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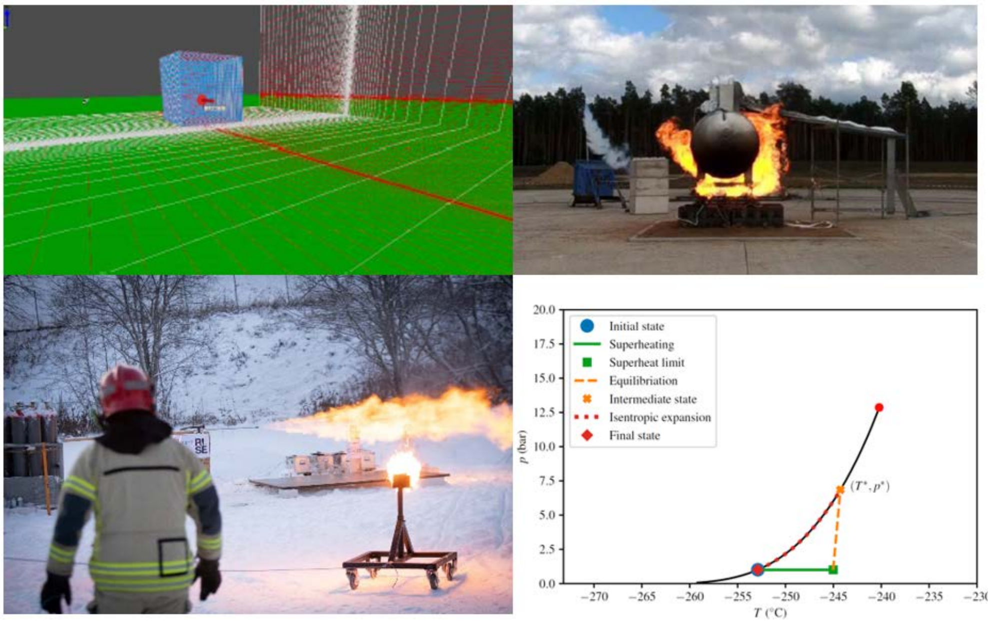
Report

D5.4: SH2IFT final project report



Safe H2 Fuel Handling and Use for Efficient Implementation – SH2IFT
2022-12-13

Report

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ABSTRACT

This report summarizes the findings of the KSP SH2IFT project, funded by the Research Council of Norway, several industry partners and Norwegian counties. The project has investigated several issues related to hydrogen safety and closed important knowledge gaps. Phenomena such as rapid phase transition (RPT) and boiling liquid expanding vapour explosion (BLEVE) are known safety hazards when it comes to handling of liquified gases, e.g., liquefied natural gas (LNG). These phenomena have been investigated both experimentally and by modelling for liquid hydrogen (LH2) in the SH2IFT project. RPT as a consequence of LH2 spills onto or into water is *not* found to be a major issue. Of three BLEVE tests performed with 1 cubic meter LH2 tanks exposed to an external fire, one failed catastrophically, with all tanks withstanding the exposure for at least one hour despite blocked safety valves. The time it took for the tank to rupture at pressures highly above the design pressure would be sufficient to evacuate the premises safely. Two other tanks did not experience this catastrophic rupture. Gaseous hydrogen jet fires have also been investigated both experimentally and by modelling and it is found that depending on external conditions, the hydrogen flame is almost invisible to the eye, and this may cause a safety hazard e.g., during a fire inside a tunnel. High heat loads were measured and modelled at the impact points of impinging jets. Public acceptance surveys suggest that knowledge on hydrogen is limited in the public and those who know more are less afraid of hydrogen.

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1 Summary

The main objective of the SH2IFT project has been to increase knowledge regarding the safety of hydrogen technology, especially focusing on consequences of handling and use of large volumes within closed and semi-closed environments and in maritime transport. Public acceptance of hydrogen introduction in transport has also been investigated. The work has been performed both with large-scale fire and explosion experiments and new models have been developed for prediction of hydrogen behaviour. The experiments were used for validation of the model framework that was built. The results have been used as foundation for new guidelines for use of hydrogen in transport and in industry.

Rapid phase transition (RPT) can represent one of the possible risks when it comes to hydrogen safety in maritime transport, however, the phenomena has been scarcely studied for liquid hydrogen (LH2). RPT is a physical explosion due to rapid vaporization of a liquid that can occur when the liquid comes in contact with another liquid with a large difference in temperature. The immediate consequence of an RPT is a pressure wave. Fires can be ignited if the hot fluid is thrown by the explosion toward combustible materials. RPTs have been investigated extensively for liquefied natural gas (LNG), but very few experiments involving LH2 leakages and RPTs have been conducted in the past. This was addressed in the SH2IFT project, both experimentally and through modelling. The experimental work showed no observations of RPT events, even for high momentum jets of LH2 into and onto a pool of water. The modelling work also displayed that the hypothetical LH2 RPT event as a consequence of an accidental spill on water is an issue of only a minor concern. This is opposed to observations made with LNG spills onto and into water, where RPT is a highly relevant safety issue. One observation made, however, from many of the RPT experiments was an unexpected ignition of the gas cloud generated during the release, resulting in blast waves. The ignition source remains unknown.

A boiling liquid expanding vapour explosion (BLEVE) can be defined as a possible vapour explosion that occurs if a vessel containing a liquid (or liquid plus vapour) at a temperature significantly above its boiling point at atmospheric pressure ruptures. This explosion can happen to any type of liquid contained in a tank if its contents is superheated. This type of tank rupture can happen for example during an accident, where the substance contained in the vessel reaches the state of either compressed liquid or supercritical fluid due to the rise in pressure and temperature. In the case of the latter, the liquid and vapour phases are not present anymore. This can be caused by different events such as a fire external to the vessel or a defect in the thermal insulation of the cryogenic tanks, leading to an undesired heat transfer between the substance and the surrounding. A catastrophic rupture of the vessel is attained when the state of the fluid is supercritical, and then the explosion is called supercritical BLEVE. Hydrogen has a low critical pressure (12.964 bar) and an extremely low critical temperature (33.145 K) compared with other substances and conventional fuels (hydrocarbons). For this reason, a supercritical BLEVE is a likely scenario for an LH2 tank. In the SH2IFT project experiments were performed with three different types of tanks containing LH2. These tanks were exposed to an external fire source. During the first experiment, the horizontal tank with vacuum perlite insulation started leaking via the seal of the blind flange connection at the filling valve on top of the vessel resulting in a visible jet fire caused by ignition by the propane flame. This type of failure did not cause a catastrophic rupture and explosion. The second experiment caused a full rupture of the tank, with fragments of the horizontal tank with vacuum multi-layer insulation (MLI) being spread to a large area surrounding the test site. The fragment that was collected furthest away was 167 m from the test spot. The main blast was, however, due to ignition of the hydrogen by the propane flame. Analysis of the pressure readings indicates only a minor pressure peak that can be related back to a BLEVE. The third tank, which was vertical, again with vacuum perlite insulation, did not rupture during the experiment, and the test was eventually terminated when the propane tank generating the outer fire around the tank was emptied. The main conclusion from these three experiments is that a BLEVE is more likely for a tank with vacuum MLI insulation, filled with LH2 and exposed to an external fire, however, the time it takes until a catastrophic rupture was so long that it allows for time to evacuate the exposed site. The

time allowing for evacuation is expected to increase for larger tanks, given the same heat load. Further, the tests were performed with the safety valves blocked. In a likely realistic scenario, the safety valve would have opened before a tank rupture. It is also important to note that the largest hazard relates to ignition of the hydrogen, in the experiments caused by the propane flame.

Analytical and numerical (computational fluid dynamics, CFD) models have been developed during the SH2IFT project to model the consequences of the BLEVE related explosions by simulating bursting tank scenario tests performed by BMW. The BMW tests were used to verify the models as the experimental BLEVE work in SH2IFT was too delayed to be used. The model was proven to be a reliable engineering tool to estimate the pressure build up inside the tank exposed to a fire and the evaporation of its content. A good agreement with the experimental measurements was achieved, with slightly conservative outcomes from the simulation. The disadvantage of the model is its inability to predict temperature build up in the vessel adequately. Regarding the assessment of the explosion consequences, it was concluded that a fraction of the energy generated by the combustion process must be considered, in addition to that from liquid/vapour expansion, to not underestimate the blast wave overpressure.

Gaseous hydrogen jet fires were investigated both experimentally and by modelling. Experiments were performed to visually investigate gaseous hydrogen jet fires in an enclosed space. Although it has been widely believed that hydrogen burns with a nearly invisible pale blue flame, yellow flames were observed at different intensity in all conducted tests of hydrogen jet fires. Such visible flames were most likely caused by the dust on the surface of the steel plates. After all the dust has been blown away, the flame started to become invisible while infrared cameras revealed hydrogen still burning. The jet fires of hydrogen and propane gas were compared, and the main findings were that the hydrogen jet fire results immediately in a high heat flux in the perpendicular direction, that rapidly decreases again. While the propane experiment shows a much slower increase of the heat flux, which can be partially explained by a delay of ca. 10 seconds before the full propane flow rate is reached. The release of hydrogen is much faster than propane release. Jet fire modelling was also performed, and the main objective of the modelling is to calculate consequences such as flame lengths, trajectory, and heat fluxes for loss of containment events and identify possibly mitigating measures that could be taken to reduce consequences. The jet fire modelling used results from the experimental work in SH2IFT and other well documented works in literature to verify the models. The FLACS-CFD code performed well for heat flux, flame length and flame trajectory for small to medium-scale hydrogen jet flames (< 15 m), however, the FLACS-CFD code overpredicts the buoyancy effect at the far end of large-scale hydrogen jet fires. This can be further improved in the model in the future.

A survey measuring the public acceptance of hydrogen as a fuel was carried out in Norway as part of the SH2IFT project. It was revealed that the perceived safety concerns for hydrogen fuel use are significantly correlated with the awareness of the 2019 hydrogen station explosion in Norway. It is suggested that active campaigns to boost familiarity with hydrogen fuel can help to increase the perceived safety. The results of the awareness show that the public perception is overall characterized by low familiarity and knowledge and is subject to change with increased demonstration activities and market rollout. It was found that those who know more about hydrogen are less scared of it. Finally, from the questions on perceived sustainability 50 % of respondents perceived hydrogen fuel to be more environmentally friendly than fossil fuels for use in cars and busses, and 44 % are in favour for government incentives to support hydrogen fuel. Efforts to introduce hydrogen fuel are increasingly focused on the heavy-duty land and maritime transport sector. The ongoing introduction activities for busses, trucks and ferries are promising. Finally, it was identified that Norway is positioned to take a leading role internationally in the introduction and use of hydrogen technology in the maritime segments.

2 Introduction

2.1 Background for the project and hydrogen safety

Hydrogen is as safe as other fuels, provided it is handled according to its unique properties. Hydrogen is the lightest element in nature, and it tends to rise in the atmosphere at normal conditions. It is neither toxic, nor corrosive, and is a clean alternative to fossil fuels as an energy carrier. According to the International Agency Research on Cancer[1], hydrogen is not carcinogenic. At atmospheric conditions, it is a diatomic gas with a very low density (0.0838 kg/m^3)[2]. It is difficult to detect since it is colourless, odourless, and tasteless. Moreover, the hydrogen flame visibility is considerably lower compared with hydrocarbon flames[3], thus difficult to see with the naked eye. Although the hydrogen flame in air has a very high temperature (2,321 K for 19.6 vol% of hydrogen in air[2]), it burns faster and produce significantly less thermal radiation than hydrocarbons such as LNG[4]. The atmospheric moisture has a significant effect on the thermal energy radiated by a hydrogen flame. In particular, the water contained in the air absorbs the thermal (infrared) radiation. However, any kind of undesirable ignition sources should always be avoided during hydrogen applications due to its low ignition energy (0.017 mJ in air[5]). Furthermore, the flammability range is wider than other fuel (4.0 % − 75.0 % in air[2]). Hydrogen has a high burning velocity which corresponds to a high explosive potential. This means that the containment or suppression of its flame and explosion are difficult to achieve. It must be noticed that hydrogen is one of the few gases that increases its temperature when expanded at a temperature above its inverse Joule-Thomson temperature (193 K)[6]. The risks in hydrogen applications are typically related to leakage with subsequent ignition, resulting in fires, gas explosions and possibly rupture of pressurized vessels.

