method. | |

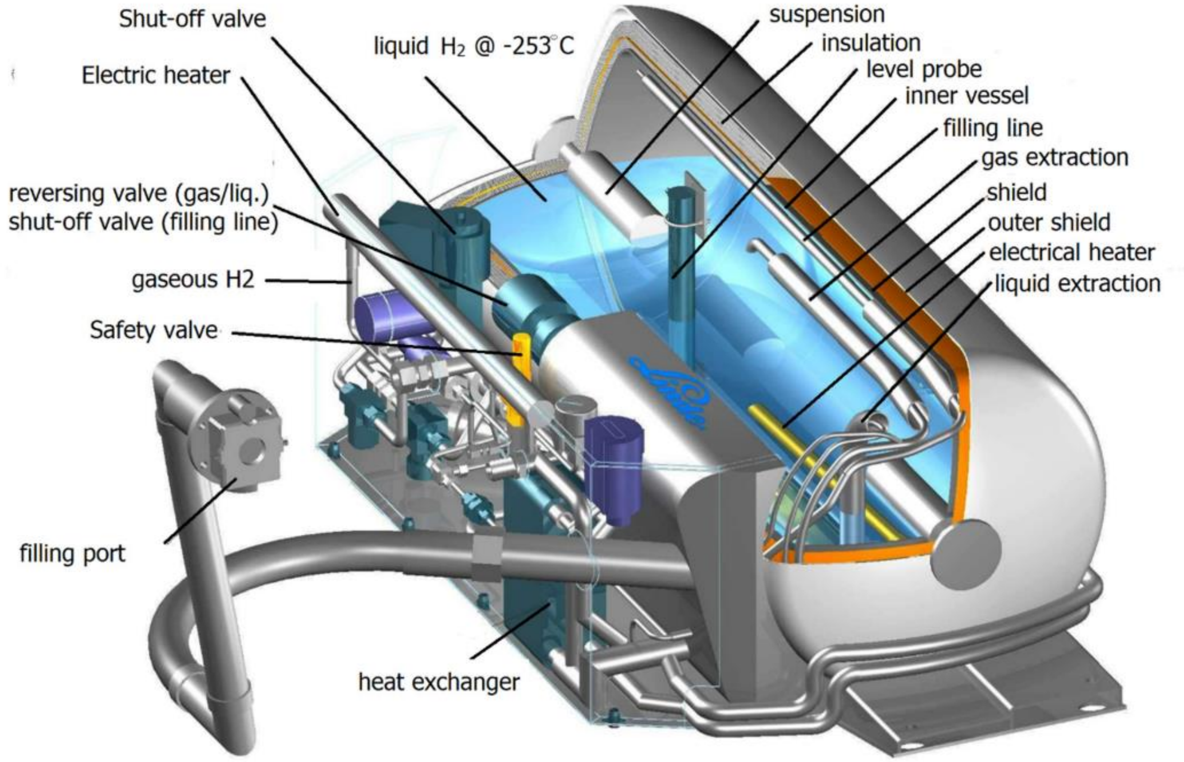



***Figure 4:*** *Schematic of a cryogenic hydrogen tank. Adapted from* [3].

The following are industry focused instructionalical videos on the safe operation of hydrogen road tankers for liquid hydrogen:


***Figure 5:*** *Linde video on the safe handling of hydrogen.*


***Figure 6****: Chart Industries video on Cryogenics.*

## 1.5 Compressed Hydrogen

Figure 4 outlines the system layout for compressed gas hydrogen ($CH_2$) storage. For storage of compressed hydrogen, the tank hold space needs to include the following items:

- $CH_2$ tank bundle(s), typically 350–700 bar.
- Fuel lines.
- Hydrogen vent system (pressure-relief system for the tank bundles).
- Ventilation system (artificial ventilation to provide continuous air changes to the tank hold space).
- Pressure regulating unit(s).
- Fire protection system.
- $H_2$ detection system.
- Safety systems (fire detection, firefighting system, emergency shutdown system).
- Structural fire protection (insulation towards neighbouring spaces).

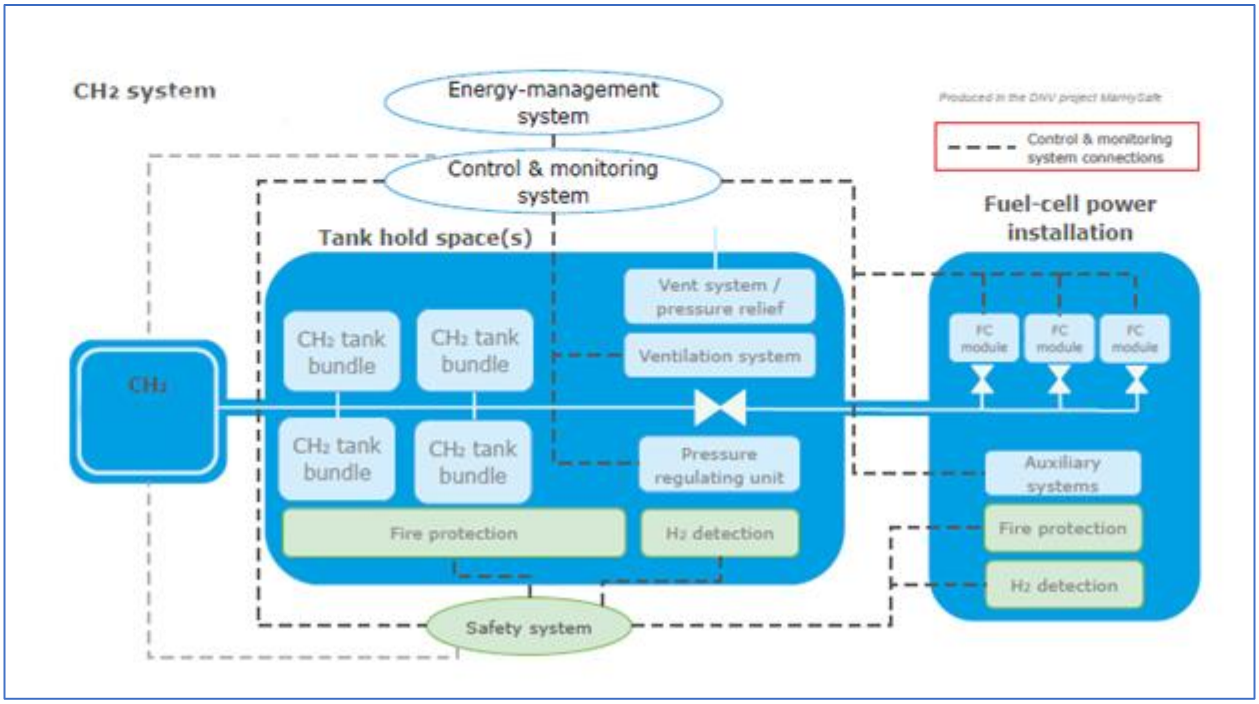



***Figure 7:*** *Generic block diagram for compressed gas hydrogen (CH2)* [2].

Transfer of hydrogen from a road tanker may be achieved by pressure balancing, or by direct compression of hydrogen gas before transfer to the storage facility. For pressure balancing, the road tanker pressure needs to be higher than that required by the receiving vessel. The alternative is to use a booster compressor to increase the pressure during transfer.

