European Train the Trainer Programme for Responders

Lecture 1

Introduction of hydrogen safety for responders

LEVEL IV

Specialist officer

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

This topic is also available at level I (Firefighter).

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

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Clean Hydrogen Partnership

Co-funded by the European Union

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Acknowledgements

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 875089. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation program, Hydrogen Europe and Hydrogen Europe Research.

Summary

This Lecture outlines the introduction of hydrogen safety for responders. Hydrogen has been extensively used in industry for quite a long period of time as a compressed gas or in a liquefied form. Hydrogen is not more or less dangerous than other common fuels, but it is different, with its own specific properties and associated risks. A growing use of FCH applications requires a deep understating of processes, hazards and risks, safety features and concepts as well as professionally trained personnel to deal with possible incidents or accidents in a safe manner. This all requires a significant change in a safety culture, especially for first responders, who will be the first ones to deal with emergency situations that might involve pressurised or liquefied hydrogen, both indoors and outdoors, in urban residential areas, on the roads, in the countryside and in many other different settings.

An overview of FCH systems and infrastructure has been given in this lecture. Potential hazards, risks, safety measures and concepts associated with both stationary and transport FCH applications were considered. An overview of the main hydrogen uses, main production methods, storage options, and distribution modes was also given. In addition, the main principles of hydrogen safety engineering are discussed.

The HyResponse project is acknowledged as the materials presented here are extended based on the original HyResponse lectures (http://www.hyresponse.eu).

Keywords

Fuel cells, hydrogen, production, storage, application, hydrogen safety, e-Laboratory

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1. Target audience

The information contained in this lecture is targeted at the level of specialist officer and above. This lecture is also available at levels I: Fire fighter.

The role description, competence level and learning expectations assumed at specialist officer level are described below.

1.1 Roll description: Specialist

Specialists assist Incident Commanders with advice and by directing and supervising technical operations that involve the use of knowledge, skills or equipment related to a specific risk or response activity. Typical incidents involve hazardous materials, transportation vehicles, climatic events, structural and other built environment failures and emergency response logistics.

1.2 Competence level: Specialist

A scientific, engineering and empirical foundation in the subject area with skills, extended by experience, to apply that information, knowledge in an interpreted and useful way to enable the Incident Commander and other first responders under the specialist's direction to respond effectively and safety to the emergency situation.

1.3 Prior learning: Specialist

EQF 5 Comprehensive, specialised, factual and theoretical knowledge within a field of work or study and an awareness of the boundaries of that knowledge. A comprehensive range of cognitive and practical skills required to develop creative solutions to abstract problems. Exercise management and supervision in contexts of work or study activities where there is unpredictable change; review and develop performance of self and others.

2. Introduction, scope and target

Fuel cell and hydrogen (FCH) applications both in transport and energy sectors are available in today's market, and it is quite likely that First Responders will deal with possible accidents/incidents in the near future. The development of FCH technologies requires a better, in-depth understanding by First Responders of the hazards, risks, processes and safety features associated with FCH systems and infrastructure. Hydrogen production by electrolysis and natural gas reforming; decentralised hydrogen production applications; gaseous and liquefied hydrogen storage; hydrogen transportation and materials handling applications; FC vehicles (e.g. cars, buses, forklifts); hydrogen refuelling stations; FC stationary applications; hydrogen-based energy storage systems remain largely unknown to First Responders. In addition to this, there is a lack of standardised procedures for intervention in the event of accidents or incidents on the above-mentioned systems and infrastructures.

The purpose of this lecture is to introduce Responders to a number of FCH applications, to familiarise them with the specific risks, and to outline the main approaches of hydrogen safety

engineering. Responders should realise that hydrogen is not more or less dangerous than any other common fuel. Hydrogen is different and the knowledge of its specific properties will facilitate in making appropriate decisions at the scene of an accident. Responders should be professionally educated to deal with hydrogen systems at pressures up to 100 MPa and temperatures down to -253 °C (liquefied hydrogen) both outdoors and indoors.

This lecture is the first of series and builds on materials developed and delivered within the HyResponse project (http://www.hyresponse.eu/). An international Curriculum in Hydrogen Safety Training for First Responders was first developed within (http://www.hyresponse.eu/curriculum.php). This was the first step in the establishment of the European Hydrogen Safety Training Platform for First Responders. This curriculum has been further developed within the HyResponder project (https://hyresponder.eu) to reflect the current state of the art and expanded to incorporate further details on liquefied hydrogen, confined spaces, pressure vessels etc.

Trainees are encouraged to use this document to assist them in their independent studies and to seek sources for further information.

By the end of this lecture a Responder/a trainee will be able to:

- Appreciate a novelty and a wealth of FCH technologies in modern society;
- Understand the role of hydrogen as a new energy carrier;
- Name the main routes of hydrogen production, transportation, delivery and use;
- Recognise the difficulties in the public perception of hydrogen and fuel cell technologies;
- Define main stream industrial hydrogen production methods. Although this lecture is not designed to provide learners with an in-depth knowledge of all production methods it gives a descriptive outline of a reformer, PEM (proton exchange membrane) and alkaline electrolysers with an emphasis placed on safety features and concepts;
- Describe the working principle of a fuel cell (FC) and a fuel cell stack;
- Explain the operational principles and safety aspects of a range of FCH applications including FC vehicles, refuelling stations, stationary hydrogen storage, materials handling and hydrogen distribution applications, back-up power generation and FC systems for combined production of heat and power;
- Give examples of incidents or accident that might occur on FCH applications;
- Give insight into the hydrogen safety engineering framework;
- Have an awareness of the e-Laboratory for hydrogen safety;
- Work out essential safety-relevant conditions/parameters for a variety of scenarios.

3. Overview of H_2 production, storage, & industrial use

3.1 Hydrogen production

Hydrogen molecules cannot be found in their pure form in nature. Thus, hydrogen must be produced from the compounds, in which it is contained, for example from water, methane, methanol, ammonia, ethanol, biomass, etc. Hydrogen production can be divided into two categories: largescale centralised production and decentralised production of a small or medium scale. The centralised production refers to established, large scale chemical plants, mass producing hydrogen, which is then transported to customers. In this case, hydrogen is transported, sometimes over long distances, either via pipelines, by road or by ship. Examples include large steam reformers owned by the major gas companies such as Air Liquide, Linde, Air Products, and others. There are several established technologies currently available on the market for the industrial production of hydrogen. There are two commercial routes for hydrogen production: electrolysis of water (dated back to late 1920) and reforming technologies (introduced in 1960).

3.1.1 Water electrolysis

Water electrolysis is a process, in which water is split into hydrogen and oxygen using electrical energy as shown in the equation (1):

$$H_2O \rightarrow H_2 + ½\ O_2 \quad (1)$$

This process occurs in an electrolyser that converts electrical energy into chemical energy and can be seen as a device which operates in the opposite way to a Fuel Cell (FC). The electricity can originate from different sources and depending on that the electrolysis can either be with or without carbon dioxide CO_2 emissions. If the electricity is produced from renewable sources (wind, hydroelectric, solar or tidal energy) no CO_2 will be emitted, if it is produced from fossil fuels then CO_2 is emitted (though distantly) as a result of hydrogen production. Produced gaseous hydrogen is very pure and can be utilized either immediately or stored for a later use. The capacity of electrolysers' ranges from less than 500 m^3/h to more than 3.3×10^5 m^3/h. The electrolyser contains two electrodes (positive and negative), water and an electrolyte, i.e. a substance containing free ions that make this substance an electrical conductor. The decomposition of water takes place when the electric current passes between two electrodes within the electrolytic cell. Hydrogen is produced at the negative electrode (cathode) and oxygen is formed at positive electrode (anode).

3.1.2 PEM electrolysers

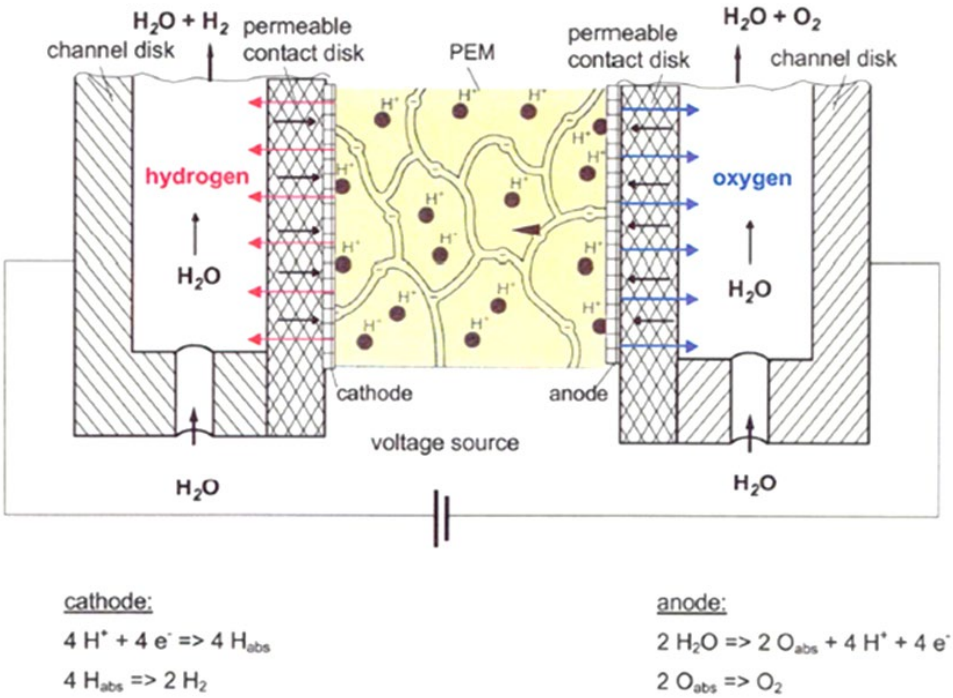
When the electrolysis takes place in two compartments/chambers, which are separated by a Proton Exchange Membrane (PEM) we will be dealing with PEM electrolysers. By application of a direct current (DC) water dissociates into hydrogen (H_2) at the negative electrode and oxygen (O_2) at the positive electrode (Figure 1). The electrodes and the membrane usually form a Membrane Electrode Assembly (MEA) and a stacking similar to a FC stack. The gases are

collected in the recovery containers. PEM electrolysers operate at low temperatures and PEM serves as the electrolyte. As it shown in Figure 2, a PEM electrolyser consists of the following elements:

- a process cabinet containing all the process components such as valves, piping, gases and water, stack, pressurised vessels, pumps, etc.
- an electrical cabinet containing all electrical components (i.e. instrumentation and control, cabling, power conditioning).
- a cooling system for electrolysis process heat dissipation.
- a weather proof enclosure.

The unwanted events that might happen are associated with the formation of an ATEX1 (i.e. H_2-O_2 explosive mixtures) either in the process compartment or in the separator (i.e. a device to separate gaseous H_2 and O_2 from water traces) usually installed downflow from a FC stack. To avoid the accumulation of hydrogen in the process compartment, the following measures should be taken:

- control pressure and pressure difference between hydrogen and oxygen lines;
- control hydrogen concentration in the container (< 0.4 vol. % H_2);
- limit as much as possible the quantity of hydrogen in the gas layer of the separator to avoid the formation of a flammable hydrogen-air mixture in the container in case of a catastrophic leak [1].



Source: Areva, 2015.

Figure 1. Working principles of PEM electrolyser.

The formation of a hydrogen-oxygen ATEX in the separator may be caused by a malfunctioning of the water transfer line or by a membrane perforation. The following safety measures are considered to avoid ATEX event in the separator:

- impose a minimum water level in the gas separator above 55% of its height;
- control the water level in the H_2 and O_2 gas separators;
- control the pressure and pressure difference in-between the H_2 and O_2 lines;
- control hydrogen concentration at the exit of the oxygen gas separator.

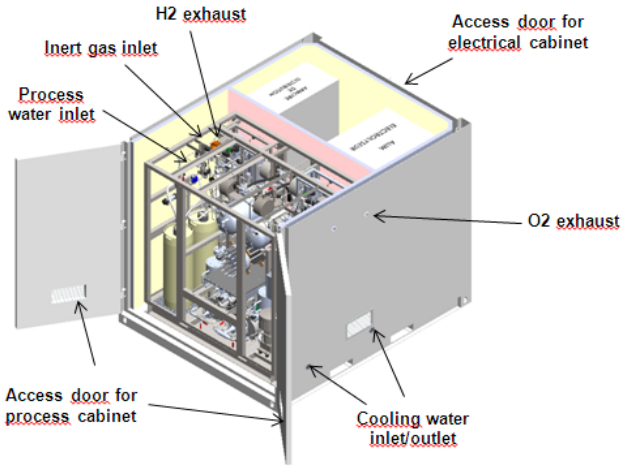


Figure 2. The scheme of a PEM electrolyser [1]

In the case of the activation of safety devices the electrolyser will shut-off, which involves not only closing of the isolation electro-valves connected to the storage tanks but also the depressurization of the system through the normally opened electro-valves. In addition, the poor isolation of electrons may lead to electrical sparks during operation in case of accidents, which may ignite the hydrogen in an oxygen rich environment.

The hydrogen production rate of different models of ITM Power electrolyser, including HGas1SP, HGas2SP, HGas3SP and HGasXMW, varies from 5.5 to 2015 m^3/h.

3.1.3 Alkaline electrolysers

Alkaline electrolysis is a matured technology for hydrogen production and also the most employed in industry. Alkaline electrolysis uses the same principle as the PEM electrolysis that is the conversion of electrical energy into chemical energy. Alkaline electrolyser has two electrodes immersed in a liquid alkaline electrolyte, potassium hydroxide or KOH aqueous solution at a level of 25% at 80°C up to 40% at 160°C. The use of KOH is preferable over the use of caustic soda NaOH due to its higher ionic conductivity, its lower chloride impurity contents and its lower saturated steam pressure. The electrodes are separated by a diaphragm as demonstrated on Figure 3. This diaphragm has two functions: first to keep the product gases (namely hydrogen and oxygen) separate and secondly to be permeable to the hydroxide ions (OH-) and water molecules. The diaphragm allows ions to pass but not hydrogen. Generally

alkaline electrolyser is made of a number of electrolytic cells consisting of a membrane with electrodes sandwiched between bipolar flow plates as illustrated in Figure 4.

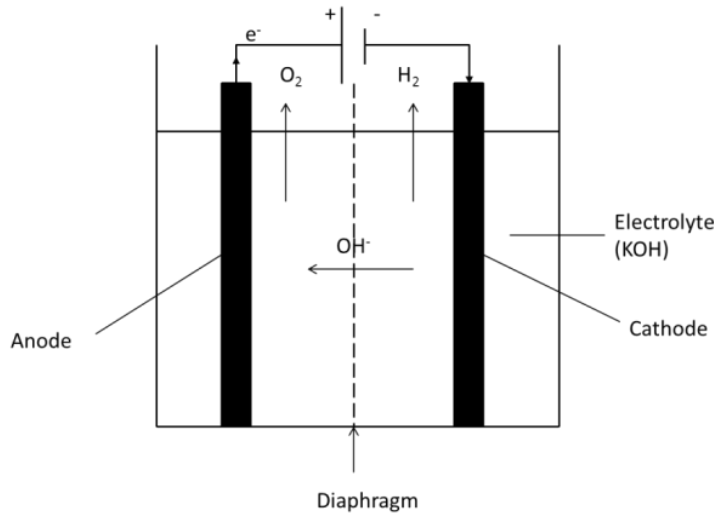


Figure 3. A scheme of an alkaline electrolyser [1]

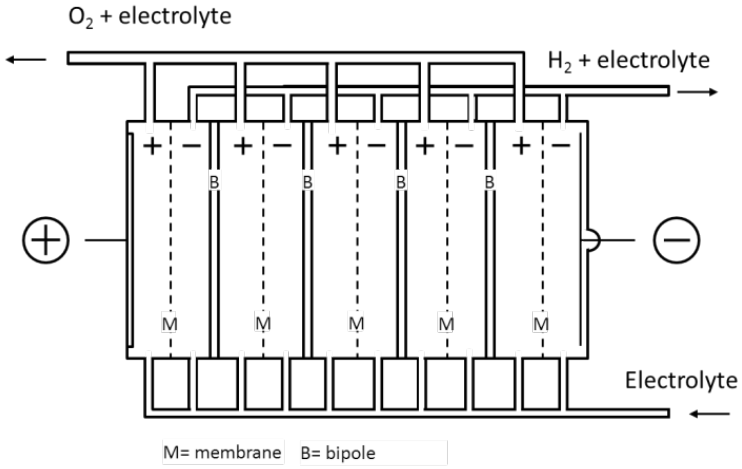


Figure 4. A scheme of electrolysis stack [1]

The reactions occurring on both electrodes are shown below:

At the anode: $2\ OH^- \rightarrow \frac{1}{2}\ O_2 + H_2O + 2\ e^-$ (2)

At the cathode: $2\ H_2O + 2\ e^- \rightarrow H_2 + 2\ OH^-$ (3)

Total reaction: $H_2O \rightarrow H_2 + \frac{1}{2}\ O_2$ (4)

A typical alkaline electrolyser is composed of:

- A power supply and a system of control and instrumentation;
- An electrolysis system containing a unit for water purification, a unit for hydrogen purification, a gas dryer, and a separator.
- A compressor.

Figures 5 and 6 show examples of industrial alkaline electrolysers.



Figure 5. Alkaline electrolyser, IHT type S-556, 760 m^3/h and 30 bars [1]



Figure 6. Outdoor and indoor HySTAT from Hydrogenics electrolysers, 10-60 m^3/h [1]

Similar to PEM electrolyser the main risk of alkaline electrolysis system comes from the formation of a hydrogen-oxygen mixture, which may lead to an internal explosion within the electrolyser. Several sensors are implemented in order to detect an electrolyser malfunction:

- measurement of hydrogen concentration in the oxygen line;
- measurement of voltage and current;
- measurement of the temperature at the entry and at the outflow of electrolysis cells;
- measurement of the ionic concentration of the electrolyte.

Another type of risk is associated with an exposure to a corrosive solution in the event of an electrolyte leak. The specification sheet of potassium hydroxide recommends the use of a leak tank in order to avoid the contact of KOH with the surroundings [1].

3.1.4 Reforming technologies

Currently the most common way of hydrogen production is by steam reforming of natural gas. The reaction of natural gas (methane CH_4) reforming is given in equation 5:

$$\underset{\text{natural gas}}{CH_4} + \underset{\text{steam}}{2H_2O} \rightarrow \underset{\text{syn-gas}}{CO_2} + 4H_2 \quad (5)$$

This is an endothermic process (i. e. requires high temperatures) of methane and steam conversion into hydrogen and carbon dioxide CO_2. This is usually a two-step process with the typical by-products of reforming being carbon monoxide CO and carbon dioxide CO_2. A reformer can be operated on 24/7 basis at a constant load. The capacity of reformers ranges from 100 to more than 100,000 m^3/h. The efficiency of the reformer rarely exceeds 80%, the disadvantage of this method is that the produced hydrogen is not pure (it is contaminated with CO/CO_2) and it is at atmospheric pressure. To improve the sustainability of the reforming process CO_2 capture and sequestration are required. An example of steam reforming installation is shown on Figure 7.

The steam reforming is a well-established industrial process and will not be treated in more detail in this lecture. For further technical details please refer to the papers on safety in the reforming industries provided in the International Curriculum on Hydrogen Safety Training for Responders. As noted above the process occurs at high temperature and pressure, thus hydrogen safety issues addressed in the coming lectures on leaks, fires, detection, mitigation etc. are of course also relevant to steam reforming.



Figure 7. AirLiquide steam reformer [1]

3.1.5 Other technologies

An overview of hydrogen production non-main stream methods is given in this lecture. First responders should be aware of a variety of hydrogen production methods as FCH market is expanding rapidly. For further information on alternative hydrogen production technologies please use the references from the International Curriculum on Hydrogen Safety Training for Responders.