Liquid hydrogen (LH2) is approximately 800 times denser than hydrogen at standard conditions. For large-scale transport where pipelines are not available, LH2 is the preferred form. It is foreseen that transport by ship will be the most effective solution to transport large amounts of hydrogen over long distances. To ensure safe handling of LH2, one should take lessons from the vast experience made with liquefied natural gas (LNG) and other liquified gases, while at the same time considering the distinct properties of LH2 – in particular, its ultra-low boiling point and density. When LNG is accidentally spilled on water, it is known to sometimes, seemingly at random, undergo a localized vapour explosion known as rapid phase transition (RPT). This could represent a safety concern also for LH2. Another safety concern is boiling liquid expanding vapour explosion (BLEVE) as a consequence of vessel damage. Both phenomena result in vapour explosions, since LH2 departs from a thermodynamic metastable or unstable state, induced by the damage, to the equilibrium state of vapour.

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2.2 Project description

Objectives

The main objective of the SH2IFT project was to increase competence within safety of hydrogen technology, especially focusing on consequences of handling and use of large volumes within closed and semi-closed environments and in maritime transport. Relevant aspects from the whole value chain from industry and authorities to end users and general public was investigated, with special emphasis on the potential obstacles and bottlenecks for early implementation of hydrogen as fuel. The project both developed new models, performed large-scale fire and explosion experiments, and provided guidelines for use of hydrogen in industry and transport.

Secondary objectives were:

- Evaluate the relevance and performance of currently available tools for estimating consequences and risks associated with hazardous events involving gaseous and liquid hydrogen.
- Fill current knowledge gaps related to safe handling of hydrogen as a fuel. This will be addressed by investigating the physical behaviour of hydrogen in medium- and large-scale experiments, as well as development and validation of numerical models.
- Address concerns and potential barriers in the Norwegian society (industry/public/authorities) regarding implementation, handling and use of hydrogen technology and infrastructure.
- Develop recommendations and guidelines for handling hydrogen.

The results and gained knowledge are expected to contribute significantly to the following areas:

- Increased relevance and accuracy of consequence models and risk assessments, resulting from experimental investigations and state-of-the-art modelling.
- Input to requirements, procedures and guidelines regarding gaseous hydrogen (GH2) and LH2 safety in road, rail and maritime applications (tunnels, parking facilities, ships and transport of hydrogen).
- Increased acceptance and accelerated implementation of hydrogen technology in society, thus contributing to reduced carbon emissions and growth in the Norwegian hydrogen industry.

Research questions as background for the project and performed activities:

- What are the main concerns and potential barriers in the Norwegian society (public/authority/ industry) regarding introduction of hydrogen technology? This question is approached using socio-technical frameworks for the study of sustainability transitions.
- Which experimental activity is required to understand consequences of the hazards related to use of hydrogen? Identified, possible hazards related to LH2 and GH2 will be addressed by experiments giving new knowledge and understanding related to consequences of possible incidents.
- Do existing risk analysis tools sufficiently address the consequences of hazardous hydrogen events? The relevance of currently used risk and consequence modelling tools will be evaluated for the chosen scenarios related to current knowledge gaps. Fire and explosion tests will be applied in order to validate theoretical models.
- Are current (national) guidelines relevant and sufficient for safe implementation of hydrogen technology in handling and use? National and international regulations, standards and procedures will be evaluated, and recommendations will be proposed.

The project was divided in the following work packages:

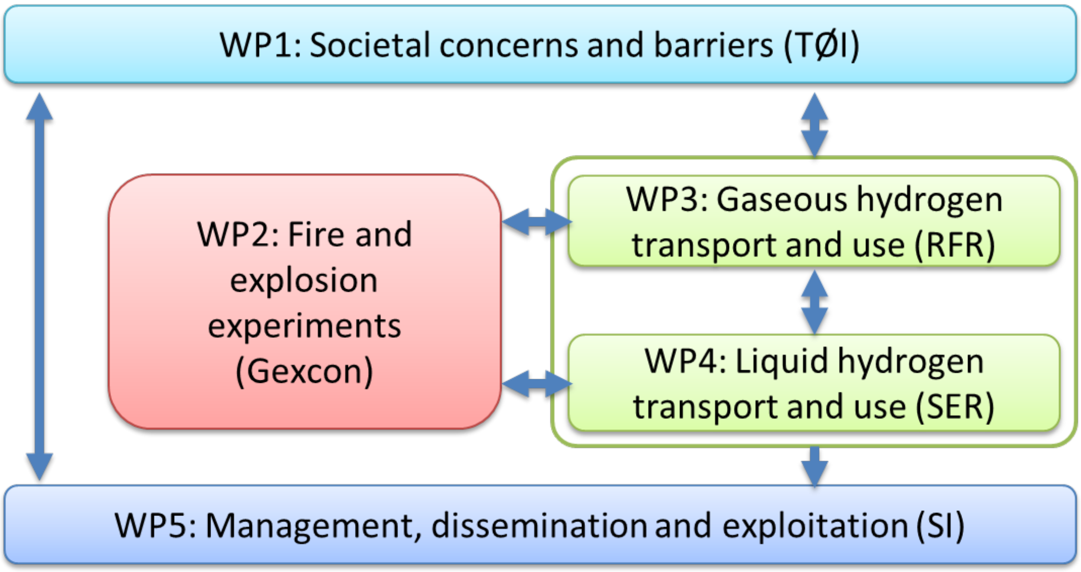

Figure 1: Work package structure and WP leads

WP1 Societal concerns and barriers
The objective of WP1 is to reveal and understand concerns and potential barriers in the Norwegian society (landscape/regime/niche) regarding introduction of hydrogen technology.

WP 2 Fire and explosion experiments
The objective of WP2 is to gain technical and physical insight into processes involving GH2 or LH2 by small and medium scale fire and explosion tests.

WP 3 Gaseous hydrogen transport and use
The objective of WP3 is to fill knowledge gaps about fire safety of GH2 transport and use and improve established risk and consequence modelling tools for GH2-related scenarios, in close collaboration with WP2.

WP 4 Liquid hydrogen transport and use
The work package focuses on consequences of the loss of containment of liquid hydrogen (LH2) by developing models for predicting triggering and estimating consequences of LH2 RPT and BLEVE.

2.3 Project partners and sponsors

Brief on each R&D partner, main contact person to each partner

SINTEF Industry (SI) is the project coordinator. SINTEF is an independent, non-profit research foundation, one of the largest independent contract research organizations in Europe. It is a multidisciplinary organization performing contract research, ranging from basic through applied research to commercialisation of results. The research teams in the department of Sustainable Energy Technology has more than 20 years' experience in hydrogen technology, varying from basic material research to coordination of demonstration projects, both nationally and internationally. Relevant examples with respect to safety, guidelines and public acceptance are related to projects on hydrogen heavy duty trucks, hydrogen ferries.

SINTEF Energy (SER) is part of the SINTEF group and is an institute for applied research dedicated to creating innovative energy solutions. SER is a leading R&D provider within hydrogen research, including liquefaction, thermo- and fluid dynamics, and process integration, and has a large portfolio of research projects. In the EU FP7 FCH-JU project IDEALHY (2011–2013), which pinpointed the long-term realistic potential for reducing the power demand for liquefaction by about 50 %, SER was leading the work packages concerning modelling and simulation activities. SER was also leading the KPN project Hyper focusing on large scale hydrogen production and liquefaction and the ACT project ELEGANCY focusing on large scale hydrogen and CCS chains. SER was also an integral part of the Hydrogen for Europe study, which supports the realisation of EU targets for 2030 and 2050. Currently, SER is leading the KSP project LH2Pioneer and is the principal research partner in the IPN project HyLASST, both looking into large-scale storage tanks for ship transport of LH2. SER is also leading the newly established national FME centre HYDROGENi.

Norwegian University of Science and Technology (NTNU) has the main responsibility for higher education in technology in Norway, and it is the country’s premier institution for education of engineers. Nicola Paltrinieri and Federico Ustolin are part of the RAMS group within the NTNU department of Mechanical and Industrial Engineering. RAMS is short for Reliability, Availability, Maintainability and Safety. The RAMS group is multidisciplinary and has deep understating of both mathematical/physical tools and industrial systems. The RAMS group is acknowledged as one of the world-leading academic groups in the domain and is involved in up to 10 research and educational projects on hydrogen safety.

The Institute of Transport Economics (TØI) has a broad competence in transportation research and unique knowledge of the transportation sector in Norway. TØI holds an extensive research experience on transport safety, technology, and transport policies. The research team from TØI have specialized competence on vehicle technology, implementation, and implementation barriers, as well as decision making processes and users perspectives. TØI is a partner and WP leader in the project ELECTRANS (ENERGIX), studying institutional barriers to electrification of the transport sector and providing management tools and policy recommendations. TØI also leads RA4-l: Policy & Techno-economic Analysis in FME MoZEES.

RISE Fire Research (RFR) is a research institute, jointly owned by SINTEF and RISE Research Institutes of Sweden. RFR offers fire technical expert services for a fire safe society to industries and parts of the society where fire constitutes a risk. RFR has one of Europe’s largest fire test facilities, and conduct small to large scale standardized and tailored fire tests, both for commercial assignments and in research projects. The main activities at RFR are analytical and experimental research on fire safety, -dynamics, -prevention and mitigation, -testing, -investigations and risk assessment. RFR has high expertise in oil and gas fires, and tunnel safety.

Gexcon is a company specialised in industrial risk. Gexcon develops and validates the CFD code FLACS that is widely used for consequence modelling related to dispersion, fire and explosion scenarios in industry. Gexcon owns all intellectual property rights for FLACS. Gexcon has extensive experience from EU-funded projects, such as Dust Explosion Simulation Code (DESC) in FP5, HySafe in FP6 and CO2PipeHaz in FP7, and is currently the coordinator for the HySEA project in Horizon 2020. At the time of the start of the SH2IFT project Gexcon was owned by **Christian Michelsen Research**, a research institute that merged with several other Norwegian research institutes into the independent research institute ***NORCE (Norwegian Research Centre)***. NORCE sold Gexcon in 2021.

Sponsors

The following companies and authorities contributed with cash sponsoring to the project:

Equinor, Shell, Ariane, Air Liquide, Statkraft, NASTA, Public Roads Administration, Railway Directorate, DSB, Nye Veier, TotalEnergies, Safetect and the counties Troms og Finnmark, Viken, Vestland, Møre og Romsdal and Trøndelag. In addition to the sponsors mentioned above, the Research Council of Norway funded the project with 16.5 MNOK.

3 Project results

3.1 Rapid phase transition (RPT)

3.1.1 Introduction

Rapid phase transition (RPT) is a physical explosion due to rapid vaporization of a liquid that can occur when a liquid comes in contact with another liquid at a much higher temperature. When liquefied natural gas (LNG) is accidentally spilled on water, it is known to sometimes, seemingly at random, undergo a localized vapour explosion, i.e., an RPT. An LNG RPT was observed for the first time by Constock Liquid Methane Corporation at Bayou Long, Louisiana, in 1956[7]. Among several definitions, Pitblado and Woodward[8] described the RPT for the interaction of LNG and water as "an explosively fast evaporation of LNG to vapour when LNG is suddenly contacted with a warm fluid, usually water". Even though this might be seen as a simplistic definition of the phenomenon, the evaporation of the LNG is primarily caused by the rapid heat transfer from water to the cryogenic mixture. The complexity is represented by the behaviour of the fluids during their interaction. RPT is also observed for fluid pairs other than LNG–water, e.g., liquid nitrogen–water and water–molten-metals[9].

The immediate consequence of an RPT is the pressure wave. Fires can be ignited if the hot fluid is thrown by the explosion toward combustible materials. For instance, fires developed during an RPT in the metallurgical industry where molten metal was shattered and spread around the facility by the shock wave. Moreover, a flammable cloud can be created after the evaporation of flammable substances (e.g., hydrocarbons and hydrogen).

The peak pressure and mechanical energy of an LNG RPT event, even without combustion, has the potential to displace and damage heavy equipment[7,10,11] and cause secondary structural damage and cascading containment failures[12]. Predicting whether an LNG RPT event will occur as a consequence of a spill has proven to be difficult. Lawrence Livermore National Laboratory performed a series of tests in the 1980s[9,13,14] that indicated that RPT occurred in about one third of the spills and that a single spill could lead to more than ten distinct RPT events. The yield of a single LNG RPT event seems to be quite random and has been reported to

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have TNT equivalents in the range of a few grams up to 6 kg (25 MJ)[12,13,15,16,17]. As a reference, one kg of TNT can destroy (or even obliterate) a small vehicle[18].

