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A comprehensive review on liquid hydrogen transfer operations and safety considerations for mobile applications

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ABSTRACT

The adoption of liquid hydrogen (LH2) as an energy carrier presents significant opportunities for distributing large quantities of hydrogen efficiently. However, ensuring safety of LH2 transfer operations requires the evolution of suitable technologies and regulatory framework. This study offers an extensive overview of technical considerations and safety aspects pertaining to liquid hydrogen installations and mobile applications. A significant lack of regulations specifically tailored for LH2 transfer operations is highlighted. Additionally, experimental findings and outcomes of the modelling activities carried out in previous research are presented, shedding light on the combustion and ignition behaviour of liquid hydrogen during accident scenarios. The identification of research gaps and ongoing research projects underscores the importance of continued investigation and development of this critical area.

1. Introduction

Liquid hydrogen is regarded as a promising sustainable energy carrier for the future, especially for energy demanding and hard-to abate economic sectors, such as transportation [1]. The possibility of LH2 to be used in both internal combustion engines without the need for major investment and in fuel cell systems makes it an attractive solution for powering different means of transport, from road vehicles to aircrafts. At present, some LH2 powered vehicles are already in operation worldwide. Relevant examples are the LH2 powered truck by Daimler Truck [2], the LH2 ferry MF Hydra operated by Norled [3], and the Suiso Frontier LH2 carrier built by Kawasaki [4]. However, the large spread of a liquid hydrogen-based transportation requires the parallel development of an efficient global distribution system. In this context, storage and delivery are key aspects [5] and one of the main challenges due to economic and safety reasons. From an economic perspective, the high cost of the construction of hydrogen delivery infrastructure hampers the spread of the hydrogen economy. Recent studies have shown that when it comes to large distances (i.e., distances >3000 km), delivering hydrogen as a liquid is the most convenient option [6]. In addition to that, the delivery process is identified as a critical phase of the hydrogen value chain. In fact, according to the literature, around 25% of the recorded incidents involving liquid hydrogen occurred during loading and unloading operations [7]. This can be a consequence of the complexity of the tasks, the involvement of personnel, and the large number of equipment items displaced in the delivery site. As a result, human errors can compromise the procedure, and releases can occur from multiple sources with possible hazardous consequences.

As mentioned above, the storage of hydrogen as a cryogenic liquid is also critical. One of the major difficulties is minimizing the inevitable heat losses to mitigate the vaporization of the cold liquid (approx. -253 °C [8]) and the consequent formation of the boil-off gas (BOG). The simplest way to prevent the excessive self-pressurization of the storage tank, resulting from the BOG formation, is to vent the vaporized hydrogen into the atmosphere. On one hand, this solution avoids additional investment costs necessary to build a dedicated infrastructure for the BOG management; on the other hand, it does not allow reusing the gas for different purposes. It, therefore, represents an energy loss,

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particularly considering the high price of hydrogen liquefaction [8]. Moreover, even if typically safe for small release rates, venting large quantities of hydrogen might not be safe due to the flammable and explosive nature of the fuel. Finally, being hydrogen an indirect greenhouse gas, venting in an open atmosphere is not an environmentally sustainable solution [9]. Alternatives technologies for the boil-off management, such as reliquefaction or compression, can be implemented depending on the LH2 application. Zero boil-off solutions have also been developed, combining thermal insulation and active cooling technologies [10]. Furthermore, catalytic hydrogen combustion (CHC) has been proposed: the process, already widely applied [11–13] is regarded as a possible way to manage hydrogen releases and mitigate related safety issues [14].

In addition to the aspects just discussed, there is a need for more precise regulations, standards and codes in the field of liquid hydrogen. In fact, at present, most of the available indications refer to cryogenic fluids in general, but only a few documents are specific to LH2.

This paper provides a comprehensive overview of the current status of cryogenic and liquid hydrogen technologies from different perspectives, emphasizing the critical gaps and suggesting a direction for future research. Generic considerations regarding hydrogen safety are provided in Sec. 2, with a focus on cryogenic liquid hydrogen. Sec. 3 describes the current LH2 applications in the transportation sector. The core and novelty of this work, provided in Sec. 4, consists of the detailed description of the standards currently available and applicable for liquid hydrogen applications. Sec. 5 summarizes the results obtained from previous research, while Sec. 6 highlights the still existing knowledge gaps and the ongoing research projects in the field of LH2. Finally, conclusions and future developments are discussed in Sec. 7.

2. Technical considerations for safe use of hydrogen

Most of the hydrogen safety concerns derive from its high flammability, that makes its use and handling particularly challenging, requiring special precautions. As discussed in Sec. 1, gaseous hydrogen (GH2) phase is always present in LH2 applications due to the very low boiling point temperature of hydrogen [15]. Thus, it is essential to consider the hazards associated to both phases when investigating LH2 safety. In the following, the most relevant safety concerns are discussed, starting from the ones common to both GH2 and LH2, then addressing the phase-specific aspects.

2.1. Hydrogen safety in general

Ignition mechanisms are relevant for both GH2 and LH2 safety. Based on the information available in the literature, several hypotheses for hydrogen ignition mechanisms were postulated [16]. However, hydrogen combustion was observed without evidence of ignition sources in past incidents [17]. Moreover, in recent experimental studies, unexpected ignition occurred when LH2 was released into water [18] and in case of contact with liquid oxygen (LOX) [19]. Accidental ignition of hydrogen gaseous leaks over sharp edges was also observed, probably due to electrostatic processes. Further investigations are required to understand ignition mechanisms, identify unknown ignition sources and prevent their presence in hydrogen facilities.

Early detection of unwanted hydrogen fires is also a field of continuous research. Standard camera surveillance or light scattering methods, such as smoke detectors, are not reliable to detect hydrogen flames due to the features of hydrogen fires, which are smokeless and generate scarcely visible flames. Other solutions, like the ones based on spectral emittance and heat effects are gaining attention as potential alternatives [20]. Nevertheless, their application is still hampered by their high cost and location-dependence.

Finally, hydrogen embrittlement is another safety issue. This phenomenon involves hydrogen permeation into materials, compromising their integrity and possibly leading to components failure. Embrittlement can be caused by the exposure to low temperature (e.g., cryogenic liquid hydrogen) or high pressure (e.g., hydrogen pipelines). More details regarding these two types are provided in the following sections.

2.2. Safety aspects of gaseous hydrogen

The use of gaseous hydrogen has been well-established in the chemical industry for decades. Therefore, safety methods and technologies are readily available for common stationary applications. In contrast, new challenges exist for emerging mobile applications (e.g., transportation [21] and maritime [22] sectors), where hydrogen permeation is still at the initial phase.

Leak detection is a significant issue for GH2, as its odourless and colourless nature makes it imperceptible to humans. Therefore, the detection of unexpected leaks is only possible using sensors. Conventional contact-based methods (e.g., catalytic sensors, metal-oxide semiconductors, and thermal conductivity sensors) are effective in small and confined sites. However, these technologies are unsuitable for outdoor or partially enclosed areas, where the lack of defined GH2 accumulation points makes sensor placement very challenging. Alternative cheap [23] and distance-based [24] solutions, such as wide-area optical scanning sensors, are under development.

In addition to detection, venting of gaseous hydrogen is another critical safety concern, particularly for applications in closed domains (e.g., garages [25] and hangars). The disposal of adequate ventilation systems [26] and openings [27] can prevent hydrogen accumulation and the formation of hazardous hydrogen-air flammable mixtures.

2.3. Considerations regarding cryogenic hydrogen facilities

The growing interest in liquid hydrogen applications increases the need for standards and codes to regulate its use and handling. Several LH2 concerns that stem from the very low operating temperature are known from other cryogenic applications, such as Liquefied Natural Gas (LNG). Regarding hazards for humans, examples are cold burns and frostbite, whose effects are already well documented [28,29]. As mentioned in Section 2.1, low temperatures can also promote hydrogen permeation into materials, leading to the so called low-temperature hydrogen embrittlement [30]. Additionally, condensation or solidification of air constituents (see Table 1) on the outside of non- or poorly insulated cryogenic installations [31] and solid agglomeration are aspects of high safety relevance. In the first scenario, the hazards typically derive from oxygen solidification, that may lead to the formation of oxygen enriched flammable compounds with risk of ignition [32]. Solutions such as avoiding tar surfaces below cryogenic installations, have been proposed and have become common to avoid flammable oxygen enriched mixtures. Effective technical mitigation mechanisms like wind blowing dry leaves into highly oxygenated zones are still to be developed to tackle self-ignition risks. In the second case, the possible device blockage and failure due to ice can be prevented using cold boxes where humid air block the entry of ice sensitive components.

In the context of storage and transport, the pressure control of LH2 tanks is an operational and safety concern. As for cryogenic installations in general, pressure relief devices (PRDs) are used to manage undesired overpressure caused by the boil-off gas (BOG) formation. PRDs

Table 1
Freezing point of air components compared to hydrogen normal boiling point (nbp).

Gas	Oxygen	Nitrogen	Argon	Carbon-dioxide	Water vapour	Hydrogen NBP (K)
Freezing point (K)	54.35	63.15	83.75	194.65	273.15	20.4

effectiveness relies on their capacity which should be designed considering vast BOG volumes potentially present in case of accidental insulation failure. PRDs inefficiency can lead to severe and costly damages if not correctly sized. This was experienced in 2008 at CERN when substantial amounts of cryogenic helium evaporated due to unforeseen loss of insulation vacuum and extensive energy input from the installation [33]. Emergency tap-off lines are also installed above the liquid level to avoid tank damage due to failure of pressure release in case of original tap-off cloggage. Another safety concern is the accidental hydrogen discharge in the environment. Crucial aspects that influence the hydrogen release consequences are the discharge location, hydrogen flowrate, and the hole characteristics (e.g., shape and location). As mentioned for GH2, hydrogen accumulation in enclosures in critical from a safety standpoint. Thus, the discharge location must be carefully selected when venting hydrogen. Previous studies investigated the possibility of discharge in both open air and enclosures, highlighting their criticality and providing recommendations to prevent hazardous consequences (e.g., installation of venting systems in closed spaces to avoid the formation of a flammable hydrogen-air mixture) [34]. The flowrate was also proved to be a critical parameter due to its influence on the formation and buoyancy of hydrogen flammable clouds [35,36]. Finally, the effects of the hole shape [37] and location [38] were also investigated.

2.4. *Liquid hydrogen transfer operations*

When it comes to the process of transferring liquid hydrogen from a giving to a receiving tank, a series of steps must be followed. According to the authors' knowledge, EIGA 06/19 [39] is one of the few, if not the only document among the international standards where the LH2 transfer process is described. This procedure foresees the transfer between an LH2 road tanker and an LH2 land-based storage facility. The steps are divided between the measures to be taken before starting the transfer operations and the process itself. It must be remarked that the procedure can be carried out only by authorised personnel, adequately trained and certified. In the following, the LH2 transfer process reported in EIGA 06/19 is described.

The first tasks must be fulfilled once the road tanker enters the LH2 storage facility and parks in the designated area. Prior the beginning of the transfer process, the driver of the truck must report to the authorised customer personnel. The personnel at the site and the driver must wear protective clothing at any time after the arrival of the road tanker to the site. Examples of protective clothing are gloves, eye protection, helmet, flame resistant overalls, and protective footwear. The vehicle must be electrically grounded to earth with its wheels blocked before any other operation is carried out. A visual inspection of the LH2 transfer lines and fuelling equipment is required to assess their mechanical integrity and the absence of any dirt in the fittings. Next, the surrounding area is checked to verify whether new safety hazards have been introduced after the truck arrival.

