ENHANCING SAFETY OF LIQUID AND VAPORISED HYDROGEN TRANSFER TECHNOLOGIES IN PUBLIC AREAS FOR MOBILE APPLICATIONS

Ustolin, F.[1], Cirrone, D.[2], Molkov, V.[2], Makarov, D.[2], Venetsanos, A.[3], Giannissi, S.[3], Scarponi G. E.[4], Tugnoli, A.[4], Salzano, E.[4], Cozzani, V.[4], Lindner, D.[5], Gobereit, B.[5], Linseisen, B.[5], Hawksworth, S.[6], Jordan, T.[7], Kuznetsov, M.[7], Jallais, S.[8] and Aneziris, O.[9]
[1] Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology NTNU, Richard Birkelands vei 2B, Trondheim, 7031, Norway, federico.ustolin@ntnu.no
[2] Hydrogen Safety Engineering and Research Centre (HySAFER), Ulster University, Newtownabbey, BT37 0QB, UK
[3] Environmental Research Laboratory, National Centre for Scientific Research Demokritos, Aghia Paraskevi, Attikis, 15341, Greece
[4] Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, via Terracini 28, Bologna, 40131, Italy
[5] Institute of Space Propulsion, DLR-German Aerospace Center Lampoldshausen, Im Langen Grund, Hardthausen am Kocher, 74239, Germany
[6] Health and Safety Executive, Harpur Hill, Buxton, SK17 9JN, UK
[7] Karlsruhe Institute of Technology, Eggenstein-Leopoldshafen, 76344, Germany
[8] Air Liquide Innovation Campus, Jouy en Josas, Paris, 78354, France
[9] Systems Reliability and Industrial Safety Laboratory, National Centre for Scientific Research Demokritos, Aghia Paraskevi, Attikis, 15341, Greece

ABSTRACT

International standards related to cryogenic hydrogen transferring technologies for mobile applications (filling of trucks, ships, stationary tanks) are missing, and there is lack of experience. The European project ELVHYS (Enhancing safety of liquid and vaporized hydrogen transfer technologies in public areas for mobile applications) aims to provide indications on inherently safer and efficient cryogenic hydrogen technologies and protocols in mobile applications by proposing innovative safety strategies which are the results of a detailed risk analysis. This is carried out by applying an inter-disciplinary approach to study both the cryogenic hydrogen transferring procedures and the phenomena that may arise from the loss of containment of a piece of equipment containing hydrogen. ELVHYS will provide critical inputs for the development of international standards by creating inherently safer and optimized procedures and guidelines for cryogenic hydrogen transferring technologies, thus increasing their safety level and efficiency. The aim of this paper is twofold: present the state of the art of liquid hydrogen transfer technologies by focusing on previous research projects such as PRESLHY, and introduce the objectives and methods planned in the new EU project ELVHYS.

1.0 INTRODUCTION

Liquid hydrogen (LH2) will be needed in the near future due to the increase in hydrogen utilization as energy carrier in several new applications. The aim of this study is twofold: to provide a brief state of the art of cryogenic and liquid hydrogen technologies and present the new Horizon Europe project ELVHYS in which safety and efficiency of liquid and cryogenic hydrogen transfer technologies will be investigated. The state of the art provided in this study includes LH2 and cryogenic storage, with focus on insulation and boil-off gas formation, LH2 equipment and safety devices, LH2 delivery, mobile applications, and standards. Therefore, the focus is placed on safety issues for LH2 technologies, and the presentations of the key points of the EU project ELVHYS: objectives, expertise in the consortium, and planned activities. It is critical to gain a broad overview on LH2 technologies in order to enhance their safety and efficiency, main objective of ELVHYS.

2.0 STATE OF THE ART OF LIQUID HYDROGEN TECHNOLOGIES

The state of the art of liquid hydrogen technologies developed for transport sector is provided in this section. The LH2 and cryogenic hydrogen storage tanks and their components and safety devices are described in Sec. 2.1, 2.2 respectively. The focus is then placed on LH2 delivery (Sec. 2.3) and applications including aerospace, aviation, automotive, maritime, and railway sectors (Sec. 2.4). Finally, the existing standards for LH2 technologies are reported by emphasizing the transfer procedure in Sec. 2.5.

2.1 LH2 and cryogenic hydrogen storage

Liquid hydrogen rapidly evaporates when in contact with the atmosphere due to its ultra-low boiling point (-253 °C) at atmospheric pressure. LH2 is stored in extremely well thermally insulated containers composed by two tanks (double-walled) separated by a space (vacuum jacket) kept at a very low pressure (order of mPa) to reduce the convective heat transfer. Conductive and radiative heat transfers from the atmosphere to the tank lading are reduced by the insulation installed in the vacuum jacket. Different types of insulation can be used [1]: expanded closed-cell foams, gas-filled powders and fibrous materials, aerogel insulation, evacuated powders and fibrous materials, opacified powder insulations, microsphere insulation, multi-layer insulations (MLI). The most common used insultation types are perlite powder and MLI [2]. MLI is composed by many thin layers of highly reflecting foil (e.g. aluminum, copper foil) alternated with a low-conductivity spacer (e.g. fiberglass paper, Dacron fabric, or silk net) [1]. The number of layers must be optimized depending on the desired insulation degree and the space and weight requirements onboard of vehicles. This is estimated for each tank during the design phase. Lately, NASA demonstrated that one of the best options for large-scale storage tank insulation is glass bubbles [3]. Additionally, vapor cooled shields (VCSs) can be installed in the vacuum jacket of the tank to keep the insulation cooled. VCSs are coils of pipes where the cool boil-off gas (BOG) flows before using it in fuel cells, internal combustion engines or being vented [2]. LH2 tanks usually have either cylindrical or spherical shape to reduce the surface to volume ratio, thus limit the heat losses and lower the BOG rate. Therefore, LH2 evaporation rate in the tank varies depending on the shape and size of the tank, and the insulation type. Moreover, hydrogen is converted from normal hydrogen (75% of ortho- and 25% of parahydrogen [4]) to 100% para-hydrogen in order to reduce the BOG rate during the liquefaction process. Usually, the BOG rate is lower than 1.5% in volume per day [5]. Despite the BOG rate for LH2 storage tanks seems reasonable, the whole boil-off losses along the LH2 value chain phases (tank depressurization, transfer) are quite larger. Petitpas [6] estimated that 15% of LH2 is lost as BOG for a 100 kg/day delivery, while only 2% for stations with a capacity of 1,800 kg/day that use a Linde LH2 cryo-pump at a pressure level of 875 bar.