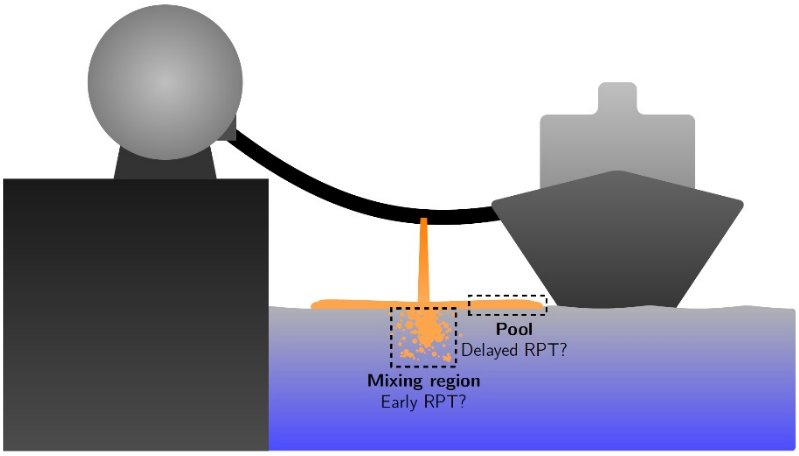

Figure 2: An illustration of an accidental release of a cryogenic fuel onto water. The origins of two kinds of RPT events are also shown: early RPT from the mixing zone and delayed RPT from the spreading pool.

Figure 2 illustrates a potential accidental spill of a cryogenic fuel such as LNG or LH2 in a marine environment. Due to an unintended event, the containment of liquid cryogen in a tank or transfer line is lost. Since the cryogen is stored at its boiling point, it will start to boil as soon as it comes in contact with the relatively hot surroundings. When the fluid comes in contact with water, the water–cryogen heat transfer will dominate the other heat-transfer contributions such as radiation and cryogen–air contact. Near the point of impact, there will be a chaotic mixing region where the cryogen is broken down to droplets. Due to gravitational forces, the cryogen, which is assumed to be lighter than water, will form a pool that spreads outwards from the impact point. The supply of fluid from the containment breach will cease after some time, and eventually, the pool will have evaporated. RPTs may occur for LNG spill events that behave in this way. It has been observed that RPTs can occur after a few seconds near the point of impact (mixing region), and sometimes also after tens of seconds further away (pool region). There are two categories of RPT, based on when and where it occurs during a spill event[9,12]:

- *Early RPT*: defined as any RPT occurring in the mixing region at any time during the spill event.
- *Delayed RPT*: defined as any RPT that is not an early RPT, which means it occurs somewhere in the spreading pool.

While RPT is a known safety concern in the LNG industry, the knowledge on the possibility and potential consequences of LH2 RPT has been limited. No LH2 RPT has ever been reported, and very few experiments have been conducted. The study by Verfondern and Dienhart[19] represents the only LH2 spill on water experiments prior to SH2IFT. They studied low-momentum LH2 releases onto a water pool, but they did not observe any RPT events. This indicates that delayed RPT is unlikely, but cannot be used to conclude on the possibility of LH2 RPT, especially early RPT. Furthermore, the potential consequences of LH2 RPT have been unknown. One of the main research questions in SH2IFT has thus been to investigate whether RPT represents

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a safety issue for LH2 releases on water. This question has been studied both by large scale experimental tests and by fluid and thermodynamic modelling.

3.1.2 RPT experimental results

Introduction

Experimental research into RPTs of LH2 upon release onto or into water has been limited. The only related work are experiments performed by Verfondern and Dienhart[19] whom tried to avoid RPTs and the aim of the study was to investigate how LH2 spreads over water. Atkinson (2020) investigated the effects of spraying water onto a pool of LH2. None of these experiments resulted in RPTs, neither early nor delayed. Modelling suggests that delayed LH2 RPTs are very unlikely, and that early RPT is less likely to occur for LH2 than for LNG (see Section 3.1.3 below). The low Leidenfrost temperature of LH2 prevents the collapse of the vapour film separating LH2 and water. The modelling also shows that if an RPT would occur, overpressures generated will be considerably lower than for LNG when released onto or into water. This chapter presents a series of experiments performed to investigate whether early RPTs are possible when releasing a LH2 jet onto water or under water.

Experimental set-up

The experiments were performed at the Test Site Technical Safety (TTS) of the Bundesanstalt für Materialforschung und –prüfung (BAM) in Horstwalde, approximately 50 km south of Berlin, Germany. At the site a 10 m x 10 m wide and long, 1.5 m deep basin was created, lined with tarpaulin and filled with fresh water to the very top. The basin is considered to provide a sufficiently large volume, behaving like open water with regard to the heat transfer during the short release durations of max. 2 minutes that were chosen. The LH2 was supplied from a 40 m³ road trailer, providing a sufficient amount of liquid hydrogen for all releases. Figure 3 shows the test set-up with the basin, road trailer and instrumentation cabin.

Figure 3: View of the test set-up to study the release of LH2 onto and under water. The picture shows the basin on the left with a bridge structure for holding the release mechanism and instrumentation. On the right the road trailer carrying the LH2. In the middle the cabin used for logging equipment.

The LH2 is released directly from the trailer via an approximately 46 m long flexible double vacuum insulated transfer line (inner diameter 39 mm) connected to a remotely operated vacuum insulated valve. From there an approximately 10 m long flexible double vacuum insulated transfer line (inner diameter 39 mm) lead to the release nozzle. The nozzle could be moved up and downwards, enabling releases over and under the water surface. The transfer line was also connected to a second remotely operated vacuum isolated valve, allowing for an initial phase to release flashed LH2. A manually operated valve at the trailer was used to vary the release rate. The release system was equipped with several pressure transducers and thermocouples to monitor the release conditions. A thermocouple directly at the nozzle was used to detect the release of liquid hydrogen. The road trailer was placed on a weighing system to determine the mass released during each release allowing for calculating the corresponding mass flow.

In addition to the measurements/monitoring mentioned above the following parameters were measured using the bridge construction over and surrounding the basin:

- Temperature: thermocouples were placed alternatingly just above or just beneath the water surface. Four pressure sensors were installed to measure blast under water and above the water surface.
- Concentration of hydrogen in air, was measured at 10 positions using sensors capable of detecting concentrations in the range of 0-100 Vol.%. Some thermocouples are directly associated to gas sensors and are mounted directly beside these respective gas sensors.
- Wind speed and direction were recorded using ultra sonic anemometers. These were mounted at two opposite corners of the basin. The location of the thermocouples, concentration probes and blast sensors are shown in Figure 4.

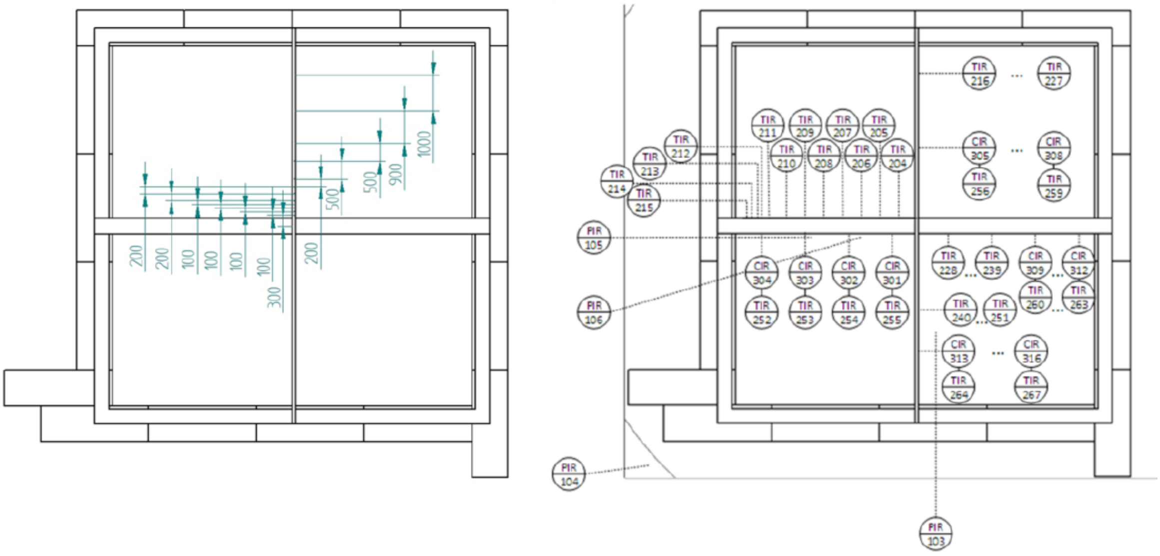

Figure 4: Schematic view of the sensor positions over the water surface (TIR = Thermocouple, CIR = Gas Sensor, PIR = Pressure Sensor)

- Heat radiation measurements were performed at distances of 70m, 90m and 110m from the point of release.
- Video recordings were done with standard cameras, a highspeed camera, an IR-Camera and by means of a UAV equipped with regular and infrared camera systems.

Test programme

In total 75 LH2 releases were performed and successfully recorded. Each trial consisted of more than one release. Three positions of the release nozzle have been investigated in these trials:

- approximately 50 cm above the water surface, oriented vertically downward (A) with 31 releases
- approximately 30 cm under the water surface, oriented vertically downward (U) with 34 releases
- approximately 30 cm under the water surface, oriented horizontally parallel to the water (UH) with 10 releases.

The number of releases, the mass flow range and the type of release for each trial are shown in Table 1. As the aim of the experiments was to investigate the possibility of occurrence and effects of RPTs when releasing LH2 on (or under) water, the trails are named “RPT xxx”.

Table 1: RPT Trials performed showing number of releases per trail, the type of release and the estimated mass flow rate (release oriented vertically downward (A) 50 cm above the water surface and (U) 30 cm under the water surface, and (UH) horizontally 30 cm under the water surface)

Trial	Type of Release	Number of successful releases	Mass flow rate (range) kg/s
RPT 001	A	1	**4
RPT 002	A	8	0.3 – 1
RPT 003	A	1	**0.1
RPT 004	U	3	0.35 – 0.85
RPT 005	A	2	**0.25
RPT 006	U	4	0.5 – 1.1
RPT 007	U	5	0.35 – 0.65
RPT 008	U	3	0.55 – 0.62
RPT 009	U	3	0.35 – 0.7
RPT 010	U	3	0.35 – 0.45
RPT 011	A	3	0.45 – 1.1
RPT 012	A	3	0.32 – 0.58
RPT 013	A	3	0.25 – 0.4
RPT 014	U	2	0.3 – 0.5
RPT 015	U	3	0.5 – 0.75
RPT 016	U	1	0.8
RPT 017	A	5	0.4 – **1.4
RPT 019	A	2	0.8
RPT 020	A	3	1.1
RPT 021	U	4	0.25 – 0.76
RPT 022	U	3	0.27 – 0.37
RPT 023	UH	3	0.53 – 0.78
RPT 024	UH	3	0.36 – 0.55
RPT 025	UH	4	0.38 – **0.93

*RPT 018 is not listed, as this trial was not recorded due to a malfunction of the logging system, and is therefore considered as “failed”

** Values are not reliable.

Results

The majority of the RPT-tests performed were carried out with a pressure inside the road trailer of around (or above) 10 bara. This caused a relatively strong momentum two-phase hydrogen jet penetrating deep into the water basin, also when the release occurred above the water surface (see Figure 5). From the underwater camera recordings, it becomes clear that there is massive evaporation, but no sudden bursts typical for an RPT can be seen. The camera recordings reveal a very chaotic mixing zone that seem to pulsate due to the interplay between volume production from evaporation, insulating bubbles, buoyancy and the continuously incoming jet. The larger bubbles only form on the sides of the impact zone and the vapour layers between LH2 and water and the bubbles themselves are disintegrated due to what appear to be Taylor instabilities. The evaporation is not homogeneous and frequent geyser-like jets propel out of the water (see Figure 5).

Figure 5: LH2 jet penetrating the water (release rate 0.8 kg/s, release location 50 cm above the water surface pointing downwards). The left picture shows a moment shortly after the jet entered the water surface. The picture in the middle shows the penetration depth of the jet. The picture to the right shows the geyser-like behaviour over the water surface caused by the evaporating liquid hydrogen.

The violent evaporation caused overpressures noticeable at the pencil probes. Measured overpressures associated to this phenomenon were all below 0.05 bar (see Figure 6).