Hydrogen can be produced - from water by:

- Nuclear methods (radiolysis or thermolysis);
- Photo-electrolysis (photovoltaic systems coupled with electrolysers);
- Thermo-chemical cycle;
- Ferro-silicon method (water, sodium hydroxide and ferrosilicon);
- Photo-biological water splitting (two steps: photosynthesis and H production catalysed by hydrogenases);
- Photo-chemical water splitting;
- Biological routes (fermentation, enzymatic, microbiological and bio-catalytic).

- from fossil fuels by:

- Partial oxidation of oil;
- Coal gasification;
- Plasma reforming (light hydrocarbons heated by plasma to 1600 ºC and produce hydrogen and carbon, no CO_2 emissions);
- Dry reforming (natural gas reformed in the stream CO_2)

- from complex metal hydrides:

- $\underset{\text{Sodium borohydride}}{NaBH_4} + 4H_2O \rightarrow NaOH + HBO_3 + 5H_2 \quad (36\ \text{wt. \%})$ (6)
- $\underset{\text{Lithium borohydride}}{LiBH_4} + 4H_2O \rightarrow LiOH + HBO_3 + 5H_2 \quad (46\ \text{wt. \%})$ (7)

These complex metal hydrides are currently under intensive research with the view to develop new materials suitable for solid storage of hydrogen.

Traditionally hydrogen is produced using reforming technologies, which are not “green” due to the fact that carbon dioxide is produced. Although hydrogen produced from natural gas is certainly a viable short-term option, it is not viewed as a long-term solution. It is envisaged that “greener” production routes such as electrolysis and nuclear will play an increasingly important role. Renewable resources for producing hydrogen include biomass, methanol, ethanol and land-fill gas, wind farms, tidal energy, hydroelectric energy, solar and gravitational energy. As renewable energy begins to play more significant role in meeting modern society energy demands the issues of grid balancing and energy storage are the subject of much investigation and this is where hydrogen as a new energy carrier comes in. A number of projects exist whereby wind or solar power is coupled to hydrogen production and storage, e.g. the Pure project (Scotland), MYRTE platform (Corsica, France), Puertollano plant (Ciudad Real, Spain), Utsira Wind Power and Hydrogen Plant (Utsira Island, Norway) and several FCH projects, e. g. SOPHIA, PECDEMO, HYDROSOL-PLANT et al.

3.1.6 Decentralised hydrogen production

The decentralised (or distributed) hydrogen production refers to the systems over a range of scales, from an island community to a home electrolyser for a personal use. A move towards distributed production can result in energy independence for the end use; however, it also means there is a need for a new "safety culture" as the public will have a greater responsibility. Some examples of home systems have been presented by Honda and ITM:

- Honda home energy station: https://apps.honda.co.uk/environment/designingthefuture/homeenergystation/
- ITM home system:

  https://www.itm-power.com/h2-stations

3.2 Hydrogen storage

This section provides an overview of hydrogen storage options. Hydrogen leaks, fires and explosions as well as the interaction of hydrogen with materials used for storage are extremely relevant and will be considered in subsequent lectures. Hydrogen storage is an enabling technology across a range of FCH applications from on-board storage in FC vehicles to stationary FC applications. There is no universal storage solution that can be installed on all the systems. A hydrogen storage solution must be selected to suit the specific application. For example, size and weight are limiting factors for passenger vehicles whereas weight can be a desirable attribute for forklifts. The storage solutions are one of the key challenges for the hydrogen economy and these technologies are a subject of considerable interest both for scientific and industrial communities.

The storage of the large quantities of hydrogen for long periods of time is a key step in the build-up of FCH infrastructure, which will regulate the hydrogen consumption and production and will ensure continuity in its supply to customers. Various underground hydrogen storage schemes are investigated. One option includes storage of gaseous hydrogen in geological formations such as depleted gas fields, aquifers, or salt caverns. Another option is the underground storage in tanks buried underground, and hydrogen is stored either as compressed gas or in a liquid form. Geologic storage is usually located close to a hydrogen production site, whilst the buried tanks are closer to the point of use, for example to refuelling stations.

Numerous hydrogen storage technologies are available and could be categorised into the following groups:

- Compressed gaseous storage
- Liquefied storage
- Solid storage

The most common way to store hydrogen as a compressed gas or as a cryogenic liquid is in metal or composite cylinders or tanks (Figure 8). Cryo-compressed technology, when gaseous

hydrogen under high pressure cooled to low temperatures, is another useful alternative. The cylinders can have different sizes, capacities (from 20 to 300 L) and pressures (20-70 MPa) and for some applications can be connected into a bundle or gathered onto a basket for transportation.



a b c

Figure 8. On-board storage of hydrogen (a), a cylinder bundle (b) and a basket of cylinders for transportation (c).

Hydrogen gas can be compressed to 20-100 MPa. The primary issues with storing hydrogen as a compressed gas is the amount of energy needed for the compression process, the inherent safety issues with storing hydrogen at such high pressures and the additional costs and weight of cylinders designed to store hydrogen at high pressures. Issues such as permeation and embrittlement are proportional to gas pressure therefore at higher pressures these may be a greater issue. In Europe, most of transportable cylinders have only a valve as a safety feature. In USA transportable cylinders are equipped with pressure relief devices. This prescription is very controversial because they often become the sources of leaks. The storage of compressed gaseous hydrogen is usually integrated for stationary hydrogen storage systems and for on-board storage of hydrogen in FC vehicles [1].

Cryogenic hydrogen is formed when it is cooled to a temperature below its boiling point 20K (- 253 °C) is the second major category of hydrogen storage. In this form hydrogen can either be stored for some time or transported. This storage option is also very costly due to considerable energy required for liquefaction. The cost and weight of suitable materials to store and maintain the hydrogen at low temperatures must also be considered. Hydrogen can also be stored either within the structure or on the surface of certain solid materials. This storage option does require neither high pressures nor low temperatures as in previous two methods; this offers advantages regarding the safety of the materials. There are three main mechanisms for storing hydrogen in materials: absorption, adsorption (Figure 9a), and chemical reactions (Figure 9, b-d). The examples of materials and compounds suitable for solid hydrogen storage are shown below on Figure 9.

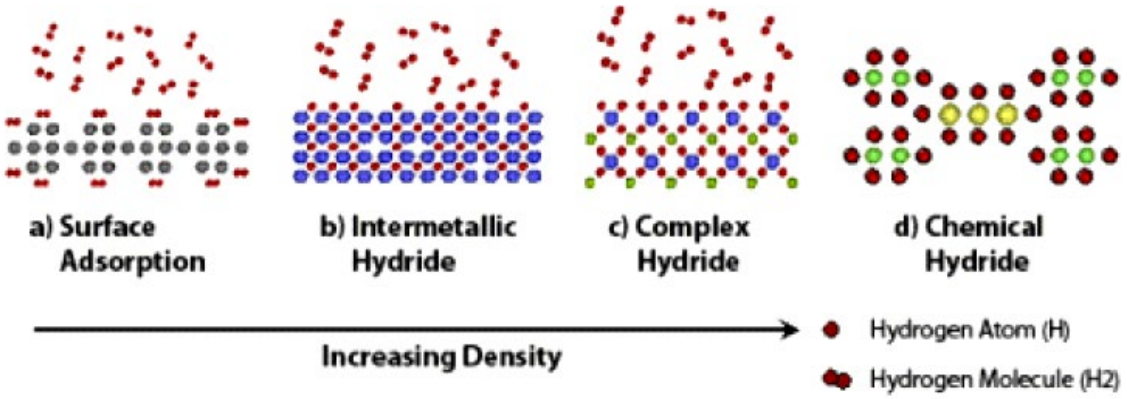


Figure 9. Materials used as solid storage of hydrogen [2]

All these three options have their own advantages and disadvantages, safety issues are also different and will be considered in detail in Lecture 3 on the 'Safety of hydrogen storage'. Hydrogen storage systems can be used for different purposes: as containers for its transportation; as on-site (under- or above the ground) stationary storage systems, or as on-board storage tanks in FC vehicles.

3.3 Hydrogen usage in industry

Hydrogen has been used in industry and stored safely as a compressed or liquefied gas for more than 100 years. Hydrogen is widely used for a range of applications including: crude oil refining; as a coolant in large turbine electrical generators; as a propellant in rocket propulsion and missiles applications; during production of ammonia for fertilizers; in metallurgy for extracting pure metals from their ores; in semiconductor, glass, pharmaceutical, petro-chemical, chemical and food industries; etc. The statistics on incidents related to hydrogen indicates that currently incidents occurring in laboratories are the most frequent (about 32 %) [3]. The low accident rate can be explained by the strict safety measures already in place for the production and end-use of hydrogen. However, this trend might change in the coming years due to the expansion of FCH applications into public domain and more frequent use of FCH technologies by private individuals without a special safety training. The incident reporting also shows that from the total number of incidents recorded so far only a small proportion results in a loss of human life (4.6 %) [4]. Although hydrogen safety issues have been efficiently controlled in the industry to date, additional safety approaches especially with regards to emergency response procedures, will be required both in the transport sector and in residential fuel markets mainly due to high pressures utilised for storing hydrogen. Hydrogen is not more or less dangerous than other flammable fuels including petrol and natural gas. In fact, some of its properties such as buoyancy provide safety benefits compared to other fuels. However, all flammable fuels must be handled responsibly. Like gasoline and natural gas, hydrogen is flammable and can behave dangerously under specific conditions. Hydrogen can be handled safely if simple guidelines are adhered to and the user has a good level of knowledge of its unique behaviour. Understanding of hydrogen specific properties and knowledge of FCH

applications leads to safe implementation of hydrogen as a fuel. There is a need to establish a new safety culture in our society, to develop innovative safety strategies and breakthrough engineering solutions. It is expected that the level of safety at the consumer interface with hydrogen must be similar or higher than that present with the fossil fuel usage. Thus, safety parameters of hydrogen and fuel cell products will directly define their competitiveness on the market [5].

4. FC vehicles

FCH technologies for road and specialty vehicles are of a high importance today. Some car manufacturers, such as Toyota already launched sales of FCH vehicles in the regions where refuelling infrastructure is already in place. The examples of road vehicles include passenger cars, buses, scooters, light trucks, etc. They use hydrogen as a fuel and have no engines as the FC and electric motor used instead. The availability of infrastructure is a key step towards commercial success of these products. These vehicles in appearance are similar to conventional vehicles. As opposed to conventional vehicles they emit no pollutants and are very quiet while in operation. Another important application is speciality vehicles. The speciality vehicles are designed for specific purposes and usually operate in fleets. FC forklifts is a good example of the specialty vehicles. This type of vehicles requires a power from 1.5 to 10 kW. At the moment many private companies are investing in a FC forklift fleet and refuelling infrastructure as they benefit from their use almost immediately.

4.1 The key features of FC vehicles

FC cars have an electric drive train powered by a FC that generates electricity in electrochemical reaction using hydrogen. Whilst there are a wide variety of prototype FC cars the following key features (Figure 10) are common for the most of them [6]:

- Hydrogen fuelling system;
- Hydrogen storage system;
- Hydrogen fuel delivery system;
- FC system;
- Electric propulsion and power management system.

During refuelling, hydrogen is supplied to the car through the fuelling receptacle (A) and flows to the hydrogen storage system (B). The hydrogen supplied and stored within the hydrogen storage system, usually in a compressed gaseous form. When a FC car starts, hydrogen gas is released from the storage system. Pressure regulators and other equipment within the hydrogen delivery system (C) reduce the pressure to the appropriate level for operation of the FC. The hydrogen is electrochemically combined with oxygen in the FC system (D) to produce high-voltage electric power. That electric power is supplied to the electric propulsion power

management system (E) where it is used to power electric drive motors or charge batteries and ultra-capacitors.

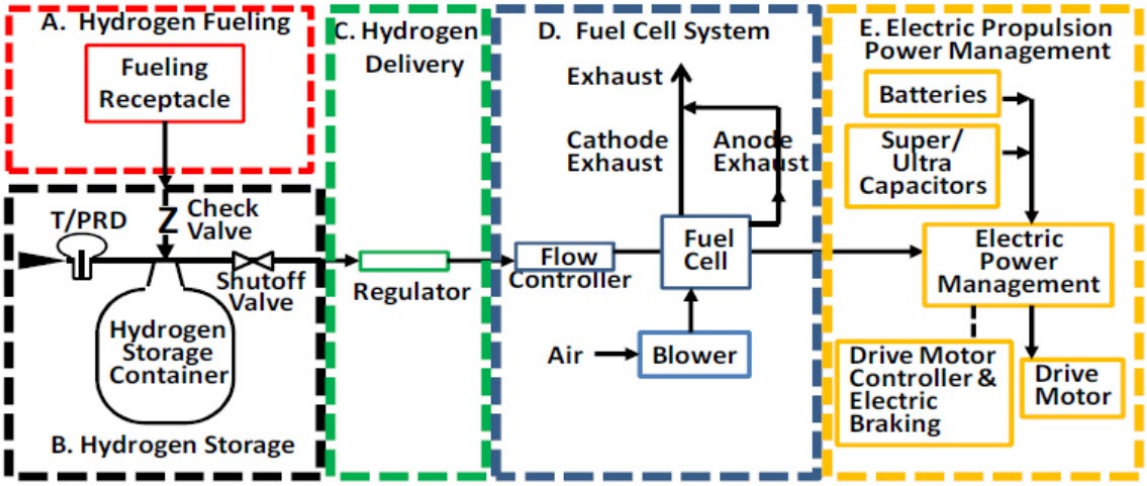


Figure 10. The key systems of an FC car [6]

4.2 FC cars

Figure 11 illustrates a typical layout of key components of a typical FC car [6]. The fuelling receptacle is positioned on the rear quarter panel of the car as in other common vehicles. As with gasoline containers, hydrogen storage containers are usually mounted transversely in the rear of the car, but could also be mounted differently, such as lengthwise in the middle tunnel of the car. Fuel cells and ancillaries are usually located under the passenger compartment along with the power management, drive motor controller, and drive motors. Given the size and weight of traction batteries and ultra-capacitors, these components are usually located in the car to retain the desired weight balance for proper handling of the car.

Hydrogen may be supplied to the car at a refuelling station. At present, hydrogen is most commonly dispensed to cars as a compressed gas pressurised up to 125% of the nominal working pressure (NWP) of the car to compensate for transient heating from adiabatic compression during fuelling.

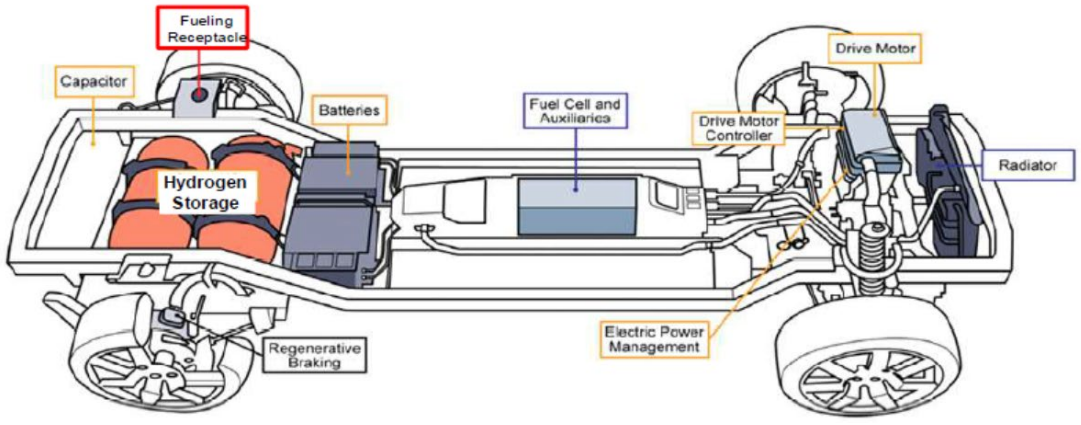


Figure 11. An example of a FC car [6]

4.2.1 Hydrogen storage system

The key functions of the hydrogen storage system are to receive hydrogen during refuelling, to contain it until needed, and then to release hydrogen to the FC system for use in powering the car. At present, the most common method of storing and delivering hydrogen fuel on-board is in compressed gas (CGH_2) form. The lightweight compressed gas cylinders at 700 bar are developed to increase storage capacity. They consist of a metallic (Type III) or polymeric (Type IV) liner placed in a fibre reinforced composite structure (Figure 12). The work is on-going to reduce the costs of these cylinders. More information related to on-board hydrogen storage systems will be available in the following lectures.



(a) (b)

Figure 12. 700 bar cylinder prototypes developed and tested within the STORHY European project: (a) Type III technology, (b) Type IV technology.

4.2.2 Hydrogen fuel delivery system

The hydrogen fuel delivery system transfers hydrogen from the storage system to the propulsion system at the adequate pressure and temperature for the FC to operate. This is achieved via a series of flow control valves, pressure regulators, filters, fuel lines (pipes), and heat exchangers. Most of the fuel lines are silver in colour, but sometimes they could be red. If the tank is shut down due to an incident only a small amount of hydrogen will be in these lines. However, first responders should not cut the fuel lines during extrication procedures.

4.2.3 FC system

The FC system generates electricity needed to operate the drive motors and to charge vehicle batteries and/or capacitors. There are several kinds of FCs, but PEM fuel cells are the common type used in automotive applications due to their lower temperature of operation, which allows shorter start up times. The PEM fuel cells electrochemically combine hydrogen and oxygen to generate electrical power. Fuel cells are capable of continuous electrical generation when supplied with hydrogen and oxygen, simultaneously generating electricity and water without producing carbon dioxide (CO_2) or other harmful emissions typical for petrol/diesel-fuelled internal combustion engines. In general, fuel cell stacks in a light duty passenger vehicle generate voltage of around 400 V DC. A converter also connects the fuel cell with the high voltage battery. The operating temperature of the FC is much lower than for internal combustion engine as it is more efficient.

4.2.4 Electric propulsion and power management system

The electric power generated by the FC system (FC stack) is used to drive electric motors that propel the vehicle as well as to power an air pump motor and an air conditioning motor. Many passenger FC cars are front wheel drive with the electric drive motor and drive-train located in the "engine compartment" mounted transversely over the front axle; however, other configurations and rear-wheel drive are also viable options. Larger sport utility vehicle-type FC cars may be all-wheel drive with electric motors on the front and rear axles or with compact motors at each wheel. The high-voltage battery pack is usually placed in a metal case and firmly mounted into the frame. Different FC vehicles use different kinds of batteries such as nickel metal hydride or lithium ion. Other high-voltage components may include a FC contactor, a battery voltage control unit, a DC-DC converter, a power drive unit and an electric heater. Electricity from the FC stack and the high-voltage battery is delivered to the motors through a number of cables, which are typically located inside or behind enclosed high-voltage components and underneath the vehicle. They can be easily identified through the distinctive orange protective covers.

4.2.5 Safety features and concepts

The FC cars are fuelled through a special fuelling nozzle on the fuel dispenser at a refuelling station that connects with the fuelling receptacle on the car to provide a "closed system" transfer of hydrogen to the car. The fuelling receptacle on the FC car contains a check valve or other device that prevents leakage of hydrogen out of the car when the fuelling nozzle is disconnected.

The components of a typical compressed hydrogen storage system are shown in Figure 13. The system includes the container and all other components that form the "primary pressure boundary" that prevents hydrogen from escaping the system. There are three safety devices as parts of the compressed hydrogen storage system:

- A check valve;
- A shut-off valve;
- A thermally-activated pressure relief device (TPRD).