## 1.6 Composite tanks for compressed Hydrogen

Composites can be defined as “made up of several parts or elements. Composite research has gained significant interest in the last few years looking at numerous fields such as medical and automotive applications, buildings and storage vessels. This is widely down to being able to selectively choose some of the enhanced material properties to suit the end use application and the ability to manufacture these composites. Recently, composite research has had a focus on developing tanks for hydrogen storage as there is a vast drive to look at decarbonisation globally to help mitigate the effects of climate change. Normally these hydrogen storage tanks contain a carbon fibre composite on the outer layer of the tank. There are several advantages with the use of composite tanks for hydrogen storage:

- They do not require an internal heat exchanger and can be used for cryogas also with extra fittings.
- Their low weight (which can be adapted by the manufacture of the composite), meets key targets and the tanks are already commercially available, safety-tested, and well-engineered since numerous prototypes phases have been completed.
- Standard size tanks are available worldwide with specific codes for pressures in the range of 350-700 bar.

Subsequently, there are also some disadvantages that come with the use of this storage medium:

- There is a large physical volume required for the tanks and their ideal cylindrical shape does not always conform to available space depending on where it may be installed.
- There is a high energy penalty with compressing hydrogen gas to very high pressures. Similarly, with the compression phase there is also waste heat generated that is not always utilised.
- They still have a high cost of use (typically in the range of $500-600/kg Hydrogen).

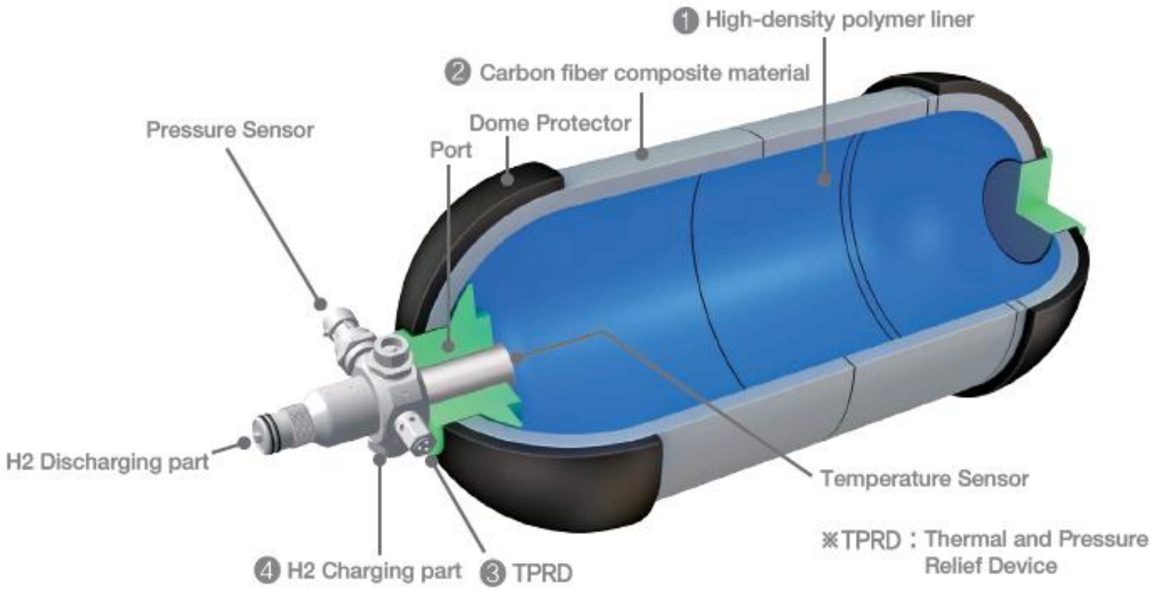



***Figure 8:*** *Hydrogen composite tank. Figure adapted from* [4].

## 1.7 Metal Hydride Storage

Using metal powder as a medium to store hydrogen has some obvious benefits: the same amount of hydrogen gas can be stored in a tank not even half the size compared to gas. Additionally, the metal powder based process works at a lower pressure and is easier to control in terms of temperature levels. In our process, the storage tanks are loaded with hydrogen gas at pressure levels below 40 bars. The pelletized metal alloy inside the tank reacts with hydrogen and builds metal hydrides.

Loading the tank with hydrogen is an exothermic process, meaning the absorption of hydrogen into the metal framework of the tank needs to be cooled and maintained at 20°C to keep the loading process stable and efficient.

For the unloading or desorption, the tank needs to be heated up to 60°C as the chemical reaction to remove hydrogen out of the metal lattice is endotherm. The higher the flow of hydrogen into or out of the tank, the more intensive is the chemical reaction. To increase the kinetic capacity for quick loading and unloading and for safety reasons, thermal management is a key aspect of the metal hydride-tank-system. Double tube tanks can assist an optimal heat transfer between the "active" material and the cooling/heating media.

***Figure 9:*** *GKN Powder Metallurgy's storage module consists of eight separately controlled storage tanks and can store 133 kWh electric power* [5].

**End of block 1**

<u>**START OF BLOCK 2**</u>

# 2 Pipeline construction materials

## 2.1 Why polyethylene?

When comparing polyethylene (PE) to other conventional pipework material such as ductile iron or steel, there are a significant number of advantages that should be considered. As polyethylene is a form of plastic, polyethylene will have a completely different type of degradation mechanism to that of the metals listed [6]. This is one advantage as the former metals would be susceptible to issues such as hydrogen embrittlement and hydrogen blistering [7].

## 2.2 PE80 vs PE100?

The denoted designations of PE80/PE100 are based on the long-term strength of the given materials, also more commonly known as the minimum required strength (MRS) in accordance with ISO 12162 - Thermoplastics materials for pipes and fittings for pressure applications - Classification and designation - overall Service (Design) coefficient [8]. The minimum required strength is determined by performing regression analysis in accordance with ISO 9080 [9] on the test data from results of long-term pressure testing. The regression analysis allows for the prediction of the minimum strength for a specific service lifetime. The data is then extrapolated to predict the minimum strength at 20 °C and at the specified 50-year design life [10].