One of the largest LH2 tanks was constructed by NASA in the 1960s and has a volume of 3,800 m^3, insulated with perlite powder under vacuum conditions, and it is currently located at NASA Kennedy Space Center [2]. Recently, NASA developed a new technology to avoid BOG formation, hence hydrogen venting from the tank [7]. This technology employs cryogenic refrigeration units to keep the temperature close to the LH2 one. This method is called Integrated Refrigeration and Storage (IRAS) and is installed in the new LH2 tank commissioned by NASA [8]. This tank claims to be the largest ever built with a volume of 1,250,000 gal (4,730 m^3) and is insulated with glass bubbles instead of perlite [9]. Although electricity is required to operate the IRAS system, it was estimated that 0.15$ is spent to avoid the venting of hydrogen that would have the value of 1.00$ [8]. The focus in this study is mainly placed on LH2 technologies in which cryogenic hydrogen can still be present due to evaporation but the pressure level is below 10 bar during normal operations. Therefore, other storage solutions such as cryo-compressed tanks are out of the scope of this analysis. Specific materials suitable for both hydrogen and cryogenic applications are necessary to build LH2 tanks and its components. The main requirements are the adaptability of materials in a LH2 environment, resistance to hydrogen embrittlement, mechanical properties, and thermophysical properties at cryogenic temperatures [10]. Additionally, the wide range of conditions that can manifest in the different LH2 applications such as maritime, aerospace, automotive, or stationary (see Sec. 2.5) affects the requirements for container materials [11].

2.2 LH2 equipment and safety devices

LH2 storage systems are complex and made of several components beyond the tank itself. When hydrogen is stored and delivered, substantial equipment is needed to move or contain it. Valves, joints, welding, gaskets, compensators (for thermal contraction), safety devices, insulation, instrumentation, and support structure. Rods or hooks are needed to keep the inner tank suspended inside the outer vessel for double-walled LH2 tanks [2]. LH2 pumps may be employed both to fill the LH2 tank and to compress hydrogen from 3 bar at 24.6 K (liquid) up to 875 bar at 30-60 K (gaseous phase) [6]. Finally, heat exchangers are equipment required in some systems where LH2 is used as a fuel. For instance, fuel cells must be supplied with gaseous hydrogen close to atmospheric temperature.

To ensure a safe operation of LH2 storage tanks and their components, many safety devices are required. One of the most important equipment that can be frequently activated to keep the tank pressure below a safety threshold is the pressure relief valve (PRV). This is a common safety device present on all vessels containing liquefied gases and it can be set at different levels depending on the substance and its thermodynamic properties (e.g. boiling and critical points). In case of LH2 tanks, the PRV can be set between 7 and 10 bar [5]. Moreover, more than one PRV can be installed to be redundant and enhance the reliability of the system. Caution must be exercised on PRV by firefighters when intervening on LH2 storage in case of emergency (e.g. fire). For instance, PRVs cannot be sprayed with water while cooling down the tank or extinguishing fires because this can cause freezing of water onto the PRV and as a result clog it. This event can provoke the rupture of the LH2 tank with a subsequent explosion as it has already happened in the past [12].

However, sprinklers are currently used to spray LH2 large-scale tanks in case of fire and keep the outer structure cooled. Sprinklers can also prevent the collapse of supporting structure and eventually extinguish the fire in the vicinity of the tank [13]. Another device that is critical during the transfer operations such as filling of vehicle tanks and bunkering is the emergency release system (ERS). ERS allows to suddenly stop the transfer procedure by detaching the hose from the tank filling system, hence blocking the LH2 flow. ERS had been designed for liquefied natural gas (LNG) technologies, especially for bunkering operations and must be implemented in LH2 transfer technologies as well. Finally, emergency shutdown valves (ESVs) also called automatic shut-off valves are activated to stop the tank filling in case a sensor (e.g. H2 concentration) is triggered due to a LH2 release.

2.3 Liquid hydrogen delivery

LH2 must be delivered from the production site to the end users, and this can be done through pipelines, trucks, trains, ships, or barges [2]. Pipelines are the only way to continuously transport LH2. LH2 pipelines should be built similarly to cryogenic tanks, i.e. double-walled with vacuum insulation to limit the BOG formation. Moreover, mechanical deformations must be allowed due to thermal expansion and contraction. Appropriate material must be selected for the pipes, gaskets and sealings. Currently, the longest LH2 pipeline has a length of 500 m and is installed at the NASA Kennedy Space Center in Florida [2]. Currently, vehicles employed to transport LH2 (e.g. trucks) are usually fuelled by other fuels (e.g. diesel) but could potentially be powered by hydrogen. LH2 is delivered by means of road tanker, contained in the double-walled tank. As mentioned before, the BOG formation is the main drawback of this storage method and may impede long distance shipments. During railway transport, hydrogen can be in liquid phase in order to increase the delivery amount. This transport method is not widely used due to a lack of LH2 tank cars availability and railway time scheduling is a factor that can increase the BOG formation [14]. Finally, maritime transport is relatively suited for large quantities of hydrogen for long distances. The CO2-free Hydrogen Energy Supply-chain Technology Research Association Commences (HySTRA) project, established by four Japanese companies, aimed to demonstrate the marine transport feasibility of large amounts of LH2 [15]. The only LH2 ship currently in operation is the Suiso Frontier that was designed and built during the HySTRA project. This is an LH2 carrier with an LH2 storage capacity of 1250 m^3 [16]. The ship delivered its first LH2 cargo on 25 February 2022 at the Port of Kobe (Japan) after being loaded in Australia and covering the 9000-km journey to Japan [17].