Once all these tasks are undertaken, the transfer process can start. Initially, the transfer line is connected to the receiving installation. Prior to introducing hydrogen into the system, purging is necessary to remove any residual air. An initial purge is typically performed using inert gases such as helium or nitrogen. A secondary purge is necessary to eliminate contaminants prone to freezing at LH2 temperatures and potentially affecting transfer equipment (e.g., valves, connections, etc.). Hydrogen may be employed for this purpose at different temperatures depending on the gas employed during the initial purging step. Specifically, helium can be extracted using cold hydrogen, while purging nitrogen from the transfer line involves utilizing warm hydrogen gas to prevent nitrogen condensation or solidification. Upon completion of the transfer operation, the lines must undergo a final purge to remove any remaining hydrogen before disconnecting it from the truck. A schematic illustration of the entire LH2 fuelling process as described in EIGA 06/19 is displayed in Fig. 1.

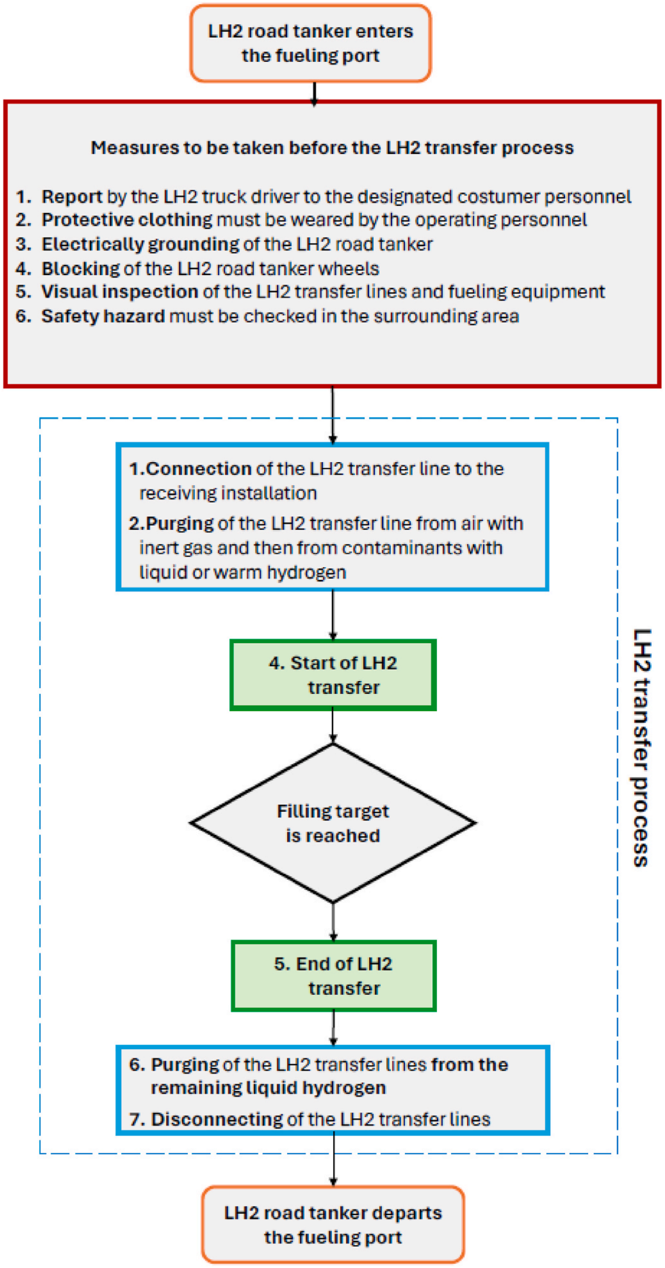


Fig. 1. Schematic illustration of the liquid hydrogen fuelling process.

Even though, this process is apparently reported in detail, some steps are missing or not thoroughly explained. First, the standard remarks the need of transfer equipment suitable for hydrogen transfer, but no information regarding its detailed design (e.g., material, type of insulation) and operating conditions is provided. Secondly, it is not clarified if the transfer should be pressure-based (i.e., LH2 flow is driven by the pressure difference between the tanks), or cryogenic pumps should be used in the process. Thirdly, the description of the control system used to monitor the transfer is missing. Thus, the criteria adopted to start and terminate the LH2 transfer to the receiving vehicle (e.g., liquid level or pressure in the receiving tank) are not clarified. Lastly, the cooling and warm up of the system prior and after the hydrogen flow are not mentioned. More details are given regarding the location of hydrogen vents. For instance, the requirement for a vent stack that collects all the vents in the system is pointed out together with some precautions for its location. However, the discussion does not include construction requirements and is still not exhaustive.

3. Liquid hydrogen mobile applications

The use of liquid hydrogen as a fuel in mobile applications dates back to the 1960s, when it was used in the aerospace industry for the first time. Since then, its utilization has grown to the point that today it is employed in various sectors, from road vehicles to ships. Examples of applications are described in Ref. [40]. In the following, the significant achievements relative to the use of LH2 in the transportation sector are presented together with the most recent and relevant examples of LH2 vehicles currently in operation. The presentation includes the aviation, road, railway, and maritime sector.

3.1. Aviation

In the last six decades, liquid hydrogen has primarily been utilized as a fuel in the aerospace industry, mainly for space missions. Relevant examples in the aviation field are the Ion Tiger [41] and Phantom Eye unmanned air vehicles (UAVs) [42] designed by the Naval Research Laboratory for long-endurance missions and presented in 2009 and 2012, respectively. Through the years, the use of LH2 as an aviation propellant was extended to aircrafts, with the goal of the developing LH2-powered commercial aeroplanes. The efforts made up until now have led to the successful conclusion of many demonstration projects [43]. A significant achievement was reached during the HEAVEN (High power density FC System for Aerial Passenger Vehicle fuelled by liquid Hydrogen, Grant Agreement No 826247) [44] project, which proved the feasibility and safety of LH2-powered aircraft by successfully completing a flight demonstration. In March 2023, the Universal Hydrogen company, founded in 2020, successfully tested a 40-passenger aircraft with one engine powered by a hydrogen-electric powertrain [45]. After few months, a hydrogen combustion engine glider by Airbus completed its demonstration flight, becoming the first aircrafts to use hydrogen as its sole source of fuel [46].

At present, research in the field is focused on exploring propulsion methods and hydrogen onboard storage solutions. For instance, the Airbus ZEROe project is investigating different propulsion concepts, from hydrogen combustion, where gas turbines with modified fuel injectors and systems operate similarly to conventional aircraft engines, to fuel cells [47]. The company also formed a joint venture, Airbus Aerostack, with automotive supplier ElringKlinger AG to develop hydrogen fuel cell stacks for electric propulsion systems [48]. Demonstrations for both hydrogen combustion and fuel-cell propulsion have been launched and are supported by dedicated development centres across Europe. Test aircraft A380 MSN1 is used to lead the testing of these crucial technologies [49]. Additional research areas include hydrogen production and supply and the development of the necessary infrastructure to operate hydrogen-powered aircrafts. The launch of the first vehicle of this kind was announced for 2035 [47]. Universal Hydrogen is also investigating propulsion systems, verifying the feasibility of retrofitting the existing aircrafts fleets with hydrogen fuel cell powertrains. Regarding on board storage, future plans include utilizing LH2 modules that can be fitted inside the airplane's fuselage [45].

3.2. Road transport

The use of liquid hydrogen as a fuel for road vehicles has a long history of development and experimentation. The first example dates back to 1971, when the Perris Smogless Association converted a Ford F250 pickup into the world's first LH2/LOX fuelled car, capable of travelling 160 km and running for 25 h [50]. Since then, cryogenic storage systems have been optimized to obtain satisfactory vehicles performances in terms of fuel boil-off and driving range (i.e., the travel distance between two consecutive refuellings). In 2022, Toyota tested its H2 Corolla, the first racing car powered by LH2 [51]. The first liquid hydrogen-fuelled truck Hyzon was tested by Hyzon Motors in 2023, completing a travel of 870 km without refuelling [52]. Today, Daimler Truck AG has been developing hydrogen fuel cell technology under its GenH2 brand, aiming at advancing the use of hydrogen fuel cells in heavy-duty trucks to provide a sustainable alternative to traditional diesel-powered vehicles. This company offers solutions with long ranges and quick refuelling times, addressing some limitations of battery-electric trucks, particularly for long-haul transportation. A significant milestone was recently achieved with the prototype of the Mercedes-Benz GenH2 Truck. The truck, approved for public road use, can cover 1047 km on a single fill of liquid hydrogen [2]. It is powered by a cell-centric fuel-cell system that features an LH2 fuel tank system. Throughout the entire journey, which involved a fully loaded truck with a gross combined vehicle weight of 40 tons.

3.3. Railway transport

Over the past two decades, hydrogen has gained traction in the railway sector. However, current applications in the field known as hydrail vehicles rely on gaseous hydrogen as a fuel. Examples are the HYBARI train, developed and tested by the East Japan Railway Company in April 2006 [53] and the Alstom's iLint train launched in 2016 [54]. Interest in LH2 locomotives has grown due to its higher energy density and avoidance of high-pressure storage hazards. By 2021, a collaboration between the Korea Railroad Research Institute and Hyundai Rotem is ongoing with the goal to launch the world's first LH2-based locomotive with a longer range and quicker fuelling than compressed gaseous hydrogen-powered trains [55]. At present, the implementation of LH2 in railways still presents challenges, such as the need for specialized components for fuel dispensing and storage infrastructures. Technical challenges persist, with feasibility studies showing promising results for hydrail technology but highlighting the importance of selecting low-carbon hydrogen supply options for optimal environmental benefits [56].

3.4. Maritime sector

Various feasibility studies have explored the potential of hydrogen-powered boats and ships, mainly focusing on fuel cell utilization for maritime applications [40]. Few applications of liquid hydrogen in the sector are known. According to the authors' knowledge, the Suiso Frontier currently is the sole LH2 tanker vessel. On board of the LH2 carrier, inaugurated in February 2022, liquid hydrogen is stored in a 1250 m^3 cryogenic tank. The vessel was designed in the frame of the HySTRA (Hydrogen energy Supply-Chain Technology Research Association) project [57], a collaborative initiative involving prominent entities, including Kawasaki Heavy Industries Ltd., Iwatani Corporation, Shell Japan, and Electric Power Development Co. Ltd. The carrier successfully completed a journey from Australia to Japan proving the feasibility of international shipping via LH2-powered ships. Another notable achievement concerning liquid hydrogen application in the maritime sector was reached by the world's first LH2 powered ferry, the MF Hydra, in operation since 2023 [3]. On board, the fuel cell system is fuelled with liquid hydrogen stored in an 80 m^3 tank.

4. Standards for liquid hydrogen technologies

The spread of liquid hydrogen on a large scale relies on the development of international standards that define the requirements for LH2 storage technologies. Thus, the current lack of standardization in the field is a relevant issue. In fact, if compared with other storage technologies, such as high-pressure hydrogen storage, the number of standards available for LH2 is much more limited. In the following sections, international standards for the design and operation of LH2 components are discussed. The standards are presented in alphabetical order; for the ones with the same name, they are further ordered based on their number, in ascending order.

4.1. Standards for design and operation of LH2 cryogenic tanks

Currently, design and operational requirements for the fabrication, inspection, and testing of cryogenic and liquid hydrogen storage tanks are regulated by the standards summarized in Table 1. They differ depending on the vessel application (i.e., fixed tank, transportable tank), size, and operating conditions. For instance, the CGA H-3-2024 [58] standard provided by the Compressed Gas Association (CGA) describes the minimum design and performance requirements for vacuum-insulated cryogenic LH2 tanks, both vertical and horizontal, intended for above ground storage with a maximum allowable pressure of up to and including 1210 kPa. For fixed storage tanks for bulk LH2 storage by tankers or containers by road, sea, and rail, design and operation requirements are specified in the EIGA 06/19 [39].