*Table 3: Material parameters for PE80 and PE100 pipes.*

| **Material type (code)** | **Minimum required strength [MRS] (MPa)** |
|---|---|
| PE80 | 8.00 |
| PE100 | 10.00 |

The standard dimensional ratio (SDR) is used to describe the relationship between a pipe’s diameter and its wall thickness. This therefore translates directly with the pressure rating of the pipe.

$$SDR = \frac{Outer\ diameter\ of\ Pipe\ (Minimum)}{Wall\ thickness\ of\ Pipe\ (Minimum)}$$

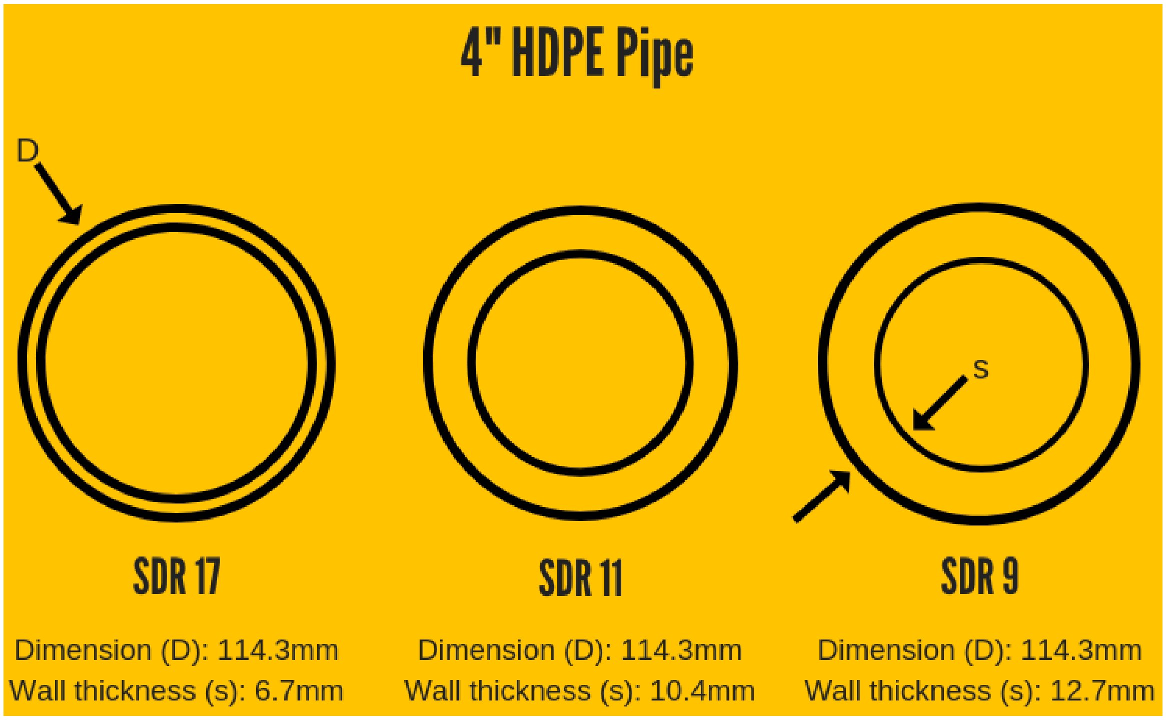



***Figure 10:*** *A sample of 4-inch HDPE pipe with an SDR rating of 17, 11, 9, respectively and their associated wall thickness. Adapted from* [11].

# 3 Hydrogen compressors

A hydrogen compressor is a type of device that compresses hydrogen gas to a higher level of pressure, occupying a smaller volume compared with atmospheric conditions. The raising of hydrogen's pressure allows more of the gas to be transported at one particular time in a given volume constraint such as a tube trailer/truck. Additionally, the increase in hydrogen pressure is needed in hydrogen filling systems and is vital in maintaining the stable operation of hydrogen refuelling stations [12].

## 3.1 Centrifugal compressor

The centrifugal compressor is by far the most ideal compressor for use in pipeline applications. This is mainly down to their moderate compression ratio and their high throughput. Centrifugal compressors work in practice by rotating a turbine at very high speed to compress a gas. Due to hydrogen's low molecular weight (2g/mol for diatomic hydrogen, $H_2$) in comparison with that of natural gas (Methane, 16g/mol, $CH_4$), hydrogen centrifugal compressors must operate at tip speeds 3 times faster than that of methane compressors to achieve the same compression ratio [13].

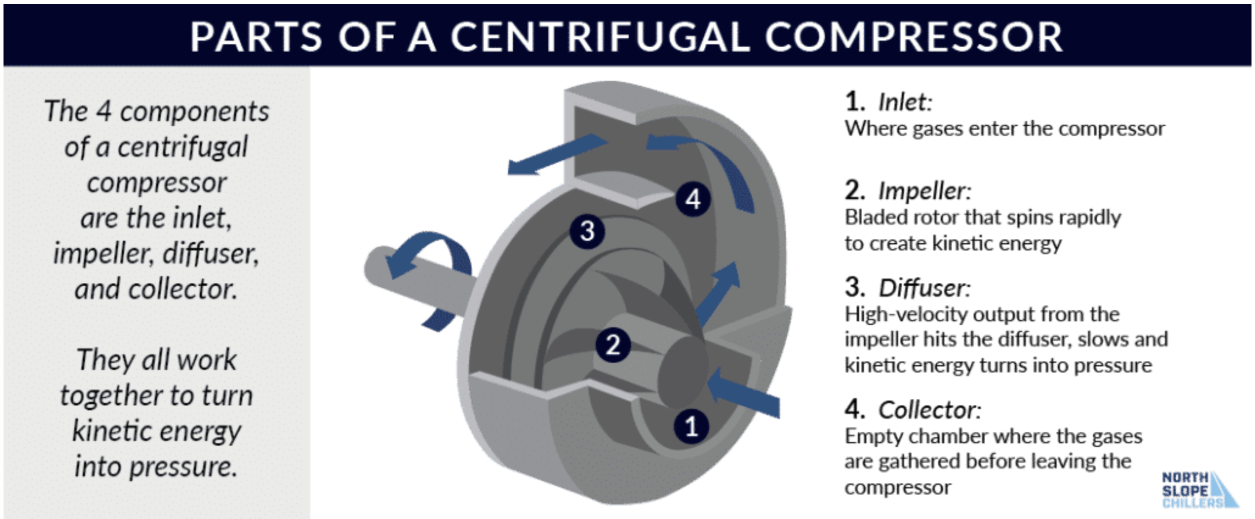



***Figure 11:*** *Principle of a centrifugal compressor and its associated parts. Adapted from* [14].

## 3.2 Rotary compressor

Rotary compressors work on the principle of rotation of gears, vanes, lobes, rollers or screws. Hydrogen compression is a challenging application for positive displacement compressors due to the tight tolerance to prevent leakage.