2.4 Liquid hydrogen mobile applications

Most of the knowledge on LH2 technologies was gathered during the 1960s in different aerospace mission programmes. The focus was placed on the storage and utilization of LH2 and liquid oxygen (LOX) as propellant on rockets and spaceships. An extensive review on the utilization of LH2 as a fuel in the transport sector including aerospace, aviation, automotive, railway and maritime can be found in [11]. It is worth noting that many new projects came to light in the last decade. For instance, the first LH2 ferry, MF Hydra was built and tested in Norway by Norled company and will be in operation in 2023 [18]. In the same year, Daimler should commercialize the first LH2 heavy duty truck. By 2021, the Korea Railroad Research Institute and Hyundai Rotem were implementing the core technology of the world's first LH2-based locomotive [19]. The aim of this project is to develop an LH2-fueled train capable of running 1,000 km at a peak speed of 150 km/h with a single load. Finally, Airbus announced in 2020 that the world's first zero-emission commercial aircraft fleet powered by hydrogen should be in operation by 2035 [20]. One of the best options for these applications is to store hydrogen in liquid form onboard.

2.5 Standards

International standards are critical for the deployment of cryogenic hydrogen technologies on a large scale. A few standards were developed for the design of LH2 storage tanks, their components and safety devices. Design, fabrication, inspection, and testing of large transportable cryogenic vacuum-insulated vessels is discussed in Part 1 of the ISO 20421 [21] standard, while Part 2 focusses on the operational requirements [22]. However, this standard gives only few generic indications on the pre- and after-fill checks, and the preparation phases in the filling procedure section. In this section of the document, hydrogen and its related issues are not mentioned. Similar topics are treated in the standard ISO 21009 on static vacuum-insulated cryogenic vessels divided in Part 1 - Design, fabrication, inspection and tests [23] and Part 2 - Operational requirements [24]. On the other hand, indications on the design of smaller tanks (< 1 m^3) are given in ISO 21029 [25, 26] . Finally, the ISO 13985 standard focuses on land vehicle fuel tanks [27].

PRV can be sized by following the Part 3 of the ISO 21013 standard on pressure-relief accessories for cryogenic service [28]. This standard explains how to estimate the heat transfer into the vessel considering the worst-case scenario (fire and loss of vacuum in the insulation). In this fashion, the hydrogen venting from the tank is allowed given an emergency situation. Thermal conductivities for LH2 tank insulations are also provided in the standard. Other standards for cryogenic vessel accessories are as follow:

- ISO 21011 [29]: Valves for cryogenic service
- ISO 21012 [30]: Hoses
- ISO 24490 [31]: Pumps

Other remarkable standards related to cryogenic vessels are ISO 21010 on gas/material compatibility [32], ISO 21028 on toughness requirements for materials at cryogenic temperature [33], ISO 21014 on cryogenic insulation performance [34], and ISO 23208 on cleanliness for cryogenic service [35]. Instead, the insights on the determination of the resistance to cryogenic spillage of insulation material in case of accident are collected in ISO20088 [36]. LH2 is briefly mentioned in the AIGA 087/14 [37] standard in the design criteria section, while the storage, handling and distribution of LH2 is at the basis of the EIGA 06/19 standard [38]. Despite some indications on the transport and distribution as well as LH2 operations, a detailed filling procedure is missing in this standard. This brief summary on international standards demonstrates the lack of knowledge in cryogenic and liquid hydrogen technologies.

3.0 SAFETY ISSUES RELATED TO LH2 TECHNOLOGIES

Many studies investigated the safety aspects related to these technologies, focussing mainly on the consequences of accident scenarios including loss of integrity and containment of LH2 storage equipment. This trend was kept in most of the research projects in the last three decades (e.g. PRESLHY [39]). In this section, the consequences of failure for LH2 and cryogenic hydrogen are described, together with the experiments and the modelling activities performed in order to assess their yield.

3.1 Consequences of failure

Several causes may provoke a loss of containment of LH2 storage or transfer components. The consequences of an LH2 release might be various, from a dispersion to fire or explosion in case of ignition. Some of the consequences are: LH2 or two-phase hydrogen jet, material embrittlement impacted by LH2 jet, pool formation, air component condensation or solidification, dispersion and flammable cloud formation, pressure peaking phenomenon (PPP). In case of ignition, fires (jet fire, pool fire, flash fire) and explosions (vapor cloud explosion (VCE), deflagration to detonation transition (DDT), condensed phase explosion (detonation), boiling liquid expanding vapour explosion (BLEVE)) may manifest. Obviously, probabilities of occurrence are quite different for each phenomenon. While leakages can be seen as a more frequent phenomenon for hydrogen technologies, in comparison detonations are rare events. One positive aspect from a safety perspective is that it was demonstrated that the rapid phase transition (RPT) explosion, which is a well-known phenomenon for LNG, is very unlikely when LH2 is spilled onto or into water [40].

3.2 Experiments and modelling on LH2 consequences

Many experiments where an LH2 release was simulated were carried out in the past. Most likely, the first time that LH2 spill tests were carried out was at the end of the 1950s, as described by Zabetakis and Burgess [41]. Afterward, a few more tests were performed in 1981 by NASA at its White Sands Test Facility in New Mexico [42], in 1994 by Federal Institute for Materials Research and Testing (BAM) in collaboration with the Research Center Juelich in Drachhausen, Germany [43], in 2012 by Health and Safety Laboratory (HSL) at its facility in Buxton, UK [44], in 2019 and 2020 by DNV at Spadeadam facility in UK [45], and in 2021 by BAM at its facility in Horstwalde, Germany [46]. A more detailed description of these LH2 release experiments can be found in [47]. Moreover, additional experiments were recently carried out with cryogenic (gaseous) hydrogen and LH2 during the European project PRESLHY [39]. During these experimental campaigns, different parameters such as release rate, spill duration, nozzle diameter, and surface (e.g., gravel, sand, concrete, water) were considered to comprehend and investigate the consequences of the loss of containment for LH2 technologies.