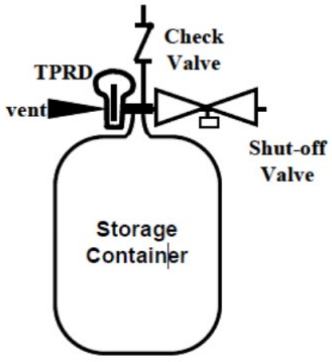


Figure 13. A typical compressed hydrogen storage system [6]

During refuelling, hydrogen enters the storage system through a check valve. The check valve prevents back-flow of hydrogen into the fuelling lines. An automated hydrogen shut-off valve prevents the out-flow of stored hydrogen when the car is not operating or when a fault is detected that requires isolation of the hydrogen storage system. In the event of a fire, thermally activated pressure relief devices (TPRDs) provide a controlled release of the gas from the compressed hydrogen storage containers before the high temperatures in the fire weaken the walls of the containers and cause their hazardous rupture. TPRDs are designed to vent the entire contents of the container rapidly. They do not reseal or allow re-pressurization of the container. Storage containers and TPRDs that have been subjected to a fire are expected to be removed from service and destroyed. The hydrogen is usually (but not always) vented outside the FC vehicle through a vent line. The exact location of these vent lines depends on a vehicle manufacturer and its model, but it will be usually at the back of the vehicle, near the hydrogen tank [6]. The fuel delivery system shall reduce the pressure from levels in the hydrogen storage system to values required by the fuel cell system. In the case of a 70 MPa NWP compressed hydrogen storage system, for example, the pressure may have to be reduced from as high as 87.5 MPa to less than 1 MPa at the inlet of the fuel cell system. This may require multiple stages of pressure regulation to achieve accurate and stable control and over-pressure protection of down-stream equipment in the event of a pressure regulator failure. Overpressure protection of the fuel delivery system may be accomplished by venting excess hydrogen gas through pressure relief valves or by isolating the hydrogen gas supply (by closing the shut-off valve in the hydrogen storage system) when a downstream overpressure condition is detected [6]. A number of hydrogen sensors are located in FC vehicles. When a potentially hazardous hydrogen leak is detected the system controller will automatically stop the flow of hydrogen from the tank. There are several areas where sensors can be found: on the instrumentation panel; beside hydrogen storage tanks; near an exhaust pipe; underneath the bonnet; above the headliner in the passenger compartment, etc. When the propulsion system is “ON,” these sensors continuously monitor hydrogen concentration in these areas. For example, according to the US First Responders (standard operating procedure) SOP, when hydrogen is detected at a “Warning Level” the driver will be alerted by the “H_2” icon located in the instrument panel cluster, and the Driver’s Information Centre (DIC) will show a “H_2 Detected” message. If hydrogen is detected at an “Alarm Level”, the “H_2” icon will blink, an audible beep will sound, and a “H_2 Detected – Evacuate Vehicle” message will appear on the DIC [7]. It is worth of noticing that different standards of different hazard levels were applied in different countries although the general SOPs were similar. Different hydrogen concentrations will trigger the different warning levels in different countries.

4.3 FC buses

FC buses use the same technology as in FC cars. Hydrogen is stored in tanks usually located on the bus roof. The total capacity is in the 40-kilogram range. The fuel cell stack is located in the rear engine compartment. The bus fuel cell stack is bigger than that for FC car and generates

higher voltage, of around 600 V. The main advantages of FC buses compared to the conventional ones are reduced pollution; lower concentration of greenhouse gases; increased energy efficiency and a quieter operation. There is a range of European projects associated with a hydrogen-based transport. For example, Clean Energy Partnership (CEP) [8] is the project that aims to test and to demonstrate the use of FCH technologies in transport applications. CEP, established in 2002, is an international cooperation of 18 partners including leading car manufacturers such as BMW Group, Honda, Daimler, Ford, Hyundai, GM/Opel, Toyota and Volkswagen. In 2011 CEP moved to its third phase 'Market preparation'. Another project is HyFLEET: CUTE, which seeks to develop and operate the world's largest fleet of FC buses. The HyFLEET: CUTE project has involved the operation of 47 hydrogen powered buses in regular public transport service in 10 cities on three continents (Amsterdam, Barcelona, Beijing, Hamburg, London, Luxembourg, Madrid, Perth, Reykjavi) [9]. These buses have been successful in providing valuable data to developers and operators as they are used under harsh conditions, through uninterrupted operation and extreme climatic conditions. Another important aspect of this project has been to familiarize the public with this new technology and to thereby gain public acceptance of its introduction [9]. London now has a fleet of 8 FC buses running on route RV1 between Covent Garden and Tower Gateway (Figure 14). A six-year FCH JU (Fuel Cells and Hydrogen Joint Undertaking) project, JIVE (Joint Initiative for hydrogen Vehicles across Europe), started from January 2017 seeks to deploy 139 new zero emission fuel cell buses and associated refuelling infrastructure across five countries. A following project, JIVE2, started in January 2018, combined the JIVE project, will deploy nearly 300 fuel cell buses in 22 cities across Europe by the early 2020s – the largest deployment in Europe to date. (https://www.fuelcellbuses.eu/public-transport-hydrogen/jivejive2mehrlin-leaflet)



Figure 14. Wright Pulsar 2 hydrogen-powered bus on route RV1 in London.

"FC-buses have evolved substantially in the last decades. A number of different design configurations have been used, including hydrogen in ICE, and various fuel cell technologies. In addition, companies have used direct drive systems and hybrid drive systems, where an energy storage device (battery or ultra-capacitor) is included within the drivetrain to reduce

peak loads and allow regenerative braking" [10]. A brief comparison between the main hydrogen bus technologies is presented in the review curried out within NextHyLights project [10]. Figure 15 shows a layout of SunLine's "All American" FC bus [11]. In this example hydrogen is stored as a compressed gas (CGH2). Adams [12] carried out a research looking into the optimum on-board storage pressure that would be required for buses equipped with CGH2 tanks. It was concluded that a standardised on-board storage pressure restricting device is required in order to ensure that a vehicle is not refilled to a pressure greater than the storage pressure to which it was designed. This standardisation would also be necessary to reduce unnecessary system development costs for vehicles and the associated refuelling infrastructure as well as reducing the risk of damaging refuelling interfaces due to incompatibility. The compression energy within the gas in a container increases for a given mass of hydrogen with increasing storage pressure; therefore sudden expansion of the gas due to the container rupturing could have severe consequences that would increase with higher pressures. Therefore when considering storage systems for buses, where volume is not as critical a constraint as in cars, optimum pressures for non-articulated single deck city buses were found to be between 20 and 35 MPa [12].

Safety devices used in FC buses are similar to those used in FC cars. Pressure relief device (PRD) is a non-reclosing thermally activated device that is designed to protect a pressurised hydrogen tank from a catastrophic failure should an emergency situation such as a fire occur. It is used to ensure that the thermal impact caused by flames does not increase the pressure in the storage vessel beyond its structural capacity. It should be noted however that fires that cause a PRD to open may not result in the hydrogen immediate ignition upon release. The hydrogen tanks are equipped with thermally activated pressure relief device (TPRDs) and the stainless steel fuel and vent lines. There is an Emergency Shut-down Device (ESD) button located at the driver's panel, and one on the fuel cell itself in the engine compartment.

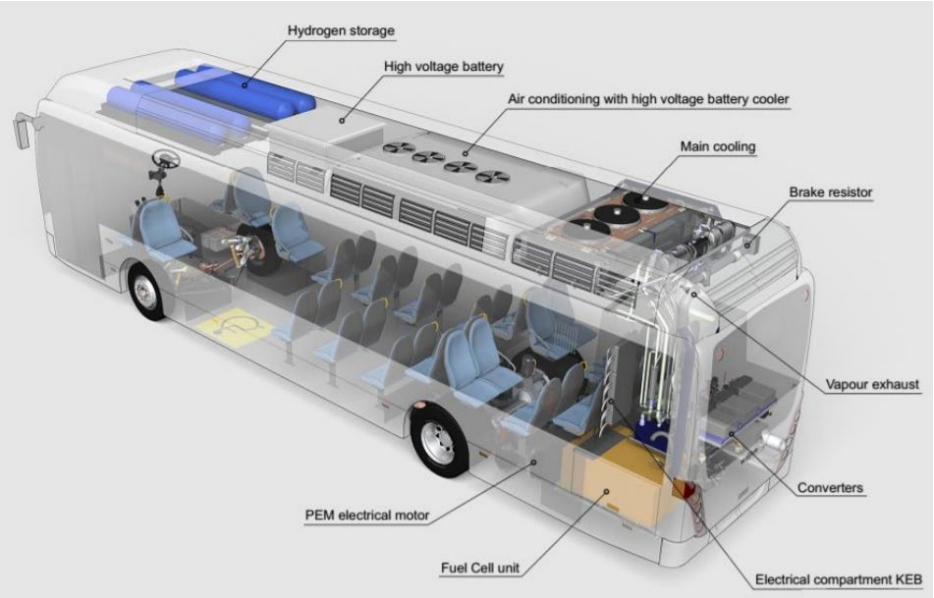


Figure 15. A layout of the main components of a FC bus [11]

First responders have to learn how to deal with FC vehicles in case of the traffic accidents. The main hazards are associated with a high voltage (up to 600 V) and with high gas pressures (up to 70 MPa). For different types of road vehicles regulation EC79/2009 in conjunction with EC406/2010 requires labelling of FC vehicles: for light duty vehicles the label has to be visibly placed near the fuelling receptacle (another label should be inside the engine compartment). Work is underway to update the guidance in this field and responders are advised to confirm requirements for labelling e.g. UN ECE Working group 13 (https://unece.org/wp29-introduction).

Rescue Data Sheets should be available for all FC vehicles and should be found on-board the vehicle. Ideally, fire brigades will have access to this information via communication links. However, it is noted that levels of access vary significantly may not always be possible. The vehicle identification parameters should also contain all high voltage and high pressure characteristics informing first responders well in advance. Similar to conventionally fuelled vehicles, the following components may pose hazards to first responders in case of a road accident: bumpers; shock absorbers; tires; hood and trunk struts; airbags; seat belt pre-tensioners; air-conditioning system; batteries. Please note that disconnecting a low-voltage cable will isolate and shut-off all vehicle systems (e.g. the hydrogen storage, highvoltage and low-voltage systems) in a FC vehicle.

4.4 FC forklifts

Many companies with large warehouses or distribution centres currently deploy FC forklift trucks to move goods, which operate on 24/7 basis [1]. FC forklift trucks are hybrid vehicle that couple a fuel cell, usually from 1.5 to 10 kW, with a battery. Hydrogen cylinders are stored outside the facility/warehouse. Hydrogen is either delivered to the site by an industrial gas supplier or produced on site using natural gas reforming or water electrolysis methods. A refuelling of a FC forklift with hydrogen mostly occurs indoors (but outdoor dispensers are also possible) and only takes a few minutes. Compared to battery powered specialty vehicles FC forklifts have longer life-span; have more power for a longer period of time and can be refuelled in less than 3 minutes. Another plus point of FC forklifts are lower operating costs and increased productivity due to a lower number trips to a battery charging station. Since there is no need for battery chargers, storage, or battery swap areas more warehouse space is available for other uses. Main industrial suppliers sell warehouse hydrogen refuelling stations for FC forklifts. An example of a FC forklift and the fuel cell unit are depicted in Figure 16.



A FC forklift



FC fuel cell of a forklift

Figure 16. A FC forklift truck and its FC unit [1]

The main components of a FC unit are demonstrated on Figure 17. They include:

- fuel cell (called PAC);
- fuel cell auxiliaries;
- hydrogen storage vessel, the volume of which varies between 20 and 70 L in water and fitted with a regulator system;
- lithium ion battery, which passed the tests required by the United Nations (UNO) specified in the United Nations Manual of Tests and Criteria, Section 38.3;
- water collection tank.

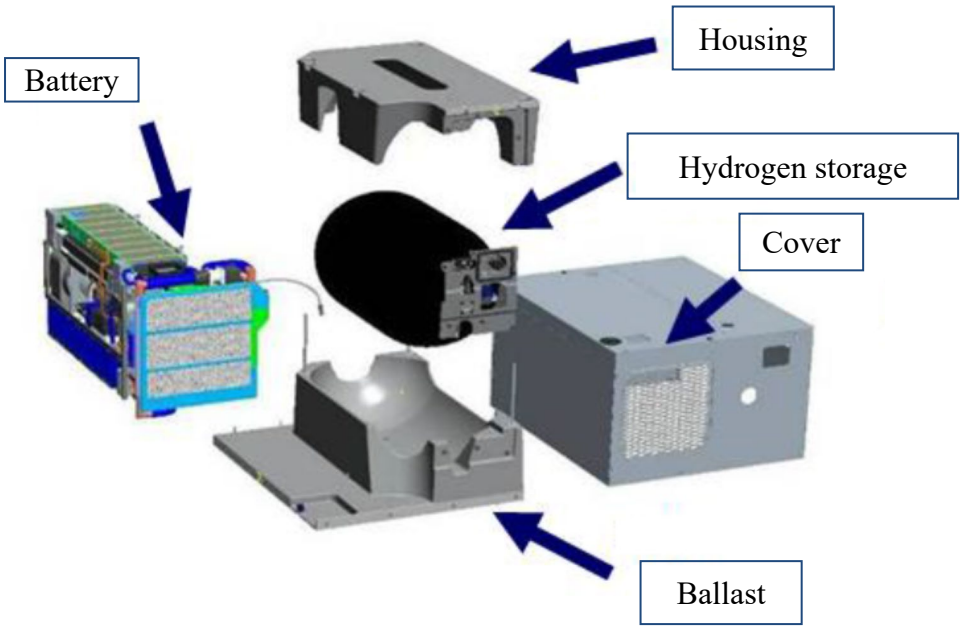


Figure 17. Forklift fuel cell unit components

From a safety point of view, the hydrogen storage is protected with a TPRD (triggered by a thermal fuse) situated between the forklift's isolation valve and the cylinder. The fuse opens at

109°C and allows the rapid release of pressurised hydrogen. There is also a non-return valve on the filling port to prevent gas in the storage from escaping. Also all the components of the FC are built into a cast iron casing, which is in turn, is protected by a cover. There are two advantages to this cast iron casing: it provides protection against external mechanical damage and allows the flow of hydrogen to be vented out in the event of an external thermal attack.

4.5 Aviation

The study of the usage of hydrogen as fuel in airplanes started in 1956. The United States achieved flying a B57 Canberra plane which using hydrogen fuel pressurized with helium in one of its engines [13]. After B57, the Soviets tested experimental conversion of an early production Tu-154 which had one engine operating on hydrogen in 1988. The liquid hydrogen powered motor was tested at heights up to 7000 m and accelerated to 900 km/h. Unfortunately, the liquid hydrogen (LH) program was reduced to only five flights and it was decided not to continue with such fuels because of high costs and lack of infrastructure of hydrogen [14]. Until today, many hydrogen prototype aircraft such as Tupolev Tu-155 (Tupolev, 2009), the Antares DLR-H2 (Fuel Cell Works, 2009), the Boeing Phantom Eye (Jackson and Haddox, 2010) and the ENFICA-FC Rapid 200-FC (European Commission, 2011) were built using compression and liquefaction storage methods [15]. The historical development timescale for liquid hydrogen and fuel cell powered aircrafts is illustrated in Figure 18. In September 2016, the world's first hydrogen fuel cell-powered four-seat passenger aircraft, HY4, completed its first flight from Stuttgart Airport. In this future electric taxi, the hydrogen fuel is stored at a pressure between 4,300 PSI and 5,800 PSI in two carbon-fibre tanks which are both located in the two fuselages. In this aircraft with a maximum speed of 200 km / h, the fuel cell converts directly converts the hydrogen to electricity and the only waste product that comes out of this process is water [16]. On 21 September 2020, Airbus has revealed three concepts for the world's first zero-emission commercial aircraft which could enter service by 2035. These concepts each represent a different approach to achieving zero-emission flight, exploring various technology pathways and aerodynamic configurations in order to support the company's ambition of leading the way in the decarbonisation of the entire aviation industry. All of these concepts rely on hydrogen as a primary power source – an option which Airbus believes holds exceptional promise as a clean aviation fuel and is likely to be a solution for aerospace and many other industries to meet their climate-neutral targets.

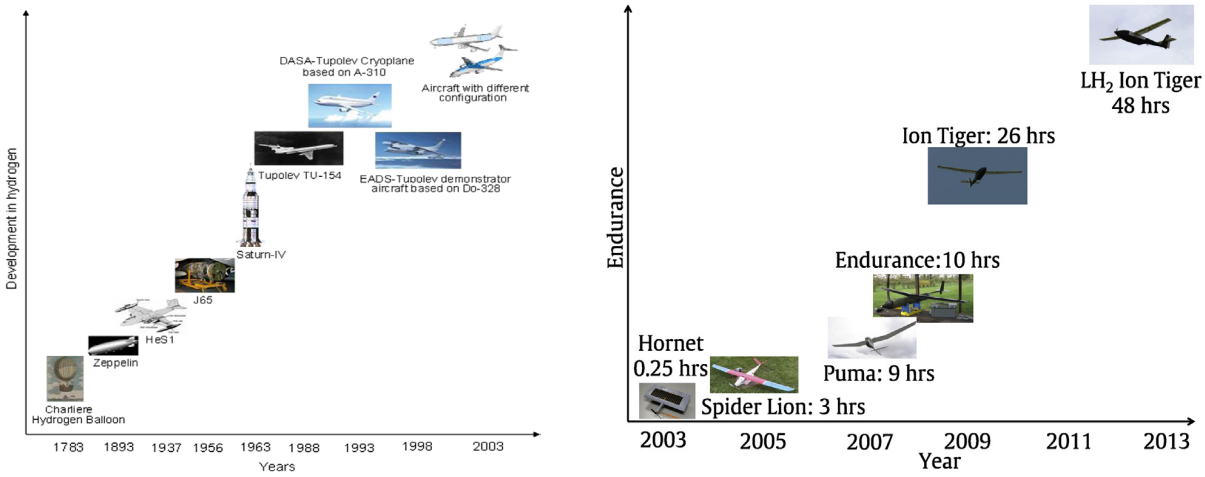


Figure 18 Historical development timescale for hydrogen (left) and fuel cell (right) powered aircrafts

An aircraft has a maximum take-off weight of up to 640 tonnes. To carry these loads, large and powerful engines are needed, and these engines require a lot of fuel. This fuel requirement presents benefits and challenges related to fuel safety, fuel cost, specific energy, and equivalent energy efficiency. Today, aircrafts mostly use petroleum-based fuels obtained from fossil fuels. Among these fuels, the cost of the most commonly used kerosene is less than other fuels [15, 17]. Although kerosene and some blends of gasoline were preferable as a fuel for aviation; their reserves are limited and increased greenhouse emissions affect the environment negatively. With these considerations, researchers and manufacturers are considering new ways and forms of energy handling with alternative/renewable fuels.

With these considerations, conventional fossil fuels used in aviation are being replaced with alternative fuels. One of the most important elements of the fuel family is hydrogen. Hydrogen has become the focus of attention for researchers and combustion experts in recent years because of availability, better specific energy properties and environmental benefits.

There are two routes in which hydrogen is typically used in airplanes, either as a fuel instead of kerosene in big airplanes or as fuel in PEM fuel cells in jet engines in small propeller airplanes [15].

4.5.1 Hydrogen as a propulsion fuel

Hydrogen, with all the properties required for its use as fuel, has the highest energy content per unit mass of all known fuels (2.8 times higher than compared to kerosene) [17, 18]. This property very important because it allows for a greater payload [19]. Another advantage is that hydrogen promises that long-term growth in aviation by protecting the environment [18].