As visible from Table 2, most of the standards are provided by the International Organization for Standardization (ISO). The ISO 13985 [59] refers to liquid hydrogen vessels permanently attached to land vehicles. The standard provides construction requirements and methods that ensure reasonable protection from loss of life and property resulting from fire and explosions. Construction, fabrication, inspection, and testing requirements for transportable vacuum-insulated tanks of 450 L (or more) attached to a mean of transport can be found in ISO 20421 Part 1 [60]. In the Part 2 of the same standard (ISO 20421 Part 2 [61]), operational requirements, such as procedures for tank filling, withdrawal and emergency procedures, are presented. ISO 21009 Part 1 [62] provides the same type of information as ISO 20421 Part 1 for static vacuum-insulated cryogenic tanks designed for a maximum allowable pressure higher than 0.5 bar. ISO 21009 Part 2 [63], summarizes the tank's operational requirements for the same components. For transportable vacuum-insulated cryogenic pressure vessels with a volume not higher than 1000 L, requirements are specified in ISO 21029 Part 1 [64]. For the bulk storage of LH2, more general rules are provided by two standards of the National Fire and Protection Agency (NFPA), the NFPA 55 [65] and NFPA 2 [66]. The first explains safety practices against fire, deflagration, and explosions, whereas the second addresses the use and handling of cryogenic fluids, including requirements for relief devices and guidelines for the location of bulk systems.

4.2. Standards for liquid hydrogen cryogenic tank accessories

Given the complexity of LH2 storage due to the extremely low operating temperatures involved, additional standards must be considered when designing the storage system, such as the LH2 tank and its accessories. A multitude of standards are available for accessories for liquid hydrogen tanks. CGA G-5.5 [67] provides design guidelines for hydrogen vent systems used with both gaseous and liquid hydrogen to ensure their safe operation in various applications and prevent hazards associated with hydrogen. EN ISO 28921–2:2017 [68] specifies requirements for type testing isolating valves used in low-temperature applications ensuring their functionality and integrity under extreme temperature conditions. ISO 21010:2017 [69] establishes gas/material compatibility requirements, including chemical resistance, for equipment used with cryogenic fluids. It also outlines testing methods to determine compatibility between materials and cryogenic fluids, considering factors such as oxygen-enriched atmospheres. ISO 21011:2008 [70] sets requirements for the design, manufacture, and testing of valves used in cryogenic service, particularly those operating at temperatures of −40 °C and lower. It covers various types of cryogenic valves, including vacuum jacketed ones. ISO 21012:2018 [71] specifies design, construction, testing, and marking requirements for non-insulated flexible hoses used to transfer cryogenic fluids with working temperatures ranging from −270 °C to 65 °C. ISO 21013–1:2021 [72] outlines requirements for the design, manufacture, and testing of reclosable pressure relief valves used in cryogenic service ensuring their safe operation at temperatures below −10 °C. For non-reclosable pressure relief valves, the same type of requirements is

Table 2
International standards for design and operation of cryogenic tanks for liquid hydrogen storage.

Standard	Title	Scope	Target equipment item	Out of scope
CGA H-3-2024 [58]	Standard for cryogenic hydrogen storage	Design and performance requirements	Vacuum-insulated storage tank	• Tanks with volume lower than 3,785 L or higher than 94,600 L • Transportable containers • Installation and operation requirements or emergency response
EIGA 06/19 [39]	Safety in storage, handling and distribution of liquid hydrogen	Design, operation requirements	Fixed storage tanks	• Portable containers • Liquid cylinders
ISO 13985:2006 [59]	Liquid hydrogen – Land vehicle fuel tanks	Construction requirements and methods for protection from loss of life and property	Refillable fuel tanks	
ISO 20421–1:2019 [60]	Cryogenic vessels – Large transportable vacuum-insulated vessels – Part 1: Design, fabrication, inspection and testing	Design, fabrication, inspection, and testing requirements	Fixed, demountable and portable vacuum-insulated cryogenic vessels	• General vehicle requirements • Specific requirements for refillable LH$_2$ tanks primarily dedicated as fuel tanks in vehicles
ISO 20421–2:2019 [61]	Cryogenic vessels – Large transportable vacuum-insulated vessels – Part 2: Operational requirements	Operational requirements	Large transportable vacuum-insulated cryogenic vessels	Specific requirements for different transport modes
ISO 21009–1:2022 [62]	Cryogenic vessels – Static vacuum-insulated vessels – Part 1: Desing, fabrication, inspection and tests	Design, fabrication, inspection and testing	Static vacuum-insulated cryogenic vessels	
ISO 21009–2:2015 [63]	Cryogenic vessels – Static vacuum insulated vessels – Part 2: Operational requirements	Operational requirements	Static vacuum-insulated vessels	Installation requirements
ISO 21029–1:2018 [64]	Cryogenic vessels – Transportable vacuum-insulated vessels of not more than 1000 L volume - part 1: Design, fabrication, inspection and tests	Design, fabrication, type test and initial inspection and test requirements	Transportable vacuum-insulated cryogenic pressure vessels	• Specific requirements for refillable LH2 tanks used as fuel tanks in vehicles • Open top Dewars
NFPA 55 [65]	Compressed gases and cryogenic fluids code	Storage, use and handling of cryogenic fluids	Bulk LH2 storage tanks	
NFPA 2 [66]	Hydrogen technologies code	Provisions for the generation, storage, installation, piping and use of LH2		

specified in ISO 21013–2:2007 [73] to ensure their reliability and performance in relieving excess pressure in cryogenic vessels. ISO 21013–3:2016 [74] provides calculation methods to determine the sizing and capacity of pressure relief accessories for cryogenic vessels including vacuum-insulated vessels with intact or partial loss of vacuum. ISO 21028–1:2016 [75] sets toughness requirements for metallic materials (e.g., unalloyed steels and cast materials) used at cryogenic temperatures below −80 °C. ISO 23208:2017 [76] outlines the standards for cleanliness in cryogenic vessels to ensure safe and efficient operation establishing the minimum requirements for the cleanliness of all surfaces and accessories that come into contact with cryogenic fluids, especially in unexpected operating conditions. The standard sets an acceptable level of contamination to minimize the risk of malfunctioning and ensures safety against ignition when in contact with oxygen or oxidizing fluids. Essentially, it aims to maintain a high level of cleanliness within cryogenic vessels to mitigate potential hazards and ensure optimal performance and safety. ISO 24490:2016 [77] provides minimum requirements for the design, manufacture, and testing of pumps intended for cryogenic service to guarantee the meeting of performance, reliability and safety standards. Various types of pumps, including centrifugal pumps and possibly others, are considered; requirements for operation and maintenance are out of scope. Design, manufacturing, and

Table 3
International standards for accessories of cryogenic tanks for liquid hydrogen storage.

Standard	Title	Scope	Target	Out of scope
CGA G-5.5 [67]	Standard for hydrogen vent systems	Design guidelines for hydrogen vent systems	Vent systems	
EN ISO 28921–2:2017 [68]	Industrial valves - isolating valves for low-temperature applications - part 2: Type testing (ISO 28921–2:2015)	Requirements for the type testing of isolating	Isolation valves	
ISO 21010:2017 [69]	Cryogenic vessels — gas/material compatibility	Gas/material compatibility requirements	Equipment of cryogenic fluids	Mechanical properties (e.g., for low-temperature applications)
ISO 21011:2008 [70]	Cryogenic vessels — valves for cryogenic service	Requirements for design manufacture and testing of valves	Equipment of cryogenic fluids	Pressure relief valves covered by ISO 21013-1
ISO 21012:2018 [71]	Cryogenic vessels - hoses	Design, construction, type and production testing, marking requirements	Non-insulated flexible hoses used for transfer of cryogenic fluids with working temperatures from −270 °C to 65 °C and normal size from DN 10 mm–100 mm	Coupling
ISO 21013–1:2021 [72]	Cryogenic vessels — pressure-relief accessories for cryogenic service — part 1: Reclosable pressure-relief valves	Requirements for the design, manufacture and testing of pressure relief valves for cryogenic service	Pressure relief valves	Capacity of relief valve(s) for a particular cryogenic vessel
ISO 21013–2:2007 [73]	Cryogenic vessels — pressure-relief accessories for cryogenic service — part 2: Non-reclosable pressure-relief devices	Requirements for the design, manufacture and testing of non-reclosable pressure-relief devices for cryogenic service	Pressure relief valves	Methods for determining the capacity of bursting disc or buckling pin devices
ISO 21013–3:2016 [74]	Cryogenic vessels — pressure-relief accessories for cryogenic service — part 3: Sizing and capacity determination	Methods for vented mass flow calculation	• Vacuum and not-vacuum insulated vessels with intact insulation and partial or total loss of vacuum due fire engulfment • Vacuum-insulated vessels with fluids with saturation temperature below 75 K at 1 bar with loss of vacuum with air or nitrogen in the insulation	
ISO 21028–1:2016 [75]	Cryogenic vessels- toughness requirements for materials at cryogenic temperature — part 1: Temperatures below −80° C	Toughness requirements of metallic materials for use at temperatures below −80 °C	Equipment in contact with fluids at temperatures below −80 °C	Unalloyed steels and cast materials
ISO 23208:2017 [76]	Cryogenic vessels — cleanliness for cryogenic service	Minimum requirement for the cleanliness of all surfaces and accessories in contact with cryogenic fluid	• Cryogenic vessels	
ISO 24490:2016 [77]	Cryogenic vessels – Pumps for cryogenic service	Requirements for the design, manufacture, and testing requirements	Pumps for cryogenic service	Requirements for operation and maintenance
ISO 28921–1:2022 [78]	Industrial valves - isolating valves for low-temperature applications - part 1: Design, manufacturing and production testing (ISO 28921–1:2022)	Requirements for design, dimensions, material, fabrication and production testing	Isolation valves	
EN 12434:2000 [79]	Cryogenic vessels — cryogenic flexible hoses	Design, construction, type and production testing, and marking requirements	Cryogenic hoses	
EN 13275:2000 [80]	Cryogenic vessels — pumps for cryogenic service	Design, manufacture and testing requirements	Pumps for cryogenic fluids	Operation and maintenance requirements
EN 13371:2001 [81]	Cryogenic vessels – Couplings for cryogenic service	Design, manufacture and testing requirements	Flexible hoses	
EN 13648–1:2008 [82]	Cryogenic vessels — safety devices for protection against excessive pressure — part 1: Safety valves for cryogenic service	Design, manufacture and testing requirements	Safety valves	
EN 13648–2:2002 [83]	Cryogenic vessels — safety devices for protection against excessive pressure — part 2: Bursting disc safety devices for cryogenic service	Design, manufacture and testing requirements	Bursting discs	NS-EN 13648–2:2002
EN 1626:2008 [84]	Cryogenic vessels — valves for cryogenic service	Design, manufacture and testing requirements	Valves for cryogenic fluids	

production testing requirements for isolating valves used in low-temperature applications are provided in ISO 28921–1:2022 [78]; EN 12434:2000 [79] provides the same information for non-insulated cryogenic flexible hoses used in the transfer of cryogenic fluids, ensuring their safety and integrity in cryogenic applications. Operation and maintenance requirements are not specified. EN 13275:2000 [80] specifies minimum requirements for the design, manufacture, and testing of pumps used in cryogenic service. EN 13371:2001 [81] outlines requirements for the design, manufacture, and testing of couplings used for connecting flexible hoses to cryogenic vessels. EN 13648–1:2008 [82] and EN 13648–2:2002 [83] outline requirements for the design, manufacture, and testing of safety valves and bursting discs, respectively. Finally, EN 1626:2008 [84] specifies the same requirements for valves used in cryogenic service.