Different authors attempted to simulate most of the abovementioned phenomena through theoretical and numerical models. These models were, in most cases, validated against the outcomes of various experiments. Most of these studies adopted a computational fluid dynamics (CFD) approach to assess the consequences of LH2 releases. A list of these investigations can be found in [47]. The developed models can be employed for the consequence analysis as part of a risk assessment. On the other hand, engineering correlations were developed for this activity to overcome the limitation of the CFD tools (e.g. requirement for high computational power and highly qualified personnel). A comprehensive database where many critical consequence analysis models were collected and free to use is NET-Tools FCH2 Education e-Laboratory [48].

4.0 ELVHYS PROJECT

The main motivation for the Horizon Europe project ELVHYS (Enhancing safety of liquid and vaporized hydrogen transfer technologies in public areas for mobile applications) is to fulfil the knowledge gap regarding the transferring of cryogenic and liquid hydrogen from tank to tank highlighted in Sec. 2. ELVHYS is a pre-normative research project that aims to contribute to the creation of international standards on LH2 transfer technologies by providing critical insights to the standard development organizations (SDOs). The ELVHYS objectives, expertise in the consortium and planned activities are described in Sec. 4.1, 4.2, 4.3, respectively.

4.1 ELVHYS objectives

Numerous ambitious objectives were established for the ELVHYS project to enhance the safety level and support the development of regulations, codes and standards (RCSs) of hydrogen technologies and applications. The main objectives of the ELVHYS project are as follow:

- Provide a state of the art of LH2 transfer operations and facilities for mobile applications including specific knowledge, international standards, regulatory challenges and barriers, safety strategies, risk analysis methodologies and knowledge gaps
- Identify the hazards and incident scenarios from cryogenic hydrogen transferring operations and derive a list of priorities with related phenomena associated with highest risk scenarios, least knowledge and lack of reference guidelines and standards
- Execute the experimental campaign addressing cryogenic hydrogen transferring operation tests for truck refuelling, ship bunkering, stationary tank filling, and on equipment and materials response to LH2 transfer and incident roots as well as releases, combustion and explosion phenomena experiments
- Develop and validate suitable models for numerical simulations (viz. CFD) and derive appropriate engineering correlations for the LH2 transferring operations, the highlighted phenomena and mitigation concepts, techniques
- Perform qualitative design reviews and quantitative risk analysis, including frequency and consequence assessment, and considering simultaneous operations (SimOps) for cryogenic hydrogen transferring of the selected mobile applications
- Propose innovative safety strategies and engineering solutions for cryogenic hydrogen transfer operations including definition of safety barriers, hazard zoning strategies and separation distances
- Provide detailed description of reliable LH2 transfer equipment, guidelines for design of LH2 transferring facilities and detailed consensual loading/unloading procedures
- Support the international Standards Developing Organisations SDOs, in particular ISO/IEC and CEN/CENELEC, in either updating existing standards or developing new international performance based and risk informed standards

Several research activities are planned to achieve the abovementioned goals (see Sec. 4.3).

4.2 Expertise in the ELVHYS consortium

The ELVHYS project brings together world leading experts from 8 partner organisations from 6 European countries: Germany, Greece, France, Italy, Norway, UK. The consortium's expertise covers all aspects of hydrogen safety in LH2 transfer technologies and systems from transfer modelling and simulations through prevention and mitigation of unscheduled releases, dispersion, fires, explosions and comprehensive risk assessment to pre-normative research underpinning Regulations, Codes and Standards (RCS). Partners represent leading actors from different sectors of European community involved in provisions of hydrogen safety and especially safety of LH2 transfer operations, including LH2 technologies company (Air Liquide, AL) and national aerospace agency DLR, Regulatory Body (Health and Safety, HSE), Research Organisations (National Centre for Scientific Research "Demokritos", NCSRD), and are complemented by a strong cohort of leading Universities in the field (Karlsruhe Institute of Technology, KIT, Norwegian University of Science and Technology, NTNU, University of Bologna, UNIBO, Ulster University, UU) all experienced in both cryogenic liquids transfer technologies and hydrogen safety engineering. Each partner is represented by internationally renowned experts with an impressive track record in hydrogen safety and/or safety of cryogenic systems. A detailed description of each partner is presented in the following.

Norwegian University of Science and Technology (Norway)

Norwegian University of Science and Technology (NTNU) is the largest university by enrolment in Norway. The Reliability Availability Maintenance and Safety (RAMS) research group of the Department of Mechanical and Industrial Engineering has been involved in 10 different research and education projects related to hydrogen technologies. NTNU was one of the partners of the Norwegian project SH2IFT where specific phenomena that might arise from the loss of containment of LH2 storage equipment were investigated experimentally as well as through modelling. More specifically, the feasibility and consequences of physical explosions (RPT during ship bunkering and BLEVE for LH2 tanks exposed to fire) were analysed. The expertise gained in consequence analysis was exploited in the ERA-NET project H2 CoopStorage where methodological tools and software allowing the deployment and management of a multi-energy (electric, heat, hydrogen) energy community integrating hybrid storage (electrochemical and fuel cell) to be able to respond to the storage of daily and seasonal energy needs were developed. NTNU is work package leader on risk-based operational safety of the of the Norwegian project SH2IFT-2, follow-up of SH2IFT, where LH2 releases and jet fires will be investigated both experimentally and numerically. NTNU is working on a similar topic also in the Norwegian Centre for Environment-friendly Energy Research (FME) HYDROGENi, and the new Horizon Europe project H2GLASS in which the employment of hydrogen as fuel for the glass and aluminium industries will be investigated. Hydrogen as fuel for high temperature heating processes in the energy intensive industries is at basis of the Horizon Europe project HyInHeat where the NTNU RAMS group is focussing on the H2 safety training of personnel. NTNU RAMS is also coordinating two critical projects, the SUSHy European-Japanese (EIG CONCERT-Japan) research project for the advancement of sustainable hydrogen technologies, and ELVHYS. Finally, NTNU is partner in two educational projects, the Norwegian research school on hydrogen and ammonia HySchool, and the first international joint master on hydrogen technologies HySET (Erasmus Mundus). These two projects reflect the education activities on hydrogen technologies and safety offered at NTNU.