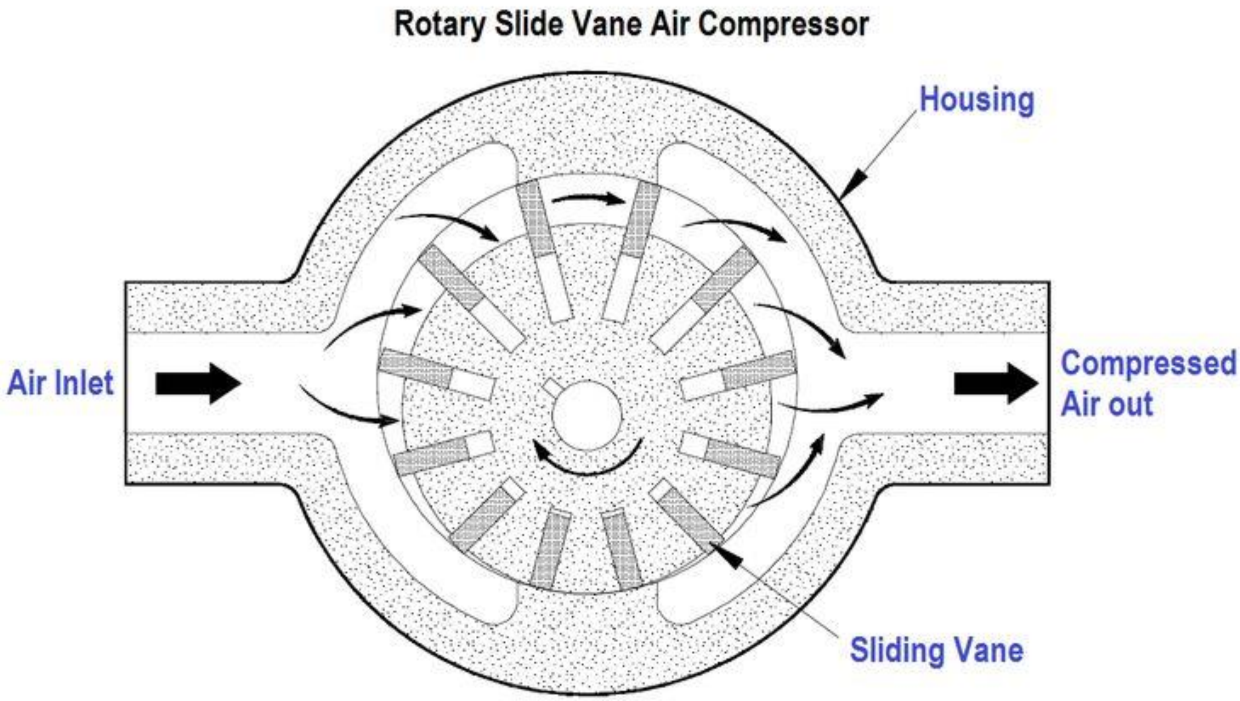



***Figure 12:*** *Principle of a rotary compressor and its associated parts. Adapted from* [15].

## 3.3 Reciprocating compressor

Reciprocating compressors utilise a motor with a linear drive to move a diaphragm or a piston back and forwards. This type of motion compresses the hydrogen by reducing the volume that the gas occupies. Reciprocating compressors are also sometimes known as “recips” as a shortened term, are the most commonly used compressor for applications that require a very high compression ratio.

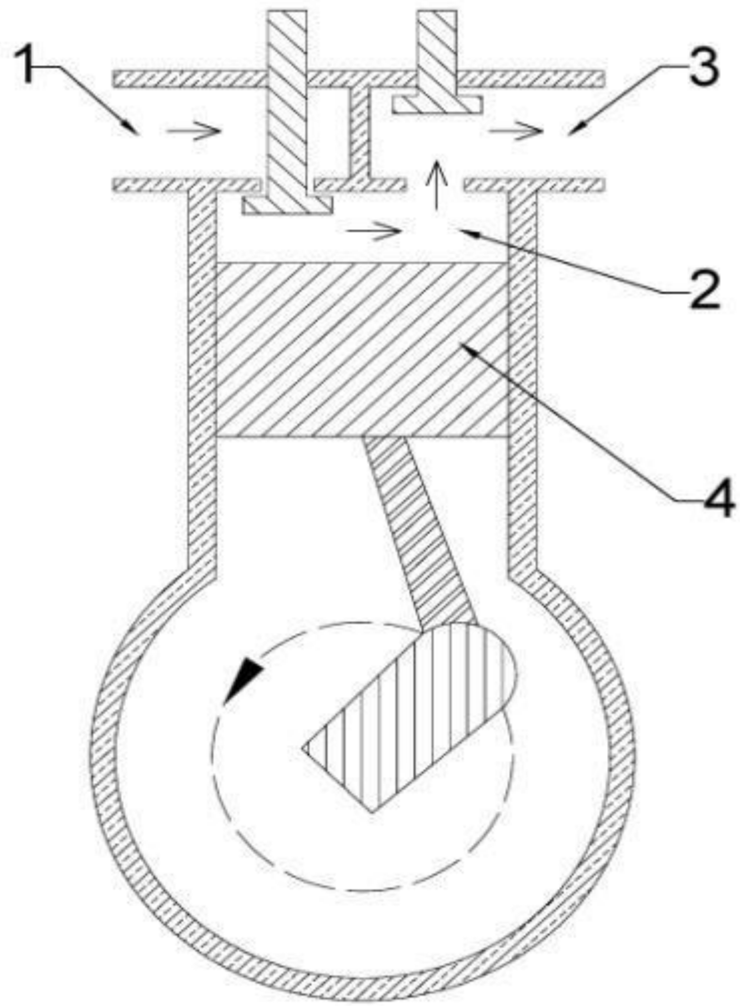



***Figure 13:*** *Diagram of a reciprocating compressor with its associated parts: 1) compressor suction area 2) working area, 3) pressure area, 4) piston. Adapted from* [16].

## 3.4 Ionic compressor

Ionic compressors are similar in nature to reciprocating compressors but use ionic liquids in place of the piston. These compressors do not require seals or bearings, which are two common sources of failure in reciprocating compressors. These types of compressors are now available at the adequate pressures and capacities needed for hydrogen refuelling stations.