4.3. Standards for LH2 transfer operations

As said before, the widespread utilization of LH2 on a large-scale benefit from the establishment of international standards that outline the criteria for LH2 storage and transfer technologies. However, only two of the international standards found in this work mention LH2 transferring operations: EIGA 06/19 [39] and ISO 13984:1999 [85] (see Table 3). The standard EIGA 06/19 [39] outlines safety protocols for the storage, handling, and distribution of liquid hydrogen. It establishes design and operational requirements for various storage and transportation methods, including fixed storage tanks used for bulk storage of liquid hydrogen delivered by tankers or tank containers via road, sea, and rail. Additionally, the standard covers safety considerations for portable containers and liquid cylinders used in the storage and transportation of liquid hydrogen. Overall, it aims to ensure the safe handling and distribution of liquid hydrogen across different applications and industries. The standard ISO 13984:1999 [85] focuses on the interface specifications for liquid hydrogen refuelling systems used in land vehicles. It defines the characteristics of LH2 refuelling and dispensing systems to mitigate the risk of fire and explosion during the refuelling process. The standard aims to ensure a reasonable level of protection for both human life and property. In essence, it provides guidelines to enhance the safety of LH2 refuelling systems installed in various types of land vehicles, promoting the safe and efficient use of liquid hydrogen as a fuel source. In the abovementioned standards, the different phases of a conventional LH2 refuelling process (i.e. grounding, visual inspection, purging, cooling down, transfer, warming up and venting) are only qualitatively described without providing any quantitative information or instruction. As described in Sec. 1 and Sec. 2, the transfer process is critical from a safety standpoint. Given that, the absence of standardization, together with the complexity of the process, is a pertinent concern that hampers the spread of the LH2.

4.4. Other standards

Other standards for cryogenic applications concern the basic safety concerns for hydrogen utilization, material resistance to cryogenic spills, and the insulation performance (see Table 5). Particularly, in ISO TR 15916:2015 [86], hydrogen safety-relevant properties are described together with hazards and risks relative to its use and storage in both gaseous and liquid forms. Based on these aspects, guidelines for safe hydrogen handling are also outlined. Safety considerations for cryogenic liquid hydrogen operations were added in the last reviewed version of the document. ISO 20088 Part 1 [87] and Part 2 [88] provide methods to determine the resistance to cryogenic liquid and vapour spills, respectively. ISO 20088 Part 3 [89] considers the resistance to cryogenic jets resulting from pressurized releases. Practical methods for defining the insulation performance are given in ISO 21014 [90] to estimate the heat leaks in the system. Finally, the EN 1252–1:1998 [91] standard specifies toughness requirements for metallic materials used at temperatures below −80 °C, that is the case of cryogenic applications. These standards are described in Table 4. It is worth remarking that they apply to cryogenic systems in general. Thus, they could be suitable for LH2 applications, even if liquid hydrogen is not explicitly mentioned.

Notably, when juxtaposed with high-pressure technologies, the quantity of available standards for LH2 is considerably more constrained. A total of 37 international standards were found for LH2 technologies. Most of the standards were created for the design of LH2 components (e.g. 18 standards on LH2 tanks accessories). On the other hand, only two standards mention the LH2 refuelling operations. All the standards mentioned Sec. 4.1, 4.2, 4.3 and 4.4 are summarized in Fig. 2.

5. Past and recent research progress on cryo-compressed and liquid hydrogen safety

In order to develop new international standards for liquid hydrogen technologies covering transferring operations, it is critical to comprehend the fuel behaviour during accident scenarios. In this perspective, the characterization of hydrogen release sources and the investigation of the behaviour of hydrogen flammable clouds is essential to prevent the occurrence of ignition. If, in the worst cases, ignition occurs, hazards distances (i.e., distances at which the thermal radiation and overpressure overcome threshold levels able to cause damages to humans and structures) should be estimated to allow the disposal of effective safety barriers and minimize the impact of fires and explosions. This analysis should be done to study the response of LH2 equipment involved in transfer operations, such as tanks and piping, in both normal adverse conditions (e.g., failures, fire exposure). In this manner, it would be possible to provide paramount insights on separation distances and hazard zones.

This section aims at providing an overview of the most relevant and recent research studies and findings addressing the knowledge gaps and open issues associated with the behaviour of LH2 and cryo-compressed hydrogen in accidental conditions. The recent developments in the experimental research investigating the fundamental phenomena involved in typical (e.g. release and dispersion, ignition, and combustion) and atypical accident scenarios (e.g. catastrophic rupture of LH2 equipment) are reported. Theoretical and numerical assessments done to develop and validate predictive models for the analysis of incident consequences and the determination of hazard zones for LH2 technologies are also presented. It must be noted that different terms, such as spill and leakage, are used in this work to indicate a release of LH2.

5.1. Past experiments on loss of containment of LH2 components

In the last decades, different experimental tests have been carried out to analyse the consequences of LH2 loss of containment, including storage tank rupture, pipeline failure, and releases. A brief overview on past experiments can be found in Ref. [92]. First experiments related to LH2 dispersion date back to 1960 and were performed by Cassut et al., employed at the Arthur D Little company [93]. These experiments involved continuous and instantaneous small- and large-scale releases of LH2 (stored close to atmospheric pressure) onto the ground. Storage and transport conditions were simulated to establish quantity-separation distance relationships to compare with hydrocarbons. It was observed that instantaneous LH2 release rapidly forms a cloud rising from the ground within few seconds. In contrast, continuous LH2 spills form a dense cloud with considerable visible extension, up to 200 m [93]. The experiments carried out by Zabetakis et al. [35] in 1961 provided more insights into hydrogen vaporisation. The results showed that the primary violent boiling phase must be neglected to determine the liquid vaporisation rate. Moreover, the influence of the ground type on the fuel evaporation was also determined. For instance, LH2 vaporized faster on gravel than on smooth macadam. The analysis of the distribution of flammable volumes did not find any relations between their location and the position of the visible cloud. In 1981, NASA carried out large-scale and small-scale tests at NASA’s White Sands Test Facility to reproduce

Table 4
International standards for liquid hydrogen transfer operations.

Standard	Title	Scope	Target	Out of scope
EIGA 06/19 [39]	Safety in storage, handling and distribution of liquid hydrogen	Design and operation requirements	Fixed tanks for LH2 bulk storage and tank containers by road, sea and rail	Portable containers and liquid cylinders
ISO 13984:1999 [85]	Liquid hydrogen — land vehicle fuelling system interface	Level of protection from loss of life and property	LH2 refuelling and dispensing systems	

Table 5
International standards for material resistance to cryogenic spills and definition of the performance of the insulation installed on cryogenic equipment.

Standard	Title	Scope	Target	Out of scope
ISO TR 15916:2015 [86]	Basic considerations for the safety of hydrogen systems	Hazards, risks and guidelines for hydrogen use and storage	Gaseous and liquid hydrogen systems	Detailed safety requirements for specific applications
ISO 20088–1:2016 [87]	Determination of the resistance to cryogenic spillage of insulation materials – Part 1: Liquid phase	Resistance to liquid cryogenic spillage	Cryogenic spillage protection	Vapour phase and jet exposure conditions
ISO 20088–2:2020 [88]	Determination of the resistance to cryogenic spillage of insulation materials – Part 1: Vapour exposure	Resistance to vapour from a cryogenic liquid release	Cryogenic spillage protection	Not applicable to high pressure cryogenic liquid releases
ISO 20088–3:2018 [89]	Determination of the resistance to cryogenic spillage of insulation materials – Part 3: Jet release	Resistance to a cryogenic jet release		
ISO 21014:2019 [90]	Cryogenic vessels – Cryogenic insulation performance	Heat-leak performance	Cryogenic vessels	Levels for insulation performance
EN 1252–1:1998 [91]	Cryogenic vessels — materials — part 1: Toughness requirements for temperatures below −80 °C	Toughness requirements of metallic materials for use at a temperature below -80 °C	Cryogenic vessels	Not applicable to cryogenic vessels for liquefied natural gas

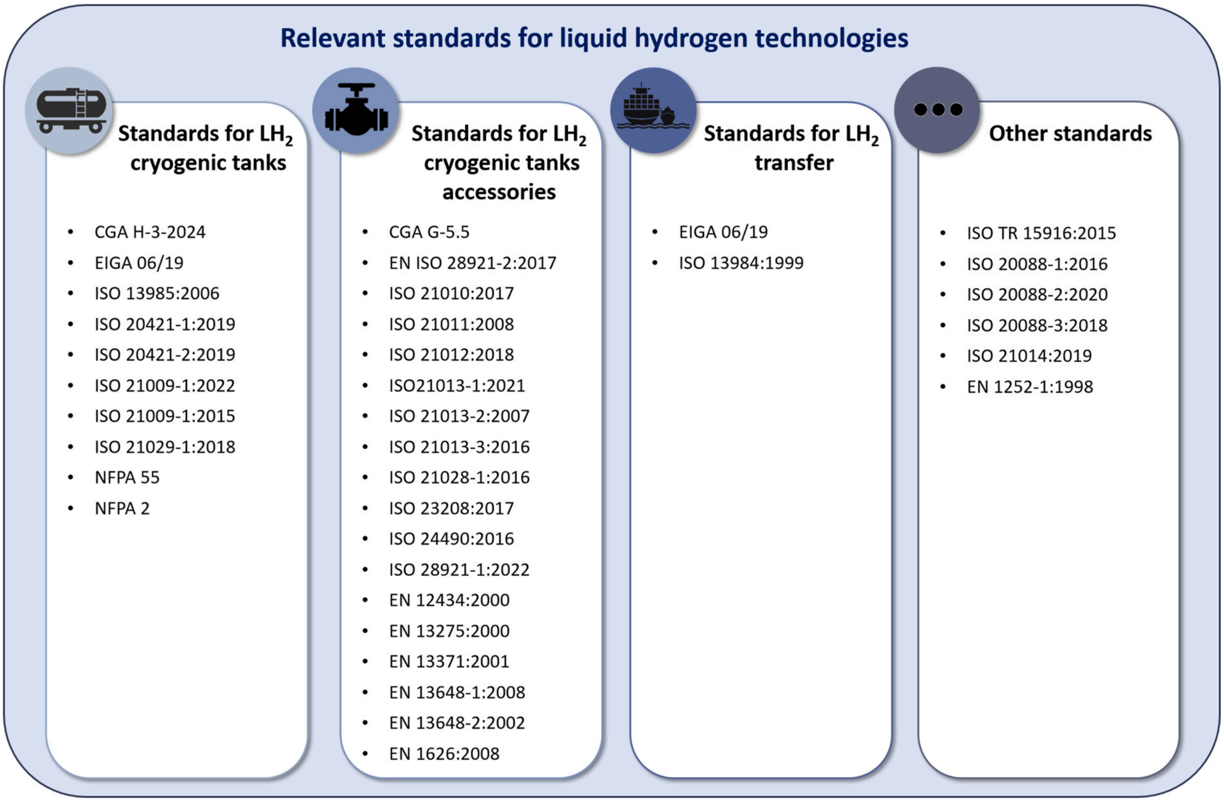


Fig. 2. International standards for liquid hydrogen technologies.

LH2 releases and dispersion from large storage tanks and pipelines [36, 94]. The velocity of the spill was proved to have a substantial effect on the dispersion of the flammable cloud. The results showed that instantaneous LH2 spills are characterized by high thermal instability and momentum inducing a severe turbulence in the flammable cloud. As a consequence of the increased turbulence level, the cloud was observed to be more buoyant and dilute more rapidly to concentration levels lower than the flammability limit. In 1994, hydrogen vaporisation was investigated again by Takeno et al. [95]. The effect of different ground types on the vaporisation was assessed. From the results of the laboratory-scale tests performed with wet and dry ground types, like concrete, dry sand, and wet sand, it was possible to conclude that, except in the moment immediately after the spill, the evaporation rate is inversely proportional to the square root of time for both surfaces. Moreover, it was observed that the freezing of water in wet sand prevented LH2 from permeating the deeper layers; the same effect was observed with dry sand due to the solidification of trapped air. In the same year, additional studies on LH2 dispersion were performed at the Bundesanstalt für Materialforschung und prüfung (BAM) and at the Research Center Juelich in the framework of the Euro-Quebec Hydro-Hydrogen Pilot project [96]. The tests aimed to analyse hydrogen dispersion in confined areas, specifically residential areas, and investigate LH2 pool formation. For the first time, LH2 release tests onto water were performed by Verfondern and Dienhart [97], showing a pulsation-like behaviour of the pool, probably due to the violent vaporisation of the liquid. The experiments conducted by Proust et al. [98] highlighted the relevance of turbulent transport during cloud formation. It was found that the coefficient of turbulent diffusion is at least twice the one for atmospheric turbulence, with an effect that increases with the amount of discharged hydrogen. Finally, in 2012, experimental works on hydrogen dispersion were carried out at the Health Services Laboratories (HSL) in Buxton, UK [99]. The findings showed the formation of an LH2 pool on concrete surfaces and, for high release rates, the generation of flammable mixtures. Moreover, the solidification of oxygen and nitrogen was also observed with the consequent formation of a potentially hazardous mixture due to hydrogen trapped in the deposit [99].