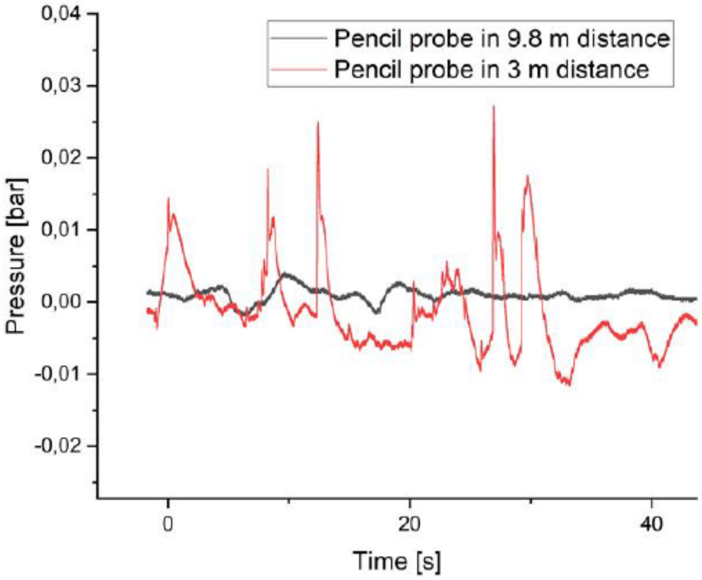

Figure 6: Pressure signal recorded by the pencil probes above the water during a trail without ignition (RPT 013).

In 80 % of the releases an unexpected ignition of the evaporated gas cloud occurred. The ensuing explosion resulted in overpressures of up to 0.4 bar. Considering all tests performed, the tests where the release occurred under water pointing downwards nearly always resulted in an ignition (94 % of the releases, see Table 2). Releases from a point above the water surface resulted in a considerably lower probability of ignition but still significant (68 %). There is a tendency that a lower release momentum results in a lower ignition probability.

Table 2: List of total number of releases per release type and corresponding number of observed ignitions

Type of release	Total number of releases	Total number of observed ignitions	Percentage of releases with ignition (%)
A	31	21	68
U	34	32	94
UH	10	7	70

The ignition source remains unknown. Using IR-cameras it was possible to locate the ignition starting point which appeared to be in “free-air” with a clear distance from the instrumentation bridge and any instrumentation (see Figure 7). Ignition also occurred when all instrumentation was switched off. A possible explanation may be an electric field generated by the ejection of water crystals from the water basin due to the hydrogen evaporation process resulting in corona discharges at pointed ice crystals (Petersen et al, 2015). Gas concentrations in the cloud varied strongly due to the non-stationary evaporation process and varying wind conditions. Still hydrogen gas concentrations often reached close to stoichiometric concentrations, i.e., those that are the most ignitable mixtures. If these coincide with the moments where corona discharges from ice crystals occur, ignition is certainly possible (assuming this is the explanation of the explosions).

From these experiments one can therefore conclude that an RPT resulting from LH2 spills onto or into water is not a major issue for safe implementation of LH2 technologies. Spills of LH2 onto water should however be avoided as much as possible since the resulting flammable cloud may explode violently after ignition by a spill-related yet unknown source.

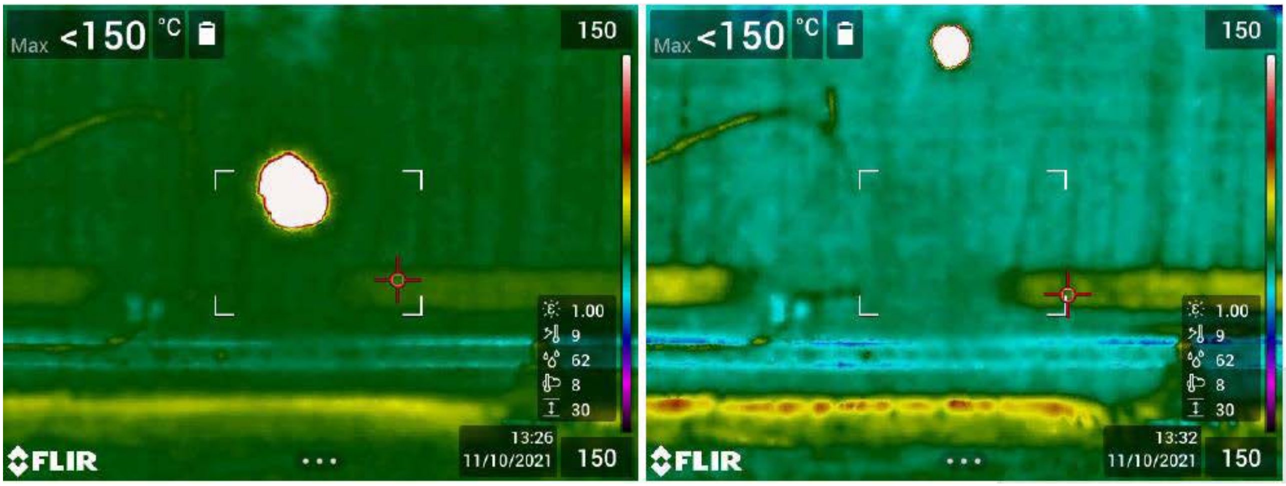

Figure 7: Moment of start of flame propagation in hydrogen-air clouds generated by releases of LH2 onto and under water with all measuring equipment over the water basin switched off. The ignition location appears to be somewhere in the cloud at a distance from any physical object.

3.1.3 RPT modelling results

A theoretical assessment of accidental spills of LH2 on water has been conducted in the SH2IFT project. This includes development and application of fluid and thermodynamic models for pool spreading, RPT triggering, and consequence quantification. The approach is based on established theory from LNG research, as well as published reports on LH2 accidents. The results are published in Odsæter et al. (2021)[20], and further reviewed here.

Pool boiling and spreading

A cryogen at the boiling temperature (T_{sat}) that comes in contact with a hot surface ($T_w > T_{sat}$) will absorb a heat flux per unit area, $\dot{q}$, and start to evaporate. For a mixture, the generated vapour will be mainly the most volatile component (e.g., methane for LNG). This increases the boiling point as the mixture becomes more enriched on heavier components, and the absorbed heat goes to evaporation and heating the fluid. LH2, on the other hand, is a single-component fluid, and the received heat contributes only to evaporation. The heat transfer between a boiling fluid and the heat source is strongly dependent on the temperature difference – this is described by Nukiyama's boiling curve, which is shown in Figure 8. If the water temperature, T_w, is higher than the Leidenfrost temperature, T_L, a stable vapour film will form between the two fluids. This is known as film boiling and gives a strong reduction in heat transfer compared to when $T_w < T_L$. Both LH2 and LNG are known to film boil on water.

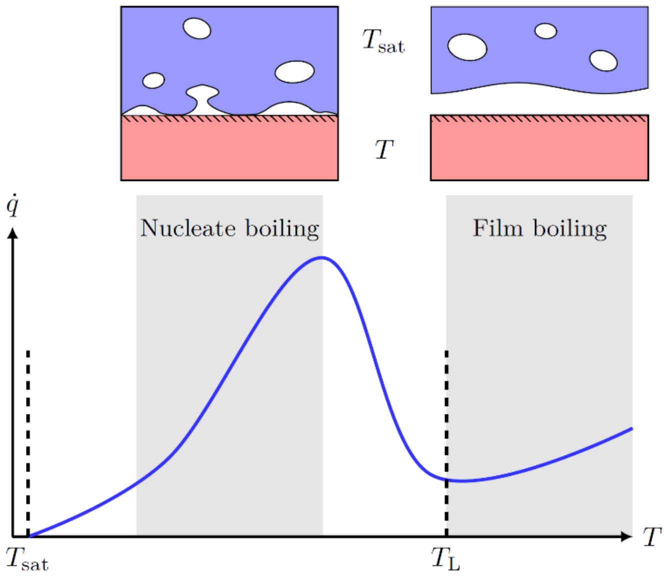

Figure 8: Illustration of a typical boiling curve for saturated pool boiling, i.e, the boiling heat flux ($\dot{q}$) as a function of surface temperature (T).

The spreading of the cryogenic pool can be estimated by a simplified model where we assume a constant volumetric spill rate and a constant boiling heat flux. The maximum estimated radius of such steady-state spill is estimated to be approximately four times larger for LNG compared to LH2. This is mostly due to the large density difference giving a large difference in volumetric latent heat of evaporation, but also due to a higher boiling heat flux for LH2.

Triggering of RPT

The theory of RPT was developed after the observation of LNG RPT in the 1960s. The description is local in the sense that it treats the occurrence at small scales at the time and position of a single RPT event. This makes it applicable to both early and delayed RPT. Furthermore, the formulation is not specific to LNG. The theory can be summarized by the following chain of events:

1. *Film-boiling stage*: If the water temperature is higher than the Leidenfrost temperature of the cryogen (see Figure 8), a stable insulating vapour film will form between the cryogen and the water. This is known as film boiling, and the lack of direct contact between the two fluids reduces heat transfer significantly. In this stage, the cryogen stays in quasi-equilibrium, and the energy transferred from the water goes to evaporating the cryogen.

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[20] Odsæter, L.H., Skarsvåg, H.L., Aursand, E., Ustolin, F., Reigstad, G.A., Paltrinieri, N., 2021. Liquid Hydrogen Spills on Water – Risk and Consequences of Rapid Phase Transition. Energies 14, 4789. https://doi.org/10.3390/en14164789

2. *Film-boiling collapse*: At some point, there is a sudden and localized collapse of the vapour film. The suggested mechanism that induces this film collapse depends on the cryogen properties and whether early or delayed RPT is considered.
3. *Rapid superheating*: The direct contact between the water and the cryogen induces a large and rapid increase in the heat flux. The evaporation rate is too low to compensate for the large heat flux and the liquid will be heated above its boiling temperature, known as superheating. A superheated liquid is in a metastable state, which equilibrates to a corresponding equilibrium if disturbed. If the metastable liquid is not disturbed, the temperature will continue to increase until a maximum temperature is reached. At this point, known as the superheat limit, the liquid will spontaneously equilibrate.
4. *Homogeneous nucleation*: When the liquid gets sufficiently close to the superheat limit, spontaneous nucleation occurs throughout the volume. This initiates the RPT, where large amounts of liquid are vapourized in a very short timeframe.
5. *Explosive expansion*: Liquid is orders of magnitude denser than vapour in mechanical equilibrium. The rapid formation of vapour leads to a large local increase in pressure that is followed by an explosive expansion. This is observed as a loud and potentially destructive vapour explosion. The expansion can be characterized and compared to conventional explosions by estimating the peak pressure and the energy released in the form of expansion work.

Once the second out of these five stages is reached (film-boiling collapse), the theory of RPT predicts that the next three stages will follow spontaneously. This chain reaction of events can be used to explain how RPT may occur. However, recall that a spill of LNG (or another cryogen) may not necessarily trigger an RPT event. The vapour film may never collapse or the transition from film boiling to nucleate boiling could occur without any violent evaporation.

The above theory predicts that a necessary requirement for RPT is the collapse of the gas film separating the liquids. For delayed RPT, this happens if the Leidenfrost temperature of the cryogen is larger than the water temperature. Hence, we formulate the following triggering criteria:

$$T_w > T_L \text{ : Film boiling (no RPT),}$$
$$T_w < T_L \text{ : Liquid-liquid contact (risk of RPT).}$$

It can be difficult to predict the Leidenfrost temperature of a fluid with good accuracy, but in general, it has been found that it can be estimated as the liquid spinodal at atmospheric pressure[21]. For LNG, T_L is dependent on the composition. For a typical LNG mixture of 90-6-3-1 wt% composition of methane, ethane, propane and normal butane, respectively, this model gives $T_L = -102°\text{C}$. The water temperature, T_w, will be close to its freezing point (0°C) or slightly above. Hence, the triggering criteria is far from being satisfied, and the model predicts no RPT event with the initial composition. However, boil-off of the lighter components cause the Leidenfrost temperature to increase due to the change in the composition. If we assume that only methane evaporates, which is a reasonable approximation when there are significant amounts of methane in the mixture, we will reach $T_L = 0$ °C when the methane composition has fallen to 12 wt%. At this point the triggering criteria is satisfied and there is a risk of RPT. This shows that the boil-off effect is essential for triggering a delayed RPT event for LNG.

The Leidenfrost temperature for hydrogen is very low. The liquid spinodal estimate gives $T_L = -245$ °C, while Wang et al.[22] reported $T_L = -241$ °C based on a survey of experimental data specifically for hydrogen

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[21] Spiegler, P.; Hopenfeld, J.; Silberberg, M.; Bumpus, C.F.; Norman, A. Onset of stable film boiling and the foam limit. Int. J. Heat Mass Transf. 1963, 6, 987–989.