Using hydrogen as an aviation fuel would eliminate most of the greenhouse gas (GHG) emissions including all carbon-based emissions, soot, and sulphur oxides [20]. The main by-products of hydrogen in a combustion process are water vapour and nitrogen oxides (NOx) [21]. However, the amounts of NOx emissions released from burning hydrogen are extremely

low compared to those released when burning kerosene [22]. Furthermore, adoption of hydrogen as a jet fuel can provide long term stable level of the fuel prices and also enhance the reliability of the fuel supply because it can be obtained from different types of sources and this reduces the reliance on fossil fuel concentrated in only few regions around the world [23, 24]. Thus, hydrogen is deemed suitable for the aviation industry because it is capable of providing clean, reliable and affordable energy supply that has extremely low pollutant emissions and thus has a low impact on the environment [21].

In order for hydrogen to be viable for the aviation industry, its volumetric density or energy density per unit volume must be increased [25, 26]. Comparing with kerosene, four times bigger volume of LH_2 is needed to deliver the same amount of energy [27]. However, despite this drawback, it has been reported that the hydrogen-powered aircraft are more weight efficient and involve lower operating costs than those aircraft powered with kerosene [27]. Generally, using hydrogen as a jet fuel necessitates modifying the design of both aircraft and engines. LH_2 used in hydrogen-powered aircraft must be kept at very low temperatures and for this it can only be stored in highly insulated tanks and not in the wings which have restricted space to accommodate LH_2 and cannot be insulated properly. With the huge volume requirements of the hydrogen fuel tanks, aircraft design needs to be modified with a greater volume and heavier fuselage, which is the best location to place LH_2 fuel tanks. For short-to-medium range aircraft, the hydrogen tanks could be placed above the passenger cabin while for the long-range aircrafts the hydrogen is stored in two big integral tanks; one of them is located directly behind the cockpit and the second is placed at the far aft of the passenger cabin [28]. The configuration of hydrogen tanks has a significant impact on the energy efficiency of hydrogen-powered aircraft [28]. The top-tank design, used in short-to-medium range aircraft, may increase the energy use by 6–19% due to the greater weight of this type of tanks. On the other hand, the integral design, suitable for long-range aircraft, can increase the energy efficiency by 12% [28]. Thus, it can be concluded that hydrogen fuel is more suitable for long-range aircraft. Since the fuselage of hydrogen-powered aircraft is used to store hydrogen tanks, a heavier and bigger fuselage is needed to support the loads generated from these tanks. The mass of fuselage in hydrogen-powered aircraft is almost 6% bigger than the normal aircraft [24]. In addition to changing the aircraft design, the engine has to be changed when converting into hydrogen due to variation in the combustion gases and properties between the kerosene and hydrogen. Smaller engines can be used for hydrogen fuel [24]. The changes in aircraft and engine designs when using hydrogen entail an increase in the production and maintenance costs which could reach up to 25% [23].

4.5.2 Hydrogen fuel cell for aviation applications

A hydrogen fuel cell is an electrochemical device that generates electricity via an electrochemical reaction between hydrogen and oxygen. Fuel cells are silent, produce little vibrations and produce no NO_x emissions which make them very attractive for wide range of applications. Among the various types of fuel cells devices, PEM fuel cells and Solid Oxide

Fuel Cell (SOFC) were mostly considered for the aviation applications. Hydrogen fuel cells could be used on-board aircraft to power different items and systems that are currently powered by batteries such as emergency door system, floor escape path lighting, emergency locator transmitter (ELT), flight data recorder (FDR), and cockpit voice recorder (CVR).

Auxiliary power unit (APU) of aircraft is a small gas turbine which functions as a source of electricity and compressed air for the operation of other components in the aircraft, such as jet engines and environmental systems, when the main engines are not running. Fuel cell systems could be used in place of the traditional APU or combined with them to form a hybrid APU system [29]. Both PEMFC and SOFC can be used for AUP systems [30]. However, SOFC is more favourable for aircraft applications particularly for powering APU [29]. SOFC is more tolerant of fuel impurities and can operate using hydrogen generated from kerosene reforming [29]. Additionally, the high operating temperature of SOFC allows the internal reforming process of jet fuel and increases the efficiency. However, the weight of the SOFC powered APU is greater than PEM fuel cell or the traditional APUs because it requires bigger balance-of-plant (BoP) items such as reformer, compressor, pumps, heat exchangers and so on. PEM fuel cell can only be used for powering the APU if the source of hydrogen is installed on the aircraft.

With the increased interest in improving the air quality around airports, fuel cells devices have received increased attention due to their potential in powering different ground support equipment (GSE) and other ground vehicles working in the airports, such as passenger shuttles and refuelling trucks, in the near future [30]. GSE or aircraft handling devices are used to service passengers, cargo, facilities and aircraft while they are in the airport between flights. GSE contain different service systems which have different power requirements. Today, many of GSE working in the airport are powered by hydrogen fuel cells. Department of Energy (DOE) has announced that around 250 million US dollars will be used to deploy fuel cells for baggage vehicles at airports [31]. The medium size fuel cell powered forklifts have been already tested in major airports such as Toronto Pearson, Hamburg, and Munich airports [32]. These forklifts incorporate many advantages such as low noise, no emissions and less maintenance. They have almost the same dimensions as traditional batteries powered ones but they do not require battery swapping which is very challenging for most conventional forklifts. Additionally, refuelling time was seen as a major advantage for fuel cell powered forklift over battery ones as it can be completed within minutes while recharging the battery needs hours [33]. The fuel cells can also be used for more than eight hours without requiring any refuelling. Thus, it can be concluded that replacing traditional batteries with fuel cells in forklifts is viable economically with respect to the initial capital cost as well as the operating costs. The Danish airport is currently using luggage trolleys that functions using fuel cells. In 2015, FedEx has rolled out the first fuel cell powered GSE cargo tractors that can pull around 15 t of cargo [34]. In addition to GSE applications, fuel cells can be used to power airport vehicles such as passenger buses. In Tokyo, some of the buses working on the route between Tokyo central and

Tokyo airport are a hydrogen fuel cell/battery hybrid system [35]. International Airport in Hawaii set a plan to use a hybrid fuel cell/ battery bus to shuttling passengers between airport terminals and the car rental facility [36].

Fuel cell is also regarded as a possible new power source alternative to existing batteries of Unmanned Aerial Vehicles (UAVs). The cost is the most attractive factor of battery-powered UAV as it is almost half the price of the fuel cell. However, increasing the weight of the battery required to achieve a long flying time has been reported as a limiting factor of battery-powered UAV [37]. The main advantage of the fuel cells for powering UAV includes allowing extended mission time and distance due to superior energy density, providing quiet and reliable operation, reducing lithium battery charging and transport obstacles [38]. PEM fuel cells are preferred for UAVs applications as they can operate at low temperature and this means smaller BoP requirements. In 2005, AeroVironment has developed the first fuel cell UAV [39]. The plane, that has a wingspan of 15 m, was powered using a PEMFC propulsion system and managed to complete more than one hour of flying using only liquefied hydrogen. Following that in 2006, Bradley et al. [40] designed and tested a fuel cell powered UAV using compressed hydrogen. With a wingspan of 6.58 m and a total mass of 16.4 kg, the authors demonstrated that the plane can be powered using a 500 W PEM fuel cell. Currently, there are considerable research efforts worldwide to design, develop, and construct fuel cell powered UAV. These efforts have resulted in a significant increase in endurance which exceeded 48 h [41]. Reducing the weight of fuel cells, improving their reliability and durability, speeding their startup, and increasing their power density will make the fuel cell technology more attractive for UAV [42].

5. Hydrogen transport

As you have learnt hydrogen was used in industry for many decades. After hydrogen is produced at a centralized production site it is usually transported to the end-users or to the relevant FC applications. Hydrogen can be transported either as a compressed gas or as a cryogenic liquid. Thus there are a number of routes for its bulk transportation: by roads in trucks/trailers and containers or via pipes.

5.1 Heavy goods vehicle (HGV)

5.1.1 Gaseous trucks

Truck fleets are currently used by industrial gas companies to transport seamless steel vessels of compressed gaseous hydrogen (CGH2) for the distances of 200-300 km from a centralised production site. Single cylinder bottles, multi-cylinder bundles or long cylindrical tubes are installed on trailers (Figure 19). Storage pressure ranges from 200 to 300 bar and a trailer can carry from 2,000 to 6,200 Nm^3 of CGH2 for trucks, subject to weight limitation of 40 tons. The amount of hydrogen transported this way is relatively low (from 180 to 540 kg depending on the number of tubes or bundles), which represents approximately 1-2 % of the total mass of the truck. Current trailers utilize Type I storage cylinders (i.e. all-metal). To increase their

performance, bundles of light-weight composite hoop wrapped cylinders or tubes (Type II) can be used. This mode of delivery is relatively easy but it has to be adapted to hydrogen quantities and distances to be cost competitive. The main restrictions in compressed gas truck delivery are capital costs, operation and maintenance including drivers' labour and fuel costs.



(a) (b)

Source: AirLiquide, 2014.

Figure 19. Two types of CGH2 trailers operated by AirLiquide in Europe: (a) tube trailer carrying 2,000 to 3,000 Nm^3 of hydrogen and (b) composite cylinder trailers carrying 6,200 Nm^3 of hydrogen.

The transportation by gaseous truck (tube trailer, cylinders) is one of the most mature modes selected for transportation on short distances and for small amounts of hydrogen. The major limitations are the low weight storage capacity for customers with high consumptions (requiring frequent delivery) and the low pressure of hydrogen delivered, which requires additional compression, for example at a refuelling station. Thus, alternative technologies with higher pressure, higher hydrogen-carrying capacity and lower-cost systems are investigated as described hereafter. Lincoln Composites develops composite tubes of higher capacities. The material of a tank is a plastic liner fully wrapped with epoxy impregnated carbon fibre for gaseous hydrogen tube trailer delivery. For example, the TITANTM tank (1.08 meters in diameter, 11.5 meters in length, 8,400 litres in water volume, and 2,087 kg in weight) operates at pressure of 250 bar. It can deliver 2-3 times more hydrogen compared to the amount of hydrogen stored/transported in steel tanks of similar masses. Figure 20 shows the storage unit holding four composite tanks capable of storing 600 kg hydrogen at 250 bar. The tanks suitable for higher pressures are currently under development.



Source: Lincoln Composites, 2014.

Figure 20. A trailer carrying four composite tanks developed by Lincoln Composites.

Hybrid technologies are explored at the Lawrence Livermore National Laboratory (LLNL) such as cryo-compression combining pressure and low temperature to increase the amount of hydrogen that can be stored per unit volume and avoid the energy penalties associated with hydrogen liquefaction. Compressed hydrogen gas at cryogenic temperatures is much denser than in regular compressed tanks at ambient temperatures. These new vessels would have the potential to store hydrogen at temperatures as low as 80 K under pressures of 200-400 bar. This approach requires development of insulated pressure composite tanks. Alternatively one could consider using cold hydrogen gas tanks that would require less cooling. There may be some optimum combination of pressure and temperature over the range of 80-200 K. Recently, LLNL has identified inexpensive glass fibre materials for cold hydrogen gas storage (~ 150 K and up to 500 bar), expecting 50% trailer cost reduction.

The main safety devices used in gaseous trucks are manual safety valves. During transportation all hydrogen storage vessels are isolated by a valve. In service, there are different safety devices and procedures:

- The semi-trailer changeover procedure takes place as follows:
  - The driver parks the semi-trailer in the location provided,
  - The driver puts chocks in position and deploys the leg stand,
  - The driver unhitches the tractor unit,
  - The driver connects the hose from the full semi-trailer, tests the seal on the draw-off hose and disconnects the empty semi-trailer,
  - The driver hitches the empty semi-trailer to the tractor unit and departs.
- A manual leak tightness test when connecting to a semi-trailer. This is done in the following stages. The operator connects the semi-trailer hose to the installation's connection post. The hose is pressurised. The operator checks for a leak tightness using detection soap and stabilisation of the pressure measured locally using a pressure gauge.

5.1.2 Cryogenic liquid trucks

Hydrogen can also be transported by roads in a liquid form (cooled below 20 K or -253 °C) to distribute larger quantities (hundreds of m^3/h). In terms of weight capacity, super-insulated liquid hydrogen (LH_2) trucks can transport up to 10 times more hydrogen than the tube trailers used for conveying CGH_2. LH_2 trucks operating at atmospheric pressures have volumetric capacities of about 50,000 – 60,000 litres and can transport up to 4,000 kg (Figure 21). It is a preferred distribution mode for medium/large amounts of hydrogen on long distances, which explains the LH_2 business has been developed most extensively in North America (the hydrogen liquefaction capacity in North America is about ten times larger than in Europe). The liquid hydrogen transported in the truck is then vaporized to a high-pressure product for use at a customer site.



Source: AirLiquide Image Bank, 2015

Figure 21. A road tanker operated by Air Liquide for conveying LH2 to the end-user.

The main issue for this transportation route is a capital-intensive liquefaction process. The liquefaction process is costly as well. The energy input for liquefaction accounts for 30-40% of the lower heating value of hydrogen (compared to 10% required for gas compression) [58]. Electricity costs account for 50-80% of the liquefaction costs. Distance is the main deciding factor between transportation of LH2 and gaseous hydrogen CGH_2. The number of LH_2 trucks will depend on the hydrogen demand and the localization of the liquefaction point. However, the liquid truck capacity being much higher than that of a compressed gas truck, this mode of delivery is less dependent upon the transport distance. The truck capital cost and operating cost (fuel, labour) are much smaller. As a consequence, liquid trucking is more economical than gaseous trucking for long distances (from approximately 400 km to thousands of kilometres) and medium amounts of hydrogen. However, one has to consider the availability of LH_2. Currently the industrial hydrogen market is served by four liquefiers in Europe and ten in North America. Larger markets would justify the construction of new liquefaction plants. Significant cost reductions due to scaling effects of liquefaction equipment are possible. However, this mode of delivery relies on the price of electricity and on the decision to install new liquefaction units. Better technologies could offer opportunities to reduce capital cost, to improve energy efficiency of liquefaction process and to reduce the amount of hydrogen lost due to boil-off during storage and transportation (the evaporation rate which depends on the size, shape, insulation of the container and time of storage, is typically of the order of 0.2 %/day for a 100 m^3 container). A number of studies are underway to improve liquefaction technologies and to propose novel approaches (for example, improvement of ortho-para conversion, development of magnetic refrigeration, etc.).

5.2 Trains

The first hydrogen train in the UK, developed through the HydroFLEX project, started its first journey on mainline rail tracks in Warwickshire in September 2020. More fuel cell trains are to be put on rails all over Germany in the next few years. But the question remains on how best to supply the hydrogen to refuelling stations for the trains. A potential route is by rail, and this is endorsed by the State Energy Agency of Hesse. It commissioned DB Energie, the energy

supplier of German national rail operator Deutsche Bahn, to investigate how this can be achieved in terms of technical, operational and legal feasibility. This question was examined based on an existing hydrogen source in the Höchst industrial park in Frankfurt am Main on two specific routes in the Rhine-Main area (see Figure 22).



Source: NPROXX, 2020

Figure 22. Hydrogen transport on rail.

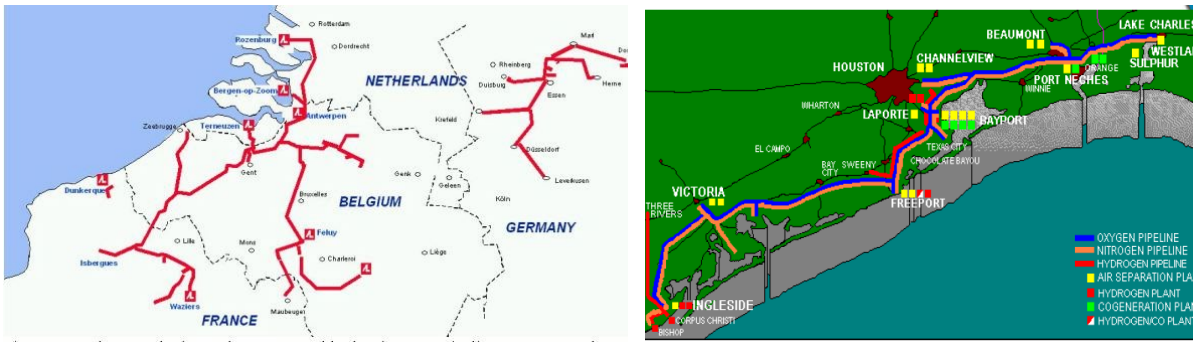
It was feasible to supply the hydrogen refuelling infrastructure with hydrogen by rail, concluded by the DB Energie experts. Compared to the road, there are many advantages, such as precise planning of transport times, the high level of reliability and safety, the possibility of transporting large quantities and the relief of road traffic in metropolitan areas. There is nothing from a technical and legal point of view speaking against transport by rail. However, there are as yet no hydrogen transport containers that are approved for train traffic – only for road traffic. Since the requirements are very similar, it is to be expected that certification for use on rails could be obtained soon. To know the feasibility and economic efficiency, a separate study should be analysed to understand whether transport by rail is more economical than transport by road. On the two routes examined, the train traffic performed slightly worse. However, general statements could not be derived from this. However, hydrogen transport by road is not a really sustainable solution, especially when fuel cell trains continue to be refuelled in the future.

5.3 Pipelines

A number of commercial hydrogen pipelines are used today to distribute large quantities (tens of thousands of m^3/h) of gaseous hydrogen to the industrial market. Their lengths range from less than one kilometre to several hundreds. The major actors are the industrial gas companies, namely Air Liquide, Air Products, Linde and Praxair. In response to an increased demand for hydrogen by mostly refineries, existing networks are expanding, and new portions are built. For example, in March 2009 Air Products have announced 60 km extension to the U.S. Gulf Coast hydrogen pipeline network in Louisiana. The hydrogen network is estimated at around

1,600 km in Europe and 1,100 km in North America. Most of the pipelines are located where large quantities of hydrogen are consumed in refining and chemical sectors. These include systems in the North of Europe, (covering The Netherlands, Northern France and Belgium), Germany (Ruhr and Leipzig areas), UK (Teesside) and in North America (Gulf of Mexico, Texas-Louisiana, California, Alberta). Smaller systems also exist in South Africa, Brazil, Thailand, Korea, Singapore and Indonesia. Overall, the lengths of these pipelines are small compared to the worldwide natural gas transport pipeline system, which exceed 2,000,000 km.

Figure 23 displays parts of the worldwide hydrogen pipeline network. For example, the 240 km long pipeline in the Ruhr area of Germany (Figure 23 a) acquired by Air Liquide in 1998 has been in operation since 1938. Within the "Zero Region" European project for hydrogen energy applications Linde has installed a 900 bar hydrogen pipeline (1" in diameter) over a distance of 1.7 km in the Frankfurt-Hoechst industrial park to supply fuel cell passenger vehicles.