In parallel with the investigation of LH2 dispersion, attention was also paid to other phenomena, such as ignition, detonation, and deflagration. In 1958, Cassutt et al. [93] investigated the possibility of detonation of hydrogen and solid air mixtures. It was concluded that detonation hazards are relatively low because of the significant oxygen enrichment required for the mixture detonation. Other studies were conducted by BMW Group during a four-year research programme from 1992 to 1995 [100]. Explosion consequences deriving from the rupture of LH2 storage tanks were assessed in different storage conditions and for different amounts of fuel (from 1.8 kg to 5.4 kg). The performance of the storage tanks designed for automotive applications was also assessed in anomalous conditions (e.g., excessive pressurization, vehicle engulfed in an external fire) [101]. In case of excessive pressurization of the equipment, a “leak before rupture” behaviour was observed. Regarding the fire engulfment, the opening of the relief valve effectively prevented the tank from failing. In 2014, experiments on LH2 ignited releases were performed at the HSL Buxton to determine safety distances based on the radiation levels [102]. The tests on the full-bore rupture of the LH2 transfer hose showed the presence of different regimes during the release (i.e., initial deflagration, secondary explosion, buoyancy-driven jet-fire, and momentum-dominated jet-fire) and safety distances in the range of 11–14 m [102]. The relevant LH2 tests described in this section are collected and chronologically ordered in Table 6.

Table 6

Past experiments on loss of containment of LH2 components.

Authors	Year	Ref.	Type of experiment	Investigated phenomenon
Cassutt et al.	1958	[93]	Continuous LH2 release	Dispersion
Cassutt et al.	1958	[93]	Failure of LH2 tank	Explosion, dispersion
Zabetakis et al.	1961	[35]	LH2 release	Dispersion and evaporation rate
Witcofski and Chirivella	1981	[36, 94]	Failure of storage facility	Dispersion
Takeno et al.	1994	[95]	Continuous LH2 release	Evaporation rate
Schmidtchen et al.	1994	[96]	Continuous LH2 release	Dispersion and pool formation
Pehr	1996	[100]	Failure of storage tank	LH2 tank response
Pehr	1996	[101]	Sudden LH2 release	Explosion
Verfondern & Dienhart	1997	[97]	Continuous LH2 release	Pool formation and dispersion
Proust et al.	2007	[98]	Continuous LH2 release	Dispersion
Royle & Willoughby	2014	[99]	Continuous LH2 release	Pool formation and explosion
Hall et al.	2014	[102]	Continuous LH2 release	Combustion (jet fire)

5.2. Most recent research activities on LH2 safety

The most recent experimental campaigns on LH2 safety were carried out as part of three research projects.

1. FFI (Norwegian Defence Research Establishment, Project No 555701) [103].
2. PRESLHY (Pre-normative Research for Safe use of Liquid Hydrogen, European Union, Grant Agreement No 779613)
3. SH2IFT (Safe Hydrogen Fuel Handling and Use for Efficient Implementation, Research Council of Norway, Grant Agreement No 280964).

Furthermore, additional research was performed by Sandia National Laboratories (see Sec. 5.2.1). The main findings of both experimental and modelling activities carried out in recent research are provided in this section. Different phenomena were investigated as part of these activities and are divided in this paper as: (i) release and dispersion outdoor, (ii) indoor and on different substrates, (iii) ignition, (iv) combustion, (v) LH2 component response to accident scenarios.

5.2.1. Release and dispersion outdoor

In the framework of the FFI project, a series of large-scale LH2 release tests were performed at the DNV test site Spadeadam to investigate accident scenarios associated with bunkering and maritime use of LH2 [103]. In the release tests where the release orientation was vertical downward, an LH2 pool with a maximum diameter of 0.5 m was developed on the concrete surface. The pool completely evaporated shortly after the release was stopped, with a lower evaporation time when moisture was present in the ground. Solid and liquid air components (nitrogen and oxygen) were detected as far as 1 m from the release point. Hydrogen concentration in the flammable cloud generated during the spills was also measured. For a cloud height between 0.1 m and 1.8 m, hydrogen concentration was higher than the low flammability limit (LFL) (i.e., 4% vol of hydrogen in the air) until 50 m from the release point. For horizontal releases no LH2 were observed and the LFL was overcome between 50 and 100 m.

It should be noticed that at 30 m from the release point, higher hydrogen concentrations were measured at 0.1 m than at 1.8 m, with respect to vertical releases. This can be explained due to the high density of hydrogen at very cold temperatures (i.e. close to its normal boiling point of 20.4 K). The authors concluded that the wind direction should be considered during bunkering operations to prevent flammable concentrations close to the vessel in case of leakages.

In the PRESLHY project, release and dispersion experiments with cryogenic hydrogen were performed with DISCHA, CRYOSTAT and POOL facilities by ProScience (PS)/Karlsruhe Institute of Technology (KIT), while rainout experiments were carried out by Health and Safety Executive (HSE) [104].

Experimental data from the DISCHA tests [105] were used to validate a theoretical model to predict the blowdown dynamics of cryo-compressed hydrogen storage tanks in Ref. [106]. The approach employs the under-expanded jet theory presented in Ref. [107], proved to be applicable to cryogenic hydrogen releases [108]. The study highlighted the importance of accounting for heat transfer through the tank and release pipe walls to well reproduce the experimental transients of temperature and pressure in the storage tank and the hydrogen mass flow rate. In 2018, Venetsanos [109] developed an engineering tool based on the Homogeneous Non-Equilibrium Mixture (HNEM) model to assess choked multi-phase cryogenic hydrogen releases. The tool was later advanced to account for the friction losses throughout a discharge line in Ref. [110] and extra resistance due to fittings in a line with variable cross sections in Ref. [111], proving good accordance with experimental mass flow rate (−0.3-12.7 % maximum variation [112]).

Hall et al. performed large scale experiments, where LH2 was released from a storage trailer ($P \leq 0.5$ MPa) via an orifice of up to 25.4 mm diameter with different release orientations and heights above ground [112]. In the experiments, no rainout but strong ice formation was observed on near field sensors. Temperature field measurements in the mixing zone showed almost perfect correlation with concentration measurements [113]. The experiments over a wide range of flow conditions were also designed to measure two distinct charging modes. Only small electric fields associated with two-phase (vapour/liquid) release effects were observed in plume measurements. Thus, it was concluded that the formation of a hazardously charged plume from an established cryogenic jet is unlikely for the considered experimental conditions. The experimental results lead to the assumption that the main reason for electrostatic field built-up in the plume relates to ice crystals that form at cold nozzles before release and that are blown off in the initial phase of the release.

To offer science-based improvements to the codes and standards that define the safe use of hydrogen, Sandia National Laboratories performed studies on the fundamental behaviour and characteristics of a hydrogen release [114–117]. High-fidelity experimental data was generated and models for their description of the abovementioned phenomena were developed, validated, and verified against the data. Experiments were performed in a well-controlled lab-scale environment outfitted with several lasers to make high-fidelity, non-intrusive measurements of both high-pressure and cryogenic hydrogen releases and combustions.

Several modelling assessments were conducted to characterise the dispersion of cryo-compressed and LH2 releases. The concentration decay in cryo-compressed hydrogen jets obeys the similarity law originally developed for momentum-dominated hydrogen releases at ambient temperature [118]. An integral model able to well reproduce the experimental hydrogen concentration and temperature distribution in cryogenic hydrogen jets measured in Ref. [116] was presented by Venetsanos et al. in Ref. [119]. The benchmark study in Ref. [119] compared the performances of large eddy simulation (LES) and Reynolds-averaged Navier-Stokes (RANS) approaches in reproducing the experimental hydrogen concentration distribution for quasi-steady-state tests performed at Sandia National Laboratories [116]. The study in Ref. [119] highlighted the good performances and computational efficiency of RANS approach to model the quasi-steady state cryogenic hydrogen jets. Benchmark assessment in Ref. [120] compared the performances of different modelling strategies and codes in reproducing hydrogen concentration dynamics in transient cryogenic hydrogen jets. It was observed that both transient notional nozzle area approach and volumetric source approach were suitable to model the transient cryogenic hydrogen jets.

Unignited releases of LH2 have been mainly investigated by means of numerical simulation [121–123]. Ichard et al. [124] modelled experiments performed at HSE facilities for horizontal and vertical releases. The authors highlighted the challenges in accurately estimating the release sources, in particular regarding the gaseous volume fractions. The authors also observed that modelling of air components condensation would enhance buoyancy of the plume originated by vertical downwards LH2 releases. According to the authors, the phenomenon can be attributed to the release of energy during oxygen and nitrogen condensation. On the other hand, the effect was observed to not be significant for horizontal LH2 releases.

Giannissi and Venetsanos in Ref. [121] observed that considering modelling of air components, humidity phase change, and slip-effects of the non-gaseous phases would affect the flammable cloud dispersion and improved reproducibility of experiments on dispersion of LH2 horizontal releases. Giannissi et al. performed a benchmark assessment on the dispersion of large scale LH2 releases [125]. The inter-comparison between different computational fluid dynamic (CFD) approaches and experimental measurements highlighted the effect of atmospheric instabilities on the model predictive capabilities in the far-field of the release. Hansen [126] modelled the hydrogen plumes produced when LH2 was released through a vent mast on a realistic LH2 ship. The study observed that, during the initial phase of the release, the heat exchange with the ambient temperature mast walls would likely cause the LH2 vaporisation. As time progresses, this effect may diminish due to the walls cooling down. CFD simulations were used to give insights on this scenario evolution, showing that, in low wind conditions, the generated plumes could reach the external base of the mast and its surroundings.

5.2.2. *Release and dispersion on different substrate and in enclosure*

Friedrich et al. performed experiments on LH2-spills over different substrates (concrete, sand, water, and gravel) with the PS/KIT POOL facility [127]. The facility mainly consists of an insulated square stainless-steel box (50 cm × 50 cm, height: 20 cm) on a scale. In four of the ten experiments, a large fan was installed to investigate the influence of side wind on the formation and evaporation of LH2 pools. In most experiments, the pool was filled 3 times with LH2 until overflowing. After each filling, the pool was left to evaporate. The pool filling level was determined using the weight of the facility and the thermocouples inside the pool at different heights. With these data, evaporation rates for the different substrates were accessible and much faster evaporation rates were found for the cases with side wind conditions.