[22] Wang, L.; Li, Y.; Zhang, F.; Xie, F.; Ma, Y. Correlations for calculating heat transfer of hydrogen pool boiling. Int. J. Hydrog. Energy 2016, 41, 17118–17131.

fitted to analytical models (all experiments were LH2 on solid surfaces). In any case, $T_L \ll T_w$ and the triggering criteria is far from being satisfied. Hence, delayed RPT for LH2 is not possible according to the model.

Early RPT occurs in the liquid–liquid mixing region where the cryogen impacts the water. The chaotic nature of this mixing makes it challenging to predict the vapour-film collapse. The boiling behavior diverges from the description by the simple boiling curve[23]. This is most likely due to impact forces between the liquids, and for mixtures (such as LNG), also the development of local variations in the composition. The necessary, detailed multiphase simulations of the mixing region over sufficient timescales has, to our knowledge, not yet been achieved. Predicting early RPT is thus an unsolved problem. Some remarks regarding the likelihood of an early RPT event, and its dependence on fluid properties and case geometry, can still be made:

- The vapour film is more robust if the Leidenfrost temperature is low relative to the water temperature. That is, if the boiling is "far from" transition boiling ($T_L \ll T_w$), then film-boiling collapse is less likely to occur.
- A low momentum impact is less likely to induce film-boiling collapse than a high momentum impact.
- Low-density cryogens have a smaller and more short-lived mixing region than high-density cryogens due to smaller impact and increased buoyancy.

LNG is about six times denser than LH2 and the Leidenfrost temperature of LNG is approximately 150 °C larger than LH2. This indicates that early RPT is much less likely for LH2 compared to LNG. If we consider a liquid cryogen jet impacting water, the large difference in density of LH2 and LNG gives a difference in penetration depth of one order of magnitude given the same volumetric spill rate. This means that the mixing region will be larger and more chaotic for LNG and, thus, increase the contact area between water and LNG. Furthermore, a higher impact is expected to destabilize the insulating gas film and, hence, increase the chance of film-boiling collapse (liquid–liquid contact). This latter effect is again strengthened by the higher Leidenfrost temperature of LNG.

The discussion and results above assume that the water surface holds an approximately constant temperature of 0 °C. Despite the very low temperature of LNG, very little or no ice has been observed for large-scale LNG spills[24,25]. However, LH2 is considerably colder, which could cause noticeable ice-formation. Formation of a continuous and thick (several mm) layer of ice was observed in the LH2 spill experiments by Verfondern and Dienhart[26,27]. It should be noted that the ice formation was likely enhanced due to hampered water circulation in the small pool. The presence of an ice sheet allows for a new potential mechanism for triggering delayed RPT since the surface temperature (T_w) is allowed to go below 0 °C. Cooling of the ice layer all the way down to the Leidenfrost temperature (≈ -245 °C) would, however, require considerable subcooling and is rather unrealistic. Another effect of LH2 spills is the condensation and freezing of air components, such as oxygen and nitrogen, which have higher freezing points than LH2. Such components can mix into the LH2 pool and may have unpredictable consequences that should be further studied.

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[23] Bøe, R. Pool boiling of hydrocarbon mixtures on water. Int. J. Heat Mass Transf. 1998, 41, 1003–1011.

[24] Cleaver, P.; Johnson, M.; Ho, B. A summary of some experimental data on LNG safety. J. Hazard. Mater. 2007, 140, 429–438.

[25] Luketa-Hanlin, A. A review of large-scale LNG spills: Experiments and modeling. J. Hazard. Mater. 2006, 132, 119–140.

[26] Verfondern, K.; Dienhart, B. Experimental and theoretical investigation of liquid hydrogen pool spreading and vaporization. Int. J. Hydrog. Energy 1997, 22, 649–660.

[27] Verfondern, K.; Dienhart, B. Pool spreading and vaporization of liquid hydrogen. Int. J. Hydrog. Energy 2007, 32, 2106–2117.

Consequence modelling

A thermodynamics model to partially quantify the consequence of an LNG RPT event was presented in Aursand and Hammer[28]. This model can estimate two important quantities: The peak pressure, p^*, which is the maximum pressure of an RPT event very close to the source, and the explosive energy yield, E, which is the mechanical work done by the expansion process given in energy per amount triggered. This model has been extended in SH2IFT to give estimates for LH2. For the thermodynamic evaluation of the two-phase equilibrium state, the SINTEF developed open-source software Thermopack[29,30] was used.

There is no way of predicting how much of the total spill will participate in a single, localized RPT event. Hence, it is not possible to predict the total energy yield of one RPT event. Assuming that the entire pool participates in the RPT event gives an upper bound on the total yield estimates. The energy yield per amount of liquid can also be used directly to compare different liquids.

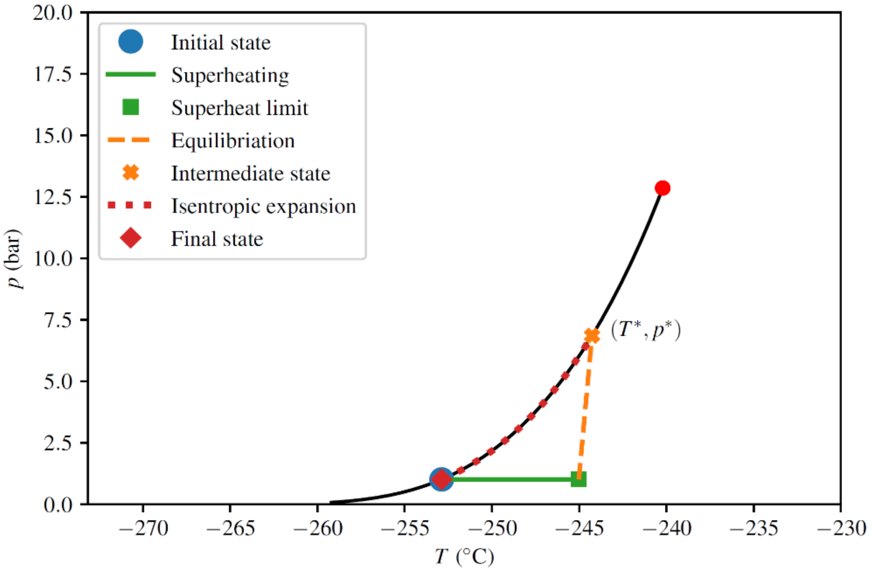

Figure 9: Thermodynamic diagram for LH2, from triggering the initial state to the final state.

The thermodynamic paths taken in the calculations for consequence quantification are depicted in Figure 9 for LH2. The predicted consequences in terms of peak pressure p^* and energy yield E are listed in Table 3 for both LH2 and LNG. We see that the peak pressure of a theoretical LH2 RPT is only 17 % of that of a theoretical LNG RPT, and that the corresponding ratio for energy yield per volume is as low as 5 %. The numbers given are in terms of triggered mass and not relative to the initially spilled amount. For LNG, calculating relative to the spilled amount would give a reduction by a factor of 9 in energy yields for the specified composition. This is because approximately 90 % of the initial LNG must evaporate before the triggering criterion is met.

Table 3: The predicted consequences of LH2 RPT compared to LNG RPT. A 90-6-3-1 wt% composition of methane, ethane, propane and normal butane, respectively, is used for LNG.

Consequence	**LH2**	**LNG**	**LH2 vs. LNG**
Peak pressure, p^* (bar)	7	40	17 %
Energy yield, E (kJ/kg)	40	68	59 %
Energy yield, E (MJ/m^3)	2	39	5 %

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[28] Aursand, E.; Hammer, M. Predicting triggering and consequence of delayed LNG RPT. J. Loss Prev. Process. Ind. 2018, 55, 124–133.

[29] Wilhelmsen, Ø.; Aasen, A.; Skaugen, G.; Aursand, P.; Austegard, A.; Aursand, E.; Gjennestad, M.; Lund, H.; Linga, G.; Hammer, M. Thermodynamic Modeling with Equations of State: Present Challenges with Established Methods. Ind. Eng. Chem. Res. 2017, 56, 3503–3515.

[30] Hammer, M.; Aasen, A.; Wilhelmsen, O. Thermopack. 2020. Available online: github.com/SINTEF/thermopack/

Summary

The main conclusion of this modelling work is that the hypothetical LH2 RPT event as a consequence of an accidental spill on water is an issue of only minor concern. For the triggering mechanism, we find that the theoretical pathways known from the LNG research are very unlikely or even impossible for LH2. This is mainly due to the very low Leidenfrost temperature of LH2. The feasibility of triggering is further reduced by the low impact forces and small degree of mixing with water due to the low density of LH2. An essential mechanism for LNG RPT is that the lighter components evaporate first, resulting in increased Leidenfrost temperature. This mixture effect is not present for LH2, which is single-component. More research on film-boiling stability for high-impact forces and in chaotic mixing regions is needed to understand triggering of early RPT more fundamentally, but the very low Leidenfrost temperature of LH2 indicates that the vapour film is stable. The estimated consequence of a hypothetical LH2 RPT event is considerably smaller than for LNG. The predicted peak pressure is only 17 % of that from LNG RPT, and the predicted explosive yield per volume is only 5 % compared with LNG. These modelling results are in good agreement with the experimental study (see Section 3.1.2 above), where no RPT events were observed, even for high momentum jets.

3.2 Boiling Liquid Expanding Vapour Explosion (BLEVE)

3.2.1 Introduction

The term BLEVE was used for the first time in 1957 by J.B. Smith, W.S. Marsh, and W.A. Walls, employees of the Factory Mutual Research Corporation[31]. This trio coined the term BLEVE after observing and analysing an explosion of a cast iron vessel employed for the production of a phenolic resin[32]. Several definitions of BLEVE were proposed by different authors in the past[33]. One of the most recent definitions was stated by Casal et al.[34]: “a BLEVE is the explosion of a vessel containing a liquid (or liquid plus vapour) at a temperature significantly above its boiling point at atmospheric pressure”. Therefore, a tank which contains a liquid (or a liquefied gas), regardless the type of substance, might undergo a BLEVE if its lading is superheated. This event occurred even for water, nitrogen and carbon dioxide several times in the past, which are not reactive nor flammable substances[35]. According to the number of major BLEVE accidents in the period 1926-2004 published by Abbasi and Abbasi and elaborated by Ustolin[36], propane seems to be one of the most hazardous substances. However, the boiler explosions, which occur when holding superheated water, were not included in this analysis. This type of explosion is particularly difficult to interpret since three causes of explosion usually coexist: flammable gas, hot surfaces and superheated water. If the boiler explosions that occurred in the past are considered as BLEVEs, water may be the substance most frequently involved in BLEVEs.

A BLEVE might occur under certain circumstances after the catastrophic rupture of the vessel, which is the critical event, due to the sudden depressurisation of its content. The loss of integrity of the tank can be provoked by several phenomena: defects in the tank material (e.g., corrosion, embrittlement), degradation of the insulation (if any), accidental events (e.g., fire, tank puncture). If the BLEVE is thermally induced (e.g., due

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[31] Abbasi, T., Abbasi, S.A., 2008. The boiling liquid expanding vapour explosion (BLEVE) is fifty ... and lives on! J. Loss Prev. Process Ind. 21, 485–487. https://doi.org/10.1016/j.jlp.2008.02.002

[32] Walls, W.L., 1978. What is a BLEVE? Fire J. 31, 46–47.

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[34] Casal, J., Hemmatian, B., Planas, E., 2016. On BLEVE definition, the significance of superheat limit temperature (Tsl) and LNG BLEVE’s. J. Loss Prev. Process Ind. 40, 81. https://doi.org/10.1016/j.jlp.2015.12.001

[35] Heymes, F., Eyssette, R., Lauret, P., Hoorelbeke, P., 2020. An experimental study of water BLEVE. Process Saf. Environ. Prot. 141, 49–60. https://doi.org/10.1016/j.psep.2020.04.029

[36] F. Ustolin. “Modelling of Accident Scenarios from Liquid Hydrogen transport and Use”. PhD thesis. 2021. ISBN: 978-82-326-5575-5.

to fire exposure) it is usually defined as "fired" or "hot BLEVE"[37]. On the other hand, if the BLEVE is not thermally induced but provoked by several causes (e.g., violent impact or safety device failure), it is named "cold BLEVE". Therefore, the BLEVE formation depends on several aspects: (i) the thermal insulation of the tank, (ii) the presence and effectiveness of the pressure relief valves (PRVs), (iii) the filling degree of the vessel, and (iv) the type of tank rupture. For instance, Birk et al.[38] observed two types of BLEVE during the fire tests on propane tanks: single and two-step BLEVEs. The first one is generated if the container rupture is complete and virtually instantaneous, while the two-step BLEVE occurs if the vessel failure time is up to 2 seconds. Birk et al. concluded that a two-step BLEVE generates the largest blast overpressures when compared with the single-step one. When the tank is completely opened, the compressed gaseous phase abruptly expands generating the first shock wave, whilst a fraction of the superheated liquid flashes (change in phase) at a slower rate.