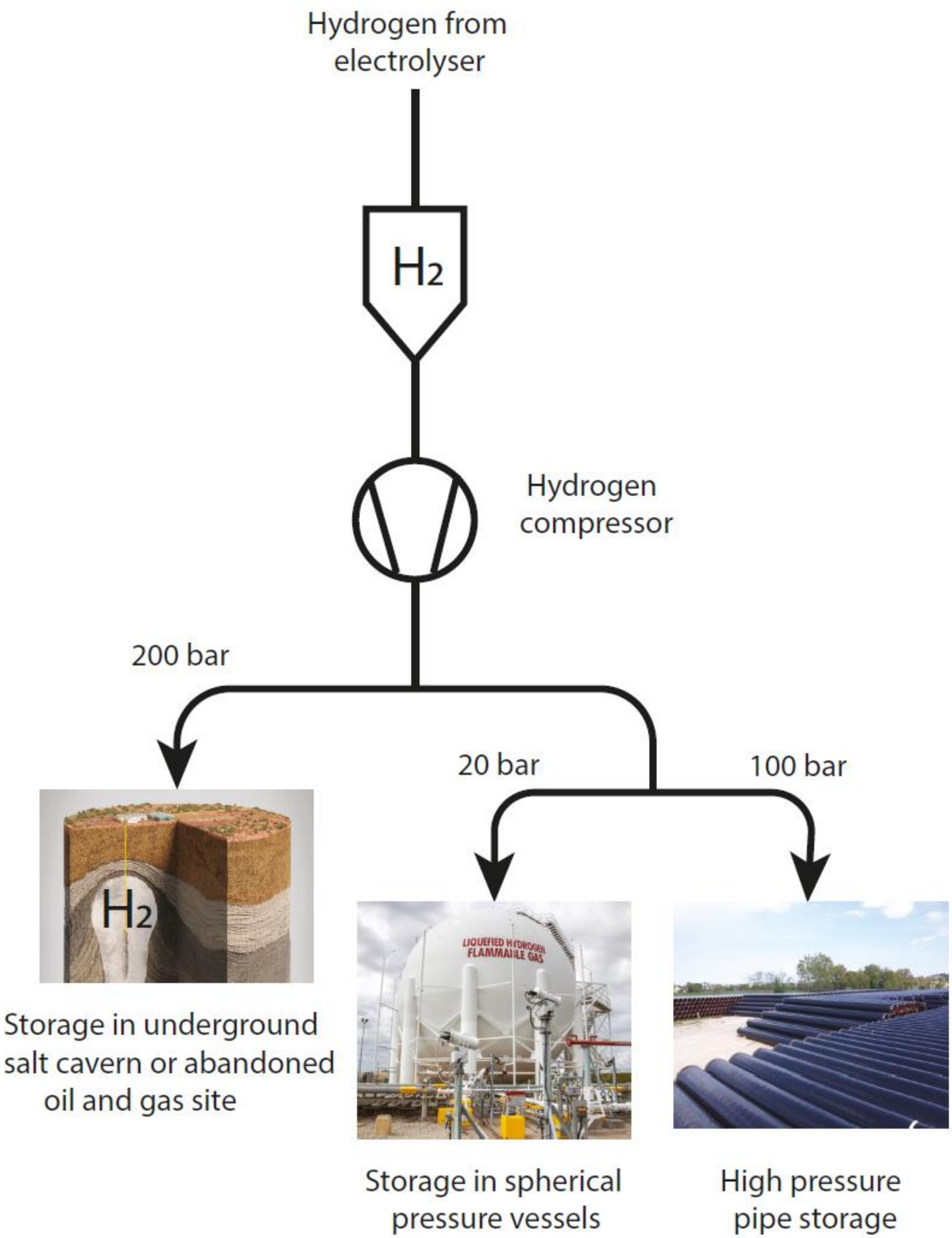



***Figure 14:*** *Overview of pressurised large scale gaseous hydrogen storage. Adapted from* [17].

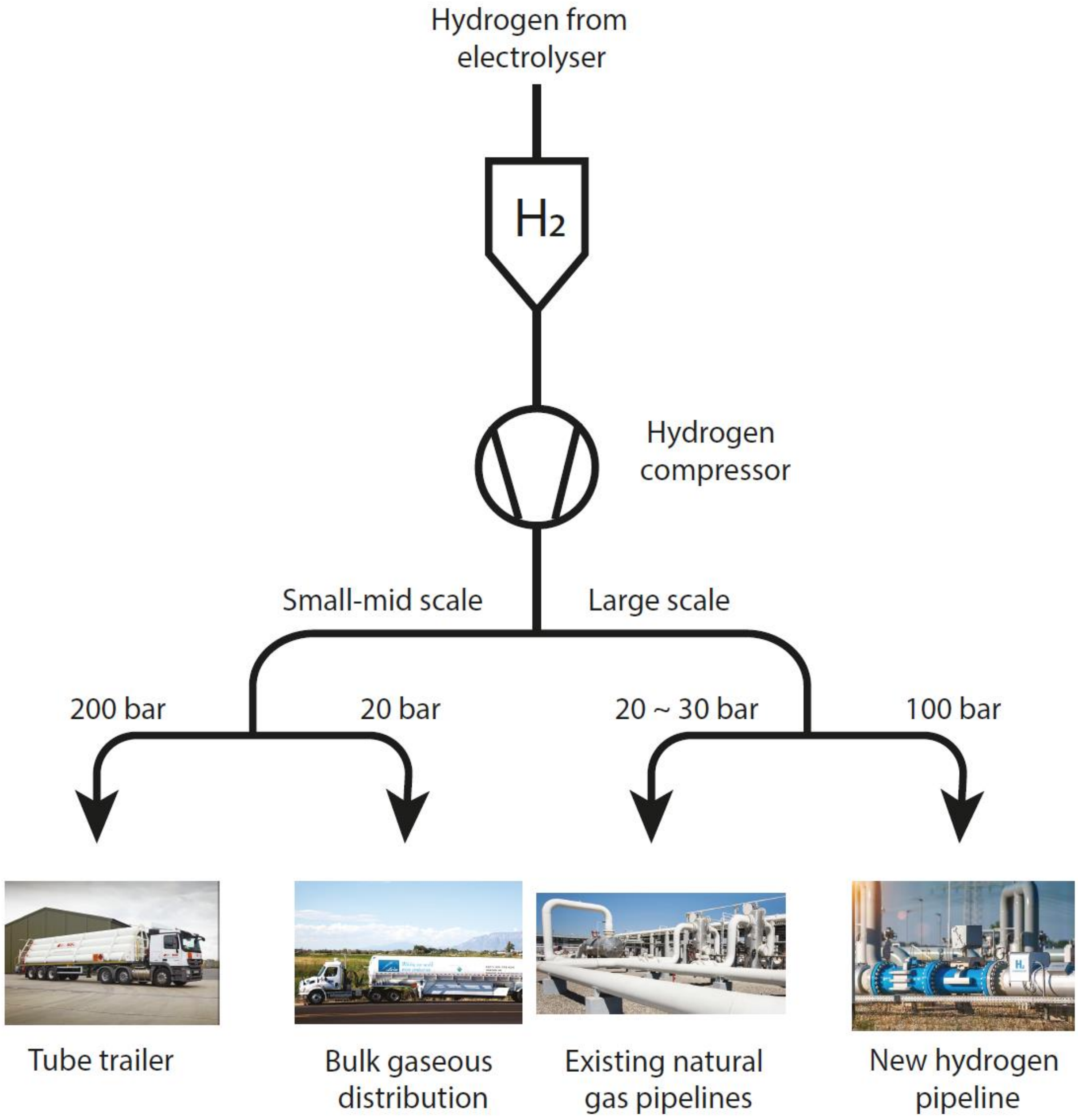



***Figure 15:*** *Pressure requirement for various methods of pressurized gaseous hydrogen distribution. Adapted from* [17].