A reduced model (HyPond) was developed by INERIS research group in Ref. [113] to assess the extent of LH2 pools spreading on a free flat ground. Several studies investigated the spreading and vaporisation of LH2 spills by means of CFD simulations. In 2012, Jaekel et al. [128] analysed the different boiling regimes and spreading of LH2 spills. In 2017, Jin et al. [129] highlighted the importance of heat exchange on the ground on the resulting behaviour of the cryogenic hydrogen plume. The increase in ground temperature was found to decrease the spreading and duration of the pool. However, in a later study [130] this was found to not have an obvious effect for steady-state continuous LH2 releases. Jäkel et al. [131] observed a high sensitivity of numerical results on the ground thermal properties and atmospheric conditions, which can be characterised by high uncertainty and variability, respectively. The effect of dike presence around LH2 release sources was assessed numerically in Ref. [132]. The authors observed that the dike presence enhances the upward development of the flammable cloud, with higher hydrogen concentrations reached near the release source and lower concentrations outside the dike, respectively. The duration of the flammable cloud dilution was observed to be affected mainly within the dike zone. Study in Ref. [133] observed that the dike presence would decrease the distance reached by the flammable cloud near the ground; in contrast, it would increase the maximum distance reached at higher height from the ground.

Gitushi et al. [134] modelled LH2 spills in a tunnel-like facility to examine the effect of cross-wind speed on the flammable cloud envelope dimensions and extensions. The flammable plume was observed to be longer and to develop closer to the ground for increasing crosswind velocities.

During the FFI project LH2 release tests performed by DNV in closed spaces, the hydrogen concentration reached almost 100% vol in the closed room approximately 30 s after the beginning of the LH2 spill. Pressure build-up in the closed room due to the LH2 release and evaporation (i.e. pressure peaking phenomenon, PPP) was not observed. In all the indoor tests, an LH2 pool with a radius between 0.5 and 1.0 m was generated. However, LH2 collected on the closed room steel floor evaporated 30–40 s after the end of each test.

Much larger experiments on LH2-spills in a 10 m × 10 m x 1.5 m water basin were performed at the Bundesanstalt für Materialforschung und prüfung (BAM) within the frame of the SH2IFT project [135]. The experiments were aimed at investigating the possibility of occurrence of a physical explosion for accidental LH2 release into water due to rapid phase transitions (RTPs) phenomena, already demonstrated for liquefied natural gas. In the tests, LH2 releases of up to about 1 kg/s were established from above the water surface pointing downwards and under the water surface pointing downwards or horizontally along the water surface. All release configurations resulted in a very chaotic LH2-water mixing zone, causing considerable evaporation and resulting in minor overpressures. No RPTs were observed. An unexpected ignition of the released gas cloud occurred, resulting in blast wave overpressures and heat radiation to the surroundings. The ignition occurred in all under-water releases and in about 90 % of the releases above the water surface. In contrast to this, no ignition was observed in the small-scale PS/KIT POOL experiments with water, most likely due to the much smaller water- and LH2-amounts used or the different release conditions (e.g. mass flow rate). In the frame of the same project, a theoretical assessment of an accidental spill of a cryogen on water, including models for pool spreading, RPT triggering, and consequence quantification, was presented by Odsæter et al. [136]. The authors concluded that delayed RPT (feasible for LNG pool on top of water) is highly unlikely when LH2 is spilled onto and into water. However, generation of an early RPT was not excluded for LH2.

The diffusion behaviour after accidental LH2 spillage was investigated by Zhang [137] in a series of open-space large-volume LH2 release experiments, in which the evolution of visible clouds during the release and the fluctuation in hydrogen concentration at different locations were monitored for different release orifice diameters and different ground materials. The visible cloud formed by air condensation during LH2 releases was generated rapidly and spread widely near the ground. With the termination of LH2 release, solid air was deposited on the ground, and the visible clouds gradually shrank from the far field to the release source. For cobblestone ground H2-concentration, fluctuations in the far field are more dependent on spontaneous diffusion by the hydrogen concentration gradient, and it has greater resistance to LH2 extension than concrete ground. The space near the source is prone to high-concentration hydrogen clouds, increasing the safety risk in this region.

5.2.3. *Ignition*

Hydrogen–air mixtures are characterized by very wide flammability limits, much wider than other fuels. At cryogenic temperatures, the flammability limits shrink from 4% to 75% vol at ambient conditions to 6%–69% vol at 123 K [137]. Within the flammability limits, two main ignition characteristics, the minimum ignition energy (MIE) and the auto-ignition temperature, have been experimentally evaluated in the PRESLHY project. It was found that at cryogenic temperatures (T = 123 K) the auto-ignition temperature by hot surface does not depend on mixture composition and initial temperature, while flow velocity has a marginal influence. Experimental auto-ignition temperatures of about 600 °C found at cryogenic temperatures agree with theoretical calculations made by Cantera-code using different chemical mechanisms and with Zabetakis experimental data at ambient conditions [138].

Measurements of MIE by spark ignition for hydrogen-air mixtures down to 123 K showed an increase in the MIE. A theoretical model was developed and validated to assess the MIE in hydrogen mixtures with air at temperatures as low as 123 K [139]. The theoretical model reproduced the tendency of MIE to increase with the temperature decrease observed in experiments. The model accurately predicts PRESLHY experiments, resulting in MIE equal to 46 μJ at a temperature of 173 K. It was complemented by a CFD approach to investigate in detail the flame kernel development process and the effect of experimental apparatus design on MIE estimations [140].

Veser et al. [105] experimentally investigated the occurrence of electrostatic ignition of cold jets and plumes in the PRESLHY project. The electric field mills were positioned at different distances from the nozzle. In none of the experiments, a spontaneous ignition due to the discharge of an electric field was observed. No significant field build-up was observed for releases at ambient reservoir temperature. In contrast to this, much higher field values were measured in the cryogenic DISCHA experiments at 80 K. A clear trend towards higher extreme values for larger nozzles and higher initial pressures was observed. Only the data acquired with the DISCHA facility were used to formulate the electric field generation model.

With the POOL facility, experiments on the ignition of LH2 spills were performed [141]. The gas cloud above the pool was ignited using an electric spark. Several experiments were performed with the four substrates: concrete, sand, water, and gravel. Different ignition time delays and locations were established. The ignition was initiated during the second evaporation phase. For the substrates with rather low or no porosity (water, concrete and sand), only minor damage was observed while in the sole experiment with the highly porous substrate of gravel, complete destruction due to the blast inside of the gravel part occurred. The probable explanation for this exceptional behaviour is the explosive interaction of LH2 located in the porous gravel layer and condensed air components.

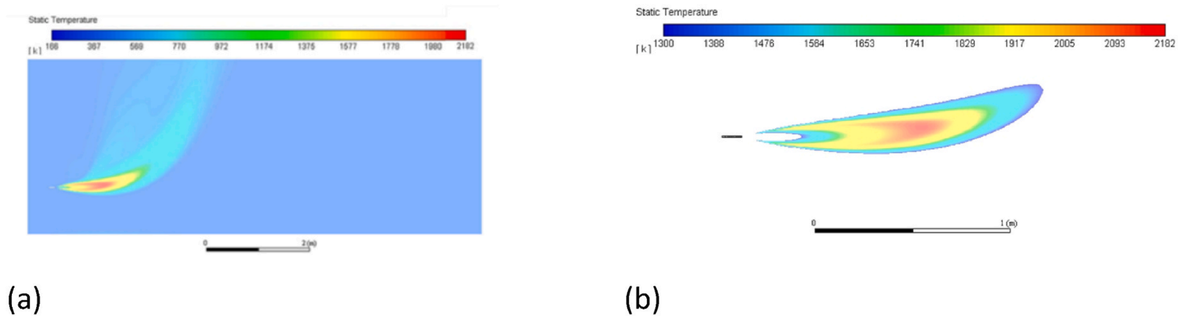
The experiments on secondary explosion (i.e., the explosion occurring after the primary ignition of the hydrogen vapour cloud) due to reaction between LH2 and solid oxygen within the porous gravel layer, were performed on ignited low-pressure horizontal releases of LH2 [102]. The secondary explosion was a particularly energetic event, accompanied by a fireball with a diameter of approximately 8 m and intense radiative fluxes. The cause of the secondary explosion was deemed to be associated with the oxygen initially accumulated in the solid deposit, which underwent a rapid phase transition during the initial flash fire or with the reaction of a condensed oxygen-enriched mixture with hydrogen [102]. The theoretical assessment in Ref. [142] observed the potential for forming solid air deposits with composition and characteristics highly dependent on the release parameters and wind conditions.

Finally, spontaneous ignition was not observed during any of the DNV tests (FFI project [103]) when LH2 was spilled outdoor and indoor, while this phenomenon might be a concern for high-pressure ($P > 350$ bar) gaseous hydrogen releases [143]. Moreover, no fast deflagration or detonation were observed when the hydrogen releases were intentionally ignited outdoor.

5.2.4. *Combustion*

Several experimental and analytical studies on cryogenic hydrogen combustion addressed laminar/turbulent combustion and detonation, hydrogen jet ignition characterization, cryogenic hydrogen combustion over an LH2 spill, and rupture of LH2 storage tank. Experiments addressing characterization of laminar/turbulent combustion and detonation in a tube were performed in Ref. [104] using the CRYOTUBE facility. Among other results, this study concludes that the maximum combustion pressure at cryogenic temperatures is 2–3 times higher than that for ambient conditions. Maximum detonation pressure prediction insight is also given.

Cryogenic hydrogen jet releases are likely to ignite, and the produced jet fires can generate hazardous conditions in their surroundings. Thermal hazards are generally associated with the jet fire flame length, the temperature of combustion products, and thermal radiation. The dimensionless correlation originally formulated for hydrogen jet fire lengths with ambient storage temperature was found to be yet suitable for cryogenic hydrogen jet flames [118]. Cirrone et al. [108,144] developed a RANS CFD approach to assess the radiative heat flux originated from cryogenic hydrogen jet fires. Experimental tests used to validate the CFD model had storage pressure up to 20 bar, temperature from 48 to 80 K, and vertical and horizontal directions. CFD simulations in Ref. [144] show that for horizontal jet fires the buoyancy of combustion products may have a reducing effect on the “no harm” axial distance calculated by temperature (see Fig. 3). Furthermore, it was



(a) (b)

Fig. 3. Simulated temperature contours for Test with P = 14 bar, T = 80 K and d = 2 mm; b) flame length for numerical Test 3 considering the temperature threshold 1300 K [144].

observed that “no harm” hazard distances defined by thermal radiation are longer than those calculated for the “no harm” temperature criteria.

Transient cryogenic hydrogen jet fire behaviour was investigated with the DISCHA facility in Ref. [104]. Cold hydrogen jets were ignited with various delay times and nozzle distances. Strong explosions with spherical shock waves might occur just after ignition (Fig. 4). In each case, overpressure, shock wave velocity, temperature, heat flux, and flame length were characterized.

After ignition, flame can either burn back to the nozzle or not. When this is correlated with hydrogen concentration measurements of unignited tests, a clear trend can be observed (Fig. 5, left). For very low H2-concentrations in the ignition position (cH2IP) no ignition occurs. For cH2IP < 10 vol%, the jet is ignited, and the flame does not burn back, while it burns back to the nozzle for cH2IP > 10 vol%.

In general, the maximum measured overpressures increase with increasing nozzle diameter, while the in-vessel gas temperature has no significant influence on this (Fig. 5, center and right). At ambient gas temperature, the measured overpressures increase with decreasing ignition distance, while in cryogenic tests highest overpressures are measured for ignition distance 62.5 cm.

Experimental data generated within PRESLHY and other data available in the literature were used to develop a conservative correlation to characterise the maximum overpressure that could be generated with either ambient or cryogenic storage temperature at arbitrary ignition location and delay of hydrogen turbulent jets [145]. Ren et al. [146] employed a LES approach with detailed chemistry to investigate the ignition kernel development and highly transient flame evolution for hydrogen jets with storage pressure equal to 200 bar at 80 K. Simulation results provided insights into the transient flame structures for different ignition positions. It was observed that, for ignition locations larger than 1.5 m, the flame would present diffused and premixed combustion around the jet. If the ignited releases are in an enclosure, the pressure peaking phenomenon (PPP) may occur in case of limited ventilation, which could hinder the facility’s structural integrity. The numerical study in Ref. [147] concluded that PPP in an enclosure with vents may be more hazardous for cryogenic hydrogen releases for a given pressure and release nozzle. However, further studies are needed to quantify the PPP hazards in the event of LH2 release in an enclosure.