According to several authors, the primary requirement for an explosion to be categorised as a BLEVE is the superheated status of the liquid phase[39,40,41]. Many authors refer to the theory of superheated liquids (or superheat limit theory) developed by Reid[42] to determine under which operative conditions (mainly tank pressure and liquid temperature) a BLEVE may be generated. If a liquid has a temperature above its expected boiling point, it is superheated and thus in a metastable state. The superheat limit temperature (TSL) is the temperature above which the substance cannot exist in liquid phase, and it varies with pressure. Moreover, the TSL is a characteristic property of each substance. The liquid spinodal curve is the locus of all the TSL values. Therefore, if the liquid temperature exceeds the TSL at the given pressure, the substance is thermodynamically unstable. In this case, homogenous nucleation is initiated, and the liquid violently boils by provoking a physical explosion. However, a liquid may flash even in a metastable status through heterogeneous nucleation, especially if triggered (e.g. by a shock wave)[7]. In this case, the yield of the explosion is lower since homogeneous nucleation is a more powerful process. Based on these considerations, Reid formulated the theory of superheated liquids by stating that a liquid explosively flashes if its temperature reaches the TSL at the given pressure. This criterion can be exploited to estimate the minimum tank pressure required prior to the vessel failure to achieve a BLEVE or similar events related to catastrophic tank failures.

The first direct consequence of the BLEVE explosion is the pressure wave generated by the expansion of the compressed gaseous phase and the flashing of the liquid. The debris of the vessel or other pieces of equipment thrown away by the blast wave represents another BLEVE aftermath: the missiles. Finally, if the substance contained in the tank is flammable (e.g., fuels) and reaches an ignition source, a fire or fireball can be generated. For the reasons previously mentioned, the BLEVE explosion is fortunately considered as an atypical scenario since it has a low frequency yet high yield consequence[43]. Nevertheless, this event continues to manifest, as in August 2018 when a BLEVE was generated after the collision of two trucks on a motorway bridge in Bologna, Italy[44]. One of the trucks was transporting a load of liquefied petroleum gas (LPG) which was engulfed in a fire erupted after a traffic collision. This event led to the destruction of the tank and formation of the BLEVE.

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[37] Paltrinieri, N., Landucci, G., Molag, M., Bonvicini, S., Spadoni, G., Cozzani, V., 2009. Risk reduction in road and rail LPG transportation by passive fire protection. J. Hazard. Mater. 167, 332–344. https://doi.org/10.1016/j.jhazmat.2008.12.122

[38] Birk, A.M., Davison, C., Cunningham, M., 2007. Blast overpressures from medium scale BLEVE tests. J. Loss Prev. Process Ind. 20, 194–206. https://doi.org/10.1016/J.JLP.2007.03.001

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[41] van der Voort, M.M., van den Berg, A.C., Roekaerts, D.J.E.M., Xie, M., de Bruijn, P.C.J., 2012. Blast from explosive evaporation of carbon dioxide: experiment, modeling and physics. Shock Waves 22, 129–140.

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3.2.2 BLEVE experiments

Introduction

A BLEVE of a vessel containing liquid hydrogen (LH2) is an accident scenario which must be considered. On the other hand, only few experimental investigations of LH2 BLEVEs have been performed so far. The only investigation performed and available in open literature is the work reported by Pehr[45]. Small LH2 tanks designed for automobiles containing 1.8 to 5.4 kg of LH2 were destroyed by means of cutting charges. The general lack of experimental data is most probably related to the fact that a LH2 BLEVE hazard was not viewed as a credible event since double walled vacuum insulated vessels are used[46]. To investigate the possibility and, if possible, the consequences of an LH2 BLEVE, realistic experiments were performed: three 1 m^3 doubled-walled vacuum insulated pressure vessels (L/D=2) containing 25-30 kg LH2 were exposed to a propane fire (100-150 kW/m^2).

Experimental set-up

The experiments were performed at the Test Site Technical Safety (TTS) of the Bundesanstalt für Materialforschung und –prüfung (BAM) in Horstwalde, Germany. The three vessels (outer and inner) were constructed from low temperature resistant stainless steel (X5 CrNi 18-10). The thickness of the shell of the inner vessel is 3 mm and that of the outer vessel 4 mm. The thickness of the heads is always 5 mm. The maximum allowable working pressure of the vessels was 9 barg implying a burst pressure of about 36 bar. The vacuum insulation in the space between the two walls was a medium vacuum with a pressure of 0.3 mbar. Two of the vessels were oriented horizontally (one insulated with perlite and one with multi-layer insulation (MLI)) and one was oriented vertically (insulated with perlite), see Figure 10. Valves and piping connection were thermally insulated and protected from the fire during the test. Moreover, the safety valves were kept closed to simulate their failure, thus the worst-case scenario.

Figure 10: The three LH2 storage vessels used during the BLEVE experiments.

The liquid hydrogen was supplied by a road trailer. During filling, the vessels were placed on load cells to determine the amount of hydrogen filled into the respective vessels. This amount was additionally monitored by a differential pressure sensor, measuring the hydrostatic pressure built-up inside the vessels. The heat load applied to the vessels was generated by an array of 36 propane burners located underneath the vessels providing a heat load of approximately 100-150 kW/m^2 (mean propane consumption rate 4.3 kg/min). The fire engulfed

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[45] Pehr, K., 1996, Aspects of safety and acceptance of LH2 tank systems in passenger cars, International Journal of Hydrogen Energy, 21, 387–395.

[46] Betteridge S., Phillips L., 2015, Large scale pressurised LNG BLEVE experiments, IChemE Symposium Series no 160

mainly the bottom half of the vessels. During the tests the conditions inside the vessel were monitored: Temperature inside the inner vessel in the gas phase and the liquid phase, on the inner and outer side of the inner vessel and on the inner and outer side of the outer vessel. In addition, the pressure inside the inner vessel (both in liquid, as a level indicator, and gaseous phase), and in the space between the inner and outer vessels (vacuum pressure) was measured. To determine the possible consequences of a BLEVE the heat radiation generated by a possible fireball/BLEVE could be measured using bolometers and to measure possible shockwaves pencil probes were positioned at up to three locations. Further, cameras were used to monitor the events: normal cameras, infrared (IR)-cameras and high-speed cameras also on board of an unmanned aerial vehicle (UAV).

Test results

Table 4 presents the details of the three BLEVE tests performed. Below the results of these 3 tests are presented.

Table 4: Test program BLEVE tests

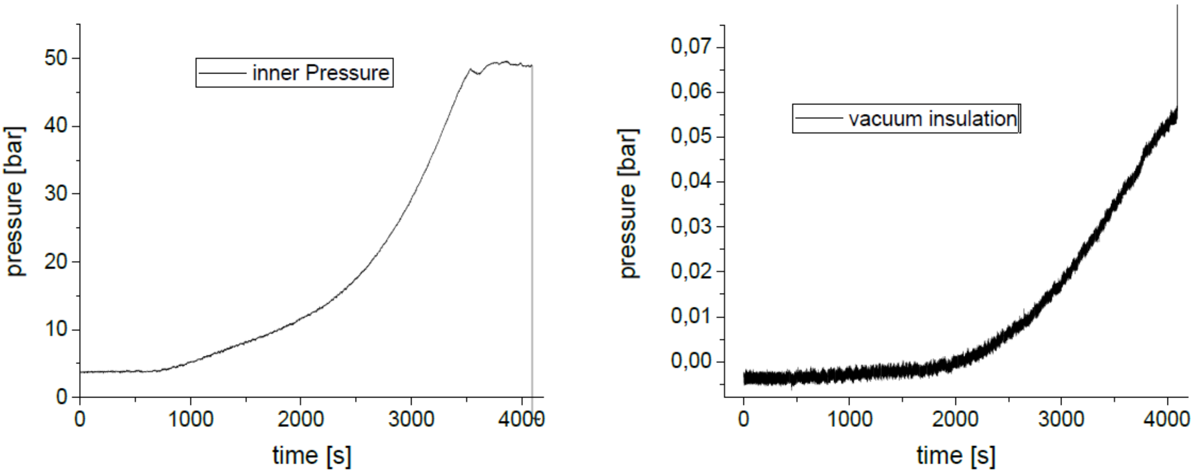
Test no.	Degree of filling of vessel	Orientation of vessel	Insulation
1	35-40 %	Horizontal	Perlite
2	35-40 %	Horizontal	MLI
3	35-40 %	Upright	Perlite

The first test was performed with the horizontally orientated vessel with perlite insulation. It could be observed that approximately 50 minutes after start of the fire loading the outer shell imploded at several locations, most likely due to weakening of the material strength by the long exposure to high temperatures and the vacuum in the space between outer and inner shell (see Figure 11b). After 75 minutes the vessel started leaking via the seal of the blind flange connection at the filling valve on top of the vessel implying that also the main filling valve, which was closed before the test, must have failed. The leak resulted in a hydrogen jet fire which was visible both on the IR cameras and by regular video due to the propane fire still burning under the vessel (see Figure 11a). The leakage caused the pressure inside the vessel to decrease considerably (from a maximum of 23.5 bar down to 10 bar within 300 s and down to 1 bar within 1000 s). This massive pressure loss led to the decision to stop the test, as the inner vessel pressure decreased so considerably that a vessel burst was impossible to achieve any more. Upon abortion the hydrogen jet fire continued but became invisible to the eye, it was detectable only with the IR-camera systems on site.


(a) (b)

Figure 11: Test with horizontal oriented vessel insulated with perlite showing (a) the jet fire during the test and (b) the damage to the vessel by the implosion of the outer shell.

The second test was performed with the MLI insulated vessel positioned horizontally. The vessel started leaking after approximately 40 minutes via an emergency release valve equipped with a pneumatic actuator, which opened at about 50 bar. After start of the leakage the pressure stayed constant at nearly 50 bar (see Figure 12a). The vessel failed catastrophically after 68 minutes. A possible contributing factor may have been that the vacuum in the space between the two shells was lost. The vacuum pressure slightly increased during the test up to 56 millibar and rapidly increased in the moment of burst (see Figure 12b). Figure 13 shows the temperature measured[47] in the upper and lower half of the vessel originally occupied by liquid and gaseous hydrogen respectively, during the second test up to the moment of vessel failure.



(a) (b)

Figure 12: Test with horizontal vessel insulated with MLI: pressure development (a) in the gas phase in the inner vessel and (b) vacuum pressure[48] in the vacuum space between the two shells.

After some time, the pressure inside the vessel was higher than the saturation pressure at the measured liquid temperature. This indicates a state of non-equilibrium. The temperature measured in the lower half of the vessel suggests together with the prevailing pressure that the hydrogen at the moment of failure of the vessel was in a supercritical condition, with a pressure of about 50 bar, well above the burst pressure of the vessel. The failure of the vessel resulted in a fireball, fragments, and blast. The fireball happening after ignition of the hydrogen had a maximum equivalent diameter of about 25.8 m. The total duration of the fire ball is about 5 s with lift-off occurring after 2 s (see Figure 14).

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[47] The thermocouples used had to be re-calibrated using liquid hydrogen, liquid nitrogen and liquid oxygen as calibration points. In spite of this small deviations from the real temperature cannot be excluded.

[48] The measured absolute vacuum pressure shows a value slightly below zero due to the influence of temperature on the pressure transducer.