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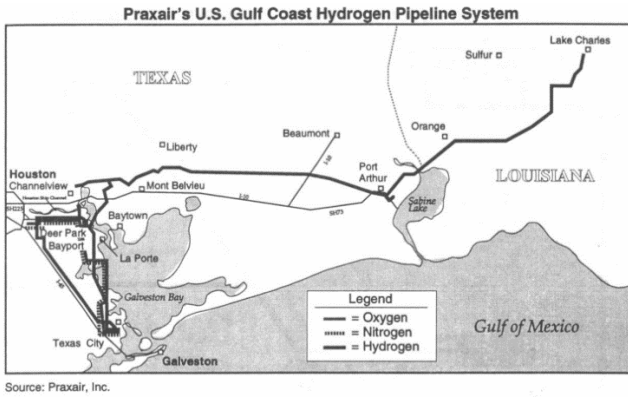

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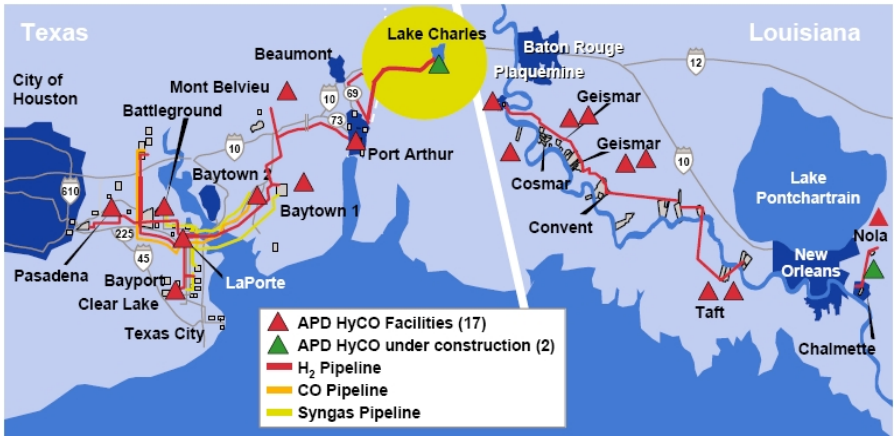

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Figure 23. Main hydrogen pipelines in the world: (a) Air Liquide hydrogen pipelines in Benelux, France and Germany (Ruhr area); (b) Air Liquide hydrogen pipelines in the Gulf Coast (USA); (c) Linde hydrogen pipelines in Germany; (d) Praxair hydrogen pipelines in the Gulf coast (USA); (e) Air Product hydrogen pipelines in the Gulf Coast (USA).

The pipelines require an appropriate design, installation and maintenance procedures. The operating pressure of hydrogen pipelines is generally lower than 100 bar (most commonly between 40 and 70 bar) and the diameter of the pipelines (D) usually ranges from 10 to 300 mm. Current pipelines are made of steels. A technical concern is hydrogen embrittlement of metallic pipelines and welds, characterized by a loss of ductility and rupture when subjected to stress. The steels used for hydrogen pipelines are low-carbon, low-alloy and low strength steels

to reduce the risk of embrittlement (e.g. API X42 steel with carbon content C < 0.2 wt. %, manganese content Mn < 1.3 wt. %). These steels combine economical affordability with an adequate range of physical properties such as strength, toughness, ductility and weldability. For safety reasons, most pipelines are buried and steels are protected with coatings or with a cathode protection to prevent corrosion.

Pipeline construction involves extensive welding for joining, with a minimum of inspections before operation for safety considerations. The exploitation of a pipeline network also requires compressor stations as hydrogen is generally available at low pressure. Hydrogen compressors feeding the pipeline system are usually found at locations where hydrogen is produced. The compressors are expensive and require high maintenance, so they are not installed if another alternative is possible. For instance, when hydrogen is produced using natural gas (steam methane reforming), the natural gas feedstock can be compressed, and the production plant operated at a higher pressure. Friction losses in pipelines with hydrogen are much lower than for those in natural gas as the viscosity of hydrogen is lower (the energy loss during transportation of hydrogen is about 4% of the energy content).

A hydrogen pipeline carries about 30% less energy compared to natural gas pipeline due to the lower volumetric density of hydrogen. The distribution of larger energy quantities in hydrogen pipelines requires a flow pressure increase (> 100 bar). This increase in pressure may have implications for the material which could be used in the pipeline construction. Furthermore, the operating conditions of a hydrogen pipeline for energy applications would be different from an industrial pipeline which today operates at nearly constant pressures, without significant pressure cycles. Hydrogen energy pipelines would have to bear variations of pressure. This may be a concern due to the susceptibility of steels to hydrogen embrittlement which affects their mechanical properties and decreases their resistance to fatigue crack. Hydrogen embrittlement phenomena will be discussed in the lecture 'Safety of hydrogen storage'. There is a renewed interest in the research for the development of new pipelines' materials compatible with hydrogen and their suitability to operate at higher pressure, and to reduce capital costs. New steels are explored to develop a better understanding of hydrogen embrittlement and to identify steel compositions and processes suitable for construction of a new pipeline infrastructure or potential use of the existing steel pipeline infrastructure.

Current research also concentrates on the alternative to metallic pipelines to achieve cost and performance targets for hydrogen transmission and distribution. Polymeric and fibre-reinforced polymeric pipelines, which present the advantages of being lighter, easier to handle, join and weld, non-sensitive to corrosion, non-sensitive to hydrogen embrittlement compared to steels are investigated. Polymeric pipes currently used in the natural gas distribution network are made of polyethylene and have a pressure rating limited to 10 bar. Polymers such as polyamide present more interest as the permeability of hydrogen is significantly reduced and its thermo-mechanical properties allow pipes to sustain a 20 bar operating pressure and 80°C operating temperature.

Therefore, plastic pipes can be a viable alternative to steel thanks to savings in installation and maintenance costs. However, the costs of these new polymeric materials can be very high. Pipes made of composite fibre-reinforced polymer/plastic (FRP) materials are composed of a thermoplastic liner (mainly polyethylene) wrapped with high strength fibres (typically aramid fibres) coated with a thermoplastic layer. This last layer protects from environmental attacks and helps to retain the wrapping responsible for the mechanical properties. Compared to simple plastic pipes, wrapping with aramid fibres allows getting pressure up to 100 bar. These reinforced plastic pipes are already used for natural gas or crude oil distribution in the middle-East and their development for hydrogen delivery is currently part of the US DOE Hydrogen program (Figure 24). FRP pipes could be cost-effective substitutes of metallic pipes when long lengths (200 to 300 meters) are installed. However, the manufacturing process cannot produce plastic pipes with diameters as high as steel pipes (100 and 150 mm). Further developments are still needed to evaluate the feasibility of large-scale manufacturing operations, assess joining technology, and develop codes and standards for hydrogen-service FRP pipelines.



Figure 24. Composite FRP pipelines.

6. Stationary applications

6.1 Combined heat and power (CHP) systems

In traditional CHP plants electricity and heat are produced by combustion of natural gas in the internal combustion engine or turbine. CHP systems based on FCs generated electricity, heat water in the electrochemical reaction described earlier. Two FC technologies are considered: Solid Oxide Fuel Cell (SOFC) and PEM FC. Natural gas is converted to produce hydrogen and a mixture of hydrogen, carbon dioxide and carbon monoxide (called syn-gas) with impurities is fed directly to the FC to generate energy. In PEM FC systems, which use lower temperatures, the syn-gas needs further purification to remove carbon monoxide and sulphur-containing compounds. Micro CHP installations have been introduced in Europe within the Callux project (http://enefield.eu/).

6.2 Back-up power generation

The main objective of this type of technology is to provide instantaneous power in case of a blackout. The power capacity of this installation is between 16 and 80 kW with up to nine hydrogen cylinders. The main advantages of this application are:

- High reliability and fast start-up.
- Scalable autonomy, only depending on gas storage volume.
- Low maintenance.
- Clean and silent operation [1].

Potential users of this type of application include: telecom, datacentres, hospitals, military, industries, luxury hotels, etc. An example of the system is depicted in Figure 25 showing a FC backup power unit used in IP Energy project (Aix-en-Provence, France). 30 kW backup power system installed in 2008 is first containerized solution. Internal gas storage allowed a 4-hour operating capacity.



Figure 25. A FC back-up power coupled with IP Energy data centre.

The safety features and concepts for the system are as follows:

- The FC system has two separated vent lines, one for oxygen and one for hydrogen, that discharge the gas on the roof of the container at a hazard distance to avoid mixing of oxygen and hydrogen during discharge. After a discharge, a residual amount of hydrogen subsists within the system.
- The process compartment is equipped with two hydrogen sensors that can trigger an emergency stop if the hydrogen concentration in the containers is above 0.4 vol. %. If an abnormal hydrogen concentration is detected a safety stop is triggered and the following actions will take place:
  - Stop all system processes.
  - Activate the mechanical ventilations.
  - Insulate the gas storages by closing the solenoid valves.

- Detection of hydrogen is monitored continually even when the system is in a standby mode. In the event of loss of detection, the system triggers a safety stop.
- The containers are equipped with fire detectors. In case of their activation the following actions should be undertaken:
  - Stop all system processes.
  - Insulate the gas storages by closing the solenoid valves.
  - Cut off ventilations.
- The hazardous explosive atmospheres resulting from potential hydrogen leaks or releases shall be prevented in the FC enclosure. Passive prevention measures include but not limited to: a use of joints that are permanently secured and constructed in a way that they limit the maximum release rate to a predictable value; and natural ventilation. Active prevention methods include but are not limited to: active ventilation; a flammable gas detection system; other means of leak detection (e.g. through pressure measurements relative to control settings).
- Inside the container, where hydrogen may leak or diffuse into, is not classified since safety barriers ensure no dangerous hydrogen ATEX at the leaking point or by accumulation. Nonetheless, all equipment installed just below the container ceiling and capable to ignite flammable hydrogen-air mixtures is certified for ATEX zone 2. In particular, it concerns the hydrogen and fire sensors and the ventilation system. Besides the electrical compartment is systematically separated from the process compartment.
- Oxygen is not flammable in air but it supports combustion process. An oxygen leak can be an origin of a fire. The fire risk is increased when the atmosphere is enriched with oxygen. Any contacts must be avoided between oxygen and the organic matters due to the fire risk.
- General measures of risk prevention are taken with the design and in the exploitation of this system:
  - Correct choice of materials (i.e. degreased stainless), use of protected pipes and without abrupt elbows, tight connections, etc.
  - Limitation of the oxygen flows according to the pressure.
  - Protection of the oxygen lines by filters in order to trap dust that is likely to ignite.
  - Natural and forced ventilation in the process compartment.
  - Lengths reduction of the pipes under high pressure, sufficient hazard of the pipes from the electric components.
  - Re-grouping of the units containing oxygen in a delimited zone (compartment).

- Adherence to the procedures of control and maintenance (periodic tests) of the facility [1].

7. Marine applications

Hydrogen fuel cells have proven their performance in a variety of applications, including buses, trucks, cars, forklifts and even passenger trains. Thanks to their success in heavy-duty land vehicles, fuel cells are now being integrated into marine vessels. Fuel cells will play a key role in helping marine industries address greenhouse gas (GHG) emissions on the water, and in ports.

Marine shipping is well-known to be a significant source of GHG emissions. The high GHGs are a result of the traditional low-grade fuel used in ships engines which generate high emissions. In recent years, public pressure regarding air pollution and climate change has prompted governments and other authorities to take action to reduce them. As a result, GHG-reduction regulations targeting marine traffic are being put into place around the world. For example:

- The Norwegian Parliament, in 2018, enacted a resolution to protect the country's world heritage fjords: this resolution will halt all emissions from cruise ships and ferries in the fjords by 2026 [59].
- The State of Alaska's Visible Emissions Standards limit the opacity of all marine vessels within three miles of their coastline.
- The International Maritime Organization (IMO) has adopted mandatory measures to reduce GHG emissions and completely phase them out by the end of this century. Their initial strategy will reduce total GHG emissions from international shipping by at least 50% of 2008 levels by 2050.
- The European Maritime Safety Organization (EMSA) plans to cut the EU's carbon dioxide emissions from maritime transport by at least 40% (from 2005 levels) by 2050. Additional ECAs are being discussed for the Arctic, Central America, the Mediterranean and Black Seas, Japan, the Koreas, and Australia.

These emissions regulations will have a significant impact on maritime vessels, and the organizations that operate them. To adjust to these changes, fleet operators need solutions that cut emissions dramatically. With so many different types of vessels on the water, the marine industry needs a true zero-emission solution that can be applied across different vessel types.

Batteries are a zero-emission power solution for smaller vessels that operate with short duty cycles, for example, small passenger ferries and lake service boats. However, lower power density and greater weight limit the usage of batteries for many applications. For marine vessels, fuel cells are the only viable, true zero-emission option. Just like batteries, fuel cells produce electricity with high efficiency through an electro-chemical process. The difference is,

with a fuel cell, energy is stored separately in the form of hydrogen fuel. As long as fuel is available, the fuel cell power systems will produce electricity as a generator. The only emissions from a fuel cell are water vapour and heat.

Additionally, hydrogen fuel can be produced from renewable sources, including solar, wind, hydroelectric, and geothermal energy. And the cost of renewable hydrogen continues to fall every year—especially as large scale production projects are starting to emerge in Europe, Australia, and Chile. When fuelled by renewable hydrogen, a fuel cell power system is a true well-to-wake zero-emission power source.

Making the transition to a new energy source is a major undertaking. In the case of fuel cells for marine vessels, the hurdles are in the refuelling infrastructure, and hydrogen availability in ports. Before operators can power their vessels using fuel cells, hydrogen supply and fuelling infrastructure need to be further developed.

In the nearer timeframe, hybrid battery/fuel cell applications are viable. They require less fuel and still meet the zero-emission objective. These applications are:

- powering smaller vessels, such as ferries and river vessels.
- powering auxiliary loads on larger vessels, such as cruise ships, where the auxiliary power demands are high.
- providing shore power to docked vessels.

There are three key benefits of using fuel cells for marine application:

- Modular power systems are adaptable for many load requirements.



Figure 26. Ballard 100 kW marine fuel cell module

Ballard PEM (proton exchange membrane) fuel cells are modular (Figure 26), which can be used in various combinations in parallel to provide the power and redundancy needed by a vessel, from 100kW to 1MW or more.

- DC power is compatible with electric architectures.

Ballard PEM fuel cells are a source of substantial DC power that's compatible with battery hybrid electric architectures. They can be deployed in parallel, dispatchable configurations to meet the variable power requirements of:

  - hybrid electric propulsion.
  - auxiliary power systems.

- Fuel cell systems have flexible configuration.

In a fuel cell system, the power generation and fuel storage elements are separate, which offers the ship architect more flexibility than batteries. Ballard's fuel cell power system has flexible configuration that will adapt to vessel space constraints. It can be broken down into several modules, positioned at different locations. Additionally, Ballard's experts can evaluate the duty cycles of any size or type of marine vessel. They can develop a viable, practical solution by determining the optimum:

- hybrid architecture.
- fuel cell power.
- turn down requirements.
- fuel storage requirements.
- estimated fuel consumption.

Fuel cells could be applied on various types of vessels, e. g. ferries, cruise ships, river vessels et al. For ferries, modular, scalable fuel cell systems can provide zero-emission propulsion for small and large ferries. The first zero-emission ferries are expected to be powered by a hybrid architecture of fuel cells and batteries. The specific ratio of batteries and fuel cells would depend on the route duration and schedule. Because fuel cells deliver substantial DC power, they can also provide power that can be distributed across a ferry (or other vessel) to power its auxiliary electrical needs, such as lighting, heating, air conditioning, vessel instrumentation, emergency systems, galleys and other onboard systems. For additional efficiencies, surplus heat generated by the fuel cells could be used to heat water for HVAC, laundry and other purposes. The water that is produced by the fuel cell can be recovered if needed.

Cruise ship applications may be among the first marine uses of fuel cells. Some cruise ship ports already require zero-emission operation. For cruise ships, the applications of fuel cell power include generating power for hotel loads, emergency systems, and a portion of the propulsive power. For the industry to meet its zero-emission targets this century, fuel cells

should provide 100% of the power on many cruise ships, as the hydrogen infrastructure matures.

Fuel cells are a viable solution for zero-emission propulsion on river vessels including barges that are pushed or towed by push-boats and tugboats, and self-propelled ships. Ballard is already working on a demonstration river vessel power project in Lyon, France (Figure 27). The project will power a push-boat as a utility vessel on one of the world's most demanding rivers, the Rhône.

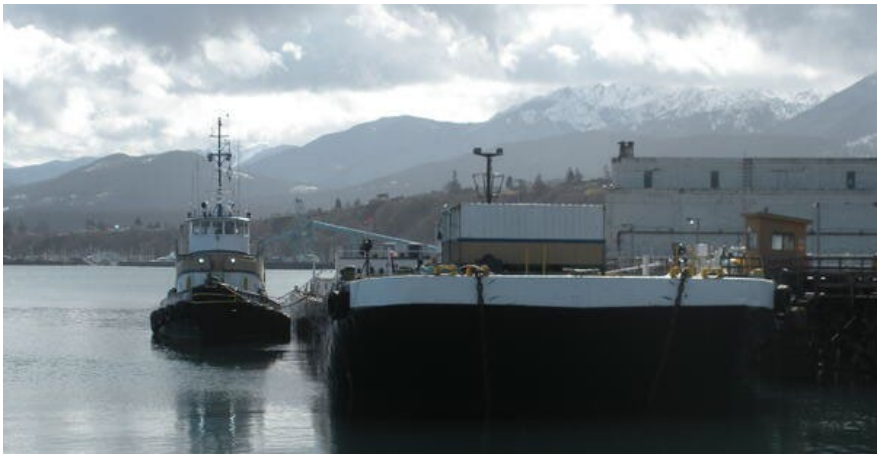

Figure 27. Ballard's river vessel power project in Lyon, France

In an effort to reduce air pollution and carbon emissions, governments, port authorities and organizations across the world are tightening emissions standards for marine vessels. As a result, the marine industry is finding itself under pressure to meet the coming zero-emission regulations. Hydrogen fuel cell power—a proven zero-emission solution for powering transit buses, trucks and other heavy-duty transport—offers real potential for a variety of marine vessels. Powered by renewable hydrogen, fuel cell systems are the most practical, viable zero-emission solution. Implementing this technology is a critical step in reducing emissions from marine vessels and cleaning up the air for a more liveable world.

8. Hydrogen-based energy storage systems

As an example of hydrogen-based energy storage system we will consider the Greenenergy Box. The Greenenergy Box™ is a containerized hydrogen chain comprising of an electrolyser, a fuel cell, a water and heat management system, and electrical converter systems coupled with hydrogen and oxygen storages. The Greenenergy Box™ is an integrated modular system that can offer a power from 50 to 500 kW with a storage capacity from 0.2 to 2 MW. Its principle is indicated in Figure 28. Several systems can be coupled to increase the power and the energy capacity providing the function of a back-up system for few hours at high power [1].

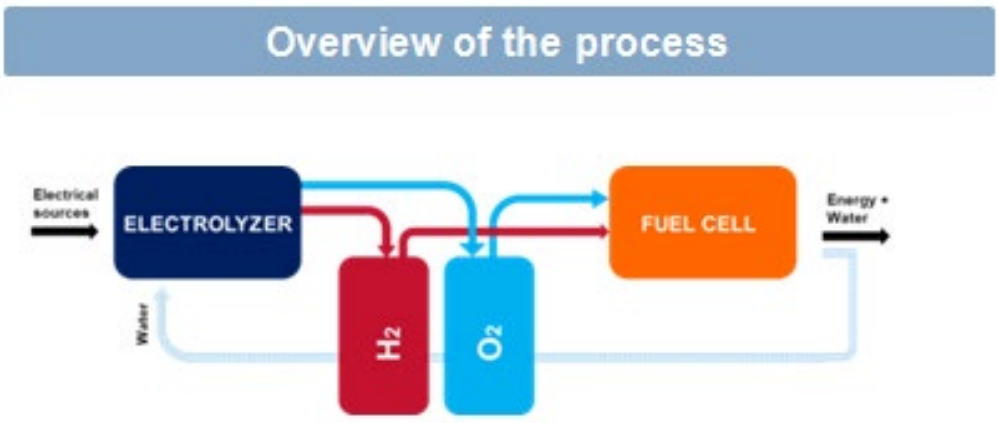

Figure 28. An overview of Greenenergy Box process.