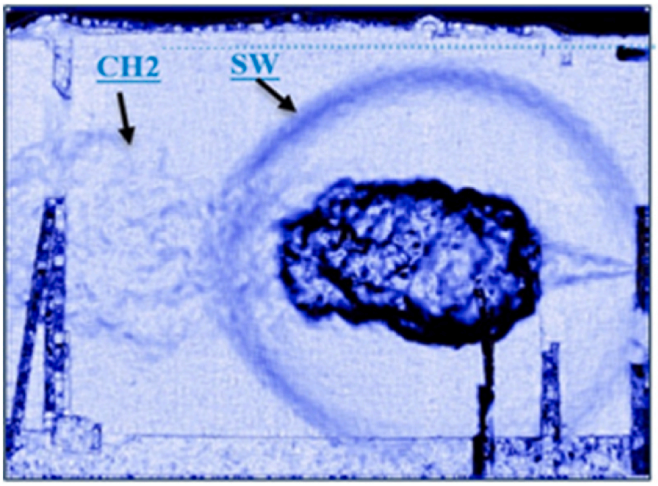


Fig. 4. Shock wave formation established under ignition of hydrogen release (ID = 4 mm; pi = 20 MPa). SW: shock wave; CH2: unignited hydrogen [104].

Regarding combustion over an LH2-spill, large-scale experiments at HSE investigated the effect of differing congestion levels on the combustion properties resulting from LH2 releases [148]. The congestion rig is a steel frame shown in FIG. 6.

According to the results, higher levels of volumetric congestion increase measured overpressures in releases with the same initial conditions. Increasing hydrogen inventory through increased release pressure or a larger nozzle may lead to a larger event upon ignition. However, mixing of the jet also plays a role: some releases through the largest nozzle showed lower overpressures, potentially due to an oversaturated hydrogen cloud. Furthermore, the ambient conditions, particularly wind speed and direction, were significantly influencing the outcome of each ignition. A strong explosion occurred in one of the trials.

A series of tests were performed by DNV [103] at Spadeadam facility as part of the FFI project on LH2 releases in an enclosure aimed at reproducing a Tank Connection Space (TCS) equipped with a ventilation mast. The ignition source was located on the top of the mast. The explosion severity in the TCS was found to depend on the airflow through the TCS by presence of other openings. Authors in Refs. [149,150] proposed a CFD approach to further investigate experiments performed at DNV and simulation results were found to reproduce conservatively experimental overpressure measurements.

5.2.5. *LH2 components response during accident scenarios*

A further relevant incident scenario involving LH2 systems is the catastrophic rupture of the storage tank following a substantial damage of the tank structural integrity or malfunction of the pressure relief device resulting in a boiling liquid expanding vapour explosion (BLEVE). The consequences of the scenario are a powerful blast wave, fireball, and projectiles. In this line, van Wingerden et al. [151] studied the possibility and effects of BLEVEs from a storage vessel containing LH2 when engulfed by fire. Experiments on three double-walled vacuum-insulated vessels engulfed in a propane fire were carried out as part of the SH2IFT program at BAM. All the vessels endured the fire for over an hour, even with the safety relief valve blocked during the tests. This result suggests that there is ample time for evacuation and emergency response if an LH2 vessel is involved in a fire. However, one of the two vessels with MLI insulation failed catastrophically and exploded after surpassing its design burst pressure. This could indicate that perlite is a more effective insulation material for tanks exposed to prolonged fire conditions. Further research is needed to better understand heat transfer within the

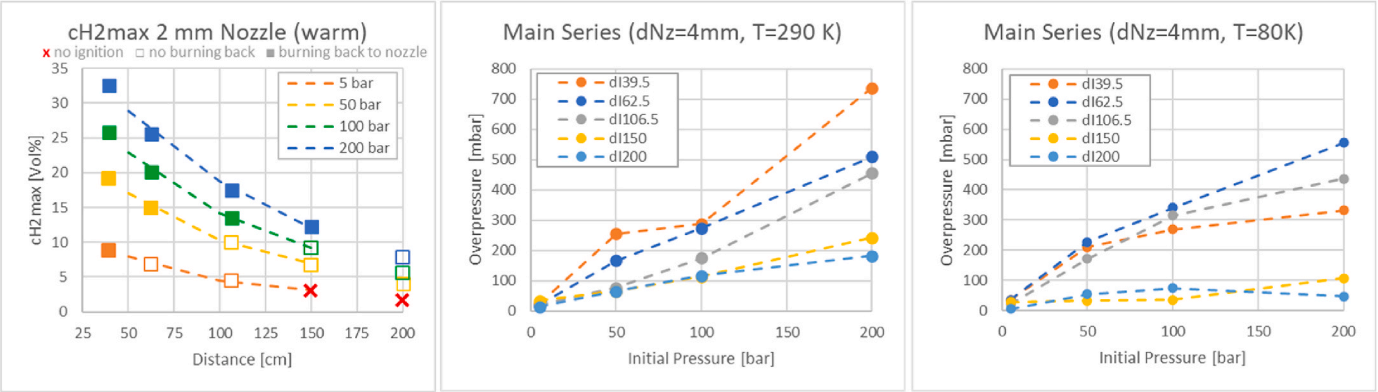


Fig. 5. Left: combination of cH2-measurements (dashed lines) and combustion behavior (symbols). Center and right: examples for maximum measured overpressures in experiments at ambient and cryogenic temperature [104].

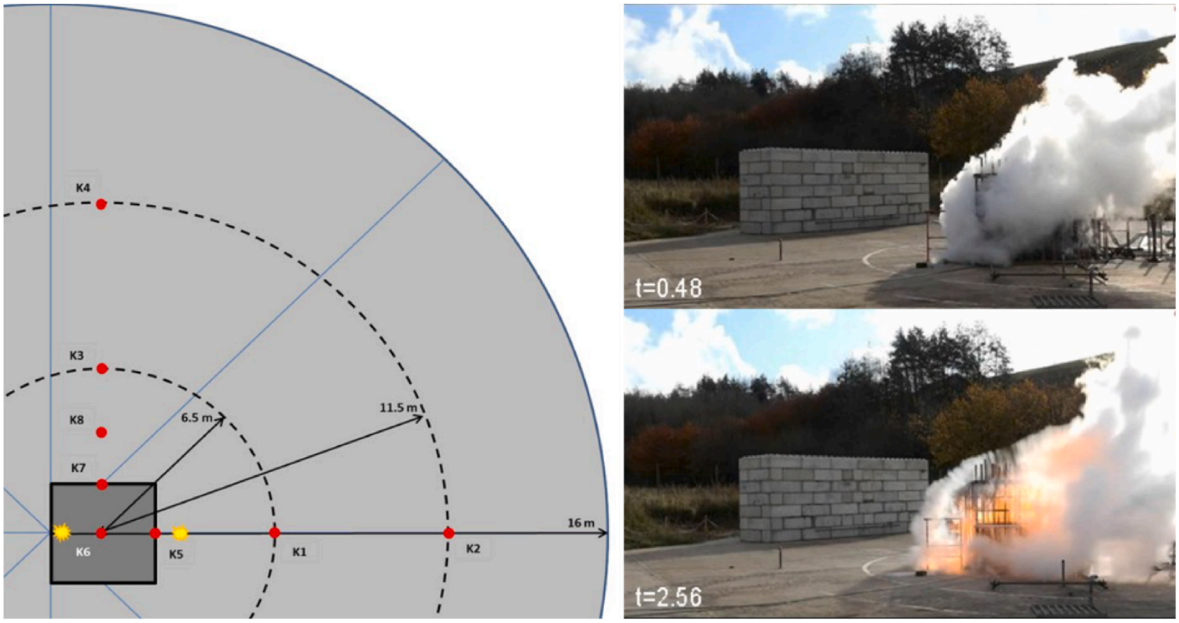


Fig. 6. Sketch of experimental layout (pressure sensors red, ignition positions yellow) and side view of trial 23 before and after ignition. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

LH2 vessel and the resulting pressure build-up, as well as to address issues related to scaling up tank size. Additionally, the performance of insulation, particularly MLI, should be examined more closely to prevent catastrophic vessel rupture. Details on the thermal conductivity of the insulation material and how it changes during fire exposure are critical for simulation model validation.

About this topic, Ustolin et al. [152] performed a thorough analytical and theoretical analysis of all the potential consequences expected from the rupture of an LH2 storage system, validating the proposed models against BMW experiments in Ref. [100]. Makarov et al. [153] presented a conservative reduced tool to estimate the dimension of the fireball produced by the combustion of LH2 spills. Ustolin et al. [154] employed CFD modelling based on a RANS approach to assess BMW experiments [100]. The authors assessed the effect of storage pressure, temperature, and filling degree on the dynamics of the blast wave. The numerical analysis suggested that the maximum blast wave overpressure is fed by both gaseous and liquid phases. Cirrone et al. [155] employed a LES approach to investigate the dynamics of blast waves generated after the catastrophic failure of LH_2 storage tanks in BMW tests [100]. The CFD approach included modelling of combustion, suggesting that the maximum blast wave overpressure is generated by the gaseous phase and that combustion energy gives a significant contribution to the strength of the blast wave. Overall, the underlying phenomena associated with a BLEVE event are not yet fully clarified, and further experimental research complemented by numerical assessments shall be performed to close this relevant knowledge gap.

All the experiments and modelling activities mentioned in Sec. 5 are summarized in Table 7.

6. Research gaps and ongoing projects

In this section, critical research gaps and the currently ongoing projects in the field of LH2 applications are discussed.

6.1. Research gaps

As highlighted in the previous section, some of the existing knowledge gaps in the field of LH2 have already been addressed by past research. However, many aspects still need to be investigated to make the hydrogen economy a feasible reality soon. Among them, critical points are relative to liquid hydrogen storage technologies, safety, and regulations codes and standards (RCS). Regarding the storage of

Table 7

Summary of the most recent experimental and modelling activities on hydrogen dispersion, ignition, combustion and response of lh2 components.

Phenomenon	Project						
	FFI	PRESHLY		SH2IFT		Other	
	Exp.	Exp.	Mod.	Exp.	Mod.	Exp.	Mod.
LH2 release and dispersion outdoor, indoor, and on different substrates	Aneby et al. [103] (LH2 on concrete outdoor and on metal indoor)	Jordan et al. [104] (LH2 on concrete outdoor) Hall et al. [112] (LH2 on concrete outdoor) Friedrich et al. [127] (LH2 on concrete, sand, water, gravel outdoor) Welch and Hooker [141] (LH2 on concrete, sand, water, gravel outdoor)	Cirrone et al. [107] Venetsanos et al. [109] Venetsanos [110] Venetsanos et al. [111] Cirrone et al. [113] Cirrone et al. [118] Venetsanos et al. [119] Giannissi et al. [120] Giannissi et al. [125]	Van Wingerden et al. [135] (LH2 on water outdoor)	Odsæter et al. [136] (LH2 on water outdoor)	Killingsworth [114] Chowdhury and Hect [115] Hecht and Panda [116] Hecht and Chowdhury [117] Friedrich et al. [127] Zhang et al. [137]	Molkov et al. [107] Cirrone et al. [108] Hecht and Venetsanos et al. [121] Giannissi et al. [122] Venetsanos et al. [123] Ichard et al. [124] Venetsanos and Giannissi [121] Hanses [126] Jaekel et al. [128] Jin et al. [129] Liu et al. [130] Jäckel et al. [131] Liu et al. [132] Sun et al. [133] Gitushi et al. [134]
Ignition	Aneby et al. [103]	Veser et al. [105] Welch and Hooker [141] Atkinson [142]	Cirrone et al. [139] Coldrick et al. [119]				Klebanoff et al. [143]
Combustion	Aneby et al. [103]	Jordan et al. [104] Jordan and Kuznetsov [148]	Cirrone et al. [108] Cirrone et al. [144] Cirrone et al. [145] Ren et al. [146] Cirrone et al. [147]				Hanses and Hansen [149] Hanses and Hansen [150]
LH2 components response during accident scenarios			Cirrone et al. [155]	Wingerden et al. [151]	Ustolin et al. [152] Ustolin et al. [154]		Makarov et al. [153]

cryogenic and liquid hydrogen, the main challenges concern the design of technological solutions suitable for different types of applications on different scales (e.g., storage tanks for road vehicles, ships, and aircraft) and the development of efficient insulation systems for the minimization of fuel and energy losses caused by the liquid boil-off. About safety, the work done during the PRESLHY project paved the way for a better understanding of the phenomena involved in hydrogen dispersion, ignition, and combustion. Nevertheless, as mentioned above, their full comprehension requires further studies and experiments. Finally, in parallel with these points, filling the current regulatory gap is urgent. The summary of available standards applicable to LH2 technologies provided in Section 4 shows that many standards were created for the design of equipment (e.g. storage tank and its accessories), even though many of them do not specifically address only LH2. On the other hand, it was shown that there is a wide gap in international standards focused on the operation of liquid hydrogen technologies. In the case of transferring technologies, only two standards were found. These documents do not provide detailed information on the transfer procedure but barely a few generic indications about the different phases of the transfer (namely, grounding, visual inspection, purging, cooling down, transfer, warming up, and venting). This is a relevant barrier hampering the permeation of LH2 in the hydrogen economy and the global market. Thus, a new and specific normative framework covering all the aspects of LH2 usage must be provided. At present, several ongoing research projects, described in detail in the following section, are focused on these topics.