National Centre for Scientific Research "Demokritos" (Greece)

National Centre for Scientific Research "Demokritos" (NCSRD) is the largest multidisciplinary research center in Greece. Two laboratories of NCSRD collaborate within this project, the Environmental Research Laboratory (EREL) and the System Reliability and Industrial Safety Laboratory (SRISL). EREL has great expertise in hydrogen energy and safety, which is established through a series of European Commission (EC) funded Projects and national projects. It is internationally recognised expert in theoretical and numerical studies of hydrogen safety phenomena, e.g. refuelling/bunkering/transfer, and simulations of incident consequences, including but not limited to scenarios of releases and dispersion outdoors, indoors and in confined spaces, free and indoor jet fires, deflagrations, tank rupture in a fire, etc. Over the years, EREL has developed in-house engineering tools and the CFD code, ADREA-HF, which are extensively validated against a variety of hydrogen applications. Open source CFD codes, like OpenFOAM, and other commercial codes are also available in the NCSRD toolkit. To meet the computational requirements EREL is equipped with an advanced high-performance computer cluster. SRISL has vast experience in risk management and quantitative risk assessment of installations handling hazardous materials, including cryogenic liquids, such as ammonia, LNG etc. SRISL has participated in several EC funded and national projects and its research efforts focus among others on problems addressing the support of decisions concerning risk management, land use planning and emergency response planning of industrial sites handling hazardous substances. SRISL has developed dynamic risk assessment methods for the process industry and has a long experience in risk assessment of industrial installations subject to the "SEVESO" directive.

University of Bologna (Italy)

University of Bologna (UniBO) is represented in the project by the Laboratory for Industrial Safety and Environmental Sustainability (LISES). LISES is a multi-disciplinary team with an internationally recognized expertise in process safety and advanced risk management of energy technologies. LISES managed several international and national research and consultancy projects addressing the safety of innovative energy processes (Super-LNG, WUIVIEW, e-Citijens, etc.). Dynamic hazard identification and risk assessment techniques were developed to address atypical scenarios and complex cascading events. Detailed models were developed and validated addressing combustion scenarios involving hydrogen mixtures. A specific experience was developed on the modelling of the vulnerability of process and storage equipment to external hazard factors as fires and explosions, as well as to natural events (e.g. floods, lightning impact) and intentional acts (e.g. IED, projectiles). Recent research work addressed the safety of cryogenic liquid storage tanks and the prevention of cascading events caused by conventional scenarios or by external factors as natural events and security scenarios [49]. More specifically, CFD models were developed and validated to investigate the behaviour of LNG storage tanks involved in external fires, also addressing the effect of vacuum failure on vessel internal pressure. The results were used to develop surrogate models able to provide specific information on possible hazardous conditions. UniBO plans to build on this experience contribute developing a modelling approach to assess the accident scenarios deriving from the transfer of LH_2 and the possible effects on the integrity of hydrogen transport and storage vessels.

German Aerospace Center (Germany)

The German Aerospace Center (DLR) is a research facility with more than 50 research institutes, which deals, among others, with hydrogen technologies. DLR covers the whole value chain from component development, system and market analysis, simulations, concepts for emission free mobility, and operation of large LH2 facilities. Especially the Institute of Space Propulsion has decades of knowledge in planning, design and erecting of large test facilities for testing rocket propulsion systems at DLR site in Lampoldshausen, Yearly consumption of LH2 in the last years was roughly about 380t. Germany. DLR operates a centralized area with a 55 and a 270 m³ LH2 tank. From the main storages hydrogen is provided to the run tanks of the test benches. Thus, DLR has gained knowledge about safety aspects for design (e.g. HAZOP), LH2 transfers, and also during operation. Since 2013, the Institute started to extend the portfolio, by erecting a 1 MW electrolyser together with ZEAG Energy AG to be able to produce green hydrogen on site, using the nearby wind park. The production capacity will be enhanced by a further electrolyser with about 2 MW peak power. Furthermore, aiming for technology transfer from space to other branches, a Hydrogen Test Center is under construction. In this facility, test positions with media supply will be provided to enable third parties for testing with GH2 and LH2. This unique infrastructure will be used together with HSE and KIT to create a beyond the state-of-the-art LH2 testing facilities.

Karlsruhe Institute of Technology (Germany)

The unique cryogenic hydrogen research infrastructure built in KIT during PRESLHY project has been enhanced further by building a 500-litre LH2 tank (to simulate truck filling) and a 100-litre LH2 tank able to withstand high pressure (60 bar). The HYKA test site is composed by an A2 vessel of 220 m3 volume and can bear an explosion up to 100 g of LH2. The experiments in the A2 vessel can be conducted in either an inert (nitrogen) or oxidizing (air) atmosphere.

Air Liquide - Innovation Campus Paris (France)

Air Liquide has several large-scale liquefiers in operation all over the world and under-development for liquid hydrogen production with an important fleet of liquid trailers for transportation and distribution. In parallel, to bring solution regarding market and needs of on-going trends, Air Liquide is deploying Liquid-to-Gas and Liquid-to-Liquid infrastructure for hydrogen mobility (light and heavy-duty fuel cell vehicles, ships, aircrafts…). Air Liquide developed significant skills in hydrogen risk management thanks to its experience of hydrogen handling and thanks to wide and long-term collaborations with academics, customers and Industry. AL R&D was involved in several pre-normative research projects - on hydrogen safety fundamentals and development of inherently safe equipment - such as PRESLHY, HyResponder, HyTunnel-CS, SH2IFT, MARHySAFE, HYSEA, HyIndoor, DIMITRHy, FireComp, HyPactor…, and brings contributions for the industrialization of hydrogen systems. Thanks to this, AL R&D has an extensive experience of risk assessment on hydrogen products and theoretical and practical problems encountered by the engineers for safety design and hydrogen acceptability. AL is also involved with fire brigades for enabling hydrogen use in public areas. In addition, Air Liquide is a key contributor to the development of Regulations Codes and Standards for gas equipment through direct participation to the relevant CEN and ISO working groups, with leadership roles in the gas industry's professional associations (EIGA in Europe and CGA in North America). In the area of hydrogen technologies, Air Liquide contributes particularly to the activities of ISO/TC 197 and provides input for regulatory developments at the UN and EC levels.