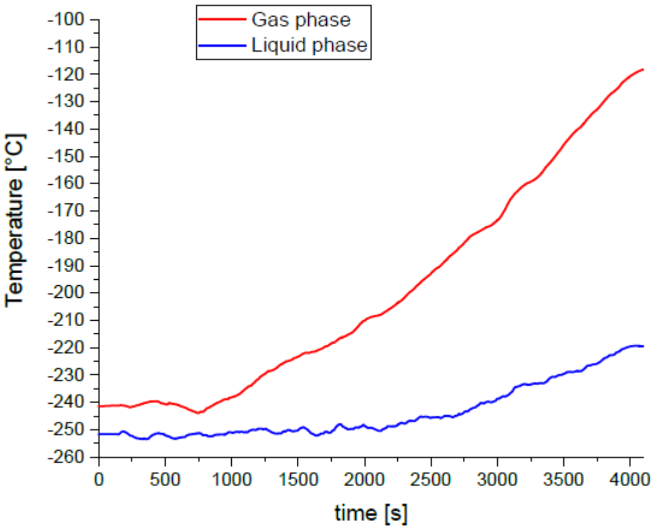

Figure 13: Test with horizontal vessel insulated with MLI: Temperature in gas phase and liquid phase.

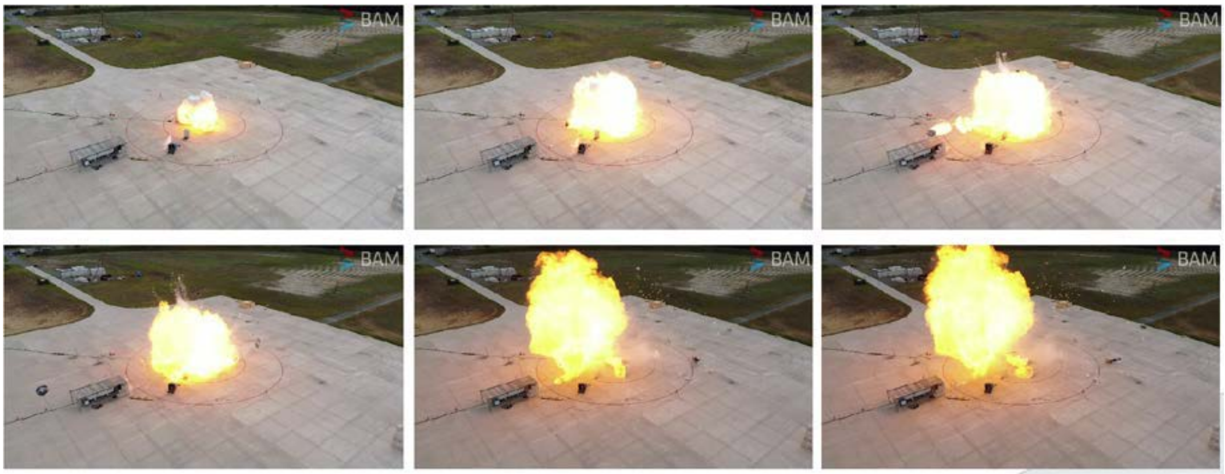

Figure 14: Test with horizontal vessel insulated with MLI: Fireball development.

Radiation measurements show a surface emissive power of the hydrogen fire ball of 60 kW/m^2 at a maximum. All together 28 fragments were recovered coming from the vessel itself. Larger parts of the vessel were found at distances between 6 m and 167 m from the original position of the vessel. Blast waves show at least two peaks occurring shortly one after another as can be seen in Figure 15 (indicated as “1” and “2” for the blast measured at 22.5 m). A third peak (“3”) occurred after 0.018 s from the moment of the first shock wave arrival at 22.5 m. At 22.5 m from the tank a maximum pressure of 133 mbar was measured and at 26.4 m 99 mbar. The first peak is probably the failure of the vessel, the second peak due to the evaporation of the liquid hydrogen whereas the third pressure wave may be related to the combustion.

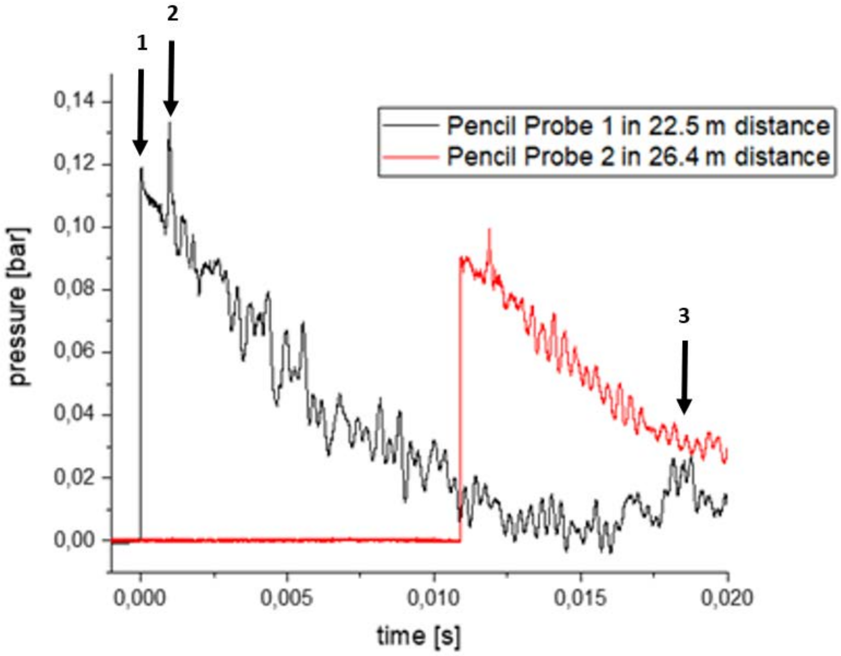

Figure 15: Test with horizontal vessel insulated with MLI: Blast waves measured at 22.5 m and 26.4 m from the centre of the vessel.

The third test was performed with the perlite-insulated vessel positioned vertically. The vessel was heated, exposed to the propane fire during 4 hours without failing. No leakage happened during this test. The test was stopped because the propane tank feeding the flame was empty. At this moment the pressure inside the vessel was 60 bar.

3.2.3 BLEVE modelling

Introduction

BLEVE can be defined as an atypical accident scenario since it is a rare event but with severe consequences. For this reason, one of the main research questions at the beginning of the SH2IFT project was “can a BLEVE explosion occur after a catastrophic rupture of an LH2 vessel?”, and if yes “what conditions are required for an LH2 BLEVE to manifest?”. During the review on LH2 BLEVE, it was confirmed that at least two BLEVEs have occurred in the past for LH2 storage systems, thus this accident scenario has an extremely low probability but severe consequences. Therefore, another research question arose: “what is the yield of the consequences of an LH2 BLEVE explosion?”. Then, the focus was placed on the formation of the phenomenon, i.e., the behaviour of both the LH2 vessel and its lading. This can provide critical information to the emergency responders intervention in case of fire and optimize their training. Therefore, the last research question for the BLEVE modelling was “what is the time to failure of an LH2 tank exposed to a fire?”. The models developed during the SH2IFT project were mainly based on adaptation of models validated for other substances (e.g., liquid hydrocarbons). Due to a delay in the experimental tests within the SH2IFT project, the safety tests carried out by BMW[45,49] were exploited to validate the developed models to simulate an LH2 BLEVE.

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[49] Pehr K. Experimental examinations on the worst-case behaviour of LH2/LNG tanks for passenger cars. Proc. 11th World Hydrog. Energy Conf. Stuttgart 23–28 June 1996, Stuttgart: 1996, p. 2169–87.

LH2 BLEVE accidents

At least two BLEVE accidents for LH2 occurred in the past. In 1974, an improper firefighting technique was the cause of an LH2 20,000 gal (approx. 76 m^3) tank failure and consequently a BLEVE explosion occurred[50]. In 1986, the Challenger Space Shuttle disaster was initiated by an O-ring rubber seal failure installed in one solid rocket booster[51]. For this reason, the hot gases which could not be held anymore in this section, escaped, and ignited. The generated flames burned against the external tank where the LH2 and LOX vessels were installed. As consequence, the vessels breached and exploded[52]. The NASA theory established that this explosion was a BLEVE[53].

Thermodynamic conditions necessary for an LH2 BLEVE to manifest

According to Reid[54], the liquid must be significantly superheated to consider the explosion after the tank rupture as severe as a BLEVE. When the superheated liquid or subcooled vapour approach the superheat limit temperature (TSL), their states may shift either from metastable to equilibrium state under small perturbations or to unstable due to large perturbations[55]. Under this thermodynamic state, a homogeneous nucleation may be attained as consequence of a rapid depressurisation. Therefore, a violent expansion which characterizes the explosion is the aftermath of this nucleation type. It must be noticed that during such event, also the vapour phase contained in the tank contributes to the explosion yield. According to Birk et al.[56], the pressure shock during a propane BLEVE is generated only by the vapour phase contribution since the liquid flashing is a slow process, thus not able to generate such an overpressure. However, this latter is responsible for fragments ejection and dynamic pressure loading of structures in the near field[56]. On the other hand, the model developed by Casal and Salla[57] to estimate the blast wave overpressure, takes into account only the liquid phase contribution.

It might happen that during an accident, the substance contained in the vessel reaches the state of either compressible liquid or supercritical fluid due to the rise in pressure and temperature. Hence, the liquid and vapour phases are not present anymore. This can be caused by different events such as a fire external to the vessel or a defect in the tank insulation of the cryogenic tanks, leading to an undesired heat transfer between the substance and the surrounding. Therefore, if the catastrophic rupture of the vessel is attained when the state

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[50] HydrogenTools. Liquid Hydrogen Tank Boiling Liquid Expanding Vapor Explosion (BLEVE) due to Water-Plugged Vent Stack 2017. https://H2tools.org/lessons/liquid-hydrogen-tank-boiling-liquid-expanding-vapor-explosion-bleve-due-water-plugged-vent (accessed June 3, 2020).

[51] NASA. Report of the Presidential Commission on the Space Shuttle Challenger Accident (1986). 1997. http://science.ksc.nasa.gov/shuttle/missions/51-l/docs/rogers-commission/table-ofcontents.html (accessed June 11, 2019)

[52] Verfondern K. Safety Considerations on Liquid Hydrogen. Forschungszentrum Jülich GmbH; 2008.

[53] Chirivella J. Analysis of the “Phantom” Fires on the Space Shuttle External Tank Base and the Nature of the Space Shuttle “Phantom” Fires: LH2 Leaks. 34th Combust. Syst. Hazards Subcomm. Airbreathing Propuls. Subcomm. Jt. Meet. JANNAF, Palm Beach, USA: 1997.

[54] Reid R. Possible Mechanism for Pressurized-Liquid Tank Explosions or BLEVE’s. Science (80-) 1979;203:1263–5.

[55] Casal J. Evaluation of the Effects and Consequences of Major Accidents in Industrial Plants. Elsevier, Amsterdam; 2008.

[56] Birk AM, Davison C, Cunningham M. Blast overpressures from medium scale BLEVE tests. J Loss Prev Process Ind 2007;20:194–206.

[57] Casal J, Salla JM. Using liquid superheating energy for a quick estimation of overpressure in BLEVEs and similar explosions. J Hazard Mater 2006;137:1321–7.

of the fluid is supercritical, the consequent explosion is called supercritical BLEVE[58,59]. Hydrogen has a low critical pressure (12.964 bar)[6] and an extremely low critical temperature (33.145 K)[6] compared with other substances and conventional fuels (hydrocarbons). For this reason, a supercritical BLEVE seems a likely scenario for a LH2 tank. In Table 5, the superheat limit temperatures estimated for normal and parahydrogen with different approaches are collected. It can be noticed that a wide range of temperature and pressure has been obtained. A thorough discussion regarding the methods used to estimate the hydrogen TSL can be found in[60,61].

Table 5: TSL and correspondent saturation pressure of normal and parahydrogen (abbreviations: EoS: equation of state, RK: Redlich-Kwong, HFE: Helmholtz Free Energy, VdW: Van der Waals, PR: Peng Robinson)

Method	EoS	Normal-hydrogen		Para-hydrogen	
		TSL (K)	P (bar)	TSL (K)	P (bar)
Empirical correlation[60]	RK	29.665	7.62	29.5	7.6
Saturated Curve Tangent[60]	-	26.765	4.68	26.2	4.2
Energy Balance[60]	HFE	32.603	11.98	32.4	11.9
Pinhasi et al.[39]	VdW	27.974	5.71	27.800	5.65
	Soave	31.256	9.80	31.061	9.69
	PR	31.421	10.04	31.225	9.93
Ustolin et al.[61]	HFE	29.143	6.99	28.940	6.89

The TSL is an important parameter that can indicate the possibility of a BLEVE to occur. However, explosions can still happen after the catastrophic loss of containment of liquefied gas containers even at temperatures below the TSL. However, in that case the explosion would not be categorised as a BLEVE due to the lower explosion yield. Nevertheless, it is not clear how to distinguish a BLEVE from a less powerful explosion based on their aftermaths such as the pressure wave yield. Finally, a limitation common to all the aforementioned methods is that the atmospheric pressure is considered as the lowest one. Instead, a pressure below atmospheric is usually reached during the negative phases of a blast wave generated by an explosion. Therefore, even a liquid at atmospheric pressure and saturation conditions is superheated when subjected to the negative phase of the pressure wave. It might be speculated that the TSL should be estimated for the lowest pressure reached during the negative phase instead of at atmospheric one. In this manner, even more conservative values can be obtained, and it may also explain why powerful explosions occurred even for liquid temperatures lower than the TSL.