6.2. *Ongoing projects*

Many projects have been launched to promote international collaborations among countries with the aim of enhancing the use of LH2 in the global economy. They cover different relevant aspects of the hydrogen value chain, from the storage to the final end-use and the cross-cutting topic of safety. Among them, the Horizon Europe project EVLHYS (Enhancing safety of liquid and vaporized hydrogen transfer technologies in public areas for mobile applications, Project number 101101381) aims at providing indications to enhance the safety of cryogenic hydrogen transfer technologies for mobile applications. The project is the continuation of the previous PRESHLY [156] project (2018–2020), which was focused on pre-normative aspects for the use of LH2 as an energy carrier. In this section, the ongoing research projects that have already established a collaboration with the ELVHYS project are briefly described (see Fig. 7).

They are presented according to their topic, following the logical order of the hydrogen value chain: first, the ones related to liquid

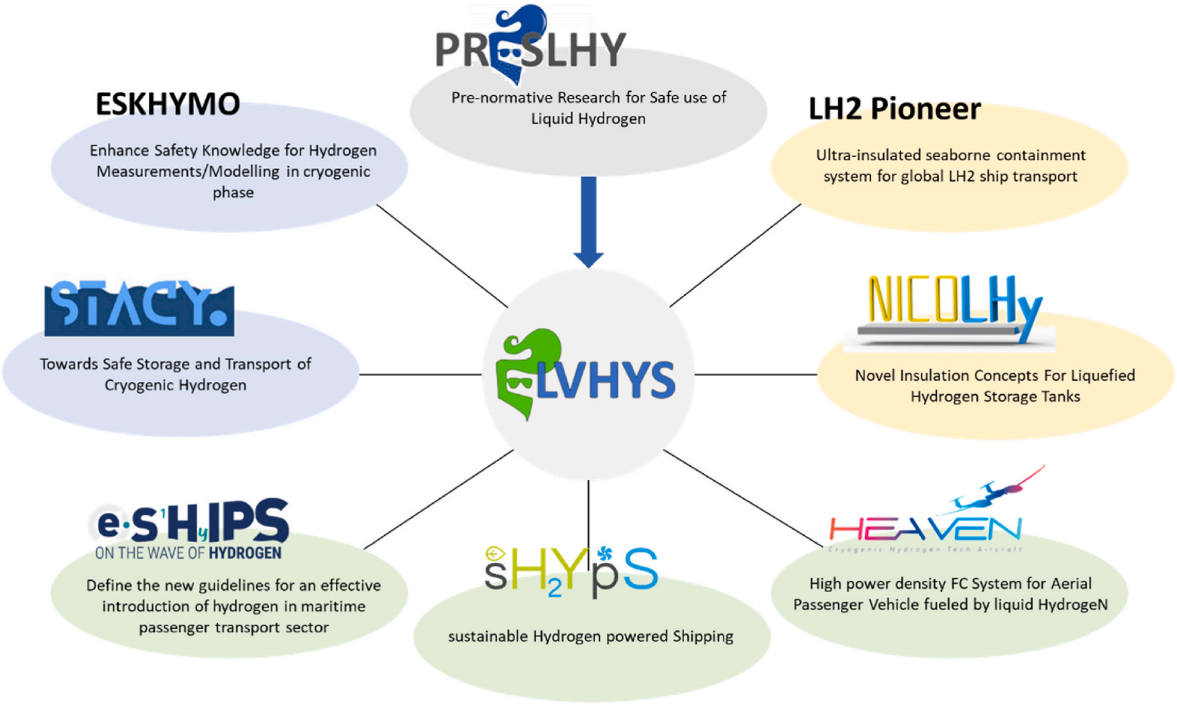


Fig. 7. International projects in partnership with the elvhys project.

hydrogen storage technologies (yellow boxes in Fig. 7) and then the ones related to LH2 applications (green boxes in 7), considering the same order as in Sec. 4. Finally, projects that address liquid hydrogen safety (blue boxes in Fig. 7), are discussed. Within the same topic, the presentation follows chronological order.

Clearly enough, storage and transportation are vital for deploying the hydrogen economy. At present, two projects are focused on developing cryogenic storage solutions, specifically for LH2 large-scale applications. The first is the Norwegian project LH2 Pioneer [157] (Ultra-insulated seaborne containment system for global LH2 ship transport) that started in 2021. The four-year project aims at producing an innovative conceptual design for hydrogen storage systems for large-scale applications (40–45,000 m^3 per tank) with a target boil-off rate of 0.1% per day and reach TRL 2–3 (analytical validation). Furthermore, the design of other key systems, such as the propulsion and boil-off management systems, will also be addressed to find the best techno-economical solutions. The second and more recent project (2024–2026) is the Horizon Europe one NICOLHy [158] (Novel Insulation Concepts For Liquefied Hydrogen Storage Tanks, Project number 101137629). Its goal is to develop innovative insulation concepts for the storage of large LH2 quantities (from 40,000 to 200,000 m^3) to be tested on a laboratory scale in normal operation and fire scenario conditions and to assess of their sustainability and scalability.

Different projects are now focused on the transportation sector, which is recognized as one of the most impactful on climate change. In 2019, the Horizon Europe project HEAVEN [44] (High power density FC System for Aerial Passenger Vehicle fuelled by liquid Hydrogen, Grant Agreement No 826247) project was launched with the ambition of producing the first aircraft powertrain based on high-density fuel cell system and LH2 and integrating it into existing 2–4 seat aircraft. The project ended in 2023 by demonstrating the safe utilization of LH2 storage technology for aeronautical applications through a demonstration flight.

As mentioned in Sec.4.4, in the maritime sector, a significant achievement was reached in 2021 when the LH2-powered ferry MF Hydra was put into operation. However, many aspects related to the use of LH2 as fuel for sea transport still need to be investigated. This is the purpose of the Horizon Europe projects e-SHyIPS [159] and the sHYpS [160]. The e-SHyIPS (Define the new guidelines for an effective introduction of hydrogen in maritime passenger transport sector, Project number 101007226) project (2021–2024) aims to fill the existing lack of normative framework for hydrogen-based fuels passenger ships by providing new regulations for the use of hydrogen and hydrogen-based alternative fuels for waterborne transport. This will be achieved through the definition of a pre-standardized plan for the sections of the IGF Code for hydrogen-based fuels for passenger ships, the implementation of international standards and RCS, the creation of a roadmap to promote the hydrogen economy in the maritime sector and the development of tools to support the safe ship design and management. The sHYpS (sustainable Hydrogen powered Shipping, Project number 101056940) project has the purpose to upgrade the containers technology and build a new hydrogen-based swappable storage solution based on the new c-type ISO containers and suitable for multiple type of vessels. Started in 2022 and with an expected end of 2026, the project will develop the first hydrogen storage intermodal cryogenic 40′ ISO c-type container and detailed guidelines for the design of modular containerised powertrain based on optimized PEM fuel cells, as well as the relative logistics. The proposed storage technology will be demonstrated on one Viking's fjord cruise vessel, and a new concept extendable to freights will be prepared.

A fundamental aspect of interest for the entire hydrogen value chain is safety. In fact, the adoption of hydrogen technologies must rely on the assessment of hydrogen safety, whose advancement should coincide with the technological one. The safety assessment of cryogenic hydrogen application is addressed by two projects, namely ESKHYMO [161] and STACY [162]. The ESKHYMO (Enhance Safety Knowledge for Hydrogen Measurements/Modelling in cryogenic phase) project runs from 2022 to 2026. It has the goal of investigating two safety-critical scenarios: the ingress of air after the rupture of the insulation casing of an LH2 cryogenic tank and the dispersion and ignition following a liquid leak. Small-scale tests will be carried out to build the bases for the scale-up of trials required for the extensive deployment of cryogenic storage technologies. The STACY (Towards Safe Storage and Transport of Cryogenic Hydrogen) project, launched in 2022, aims at assessing the safety of large-scale LH2 storage and transport technologies. The scope of the safety assessment includes the experimental determination of fundamental combustion parameters (i.e., flammability domain, laminar flame speed and expansion ratio) for low temperature hydrogen (from −50° to −100 °C), the development and qualification of catalyst able to prevent the formation of flammable hydrogen mixtures and the application of well-known numerical models to verify the efficiency of mitigation measures.

7. Conclusions

An extensive review of the status of LH2 transfer technologies and safety consideration for mobile applications was conducted in this study. An increasing interest of industries and government towards hydrogen-fuelled transports emerged from the review of the most recent LH2 applications in the transportation sector. A significant lack of standardization for LH2 technologies was highlighted, especially for safety-critical operations, such as the LH2 transfer from tanks in mobile applications in public areas. In fact, only in two of the standards currently available the LH2 transferring operations are mentioned. Moreover, they do not provide detailed information on the procedures, yet only generic indications about the different phases of the transfer process. Previous experimental campaigns investigated the fundamental phenomena of typical accident scenarios: release and dispersion, ignition, and combustion. Predictive models for assessing incident consequences were developed and validated with experimental results. Even if the findings allowed for a better understanding of the safety issues associated with LH2 handling and storage, significant challenges highlighted in this work need to be addressed. Several international research projects are currently addressing these challenges, covering various aspects of the hydrogen value chain, from storage to end-use, along with cross-cutting topics like safety and pre-normative research. In particular, the Horizon Europe project EVLHYS aims to enhance the safety of cryogenic hydrogen transfer technologies for mobile applications. This project will provide a better understanding of LH2 transferring operations to facilitate the development of new standards and foster the market penetration of LH2 in the global economy.

CRediT authorship contribution statement

A. Schiaroli: Writing – review & editing, Writing – original draft, Visualization. **L. Claussner:** Writing – review & editing, Writing – original draft. **A. Campari:** Writing – review & editing. **D. Cirrone:** Writing – review & editing, Writing – original draft. **B. Linseisen:** Writing – review & editing, Writing – original draft. **A. Friedrich:** Writing – review & editing, Writing – original draft. **E.L. Torres de Ritter:** Writing – review & editing, Writing – original draft. **M. Kuznetsov:** Writing – review & editing, Writing – original draft. **F. Ustolin:** Writing – review & editing, Visualization, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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