Ulster University (UK)

Ulster University (UU) is represented in the project by the Hydrogen Safety Engineering and Research Centre (HySAFER). HySAFER is an international multi-disciplinary team of researchers and academics with knowledge and expertise accumulated through 37 national and EU projects, e.g. HyTunnel-CS, HyResponder, PRESLHY, etc. The research is focused on closing knowledge gaps and resolving technological bottlenecks in hydrogen safety, including breakthrough safety strategies and innovative engineering solutions, e.g. the safety technology of explosion free in a fire self-venting (TPRD-less) tank. UU's expertise in theoretical and numerical studies spans across all areas relevant to hydrogen safety research: gaseous and liquified hydrogen releases and dispersion, jet fires, deflagrations, detonations and DDT; dynamics of blast wave and fireball after high-pressure hydrogen tank rupture in a fire; safety design of tank-TPRD systems; CFD modelling of mass and heat transfer for entire hydrogen refuelling station; novel safety strategies for hydrogen systems use in confined spaces; original quantitative risk assessment methodology; etc. In PRESLHY project, UU developed and validated predictive CFD models and reduced tools to assess accident consequences and determine hazard zones for LH2 technologies. Among these should be mentioned the reduced and CFD models to simulate hydrogen steady state and transient releases taking into account heat transfer through a tank and discharge pipe walls, models to evaluate MIE by spark ignition in cryogenic H2-air mixtures [50], and assess thermal hazards from hydrogen jet fires [51]. CFD simulations were used to provide insights into the blast wave generated by rupture of LH2 storage tanks in a fire ("BLEVE") [52], the phenomena of spontaneous ignition and pressure peaking in enclosures for cryo-compressed hydrogen. UU intends to exploit these models in ELVHYS, along with development of novel methodologies and mitigation strategies for the incident scenarios associated with cryogenic hydrogen transfer.

Health and Safety Executive (UK)

The Science and Research Centre, part of the Health and Safety Executive (HSE), has been on the 550-acre Buxton site in the United Kingdom for almost 100 years and is the home to a state of art laboratory, which opened in 2005. It has many large-scale external test facilities which include several test facilities for research into LH2 and for GH2 at pressures up to 100 MPa. HSE has undertaken and been part of many major experimental and research programmes over the past 15 years, into the hazards and associated risks of hydrogen use, for industry and government. We have been heavily involved in understanding and communicating the safety aspects of the emerging hydrogen energy technologies and have been instrumental to dissemination activities within the hydrogen community. Our experimental results have been used for Regulations, Codes and Standards (RCS) and computational modelling, to refine existing models and to establish important parameters such as hazard distances. We are a co-founder and a key partner in the International Association of Hydrogen Safety and have been involved in recent EU collaborative projects, HyIndoor and H2FC, providing key experimental input relating to hydrogen safety and storage. In the HYPER and HyApproval projects we played a key role in converting research knowledge into guidance for stationary applications and Hydrogen Refuelling Stations (HRS). HSE published a position paper in 2010 on the hazards of LH2 and has since published several research and conference papers on topics including: modelling of LH2 spills, release of unignited LH2 and ignited releases of LH2. Previous work by HSE, as part of the PRESLHY liquid hydrogen project, allowed us to quantify the physical phenomena in a cryogenic tank following the loss of vacuum and provided fundamental understanding of the kinetics of LH2 evaporation during spillage. The work also provided invaluable data to help predict the size of flammable clouds and the explosion severity, if those clouds were ignited, following a LH2 spill.

4.3 Planned activities in ELVHYS project

ELVHYS has been designed to provide a solid basis for future standardisation and safety regulation and focuses on pre-normative research. Firstly, an extensive state of the art analysis on cryogenic hydrogen transferring technologies will be carried out by highlighting the knowledge gaps and barriers in the existing RCS in public areas for mobile applications. Moreover, the hazards and key incident scenarios for cryogenic hydrogen transferring operations and the existing risk analysis methodologies will be identified. Therefore, a refined research programme on safety of cryogenic hydrogen transfer systems will be provided. The cryogenic hydrogen transferring procedures will be defined through testing and modelling of the systems composed by stationary and mobile (truck and ship) tanks, pipes, hoses, valves, and connections. Already validated models (e.g. engineering tools) will be used to support the design of the experimental setups together with the information provided by the state of the art. The experiments on normal operating procedures of cryogenic hydrogen transferring systems will define optimal process parameters (bulk pressure, temperatures, and mass flowrate), depending on the initial conditions of the giving and receiving tanks. Critical insights on the different steps required for this type of operations (purging, cool down, transfer, venting, warm up) will be produced. The existing models based on heat and mass transfer phenomena will be validated and new models could be developed if needed.

Some of the phenomena that might arise from the loss of containment of cryogenic hydrogen equipment during transferring operations will be studied in ELVHYS. Large part of the project is dedicated to studying unignited and ignited (jet fire) releases and explosions (condensed phase and BLEVE) as result of an accident scenario. Moreover, the resistance of components (e.g. pipes) to fire will be investigated together with the performance of fire protection and insulation materials against cryogenic hydrogen releases (both ignited and unignited). Critical knowledge on innovative safety barriers such as emergency release devices (breakaway) will be shared by industrial partners. Experimental, theoretical and numerical studies are conducted to investigate the consequences of the phenomena mentioned heretofore. An effective and complementary experimental campaign will be organised by exploiting the outputs of previous projects such as PRESLHY and SH2IFT. Models and tools already validated against previous fire and explosion experiments will be employed. Suitable safety indications such as procedures, hazardous zoning strategies and safety barriers can be generated only by fully comprehending the consequences of these phenomena.