*Table 4: An overview and comparison between numerous types of hydrogen compressors.*

| Compressor type | Max Flow [Nm$^3$/h] | Max pressure [MPa] | Compression Method | Disadvantages | Advantages |
|---|---|---|---|---|---|
| **Electrochemical compression** | 470 | 100 | Electrochemical – positive displacement. | Difficult in manufacturing cell assembly. | Low cost. |
| **Cryogenic hydrogen compressor** | 1000 | 90 | Thermal – Positive displacement. | High energy cost for liquefaction. | High hydrogen density. |
| **Diaphragm compressors** | 581 | 28.1 | Positive displacement. | Diaphragm failure. | Seal less design. |
| **Centrifugal compressor** | 50,000 | 84.7 | Dynamic. | Operational complexity. | Low moving parts. |
| **Liquid piston compressor** | 750 | 100 | Positive displacement. | Cavitation phenomena. | Long service life. |
| **Linear compressor system** | 112 | 95 | Positive displacement. | Sophisticated piston control. | High reliability. |
| **Adsorption compressor** | 560 | 10 | Thermal. | Difficult in thermal management. | No moving parts. |
| **Reciprocating piston compressor** | 4800 | 85.9 | Positive displacement. | Difficult maintenance. | Very high discharge pressure. |
| **Metal hydride** | 10 | 30 | Thermal. | Low efficiency. | No moving parts. |

# 4 Relevant Regulations and Standards:

## 4.1 International hydrogen Standards

Hydrogen has been used throughout the world for a long time as an industrial gas (chip manufacture, glass manufacture and cooling gas in power plant generators) and in the space industry. Therefore, some standards and codes covering industrial use of hydrogen are in place, and some of these may be relevant for the use of hydrogen as energy vector to achieve net zero. Standardisation work related to the use of hydrogen as fuel in the transport sector is newer, but the regulatory regime for the required hydrogen filling stations, and for hydrogen FC vehicles, is becoming established. These include standards from the American Society of Mechanical Engineers (ASME) and the American Petroleum Institute (API), EU directives and standards as well as ISO and IEC standards.

Global standard development organisations such as ISO (International Organisation for Standardisation) and IEC (International Electrotechnical Commission) focus on developing component standards and generic protocols. International (ISO and IEC) component standards are being developed to eliminate global barriers to trade. In this way, a hydrogen component (such as a hose) or an assembly (such as a reformer or dispenser) can meet the same design and testing criteria and thus can be sold across the globe without additional requirements.

Installation requirements of those components or assemblies (for example, separation distances) can vary by jurisdiction, but their design and testing requirements should not. Since ISO and IEC standards are developed by the broadest spectrum of international stakeholders, they become ‘super’ standards. They should thus replace any existing similar or analogous national component standards. This consideration has the following implications:

- National component standards including those that served as seed documents for the development of international standards must be prepared to harmonize their design and testing requirements with the international standards. National standards should become harmonized with adopted international standards, where the only deviations are references to specific relevant national standards and regulations and, when justified, to climatic conditions.

- National legislation and installation codes should recognise international standards or their national harmonised adoptions as the only/preferred listing or certification components standards.
- National installation codes should remove any design and testing requirements related to components and assemblies and focus solely on their installation requirements. They should also explicitly reference available international component standards or their national harmonized adoptions for design and testing requirements.

### 4.1.1 Hydrogen technologies

The ISO (International Organisation for Standardisation) with its Technical Committee (TC) 197 is a leading international body for standard documents for hydrogen technologies. The secretariat of this TC is held by the Standards Council of Canada (SCC). ISO/TC 197 is composed of 20 participating countries, including active participation from all the G7 countries, as well as China, Korea, India, Russia, etc. In combination with observing members, ISO/TC 197 global participation covers most of the biggest world economies. The scope of ISO/TC 197 is standardization in the field of systems and devices for the production, storage, transportation, measurement and use of hydrogen. A recently planned and launched project for the development of a three-standards package for gaseous hydrogen fuelling protocols for hydrogen-fuelled vehicles (under the ISO 19885 series) is particularly relevant. A separate series number has been reserved for liquid hydrogen fuelling protocols – ISO 19886. This is currently a placeholder for future new work item proposals.

ISO TR 15916 Basic considerations for the safety of hydrogen systems and gives an overview of safety-relevant properties and related considerations for hydrogen. Annex C gives an overview of low-temperature effects of hydrogen on materials, and the document also suggests suitable material-selection criteria, including how to consider hydrogen embrittlement.

### 4.1.2 Storage Vessels

- ISO 11114-2. Gas cylinders Compatibility of cylinder and valve materials with gas contents — Part 2: Non-metallic materials.
- ISO 21013-1. Cryogenic vessels Pressure relief accessories for cryogenic service —Part 1: Re-closable pressure relief valves.
- ISO 21013-3. Cryogenic vessels Pressure relief accessories for cryogenic service —Part 3: Sizing and capacity determination.
- ASME VIII-1, Div.1
- ASME Boiler and Pressure Vessel Code.
- ASME B 16.34 Valves Flanged, Threaded and Welding End.
- API 520Sizing, Selection and Installation of Pressure-relieving devices.

### 4.1.3 Standards for all valve types

- EN 12516-1/-2/-3/-4 Industrial valves:
  - Part 1 - Shell design strength
  - Part 2 - Calculation method for steel valve shells
  - Part 3 - Experimental method
  - Part 4 - Calculation method for valve shells manufactured in metallic materials other than steel
- EN 13445 Unfired pressure vessels.
- ASME B 16.34: Valves Flanged, Threaded, and Welding End.

### 4.1.4 Pressure relief valve applications:

- EN ISO 21028-1 Cryogenic vessels — Toughness requirements for materials at cryogenic temperatures — Part 1: Temperatures below -80 °C
- ISO 4126 Safety devices for protection against excessive pressure —
  - Part 1: Safety valves
  - Part 4: Pilot operated safety valves
- EN 13648-1 Cryogenic vessels — Safety devices for protection against excessive pressure — Part 1: Safety valves for cryogenic service.
- ISO 11114-1. Gas cylinders; Compatibility of cylinder and valve materials with gas contents — Part 1: Metallic materials.
- ISO 21013-1. Cryogenic vessels; Pressure relief accessories for cryogenic service — Part 1: Re-closable pressure relief valves.
- ISO 21013-3. Cryogenic vessels; Pressure relief accessories for cryogenic service — Part 3: Sizing and capacity determination.
- ASME VIII-1, Div.1; ASME Boiler and Pressure Vessel Code.
- ASME B 16.34: Valves Flanged, Threaded and Welding End.
- API 520; Sizing, Selection and Installation of Pressure-relieving Devices.