The photovoltaic panels provide electricity to the electrical network and its surplus is used by the electrolyser to generate gaseous hydrogen and oxygen. Once produced gaseous hydrogen and oxygen are stored in separated tanks installed aside of the Greenenergy Box^{TM}. Owing to the FC system stored hydrogen and oxygen can be used to produce electricity to ensure partial energetic autonomy of the buildings as well as the backup system in case of power cuts. The Greenenergy Box^{TM} manages itself the electricity received by the photovoltaic panels to electrolyze water or to provide electricity to the network. Furthermore heat, which is also produced by the system during both electrolysis and fuel cell processes, is also managed and valorised for the adjacent buildings. The waterproof and wind resistant Greenenergy Box^{TM} has three different compartments: an electrical compartment, a fuel cell compartment and an electrolyser compartment as shown in Figure 29.

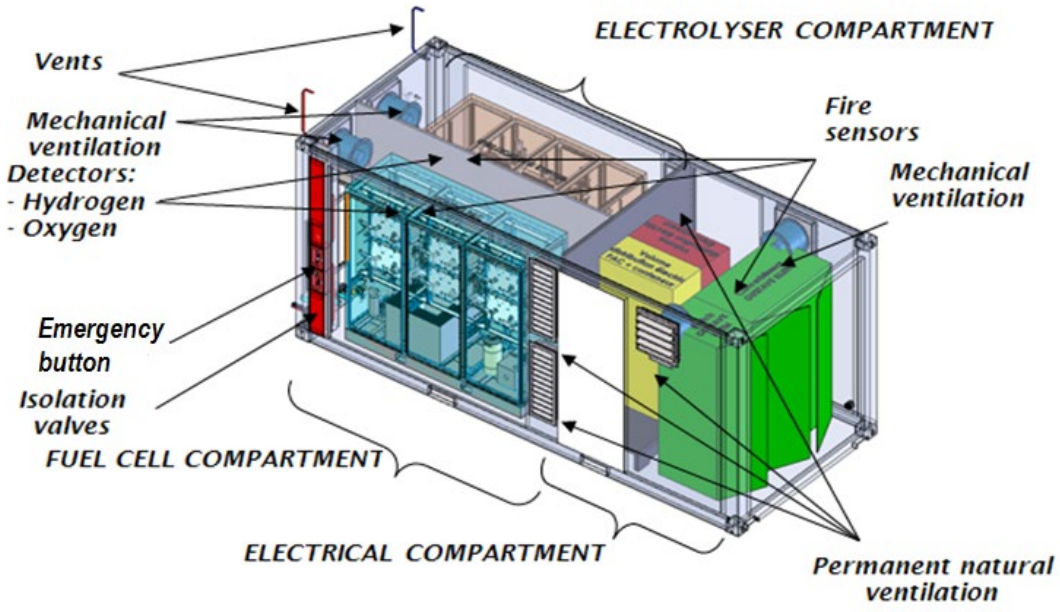

Figure 29. A schematic of the Greenenergy BoxTM [1]

The Greenenergy Box™ is CE certified by following the Low Voltage Directive LVD 73/23/EEC, the Electromagnetic Compatibility Directive EMC 89/336/EEC, Machinery Directive MD 98/37/EC, Pressure Equipment Directive PED 97/23/EC. The risk assessment for this system is carried out in three steps. First, a document called "Basic safety considerations" describing the main safety requirements, which should followed for the architecture and conception stages of the hydrogen chain, is prepared. Once the architecture of the system is sufficiently detailed, a HAZOP (HAZard and OPerability Study) review of each subsystem is performed to define the potential causes of each process deviations, associated potential consequences and assess the existing barriers. As third stage, a fault tree analysis completes the HAZOP review to highlight the conception failure, inappropriate system configuration and external sources of danger. All the safety study is collected in a document entitled "Synthesis of the safety studies of the Greenenergy Box™ [1]. The overall safety strategy of the hydrogen chain is detailed below in following different parts.

- Leak suppression and control.
    - Equipment and piping materials are chosen to be compatible for hydrogen and oxygen use. In particular, hydrogen material embrittlement and oxygen corrosion are selected from the IGC15/06, ISO/TR 15916 and ISO 11114-4. Steel cylinders are commonly used to store pressurized hydrogen and oxygen. The maximum carbon equivalent for hydrogen is 0.43 as described in the IGC 121/04, § 3.
    - Welded connections are preferred and are used in a practical way to minimize potential leak sources. The number of joints and fitted connections is minimized.
    - Both electrolyser and fuel cell compartments of the Greenenergy Box™ are equipped with two hydrogen sensors and an oxygen sensor. A safety shut-off valve triggers at 10% of the hydrogen LFL (0.4 vol. % H_2 in air) and an emergency shut-off occurs at 25% of the LFL (1 vol. % H_2 in air). Oxygen detection triggers whenever the oxygen concentration reaches more than 23 vol. % in air.
    - Furthermore, hydrogen and oxygen leaks are also detected by difference of pressure during standby phases. If a tank or a portion of pipe loses pressure during a standby stage, it potentially means that there is leak. If there is a minor loss of pressure during the standby stage, an alarm triggers and if the pressure loss is too significant the system will not be able to restart.
    - Before commissioning, hydraulic and leak tests are performed as required by the Pressure Equipment Directive.
    - Regular inspections and preventive maintenance program are organized to ensure the maximum safety level. In particular, leak tests on pressure regulators, valves, pipes, joints and connections etc. are realized regularly. Regular visual inspections are

organized to check the level of corrosion. Information regarding inspection and maintenance frequency is in the Appendices F of the IGC 121/04 and IGC 13/02.

- Prevention of formation of flammable or over-oxygenated atmospheres.
  - Three compartments of the Greenenergy Box™ are naturally ventilated thanks to lateral vents located on both sides of the container (Figure 33).
  - The fuel cell and electrolyser compartments are both equipped with ATEX type ventilation that triggers for hydrogen and oxygen concentration above respectively 0.4 vol. % hydrogen or 23 vol. % oxygen in air. The maximum flow rates are set for thermal dissipation i.e. 2,500 m^3/h for the FC compartment and 2,700 m^3/h for the electrolyser compartment.
  - Modelling of an accidental hydrogen leak of 750 L/min flow rate using the LES (Large Eddy Simulation) approach developed at the University of Ulster highlights that it takes about 10 s for a hydrogen sensor to detect a hydrogen concentration greater than 0.4 vol. % in the naturally ventilated electrolyser compartment. Considering the conservative hypothesis of 30 s for a response time of the hydrogen sensor, it can be observed that after 40 s of continuous constant release the hydrogen-air concentration formed below the ceiling is still below the LFL of hydrogen in air i.e. less than 4 vol. % by air. From this moment, the hydrogen sensor sends a signal to the control command that triggers the air intake fan to its maximal speed. It can be observed that the hydrogen air cloud is entirely diluted in less than 2 s.
- Suppression/Reducing ignition sources.
  - The inside of the Greenenergy Box™ where hydrogen may leak or diffuse into is not classified since safety barriers ensure no dangerous hydrogen ATEX at the leaking point or by accumulation. Nonetheless all equipment installed just below the container ceiling and capable to ignite a flammable hydrogen-air mixture is certified for ATEX zone 2. In particular, it concerns the fire detectors, hydrogen and oxygen sensors and the ventilation system.
  - The Greenenergy Box™ and reservoirs are earthed and bonded to give protection against the hazards of stray electrical currents and static electricity.
- Protection against overpressures.
  - Each reservoir and piping lines from the Greenenergy Box™ to the storage tanks are equipped with a pressure relief valve (PRV). The tare pressure of the pressure relief valve is set so that the PRV actuates when the pressure within the reservoir reaches 1.15 of the maximal operating pressure.

- The storage tank vents are mounted vertically at a minimum high of 3 m. They are equipped with a 'hat', for which the weight is calibrated to lift under pressure in order to avoid the introduction of water within the vent.
- The Greenenergy Box™ is equipped with two distinct hydrogen and oxygen vents located at a minimum height of 1 m above the roof of the container and well separated to avoid oxygen-enriched hydrogen-air mixture. Each distinct venting line is common to the electrolyser and the FC and allows the depressurization of the system in less than 2 minutes in case of emergency shutdown.

- Emergency and safety shutdown.
  - The control command that is used for piloting automatically the system is also used to trigger the safety functions. About 70 safety functions are recorded into the control command to detect any process deviation or gaseous leak or fire within the system. Depending on the amplitude of the deviation compared to the safety threshold of the parameter, an emergency or and safety shut-down is triggered and is followed by power shut-down, system depressurization, inerting and ventilation activation (except for fires).
  - The main safety functions i.e. hydrogen, oxygen and fire detections, emergency shut-down button and watchdog of the control command are realized by logic cable and respect a SIL (Safety Integrity Level) 1 [1].

9. Overview of incidents and accidents

9.1 Incidents and accidents on FCH systems and infrastructure

An incident is an event that has the capacity to lead to loss of or a disruption to operations, services, or functions – which, if not managed, can escalate into an emergency, crisis, or disaster [43], and an accident is an unforeseen and unplanned event or circumstance causing loss or injury. Reporting incidents/accidents, which occurred on the FCH systems or infrastructures, as well as a complex evaluation of their principal causes and the lessons learnt from them, are extremely valuable exercise for both private and public sectors. Information on accidents or incidents related to FCH technologies can be found in the following well-known databases:

- Hydrogen lessons learned from incidents to and near-misses: http://h2tools.org/lessons/
- Hydrogen Incidents and Accidents Database HIAD database: https://odin.jrc.ec.europa.eu/odin/index.jsp
- Bureau d'Analyse des Risques et Pollutions Industries (BARPI) https://www.aria.developpement-durable.gouv.fr/the-barpi/?lang=enbarpi/

All the databases should be regularly updated.

For example, H2Incidents database (recently renamed to Hydrogen Tools. Lessons Learned) has been created by the Pacific Northwest National Laboratory with funding from the U.S. Department of Energy (https://h2tools.org/lessons). In this database, incidents and near-misses are reported without including the names of the companies and other details in a way that confidentiality encourages reporting the events. The incidents are classified according to settings, equipment, damage and injuries, probable causes and contributing factors [3].

Rigas and Amyotte [3] defined the following major causes of incidents/accidents:

- Mechanical material or equipment failure.
- Corrosion attack.
- Over-pressurisation.
- Hydrogen embrittlement at low temperatures.
- Boiling Liquid Expanding Vapour Explosion (BLEVE).
- Storage tank rupture due to impact of shock waves or missiles from adjacent explosions.
- Human error.

In this first lecture we will only discuss a few examples of incidents/accidents related to FCH technologies. However the following lectures will include a number of relevant examples to each FCH system studied.

9.2 Accidents occurred during hydrogen production



Source: Millet et al, 2011 [45]

Figure 30. Damaged parts of high pressure PEM electrolyser.

An explosion of an electrolyser at the operational pressure of 40 MPa happened on the 7th of December 2005, at a demonstration hydrogen stand at the Kyushu University (Japan) [44]. Possibly, following a membrane leak, an internal hydrogen-oxygen jet fire resulted in a metal (titanium) fire and explosion or rupture of the electrolyser shell. The internal fluid and combustion products were released into surrounding including parking area outside the laboratory building. The windscreens of several vehicles were damaged due to the exposure to hydrogen fluoride which formed during the decomposition of a membrane polymer material

[44]. A French-Russian study [45] reported the analysis of the failure mechanisms of PEM water electrolytic cells, which can ultimately lead to a destruction of the electrolyser. A two-step process involving initially the local perforation of the solid polymer electrolyte followed by a catalytic recombination of hydrogen and oxygen stored in the electrolysis compartments has been evidenced. The photographs of a stainless steel fitting and a nut perforated by a hydrogen-oxygen flame formed inside the PEM stack are presented on Figure 30.

9.3 An incident at a refuelling station

Hydrogen gas release occurred at Emeryvile fuelling station [60]. A PRD had failed, 300 kg of hydrogen released and subsequently ignited. The gas ignited at the exit of the vent pipe and burned for 2.5 hours until technicians were permitted by the local fire department to enter the station and stop the flow of gas. During this incident the fire department evacuated nearby businesses and schools, closed adjacent streets.

The identified root causes of this event are:

- the use of incompatible materials in the manufacturing of the PRD.
- improper assembly resulting in over-torquing of the inner assembly.
- over-hardening of the inner assembly materials by the valve manufacturer.

These problems could have been avoided by adequate quality assurance/quality control procedures during the design and safety reviews.

10. Introduction to hydrogen safety engineering framework & standards

Hydrogen safety engineering (HSE) is defined as an application of scientific and engineering principles to the protection of life, property and environment from adverse effects of incidents/accidents involving hydrogen [46]. Despite the progress in hydrogen safety science and engineering during the last decade, especially through the HySafe partnership [47], an overarching performance-based methodology to carry out HSE is still formally absent. HSE comprises a design framework and technical sub-systems. A design framework for HSE, developed at the University of Ulster, is similar to British standard BS7974 for application of fire safety engineering to the design of buildings [48] and is expanded to reflect specific hydrogen safety related phenomena, including but not limited to high pressure under-expanded leaks and dispersion, spontaneous ignition of sudden hydrogen releases to air, high momentum jet fires, deflagrations and detonations, mitigation techniques, e.g. venting of deflagration and natural/forced ventilation, etc. The HSE process includes three main steps as indicated in Figure 31.

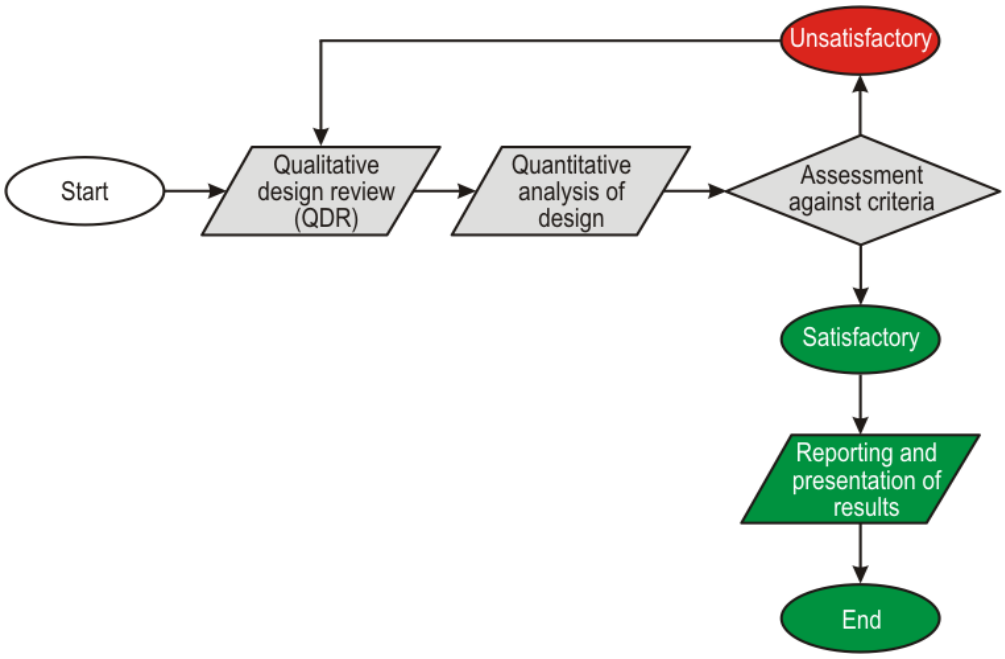

Figure 31. Steps of hydrogen safety engineering process [44]

At first, a qualitative design review (QDR) is undertaken by a team that can include owner, hydrogen safety engineer, architect, representative of authorities having jurisdiction, e.g. emergency services, and other stakeholders. The team defines accident scenarios, suggests trial safety designs, and formulates acceptance criteria. Secondly, a quantitative safety analysis of selected scenarios and trial designs is carried out by qualified hydrogen safety engineer(s) using the state-of-the-art knowledge in hydrogen safety science and engineering and validated models and tools. Thirdly, the performance of a hydrogen and/or fuel cell system under the trial safety designs is assessed against predefined acceptance criteria. The QDR is a qualitative process based on the team's experience and knowledge. It allows its members to establish a range of safety strategies. Ideally, QDR has to be carried out early in the design process and in a systematic way, so that any substantial findings and relevant items can be incorporated into the design of HFC application or infrastructure before the working drawings are developed. In practice however, the QDR process is likely to involve some iterations as the design process moves from a broad concept to greater detail. Safety objectives should be defined during the QDR. They should be appropriate to the particular aspects of the system design, as HSE may be used either to develop a complete hydrogen safety strategy or to consider only one aspect of the design. The main hydrogen safety objectives are safety of life, loss control and environmental protection. The QDR team should establish one or more trial safety designs taking into consideration selected accident scenario(s). The different designs could satisfy the same safety objectives and should be compared with each other in terms of cost effectiveness and practicability. At first glance, it is essential that trial designs should limit hazards by

implementing prevention measures and ensuring the reduction of severity and frequency of consequences. Although HSE provides a degree of freedom, it is mandatory to fully respect relevant regulations when defining trial designs.

The QDR team has to establish the acceptance criteria against which the performance of a design can be judged. Three main methods can be used: deterministic, comparative, and probabilistic. The QDR team can, depending on trial designs, define acceptance criteria following all three methods. The QDR team should provide a set of qualitative outputs to be used in the quantitative analysis: results of the architectural review; hydrogen safety objectives; significant hazards and associated phenomena; specifications of the scenarios for analysis; one or more trial designs; acceptance criteria and suggested methods of analysis. Following QDR the team should decide which trial design(s) is likely to be optimum. The team should then decide whether quantitative analysis is necessary to demonstrate that the design meets the hydrogen safety objective(s). Following the QDR a quantitative analysis may be carried out using Technical Sub-Systems (TSS) where various aspects of the analysis can be quantified by a deterministic study or a probabilistic study. The quantification process is preceded by the QDR procedure for two main reasons: to ensure that the problem is fully understood, and that the analysis addresses the relevant aspects of the hydrogen safety system; and to simplify the problem and minimise the calculation effort required. In addition, the QDR team should identify appropriate methods of analysis among: simple engineering calculations; CFD simulations; simple probabilistic study; full probabilistic study, etc. A deterministic study using comparative criteria will generally require fewer data and resources than a probabilistic approach and is likely to be the simplest method of achieving an acceptable design. A full probabilistic study is only likely to be justified when a substantially new approach to hydrogen system design or hydrogen safety practice is being adopted. The analysis may be a combination of some deterministic and some probabilistic elements. Following the quantitative analysis, the results should be compared with the acceptance criteria identified during the QDR exercise. Three basic types of approach can be considered to access the performance of safety system against criteria:

- Deterministic approach shows that on the basis of the initial assumptions a defined set of conditions will not occur;
- Comparative approach shows that the design provides a level of safety equivalent to that in similar systems and/or conforms to prescriptive codes (as an alternative to performance based HSE);
- Probabilistic approach shows that the risk of a given event occurring is acceptably low, e.g. equal or below the established risk for similar existing systems.

If none of the trial designs developed by the QDR team satisfies the specified acceptance criteria, QDR and quantification process should be repeated until a hydrogen safety strategy satisfies acceptance criteria and other design requirements. Several options can be considered

when reconducting QDR following recommendations [48]: development of additional trial designs; adoption of more discriminating design approach, e.g. using deterministic techniques instead of a comparative study; re-evaluation of design objectives, e.g. if the cost of hydrogen safety measures for property loss prevention outweighs the potential benefits. When a satisfactory solution has been identified, the resulting HSE strategy should be fully documented. Depending on particularities and scope of the HSE study, the reporting of the results and findings could contain the following information similar to requirements [48]:

- Objectives of the study;
- Full description of the HFC system/infrastructure;
- Results of the QDR;
- Quantitative analysis (assumptions; engineering judgments; calculation procedures; validation of methodologies; sensitivity analysis);
- Assessment of analysis results against criteria;
- Conclusions (hydrogen safety strategy; management requirements; any limitations on use);
- References (e.g. drawings, design documentation, technical literature, etc.). To simplify the evaluation of a HSE design, the quantification process is broken down into several technical sub-systems (TSSs).