A detailed and complete risk analysis on the cryogenic hydrogen transferring operations will be carried out in ELVHYS for the following mobile applications: truck tank filling, ship bunkering, stationary filling. The results from the state of the art on LH2 transfer technologies, the experimental campaign and modelling activities on LH2 transfer procedure and consequences of the loss of containment will be exploited in the risk analysis to tune and adapt existing risk assessment methodologies. Both frequency and consequence analyses will be carried out. A unique study on frequency of failure based on internal databases to aid the frequency analysis will be undertaken. Furthermore, hazard and safety distances will be estimated by accounting for Simultaneous Operations (SimOps). Afterwards, preventive or mitigative risk reducing safety measures will be proposed and their efficiency will be validated. Finally, suitable hazard zoning strategies and separation distances including safety barriers will be suggested. The outcomes of the risk analysis will serve to create recommendations and guidelines on cryogenic hydrogen operations for mobile applications in public areas, thus update the state of the art. All these outputs will assist the development of appropriate international standards.

5.0 CONCLUSIONS

The state of the art of liquid and cryogenic hydrogen technologies was provided in this work. The focus was placed on LH2 storage tanks, their insulation, components, and safety devices. Critical information was given on the BOG rate of this type of systems. A description on the LH2 delivery and mobile applications was reported as part of the state of the art, together with an overview of the available international standards on the design and transfer of LH2. The aim of the state of the art was to highlight the knowledge gap still existent on the LH2 transfer technologies. The Horizon Europe project ELVHYS was presented in this paper by explaining its objectives, expertise in the consortium and planned activities. The main objective of ELVHYS is to fulfil the dearth of knowledge on LH2 transfer technologies, thus enhance their safety and efficiency and aid the deployment of large-scale hydrogen technologies.

ACKNOWLEDGMENTS

This work was undertaken as part of the ELVHYS project No. 101101381 supported by the Clean Hydrogen Partnership and its members. UK participants in Horizon Europe Project ELVHYS are supported by UKRI grant numbers 10063519 (University of Ulster) and 10070592 (Health and Safety Executive). Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Clean Hydrogen Partnership. Neither the European Union nor the Clean Hydrogen Partnership can be held responsible for them.

REFERENCES

1. Barron, R. F., Nellis, G. F., Cryogenic Heat Transfer, 2016, CRC Press, Boca Raton.
2. Peschka, W., Liquid Hydrogen - Fuel of the Future, 1992, Springer-Verlag, Wien.
3. Fesmire J. E., Research and Development History of Glass Bubbles Bulk-Fill Thermal Insulation Systems for Large-Scale Cryogenic Liquid Hydrogen Storage Tanks
4. Edeskuty F, Stewart W., Safety in the Handling of Cryogenic Fluids, 1996, Springer Science +Business Media, LLC, New York.
5. Verfondern, K., Safety Considerations on Liquid Hydrogen, 2008, Forschungszentrum Jülich GmbH: Jülich, Germany.
6. Petitpas, G., Boil-off losses along the LH2 pathway, 2018, Lawrence Livermore National Laboratory, LLNL-TR-750685
7. Notardonato, W.U., Swanger, A.M., Fesmire, J.E., Jumper, K.M., Johnson, W.L., Tomsik, T.M., Zero Boil-off Methods for Large-Scale Liquid Hydrogen Tanks Using Integrated Refrigeration

and Storage, 2017, In Proceedings of the IOP Conference Series: Materials Science and Engineering, Madison, WI, USA, 9–13 July 2017; Institute of Physics Publishing: Bristol, UK, 2017; Volume 278, p. 012012.

8. NASA, Sempsrott, D., Kennedy Plays Critical Role in Large-Scale Liquid Hydrogen Tank Development. Available online: https://www.nasa.gov/feature/kennedy-plays-critical-role-in-large-scale-liquid-hydrogen-tank-development (accessed on 15 March 2023).
9. NASA; Granath, B. Innovative Liquid Hydrogen Storage to Support Space Launch System. Available online: https://www.nasa. gov/feature/innovative-liquid-hydrogen-storage-to-support-space-launch-system (accessed on 15 March 2023).
10. Ustolin, F., Paltrinieri, N., Berto, F., Loss of Integrity of Hydrogen Technologies: A Critical Review. Int. J. Hydrogen Energy, 45, 2020, 23809–23840.
11. Ustolin, F., Campari, A., Taccani, R., An Extensive Review of Liquid Hydrogen in Transportation with Focus on the Maritime Sector. Journal of Marine Science and Engineering, 10, 2022, 1222.
12. Ustolin, F., Song, G., Paltrinieri, N., The influence of H2 safety research on relevant risk assessment. Chemical Engineering Transactions, 74, 2019, 1393–1398.
13. Sakamoto, J., Nakayama, J., Nakarai, T., Kasai, N., Shibutani, T., Miyake, A., Effect of gasoline pool fire on liquid hydrogen storage tank in hybrid hydrogen–gasoline fueling station, Int J Hydrogen Energy, 41, 3, 2016, 2096–2104.
14. Melaina, M., Penev, M., Heimiller, D., Resource Assessment for Hydrogen Production, Hydrogen Production Potential from Fossil and Renewable Energy Resources, 2013, NREL/TP- 5400-55626.
15. HySTRA, CO2 Free Hydrogen Energy Supply Chain Technology Research Association, https://www.hystra.or.jp/en/ (accessed on 16 March 2023).
16. Kawasaki Heavy Industries Ltd, World’s First Liquefied Hydrogen Carrier Suiso Frontier Launches Building an International Hydrogen Energy Supply Chain Aimed at Carbon-Free Society, https://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20191211_3487&wovn=it (accessed on 16 March 2023).
17. HySTRA, “Suiso Frontier” Loaded Liquefied Hydrogen Derived from Australian Brown Coal Returns to Kobe, https://www.hystra.or.jp/en/gallery/article.html (accessed on 16 March 2023).
18. LMG Marin, MF HYDRA, https://www.lmgmarin.no/references/485/hydra (accessed on16 Marc 2023).
19. Hyundai Rotem Company. Why Is Hydrogen Energy the Future of Trains? https://tech.hyundai-rotem.com/en/green/why-is-hydrogen-energy-the-future-of-trains/ (accessed on 16 March 2023).
20. Airbus. Airbus Reveals New Zero-Emission Concept Aircraft. https://www.airbus.com/en/newsroom/press-releases/2020-09-airbus-reveals-new-zero-emission-concept-aircraft (accessed on 16 March 2023).
21. ISO, Cryogenic vessels — Large transportable vacuum-insulated vessels — Part 1: Design, fabrication, inspection and tests, ISO20421-1:2019.
22. ISO, Cryogenic vessels — Large transportable vacuum-insulated vessels — Part 2: Operational requirements, ISO20421-2:2019.
23. ISO, Cryogenic vessels — Static vacuum insulated vessels — Part 1: Design, fabrication, inspection and tests, ISO21009-1:2022
24. ISO, Cryogenic vessels — Static vacuum insulated vessels — Part 2: Operational requirements, ISO21009-2:2015
25. ISO, Cryogenic vessels — Transportable vacuum insulated vessels of not more than 1 000 litres volume — Part 1: Design, fabrication, inspection and tests, ISO21029-1:2018
26. ISO, Cryogenic vessels — Transportable vacuum insulated vessels of not more than 1 000 litres volume — Part 2: Operational requirements, ISO21029-2:2015
27. ISO, Liquid hydrogen — Land vehicle fuel tanks, ISO13985:2006.
28. ISO, Cryogenic vessels — Pressure-relief accessories for cryogenic service — Part 3: Sizing and capacity determination, ISO21013, 2016.