# 5 Safe Gaseous Hydrogen Delivery Procedure

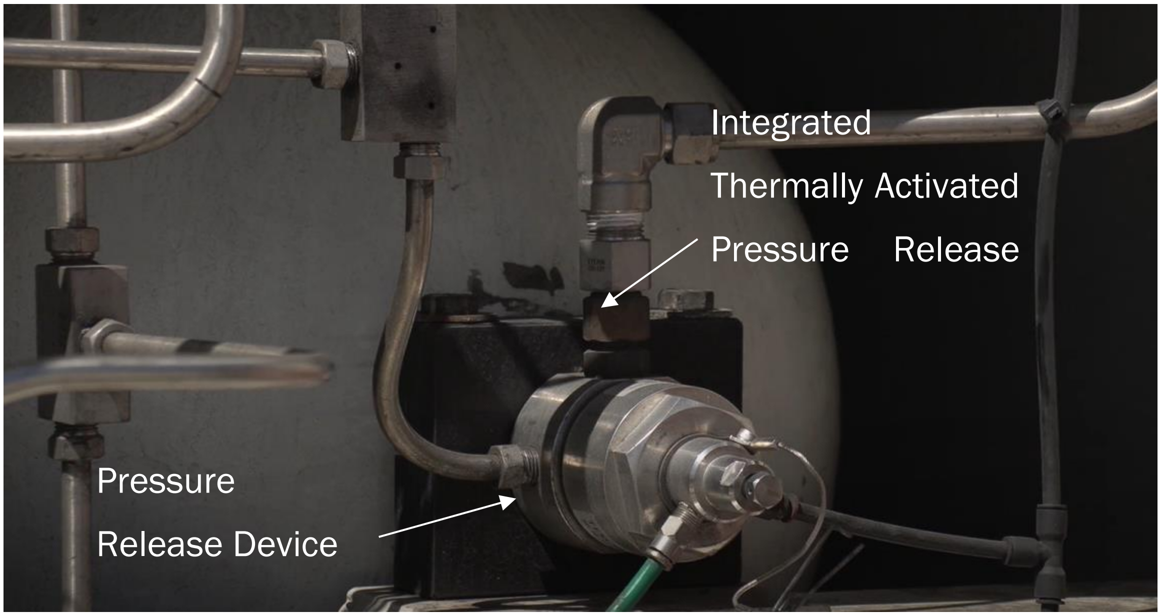
Name_______________________ Work Based Recorder________________________ Assessor______________________ Date__________ Location of Hydrogen Storage Facility___________________________________ Job Reference__________________________________________

| | Yes | No |
|---|---|---|
| You identify every item of your clothing is non-sparking and fire resistant. | | |
| You receive permission to enter hydrogen storage facility. | | |
| You identify any obstacles preventing safe offloading and have them removed. | | |
| You park your tanker in designated hydrogen offloading bay. | | |
| You place four chocks on opposite sides of front and rear wheels | | |
| You identify storage facility tube types: steel or composite. | | |
| You identify the facility's emergency shut off value in case of leak | | |
| You identify correct hydrogen receiving coupling. | | |
| You bond the receiving facility to your truck to ensure there is no sparks generated when connecting pipes | | |
| You ground your truck to ensure there are no sparks generated by build-up of static electricity | | |
| You identify maximum pressure of receiving facility. | | |
| You identify non-sparking tools. | | |

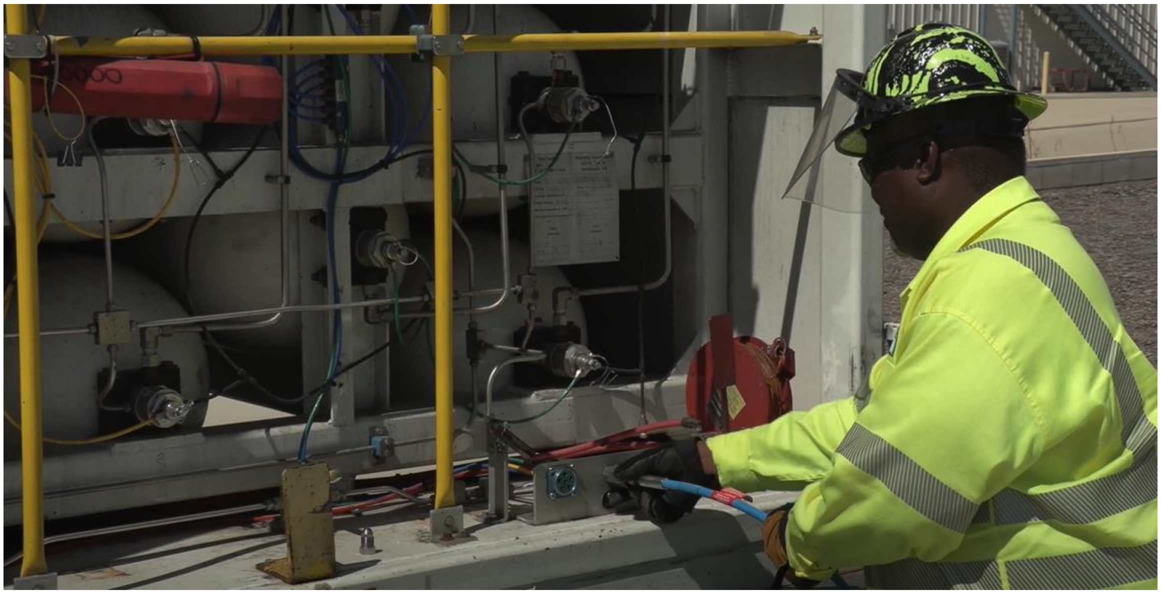
| | | |
|---|---|---|
| You fit coupling onto delivery hose. | | |
| You identify correct connection tightness. | | |
| You open receiving valve on facility. | | |
| You prove there are no leaks by using hydrogen leak detectors. | | |
| Run the instruments sensitivity test to ensure that the detector has the sensitivity to detect hydrogen 1 ppm | | |
| You hold the detector within 10 mm of every connection you have made while you take a hydrogen concentration measurement. Due to rapid dispersion, electronic hydrogen detectors have difficulty detecting leaks and it is time consuming to locate the leaking fitting. | | |
| You slowly open discharge valve on tanker. | | |
| You monitor the quantity of hydrogen unloading on flow meter. | | |
| You monitor pressures in the tanker and facility | | |
| You identify when the maximum working pressure of facility is approached and operate below this pressure at all times using the tanker discharge valve. | | |
| You identify that hydrogen pressures have equalized. | | |
| You close the tanker discharge valve. | | |
| You open venting valve in the connection hose. | | |

| | | |
|---|---|---|
| You identify that pressure in the connection hose is eliminated. | | |
| You uncouple the receiving connection hose. | | |
| You identify hydrogen leaks by observing monitoring sensors. | | |
| If a leak is detected you operate the emergency shut off valves on both the tanker and the receiving facility, move to the furthest perimeter away from buildings and report the leak to your line management. | | |
| You report any leaks to your line management. | | |
| You remove the bonding (grounding) wire from you trailer. | | |
| You identify hazards to exiting the facility and have them removed. | | |
| Request the removal of hazards as appropriate. | | |
| You remove the chocks from the front and back wheels | | |
| You exit facility | | |
| **For Assessor use only** | | |
| Industrial standards for Safe Hydrogen Delivery followed and achieved | | |


All the tubes on a gaseous trailer are interconnected via a manifold. Identify the type of tube construction: Steel tubes have Pressure Release Devices (PRD's) only and can withstand elevated temperatures. Composite tubes are reinforced with combustible materials and lose their strength in a fire. Therefore, composite tubes have Pressure Release Devices (PRD's) with integrated Thermally Activated Pressure Release Device (TPRD's)




Connecting the delivery hose of the hydrogen storage facility.