The following requirements should be accounted for development of individual TSS:

- TSS should together, as reasonably as possible, cover all possible aspects of hydrogen safety engineering;
- TSS should be balanced between their uniqueness or capacity to be used individually, and their complementarities and synergies with other TSSs;
- TSS should be a selection of the state-of-the-art in the particular field of hydrogen safety, validated engineering tools, including empirical and semi-empirical correlations and contemporary tools such as CFD models and codes;
- TSS should be flexible to allow update of existing or use of new appropriate and validated methods, reflecting recent progress in hydrogen safety science and engineering.

The following TSSs are currently suggested and under development for [46]:

- TSS1: Initiation of release and dispersion;
- TSS2: Ignitions;
- TSS3: Deflagrations and detonations;
- TSS4: Fires;

- TSS5: Impact on people, structures, and environment;
- TSS6: Mitigation techniques;
- TSS7: Emergency services intervention.

Hydrogen safety engineering is a key to the success of the hydrogen economy. It is the powerful tool for provision of hydrogen safety by qualified specialists in the growing market of HFC systems and infrastructure. Last but not least the HSE can secure high level of competitiveness for hydrogen and fuel cell products.

11. Introduction to the e-Laboratory

Education and training for the emerging fuel cell and hydrogen (FCH) sector is critical for professional development of the current and future workforce. This underpins the leadership and competitiveness of European FCH products. An online repository of digital tools – the e-Laboratory, was first developed within The European project "Novel Education and Training Tools based on digital Applications related to Hydrogen and Fuel Cell Technology" (NET-Tools). The original NET-Tools e-Laboratory incorporates an extensive suite of digital tools. Those tools deemed most pertinent to Responders have been made available through the e-Laboratory for Hydrogen Safety, which can be accessed through the HyResponder e-Platform (https://hyresponder.eu/e-platform/) or directly at https://elab.hysafer.ulster.ac.uk/

Performance-based calculation of hazard distances, the term introduced recently by ISO TC197 Hydrogen Technologies, is a key element of hydrogen safety engineering of FCH systems and infrastructure, e.g. refuelling stations. The principles behind the e-Laboratory of Hydrogen Safety allow assessing hazard distances for unignited releases (flammable envelope size); ignited releases (jet fires); blast wave decay from deflagrations, detonations and high-pressure hydrogen storage tank rupture in a fire, fireballs, etc. This long expected by hydrogen industry toolbox provides determination of hazard distances for unignited releases and jet fires in interactive regime, e.g. by varying system parameters like pressure and pipe (leak) diameter. The state-of-the-art safety tools of the e-Laboratory of Hydrogen Safety is a free-access expanded European analogy of the HyRAM (Hydrogen Risk Assessment Methods) tool, which has been developed by Sandia National Laboratories (SNL) during last decade under funding of the US Department of Energy. The e-Laboratory demonstrates European leadership in hydrogen safety engineering, e.g. by capability to calculate hazard distances determined by thermal and pressure effects from a fireball and blast wave after tank rupture in a fire, which are absent in the HyRAM tool and similar Canadian (UTRQ) framework is implemented using Smalltalk Seaside web development environment.

11.1 Scientific principles

This section describes scientific principles behind the engineering tools of the e-Laboratory of Hydrogen Safety. The tools are gathered in groups by similarity of applications.

11.1.1 Unignited releases

The under-expanded jet theory [44, 49] is behind the "Jet parameters" and other tools related to under-expanded jets. It allows calculation of hydrogen flow parameters in real and notional nozzles. Density in the real nozzle is needed for the use in the similarity law for concentration decay in hydrogen jet [54, 50] and parameters at the notional nozzle, which are widely used as boundary conditions for computational fluid dynamics (CFD) simulations. The tool allows calculation of mass flow rate of high-pressure hydrogen release through both a hole in a storage vessel and a narrow channel with losses. The tool for prediction of axial concentration decay of a leaking hydrogen for sub-sonic, sonic, and super-sonic jets employs the similarity law, which is validated in a wide range of conditions from expanded to highly under-expanded jets [44]. This tool calculates hazard distance, i.e. length of the flammable envelope, for momentum-dominated jets, which represent practically all realistic releases from high-pressure hydrogen equipment and storage.

The under-expanded jet theory is used to build and validate described in the next section the universal similarity law, which is valid for both expanded and under-expanded jets in the momentum-controlled regime. The theory is applied to derive: the universal correlation for hydrogen jet flame length, the tool for calculation of blow down time of hydrogen release from the storage vessel, etc. The theory is essential to carry out hydrogen safety engineering for different applications.

11.1.2 The similarity law

It must be noted that thermal effects of jet fires, pressure effects of deflagration or detonation, and pressure and thermal effects of high-pressure storage rupture in a fire (blast wave and fireball) could override the hazard distance determined by the size of flammable envelope or hazard distances of a jet fire. Thus, knowledge of laws describing hydrogen dispersion and flammable cloud formation, including axial concentration decay for arbitrary jets is essential for hydrogen safety engineering.

Figure 32 shows the similarity law for prediction of axial concentration decay of a leaking gas for sub-sonic, sonic, and super-sonic jets is derived and presented in [44, 50]. It is valid in a wide range of conditions from expanded to highly under-expanded jets. It can be applied for calculation of hazard distances informed by the size of the flammable envelope. The non-ideal behaviour of hydrogen at high pressures and the under-expansion of flow in a nozzle exit are considered by employing the Abel-Noble equation of state (EoS) for real gas.

For hydrogen jets into stagnant air for a fixed concentration expressed in percent by mass C_{ax}, the ratio of a distance, x, to the nozzle diameter is a constant, i.e. x/D=const. This means that the distance to the lower flammability limit (hazard distance) is directly proportional to the leak diameter. Thus, the design of hydrogen and fuel cell systems has to be carried out bearing in mind the requirement to minimise the internal diameter of piping, i.e. leak size for conservative full bore rupture scenario, yet keeping technological requirements to mass flow rate.

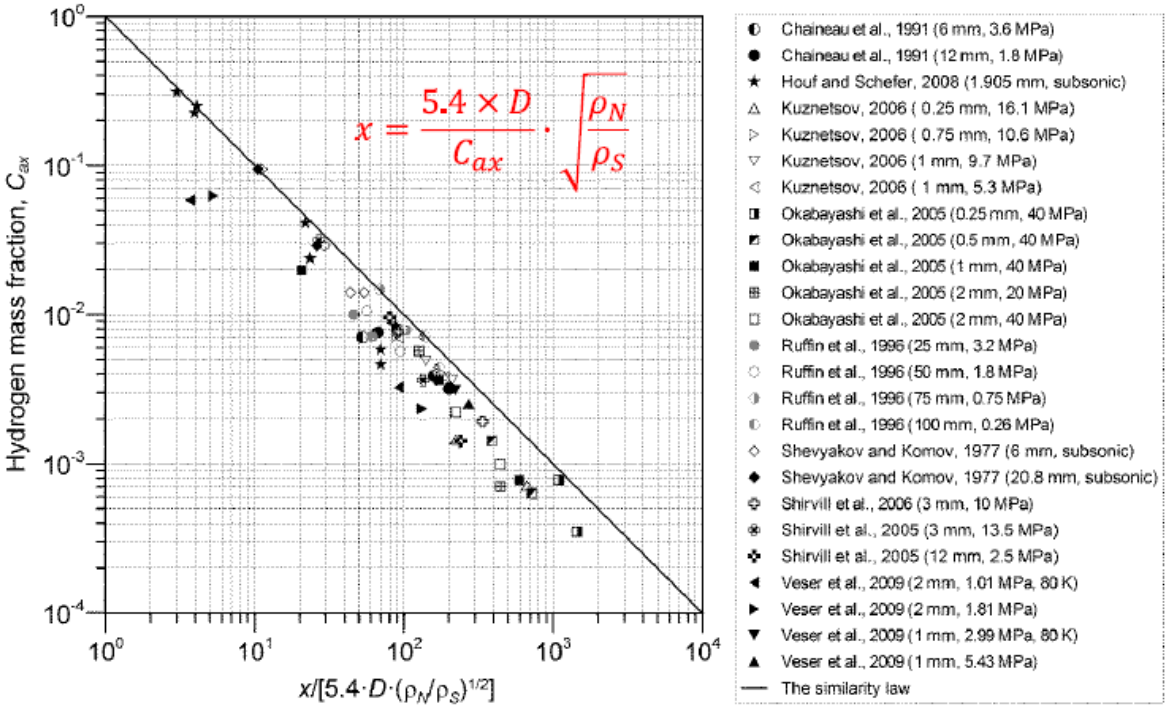

Figure 32. Similarity law [44]

11.1.3 Effect of buoyancy

The "Effect of buoyancy" tool allows to calculate the decrease of hazard distance for initially momentum-dominated hydrogen jets when it transforms to buoyancy-controlled jet. It is based on validated against experiments the theory of Shevyakov which can be found elsewhere [44]. The engineering technique [44] qualifies which part of hydrogen jet (both expanded and under-expanded) is momentum-controlled with the rest of the jet downstream being buoyancy-controlled.

There are three types of jets depending on the role of buoyancy Figure 33 (left): fully momentum-controlled jets are not affected by buoyancy; fully buoyancy-controlled jets are quickly diverted from the horizontal to vertical flow direction; the third type of jets is transitional with momentum-dominated part closer to the nozzle and buoyancy-controlled flow further downstream when the jet velocity drops and diameter increases. For hydrogen safety engineering it is important to know when this transition takes place. This has direct implication on hazard distance and thus the infrastructure cost.

Five theoretical curves (solid lines) and experimental data for expanded jets, and data of other researchers for under-expanded jets are shown in Figure 33 (right). Practically all under-expanded jets in hydrogen incidents/accidents will be in the momentum-controlled regime as follows from available tests applied to validate the correlation. Four of five theoretical curves in the graph are related to hydrogen concentrations of 4%, 17%, 30%, and 60% by volume respectively. Each of these four curves has an ascending buoyant part and a momentum

"plateau" part. The fifth curve "Downward jets" is of special interest. It gives for a jet directed vertically downward a dimensionless distance from the nozzle to the turning point, where the jet changes direction of flow from downward to upward. The fifth curve intersects each of the four other curves in the graph in the region of transition from momentum-dominated to buoyancy-controlled flow as expected.

The easy to apply technique Figure 33 (right) can be very useful to develop cost-effective hydrogen safety engineering solutions. For instance, hazard distance for a horizontal jet release can be essentially reduced as only the length of the momentum-dominated part of the jet can be taken as an indication of the separation rather than the aggregated distance, i.e. both momentum- and buoyancy-controlled parts of the jet to the lower flammability limit (LFL) of 4% by volume of hydrogen.

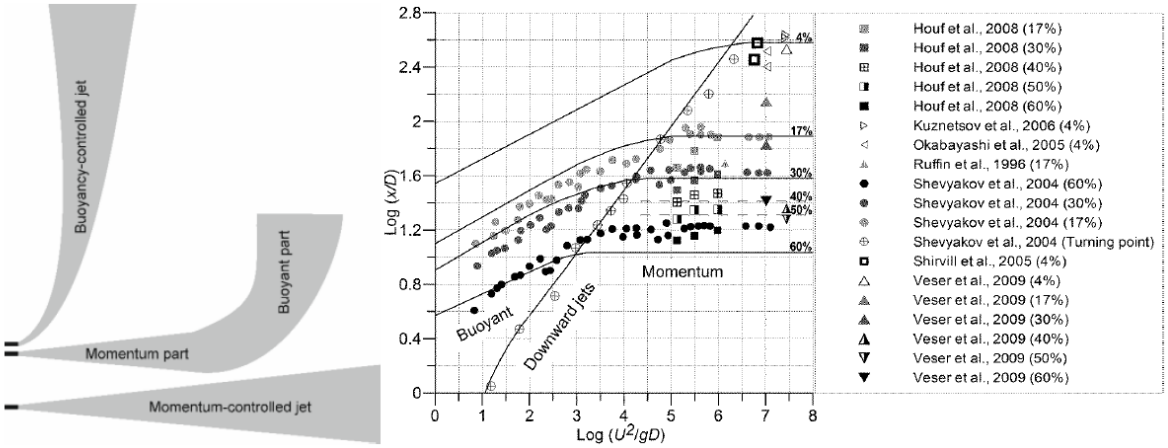

Figure 33. Types of jets depending on the role of buoyancy (left), dependence of the distance to the nozzle diameter ratio x/D, for particular hydrogen concentration in air, on the Froude number (right).

11.1.4 Blowdown

The "Blowdown of storage tank" tool calculates pressure dynamics inside the tank during release for adiabatic and isothermal conditions, which can be combined to reproduce blowdown dynamics closer to reality. Both models give close pressure dynamics but different temperature dynamics of the released hydrogen.

The adiabatic blowdown model is based on the assumption of a quick release from a high-pressure reservoir and negligible heat transfer effects to the released hydrogen temperature. The adiabatic model gives lower temperature of released hydrogen at the end of the process. While, the isothermal blowdown of a storage tank assumes of a relatively long release from a high-pressure reservoir, so that heat transfer significantly changes the temperature of the outflowing hydrogen. The combination of adiabatic at the beginning and then isothermal model afterwards gives a good approximation for dynamics of temperature of released hydrogen observed in experiments.

Both models are built on the model for expanded and under-expanded jet parameters, which describes parameters in an expanded and under-expanded jet through the characteristic stages of its development – in the storage reservoir, the orifice, and the notional (effective) nozzle exit and utilises Abel-Noble EoS and the conservation equations for mass and energy.

The tool can be used to formulate mitigating measures and safety strategies based on fire resistance rating of on-board hydrogen storage tank. The fire resistance rating should be greater than the sum of time for a thermally activated pressure relief devices (TPRD) initiation and blowdown time of the storage tank to exclude its catastrophic failure in the case of fire. Obviously, the use of a TPRD with a larger diameter would create a larger flammable cloud or a jet flame. It would generate higher overpressure during "delayed ignition" or deflagration of turbulent flammable cloud. By this reasoning the TPRD diameter should be reduced as much as possible provided the fire resistance rating is increased consequently.

11.1.5 Passive ventilation

The "Passive ventilation" tool allows to calculate hydrogen concentration in an enclosure with known vent size for the given release rate or solve inverse problem method (calculate vent size to keep concentration below desirable level for known hydrogen release rate).

The model is developed in the assumption of perfect mixing and equations for passive (release of flammable or toxic gas) and natural (air quality problems) ventilation were compared [51] to show the essential difference between two approaches. The natural ventilation equations are usually derived in the assumption that the neutral plane is located at the half of the vent height, however for the passive ventilation of accidental release in an enclosure the neutral plane can be located anywhere below the half of the vent height. The development of passive ventilation model has demonstrated that the accurate analytical solution for passive ventilation differs from the approximate solution for natural ventilation by more than 2 times for lean and rich mixtures as shown in Figure 34, where X is hydrogen mole fraction.

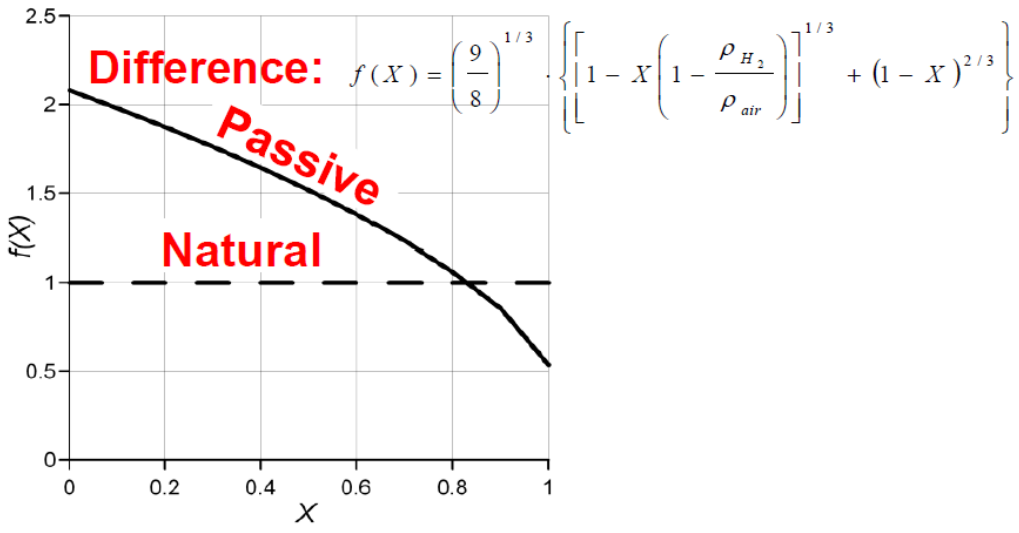

Figure 34. Difference between passive and natural ventilation

This could have serious safety implications and should be dealt with care while performing safety engineering involving hydrogen releases. The passive ventilation theory states that, vertical vent is more efficient compared to horizontal vent of the same area and this should be taken into account during the design of passive ventilation systems.

11.1.6 Forced ventilation

The "Forced ventilation" tool calculates parameters of the mechanical ventilation system to keep hydrogen concentration below required level. The parameters include the volume flow rate of air required for the given mass flow rate of hydrogen to be lower that specified limit in the assumption of perfect mixing. The model is based on the principles of passive ventilation and its calculation of ventilation flow rate to provide hydrogen concentration in an enclosure below required level. Application of forced ventilation in numerical experiments proved calculations and demonstrated a decreased gas concentration to the required level. This confirms that the proposed methodology can be applied to calculate the ventilation rate for fuel cell and hydrogen systems and can be used as a tool for hydrogen safety engineering.

11.1.7 Pressure peaking phenomenon

The revealed in 2010 at Ulster the pressure peaking phenomenon (PPP) [52] is another unique of the e-Laboratory of Hydrogen Safety not available in other similar hazard and risk assessment software. It allows calculation of pressure dynamics in an enclosure like garage in case of unscheduled release of hydrogen. Both hydrogen blowdown release and constant mass flow rate release options are available. The tool is applicable for both ignited (fire from TPRD) and unignited (TPRD failure) releases.

The pressure peaking phenomenon is characteristic only for gases lighter than air when they are released into an enclosure with limited area of vents. The PPP is more pronounced for ignited release compared to unignited release from the same source [53], see Figure 35. ISO standard requires the PPP to be taken into account when performing hydrogen safety engineering for indoor use of hydrogen and fuel cell systems.

The prevention and mitigation of the PPP can be achieved only through the decrease of mass flow rate from TPRD, i.e. its nozzle diameter. This is turn will require higher fire resistance rating of on-board storage tanks.

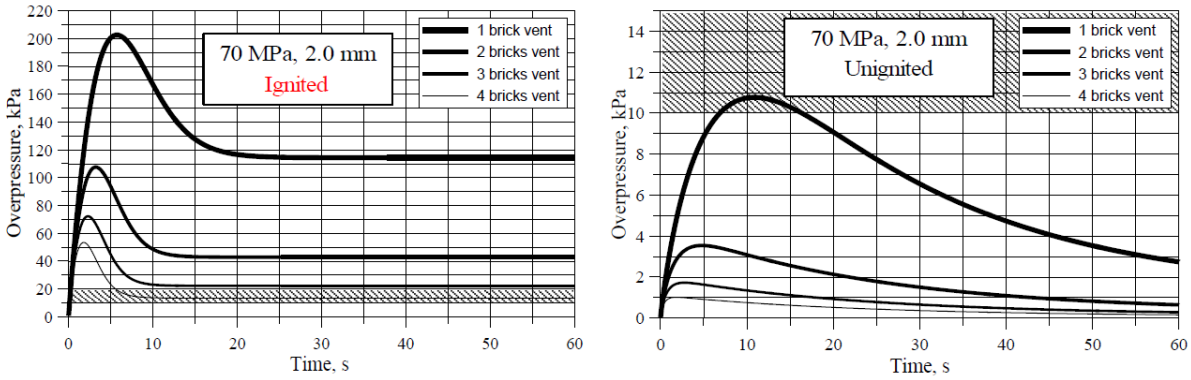

Figure 35. Overpressure dynamics of hydrogen jet fire in the garage: TPRD diameter 2 mm and storage pressure 70 MPa (release rate 107 g/s) Ignited (left) vs unignited (right) [53].