29. ISO, Cryogenic vessels — Valves for cryogenic service, ISO21011:2008.
30. ISO, Cryogenic vessels — Hoses, ISO21012:2018.
31. ISO, Cryogenic vessels — Pumps for cryogenic service, ISO24490:2016.
32. ISO, Cryogenic vessels — Gas/material compatibility, ISO21010:2017.
33. ISO, Cryogenic vessels — Toughness requirements for materials at cryogenic temperature — Part 1: Temperatures below -80 degrees C, ISO21028:2016.
34. ISO, Cryogenic vessels — Cryogenic insulation performance, ISO21014:2019.
35. ISO, Cryogenic vessels — Cleanliness for cryogenic service, ISO23208:2005.
36. ISO, Determination of the resistance to cryogenic spillage of insulation material — Part 1: Liquid phases, ISO20088-1:2016.
37. AIGA, 087/14, Standard for Hydrogen Piping Systems at User Locations, AIGA, 087/14.
38. EIGA, Safety in Storage, Handling and Distribution of Liquid Hydrogen, EIGA 06/19, 2019.
39. PRESLHY, FCH 2 JU project "Pre-normative research for safe use of liquid hydrogen", ID: 779613, 2018-2021. https://preslhy.eu/
40. Ødegård, A., D5.4: SH2IFT final project report
41. Zabetakis, M. G., Burgess, D. S., Research on the hazards associated with the production and handling of liquid hydrogen, US Department of the Interior, Bureau of Mines, 1961, Vol. 5707.
42. Witcofski, R. D., Chirivella, J., Experimental and analytical analyses of the mechanisms governing the dispersion of flammable clouds formed by liquid hydrogen spills, Int J Hydrogen Energy, 9, 5, 1984, 425–435.
43. Schmidtchen, U., Marinescu-Pasoi, L., Verfondern, K., Nickel, V., Sturm, B., Dienhart, B., Simulation of accidental spills of cryogenic hydrogen in a residential area, Cryogenics, 34, 1994, 401–404
44. Hall, J. E., Hooker, P., Willoughby, D., Ignited releases of liquid hydrogen: Safety considerations of thermal and overpressure effects, Int J Hydrogen Energy, 39, 35, 2014, 20547–20553.
45. J. Aaneby, T. Gjesdal, Ø. A. Voie, Large scale leakage of liquid hydrogen (lh2)–tests related to bunkering and maritime use of liquid hydrogen, Tech. rep., Forsvarets forskningsinstitutt (FFI) Norwegian Defence Research Establishment 2021.
46. van Wingerden, K., Kluge, M., Habib, A. K., Skarsvåg, H. L., Ustolin, F., Paltrinieri, N., Odsæter, L. H., Experimental investigation into the consequences of release of liquified hydrogen onto and under water, Chemical Engineering Transactions, 90, 2022, 541–546.
47. Ustolin, F., Asholt, H.Ø., Zdravistch, F., Niemi, R., Paltrinieri, N., Computational fluid dynamics modelling of liquid hydrogen release and dispersion in gas refuelling stations, Chemical Engineering Transactions, 86, 2021, 223–228.
48. FCH2 Education, e-laboratory, https://elab-prod.iket.kit.edu/ (accessed on 16 March 2023).
49. Iannaccone, T., Scarponi, G. E., Landucci, G., Cozzani, V., Numerical simulation of LNG tanks exposed to fire, Process Safety and Environmental Protection, 149, 2021, 735-749.
50. Cirrone, D., Makarov, D., Proust, C., Molkov, V., Minimum ignition energy of hydrogen-air mixtures at ambient and cryogenic temperatures, Int J Hydrogen Energy 2023, 1–15.
51. Cirrone, D., Makarov, D., Kuznetsov, M., Friedrich, A., Molkov, V., Effect of heat transfer through the release pipe on simulations of cryogenic hydrogen jet fires and hazard distances, Int J Hydrogen Energy, 47, 2022, 21596–611.
52. Cirrone, D., Makarov, D., Molkov, V., Rethinking "BLEVE explosion" after liquid hydrogen storage tank rupture in a fire, Int J Hydrogen Energy, 48, 2023, 8716–30.