## 5.1 Safe Gaseous Hydrogen Safety Checklist

List every precaution that is required to prevent hydrogen fires:

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1. Record below the two tube construction types and how they are identified?

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2. How are hydrogen leaks detected?

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3. Why is it important to report any leaks/deviations to your line manager?

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| |

# 6 Safe Liquid Hydrogen Delivery Procedure

Name______________________ Work Based Recorder_______________________ Assessor_____________________ Date__________ Location of Hydrogen Storage Facility__________________________________ Job Reference________________________________________

| | Yes | No |
|---|---|---|
| You identify every item of your clothing is non-sparking and fire resistant. | | |
| You receive permission to enter hydrogen storage facility. | | |
| You identify any obstacles preventing safe offloading and have them removed. | | |
| You park your tanker in designated hydrogen offloading bay. | | |
| You wear correct PPE including eye and face protection and cryogenic gloves. | | |
| You never touch the pipelines during liquid hydrogen transfer. Severe frostbite results from any contact and beware of hydrogen vapour especially in eyes. | | |
| Should your skin come into contact with any cooled surface run warm water over affected area. | | |
| You place four chocks on opposite sides of front and rear wheels. | | |
| You identify storage facility is for liquid hydrogen in insulated tanks. | | |
| You identify the facility's emergency shut off value in case of leak. | | |
| You bond the receiving facility to your truck to ensure there is no sparks generated when connecting pipes | | |

| | | |
|---|---|---|
| You ground your truck to ensure there are no sparks generated by build-up of static electricity | | |
| Identify if the tanker is vented through the vent on the receiving facility and connect tanker venting hose to the receiving facilities venting system. | | |
| You identify correct hydrogen receiving coupling and ensure that it is clean and free of defects. | | |
| You identify maximum pressure of receiving facility. | | |
| You identify maximum differential pressure of receiving facility. | | |
| You identify non-sparking tools. | | |
| You identify adaptor coupling, check it is clean and free of defects and fit it onto receiving coupling. | | |
| You identify correct connection tightness. | | |
| You open vent valve on facility. | | |
| Identify type of transfer system installed on the tanker. You start the tanker discharge hydraulic pump/generator if present. | | |
| You identify tanker hose is clean and free of defects and fit it to adaptor coupling | | |
| For pump transfer systems start the tanker discharge pump. On pressure transfer systems open the Pressure Building (PB) valve. | | |

| | | |
|---|---|---|
| You test for leaks by using hydrogen leak detectors. | | |
| Run the instruments sensitivity test to ensure that the detector has the sensitivity to detect hydrogen 1 ppm | | |
| You hold the detector within 10 mm of every connection you have made while you take a hydrogen concentration measurement. Due to rapid dispersion, electronic hydrogen detectors have difficulty detecting leaks and it is time consuming to locate the leaking fitting. | | |
| If no leaks are detected, conduct seven nitrogen purges of the tanker hose to eliminate contaminants such as air and water from the piping. | | |
| On pump transfer systems open automatic valve and adjust the flowrate to the designed flowrate. On pressure transfer systems open the manual valve and then the automatic valve. | | |
| You open the top filling valve on the receiving facility. The addition of colder liquid hydrogen to the gaseous hydrogen in the top of the tank condensed the gaseous hydrogen and reduces the tank pressure. | | |
| You open the bottom filling valve on the receiving facility. The addition of liquid hydrogen to the bottom of the tank increased the volume of liquid hydrogen at the bottom of the tank and increases the tank pressure. The correct tank pressure is maintained by the adjustment of the top and bottom valves. | | |

| | | |
|---|---|---|
| If air starts to liquify around hydrogen piping turn off the automatic valve and call your supervisor. | | |
| You monitor the quantity of hydrogen unloading on flow meter. | | |
| You monitor pressures in the tanker and facility, reducing the flow to the bottom reduces the receiving tank pressure. | | |
| You identify maximum differential working pressure of facility approaching to indicate that the tank is full. | | |
| You identify if the hydrogen vent is indicating the receiving vessel is full. | | |
| You close top and bottom filling valves on facility. | | |
| You close vent valve. | | |
| You switch off the hydrogen pump and hydraulic pump/electrical generator if present and close the automatic valve and then the manual valve. | | |
| You identify the pressure in the tanker and should it be out of specification you vent the tanker until it is within specification. | | |
| If a leak is detected you operate the emergency shut off valves on both the tanker and the receiving facility, move to the furthest perimeter away from buildings and report the leak to your line management. | | |
| You warm the receiving connection hose to ambient temperature and then uncouple. | | |
| If connected, you uncouple the tanker venting hose from the receiving facility. | | |

| | | |
|---|---|---|
| You remove the ground and bonding wire from your trailer. | | |
| You identify hazards to exiting the facility and have them removed. | | |
| Request the removal of hazards as appropriate. | | |
| You remove the chocks from the front and back wheels | | |
| You exit facility | | |
| **For Assessor use only** | | |
| Industrial standards for Safe Hydrogen Delivery followed and achieved | | |


***Figure 16:*** *Liquid hydrogen transportation in insulated tank.*

Red arrows above indicate hazards and potential failure scenarios associated with $LH_2$ transfer: mishandling of the valve operation sequence by the operator leads to potential leaks and leaks / spills from the transfer hose that could be directed downwards or parallel to the ground (from HySafe). Example of cold hydrogen routine venting during the depressurization of the $LH_2$ transport tank through the ground storage Dewar vent stack after the completion of $LH_2$ transfer (from HySafe).

## 6.1 Liquid Hydrogen Safety Checklist

List every precaution required to prevent hydrogen fires:

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1. Record the measures required to protect from cold burns.

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2. How are hydrogen leaks detected?

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3. Why is it important to report any leaks deviations to your line manager?

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KEEP SAFE WHEN WORKING ON HYDROGEN EQUIPMENT

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