11.1.8 Jet fire hazard distances

The "Jet fire" tool uses the dimensionless hydrogen flame length correlation [50] to calculate three hazard distances, i.e. "no harm" distance to T=70 °C, which is 3.5 times of flame length; "pain limit" (115 °C, 5 min), which is 3 times of flame length; and "fatality limit" (309 °C, 20 s), which is 2 times of flame length. The universal flame length correlation includes laminar and turbulent flames, buoyancy- and momentum-controlled fires, expanded (subsonic and sonic) and under-expanded (sonic and supersonic) jet fires, thereby covering the entire spectrum of hydrogen reacting leaks [50]. Theoretical and experimental results indicate that the flame length has to be a function of not only the Froude number (Fr) but also the Reynolds (Re) number and the Mach (M) number and in this correlation, all are taken into account. One of its advantages is the absence of parameters at the notional nozzle exit, which are derived in the limited validity range assumption of sonic flow at the notional nozzle. The parameters needed to predict the flame length are those at the actual nozzle exit only: diameter, hydrogen density and flow velocity, the speed of sound at pressure and temperature at the real nozzle exit. The dimensionless correlation for hydrogen jet flame length in still air is $L_F/D\text{-}(\rho_N/\rho_S)(U_N/C_N)^3$ and shown in Figure 36. Here L_F is the flame length, D is the nozzle diameter, ρ_N and ρ_S are release densities at the nozzle and surrounding air respectively, while U_N and C_N are velocity at the nozzle and speed of sound in the released gas in the nozzle.

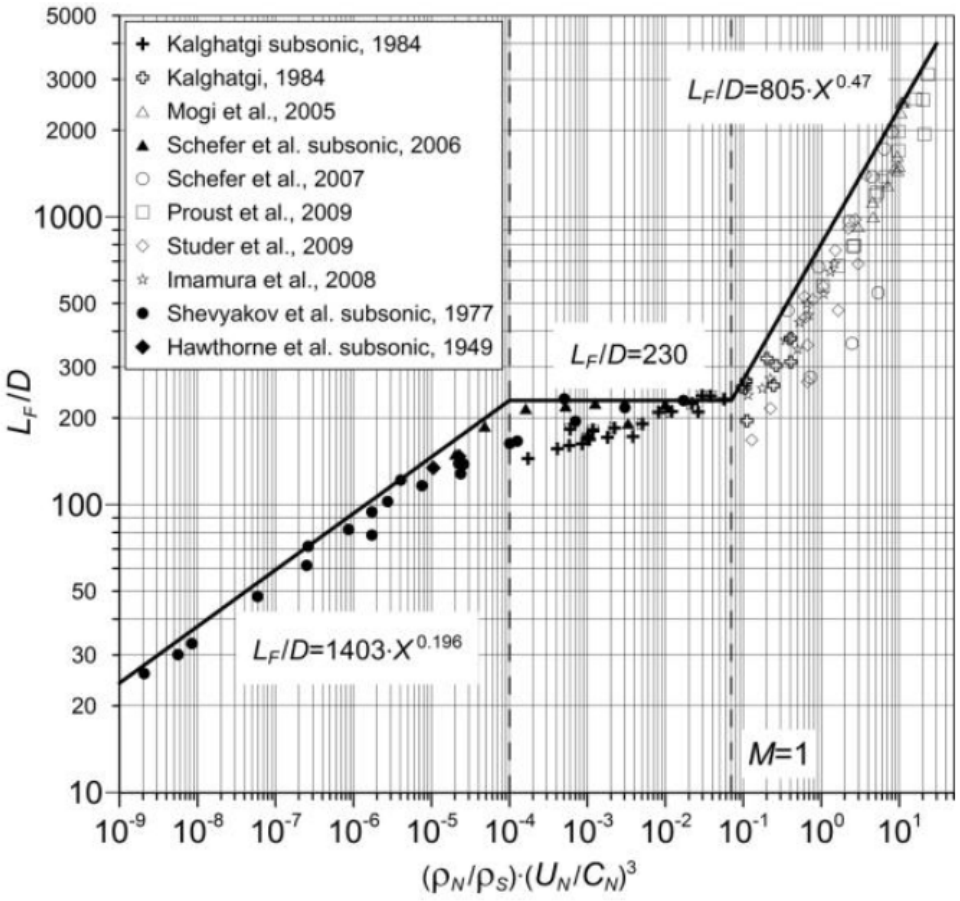

Figure 36. Dimensionless flame length correlation [50]

The use of the correlation requires application of an under-expanded jet theory to calculate these parameters. There is lesser uncertainty in calculation of flow parameters in the actual nozzle exit compared to uncertainties at the notional nozzle. Indeed, there is a strong non-uniformity of velocity downstream of the Mach disk that deviates from the common for all under-expanded jet theories assumption of uniform velocity at the notional nozzle exit.

11.1.9 Mitigation of deflagrations

There are three deflagration mitigation tools in e-Laboratory of Hydrogen Safety: vent sizing of enclosure with uniform hydrogen-air mixture [54], vent sizing of enclosure with localised non-uniform mixture [55], calculation of upper limit of hydrogen inventory that can be allowed in a closed space like warehouse [55].

The vent sizing correlation for the uniform hydrogen-air mixture in vented enclosure [54] is based on recent advancements in understanding and modelling of combustion phenomena relevant to hydrogen–air vented deflagrations and unique large-scale tests carried out by different research groups. The combustion phenomena accounted for by the correlation include: turbulence generated by the flame front itself; leading point mechanism stemming from the preferential diffusion of hydrogen in air in stretched flames; growth of the fractal area of the turbulent flame surface; initial turbulence in the flammable mixture; as well as effects of

enclosure aspect ratio and presence of obstacles. The tool allows to calculate the vent area to reduce the deflagration pressure to the desired limit and estimate the overpressure inside vented enclosure for the vent of given size.

The model for localised non-uniform mixture [55] describes deflagrations of hydrogen-air mixtures and defines safety requirements for vented deflagrations of localised mixtures in an enclosure. Examples of localised mixtures include 'pockets' of gas within an enclosure as well as stratified gas distributions which are especially relevant to hydrogen releases. It allows to estimate the maximum overpressure inside vented enclosure as well as calculating the vent size in order not to exceed the required safety limit.

Thermodynamic model to predict maximum mass of hydrogen, which may be allowed to be released in an enclosure of particular volume without causing destructive deflagration overpressure was developed [55] and realised as a tool in e-Laboratory. The model presumes that an enclosure is partially filled with air and hydrogen-air mixture. If this hydrogen-air mixture is burnt in a sealed enclosure, the model solution for resulting absolute pressure may be found. The tool allows to calculate the inventory mass for the given overpressure and enclosure volume and enclosure volume for the given overpressure and inventory mass.

11.1.10 Blast wave and fireball after tank rupture in a fire

The "Blast wave" overpressure decay tool is available for stand-alone and under-vehicle storage tank scenarios. The model developed accounts for the real gas effects and combustion of the flammable gas released into the air (chemical energy) as a contribution into the blast wave strength [56]. The chemical energy of combustion is dynamically added to the mechanical energy and is accounted for in the energy-scaled non-dimensional distance. The model can be applied as a safety engineering tool for typical hydrogen storage applications, including on-board vehicle storage tanks and a stand-alone refuelling station storage tanks. The predictive model for calculation of hazard distances defined by the parameters of a blast wave generated by a high-pressure gas storage tank rupture in a fire.

The tool for calculation of "Fireball" diameter after hydrogen tank rupture in a fire is based on the assumption of complete combustion of released hydrogen in air [56, 57]. It is based on limited amount of experimental data and thus requires further validation.

11.2 Summary of e-Laboratory

The scientific principles behind engineering tools of the e-Laboratory of Hydrogen Safety available at https://hyresponder.eu/e-platform/ are overviewed. The developed engineering tools are being implemented for the stakeholders' free access. The models implemented in online tools are based on peer-reviewed journal publications and validated against experiments.

References

1. HyResponse Deliverable D2.1-Description of selected FCH systems and infrastructure, relevant safety features and concepts (2014). Available from: http://www.hyresponse.eu [accessed 10.10.20].
2. Mays, T. (2014). Scientific progress and technological bottlenecks in hydrogen storage. H2FC European Technical School on Hydrogen and Fuel Cells. 23-27 June 2014, Crete, Greece.
3. Rigas, F and Amyotte, P (2013). Hydrogen safety. Boca Raton: CRC press. Taylor and Francis Group.
4. Rigas, F and Amyotte, P (2013). Myths and facts about hydrogen hazards. Chemical Engineering Transactions. Vol. 31.
5. ENVIRONMENTAL GRAFFITI ALPHA (2010). The Hindenburg Disaster in Pictures. Available from: http://www.environmentalgraffiti.com/anthropology-and-history/news-hindenbergdisaster-accident-waiting-happen. [accessed 24.12.11].
6. World Forum for Harmonization of Vehicle Regulations (WP.29), 160th Session, Geneva, 25-28 June 2013.
7. US DoE, US Department of Energy (2008). Hydrogen safety training for first responders. Available from: http://hydrogen.pnl.gov/FirstResponders/ [accessed on 06.11.20].
8. CEP, Clean Energy Partnership, 2014. Available from: http://www.cleanenergypartnership.de/tech/site.php?l=en [accessed on 01.05.14].
9. HyFLEETE-CUTE (2006-2009). Available from: https://www.fuelcellbuses.eu/wiki/history-fuel-cell-electric-buses/hyfleet-cute-2006-2009 [accessed on 04.11.2020].
10. Zaetta, R and Madden, B (2011). Next HyLights project. Deliverable 3.1: Hydrogen Fuel Cell Bus Technology State of the Art Review.
11. California Fuel Cells Partnership, 2014. Available from: http://cafcp.org/ [accessed on 06.11.20].
12. Adams, P (2004). Identification of the optimum on-board storage pressure for gaseous hydrogen city buses. European Integrated Hydrogen project – Phase 2 (EIHP2), March 2004.
13. Şenel, K. (2007), Hidrojenin yakıt olarak uçaklarda kullanımı. yüksek lisans tezi, Eskişehir Osmangazi Üniversitesi, Fen Bilimleri Enstitüsü.
14. http://ram-home.com/ram-old/tu-155.html [Accessed 06.11.2020]
15. Dincer, I., Acar, C. (2016). A review on potential use of hydrogen in aviation applications. International Journal of Sustainable Aviation, 2: 74-100.
16. http://www.aerospace-technology.com/projects/hy4-aircraft/ [Accessed 06.11.2020].
17. Bicer, Y., Dincer, I. (2017). Life cycle evaluation of hydrogen and other potential fuels for aircrafts. International Journal of Hydrogen Energy, 42: 10722-10738

18. Koroneos, C. J., & Moussiopoulos, N. (2002). Cryoplane –hydrogen vs. kerosene as aircraft fuel. Proceedings of the Geophysical Society XXVII General Assembly, Nice, France, p. 21-26.

19. Contreras, A., Yiğit,., Özay, K., & Veziroğlu, T. N. (1997). Hydrogen as aviation fuel: a comparison with hydrocarbon fuels. International Journal of Hydrogen Energy, 22: 1053-1060

20. Lee DS, Pitari G, Grewe V, Gierens K, Penner JE, Petzold A, Prather MJ, Schumann U, Bais A, Berntsen T, Iachetti D, Lim LL, Sausen R. Transport impacts on atmosphere and climate: aviation. Atmos Environ 2010;44(37):4678–734

21. Contreras A, Yiğit S, Özay K, Veziroğlu TN. Hydrogen as aviation fuel: a comparison with hydrocarbon fuels. Int J Hydrog Energy 1997;22(10–11):1053–60.

22. Khandelwal B, Karakurt A, Sekaran PR, Sethi V, Singh R. Hydrogen powered aircraft: the future of air transport. Prog Aerosp Sci 2013;60:45–59.

23. Verstraete D. Long range transport aircraft using hydrogen fuel. Int J Hydrog Energy 2013;38(34):14824–31.

24. Verstraete D. The potential of liquid hydrogen for long range aircraft propulsion; 2009

25. Sharpe JE, Bimbo N, Ting VP, Rechain B, Joubert E, Mays TJ. Modelling the potential of adsorbed hydrogen for use in aviation. Microporous Mesoporous Mater 2015;209:135–40

26. Nojoumi H, Dincer I, Naterer GF. Greenhouse gas emissions assessment of hydrogen and kerosene-fueled aircraft propulsion. Int J Hydrog Energy 2009;34(3):1363–9

27. Cecere D, Giacomazzi E, Ingenito A. A review on hydrogen industrial aerospace applications. Int J Hydrog Energy 2014;39(20):10731–47

28. Verstraete D. On the energy efficiency of hydrogen-fuelled transport aircraft. Int J Hydrog Energy 2015;40(23):7388–94.

29. Fernandes MD, de ST, Andrade P, Bistritzki VN, Fonseca RM, Zacarias LG, Gonçalves HNC, de Castro AF, Domingues RZ, Matencio T. SOFC-APU systems for aircraft: a review. Int J Hydrog Energy 2018;43(33):16311–33

30. S Eelman, de Poza, Krieg T. Fuel cell APU'S in commercial aircraft – an assessment of SOFC and PEMFC concepts. In: Proceedings of 24th international congress of aeronautical sciences; 2004.

31. Staffell I, Scamman D, Velazquez Abad A, Balcombe P, Dodds PE, Ekins P, Shah N, Ward KR. The role of hydrogen and fuel cells in the global energy system. Energy Environ Sci 2019.

32. DOE funds to deploy fuel cells for baggage vehicles at airports. Fuel Cells Bull. vol, no. 5; 2012. p. 3–4.

33. McConnell VP. Fuel cells in forklifts extend commercial reach. Fuel Cells Bull 2010;2010(9):12–9. 33. 44. Fuel cell forklift from German partnership. Fuel Cells Bull. vol, no. 12; 2003. p. 9.

34. Plug Power, FedEx project rolls out fuel cell airport tractors. Fuel Cells Bull. vol, no. 5; 2015. p. 2–3.

35. Toyota, Hino deliver fuel cell bus for Haneda airport route in Tokyo. Fuel Cells Bull., vol, no. 1; 2011, p. 3.

36. US Hybrid, BYD to develop fuel cell bus for Honolulu Airport. Fuel Cells Bull. vol, no. 6; 2018. p. 2.

37. Belmonte N, Staulo S, Fiorot S, Luetto C, Rizzi P, Baricco M. Fuel cell powered octocopter for inspection of mobile cranes: design, cost analysis and environmental impacts. Appl Energy 2018;215:556–65.

38. Fuel cell and hybrid power systems offer compelling value for UAVs whose missions demand greater runtime than batteries can support. [Online]. Available: ⟨http://www.ballard.com/markets/uav⟩. [Accessed 20. Oct 2018].

39. AeroVironment flies world's first hydrogen powered plane. Fuel Cells Bull. vol, no. 9; 2005. p. 2–3.

40. Bradley TH, Moffitt BA, Mavris DN, Parekh DE. Development and experimental characterization of a fuel cell powered aircraft. J Power Sources 2007;171(2):793–801.

41. Gong A, Verstraete D. Fuel cell propulsion in small fixed-wing unmanned aerial vehicles: current status and research needs. Int J Hydrog Energy 2017;42(33):21311–33.

42. Kim T, Kwon S. Design and development of a fuel cell-powered small unmanned aircraft. Int J Hydrog Energy 2012;37(1):615–22

43. Bird, L. (2011). Dictionary of Business Continuity Management Terms. Business Continuity Institute. Available from: http://www.thebci.org/glossary.pdf [accessed on 27.12.15].

44. Molkov, V (2012). Fundamentals of hydrogen safety engineering, Part I and Part II. Available from: www.bookboon.com, free download e-book.

45. CEP, Clean Energy Partnership, 2014. Available from: http://www.cleanenergypartnership.de/tech/site.php?l=en [accessed on 01.05.14].

46. Saffers, J-B and Molkov, V (2014). Hydrogen safety engineering framework and elementary design safety tools. International Journal of Hydrogen Energy, 39 (11). pp. 6268-6285.

47. BRHS, Biennial Report on Hydrogen Safety (2009). The European network of excellence "Safety of hydrogen as an energy carrier" (NoE HySafe). Available from: www.hysafe.org [accessed on 06.11.20].

48. BSI (2001) British standard BS7974:2001 “Application of fire safety engineering to the design of buildings - Code of Practice”. Published Document PD 7974–0:2002 (2002) Application of fire safety engineering principles to the design of buildings – Part 0: Guide to design framework and fire safety engineering procedures, British Standard Institution.
49. V. Molkov and M. Bragin, High-Pressure Hydrogen Leak Through a Narrow Channel, Nonequilibrium Phenomena: Plasma, Combustion, Atmosphere, (2009), 332–338.
50. V. Molkov and J.-B. Saffers, Hydrogen Jet Flames, International Journal of Hydrogen Energy, vol. 38, no. 19, (2013) 8141–8158.
51. V. Molkov, V. Shentsov, and J. Quintiere, Passive Ventilation of a Sustained Gaseous Release in an Enclosure With One Vent, International Journal of Hydrogen Energy, vol. 39, no. 15, (2014) 8158–8168.
52. S. Brennan and V. Molkov, Safety Assessment of Unignited Hydrogen Discharge From Onboard Storage in Garages With Low Levels of Natural Ventilation, International Journal of Hydrogen Energy, vol. 38, (2013) 8159–8166.
53. D. Makarov, V. Shentsov, M. Kuznetsov, and V. Molkov, Pressure Peaking Phenomenon: Model Validation Against Unignited Release and Jet Fire Experiments, International Journal of Hydrogen Energy, vol. 43, no. 19, (2018) 9454–9469.
54. V. Molkov and M. Bragin, Hydrogen–Air Deflagrations: Vent Sizing Correlation For Low-Strength Equipment and Buildings, International Journal of Hydrogen Energy, vol. 40, no. 2, (2015) 1256–1266.
55. D. Makarov, P. Hooker, M. Kuznetsov, and V. Molkov, Deflagrations of Localised Homogeneous and Inhomogeneous Hydrogen-Air Mixtures in Enclosures, International Journal of Hydrogen Energy, vol. 43, (2018) 9848–9869.
56. V. Molkov and S. Kashkarov, Blast Wave From a High-Pressure Gas Tank Rupture in a Fire: Stand-Alone and Under-Vehicle Hydrogen Tanks, International Journal of Hydrogen Energy, vol. 40, no. 36, (2015) 12581–12603.
57. M. Dadashzadeh, S. Kashkarov, D. Makarov, and V. Molkov, “Socio-Economic Analysis and Quantitative Risk Assessment Methodology for Safety Design of Onboard Storage Systems, in International Conference on Hydrogen Safety, Hamburg, Germany, (2017) vol. 184.
58. Barthelemy H, Weber M, Barbier F. Hydrogen storage: recent improvements and industrial perspectives. Int J Hydrogen Energy (2017) 42:7254-7262.
59. Norwegian parliament adopts zero-emission regulations in World Heritage fjords. https://www.rivieramm.com/news-content-hub/news-content-hub/norway-adopts-zero-emission-regulations-in-world-heritage-fjords-24820 [accessed on 04.11.2020]
60. Harris, AP, Marchi CWS. (2012). Investigation of the hydrogen release incident at the AC transit Emeryville facility (Revised). Sandia report. SAND2012-8642.