BLEVE consequences

During the SH2IFT project[60,61], analytical and numerical (CFD) models were developed and employed to model the consequences of the BLEVE explosions by simulating the BMW bursting tank scenario tests[45]. The focus was mainly placed on the blast wave overpressure and the yield of the physical explosion, i.e., the

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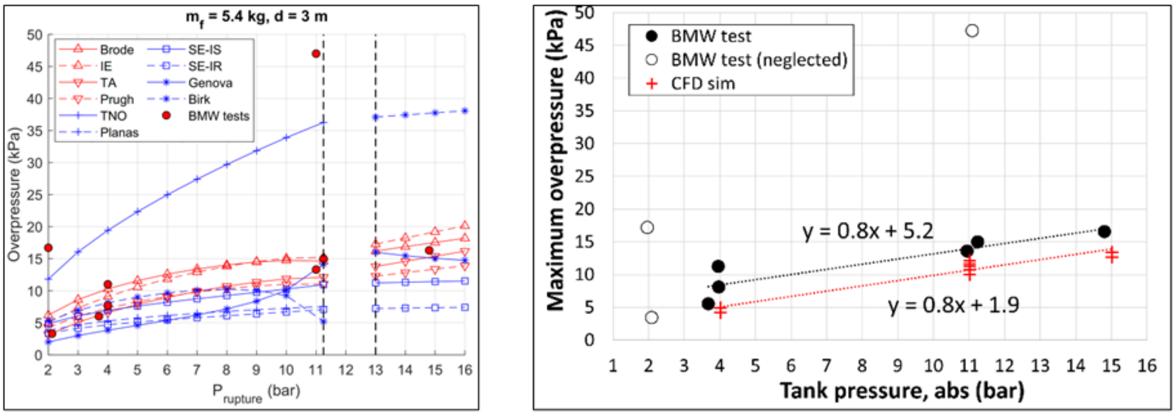
[58] Laboureur D, Heymes F, Lapebie E, Buchlin J, Rambaud P. BLEVE Overpressure: Multiscale Comparison of Blast Wave Modeling. Process Saf Prog 2014;33:274–84.

[59] Zhang J, Laboureur D, Liu Y, Mannan MS. Lessons learned from a supercritical pressure BLEVE in Nihon Dempa Kogyo Crystal Inc. J Loss Prev Process Ind 2016;41:315–22.

[60] Ustolin F, Paltrinieri N, Landucci G. An innovative and comprehensive approach for the consequence analysis of liquid hydrogen vessel explosions. J Loss Prev Process Ind 2020;68:104323.

[61] Ustolin F, Tolias IC, Giannissi SG, Venetsanos AG, Paltrinieri N. A CFD analysis of liquefied gas vessel explosions. Process Saf Environ Prot 2022;159:61–75.

combustion process was not considered. Both analytical and numerical models underestimated the maximum blast wave overpressure yield recorded during the BMW experiments as it can be noticed in Figure 16.



(a) (b)

Figure 16: Overpressure from the blast wave at 3 m from a sub- and supercritical BLEVE of an LH2 tank simulated by (a) analytical[60] and (b) numerical (CFD) models[61].

Therefore, it was speculated that a fraction of the energy generated by the combustion process (e.g., 5.2 %) should be considered for LH2 when estimating the blast wave overpressure. This was already demonstrated by Molkov and Kashkarov[62] for compressed gaseous hydrogen tanks. A methodology similar to the one proposed in [62] was recently adapted for LH2 tanks by Ustolin et al.[63] during the SH2IFT project. The new model is able to predict the highest blast wave overpressure measured during the BMW experiments but overestimates the overpressure generated at low tank pressures as it can be observed in Figure 17.

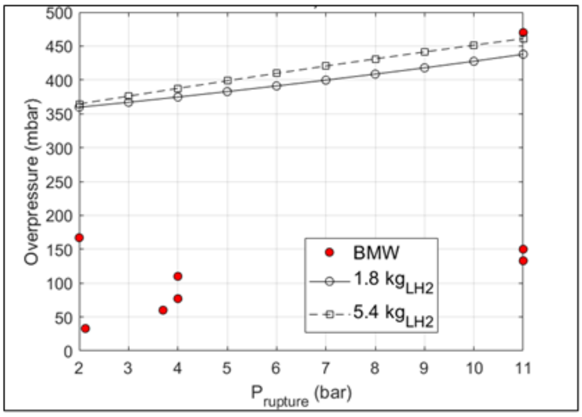


Figure 17: Overpressure of the blast wave calculated at 3 m from the LH2 tank centre for different initial tank pressures[64].

Two other typical consequences of the BLEVE explosion (missiles and fireball) were analysed by means of analytical models by Ustolin et al.[60,64]. Despite the BMW bursting tank scenario tests were simulated, it was not possible to simulate the models due to the lack in information (e.g., number of fragments, fireball radiation).

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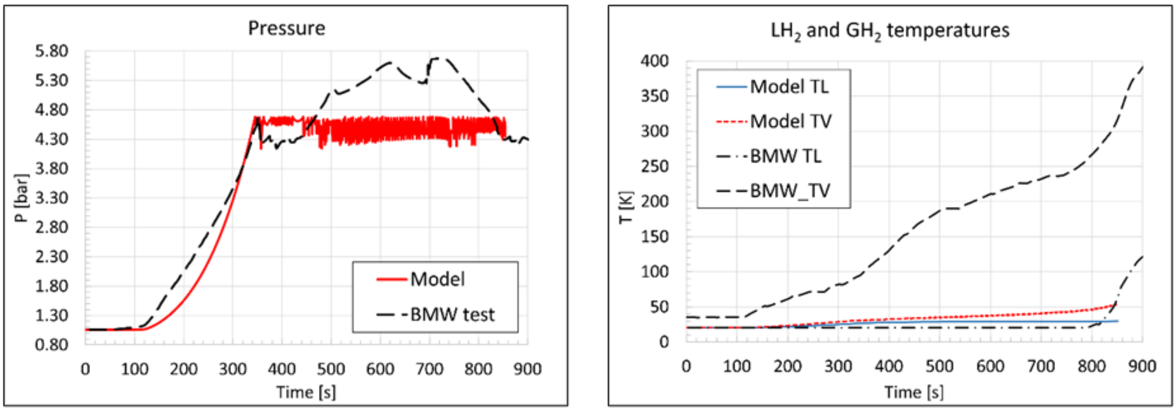
[62] Molkov V, Kashkarov S. Blast wave from a high-pressure gas tank rupture in a fire: Stand-alone and under-vehicle hydrogen tanks. Int J Hydrogen Energy 2015;40:12581–603. https://doi.org/10.1016/J.IJHYDENE.2015.07.001.

[63] Ustolin F, Giannini L, Pio G, Salzano E, Paltrinieri N. On the Mechanical Energy Involved in the Catastrophic Rupture of Liquid Hydrogen Tanks. Chem Eng Trans 2022;91:421–6. https://doi.org/10.3303/CET2291071.

[64] Ustolin F, Paltrinieri N. Hydrogen fireball consequence analysis. Chem Eng Trans 2020;82:211–6.

Performance of the cryogenic LH2 tank engulfed in a fire

The ignition of an accidental fire in the vicinity of the tank containing a liquefied gas is usually one of the main causes that may lead to the catastrophic rupture of the vessel and eventually to a BLEVE. During SH2IFT, the behaviour of the tank lading when the container is engulfed in a fire was simulated by means of both analytical and numerical models. The case study was the BMW fire test on an LH2 tanks designed for automotive purposes[49]. The lumped model developed in [65] based on the thermal nodes approach was able to estimate the heat and mass balances on the vessel and its content exposed to the fire by considering the boiling regime phenomena, heat-up and pressure build up in the cryogenic tank. Therefore, the opening and closing of the pressure relief valve (PRV) and the hydrogen venting could also be simulated.



(a) (b)

Figure 18: Comparison between the experimental measurements and the analytical model results of the evolution in time of (a) the pressure build up inside the tank and (b) LH2 (TL) and gaseous hydrogen (TV) temperatures inside the vessel during the fire test[65].

The model was proven to be a reliable engineering tool to estimate the pressure build up inside the tank exposed to a fire and the evaporation of its content. A good agreement with the experimental measurements was achieved, with slightly conservative outcomes from the simulation (see Figure 18a). The advantage of the analytical model is the relatively low computational demand, thus short total simulation time compared with other techniques such as computational fluid dynamics (CFD). Furthermore, the model can be easily tuned for different substances by changing the thermodynamics properties. On the other hand, the main limitation of the model is the inaccurate estimation of the temperatures (see Figure 18b). This is an intrinsic limitation of the thermal nodes approach which is not able to simulate the thermal gradients developed in the vessel during a real case scenario.

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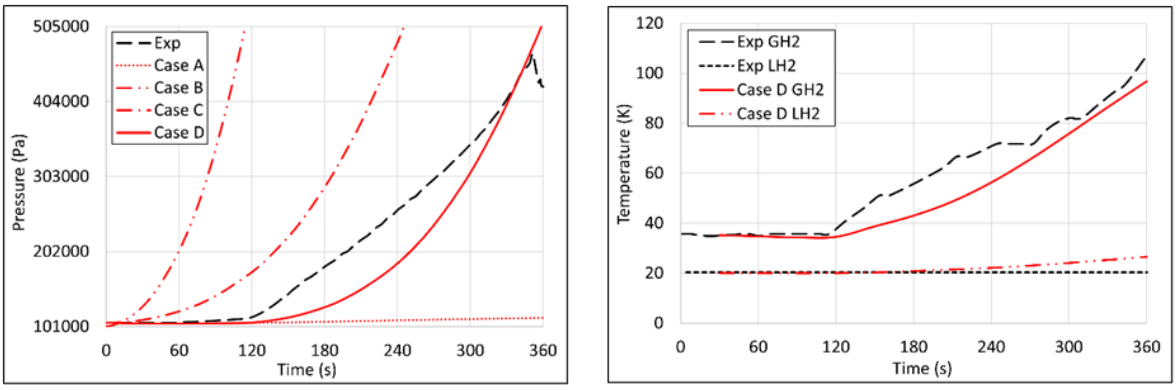
[65] Ustolin F, Iannaccone T, Cozzani V, Jafarzadeh S, Paltrinieri N. Time to Failure Estimation of Cryogenic Liquefied Tanks Exposed to a Fire. 31st Eur. Saf. Reliab. Conf., 2021, p. 935–42.



(a) (b)

Figure 19: Comparison between the (a) pressures and (b) lowest LH2 and highest GH2 temperatures estimated by the CFD analysis for the different case studies (red lines) and measured during the experiment (black lines)[66].

The main advantage of the numerical (CFD) model developed by Ustolin et al. [66] when simulating the same experiment was a higher accuracy compared to the analytical model. A common issue to both types of models is the determination of the thermal conductivity value which increases when the tank is exposed to the fire due to the degradation of the insulation material and the loss of vacuum. In Figure 19a, the results (tank pressure build up) of the simulations carried out with different values of thermal conductivity of the tank insulation are shown, while the trends of the lowest LH2 and highest GH2 temperatures in Figure 19b are displayed. Both models could be employed to assess the time to failure of the tank by estimating the mechanical stresses generated by the internal tank pressure as well as the decrease in mechanical properties of the tank materials provoked by the raise in temperature.

3.3 Gaseous hydrogen jet fire

3.3.1 Introduction

The nature of a hydrogen jet flame is fundamentally different compared to other fires that can be expected in vehicles. As the pressure in the GH2 tank in the vehicle can be several hundred bar and will be released if the thermally activated pressure relief device (TPRD) is activated. This will result in a high-pressure transient jet release. When ignited, this will have the highest heat release immediately and gradually decrease as the tank is emptied. Compared to other gaseous fuels, hydrogen has a very high speed of combustion and low radiative fraction. This means that the gas temperatures in the jet flame will be higher and the radiative heat from the flame will be lower than a comparable jet flame with other gaseous fuels[67]. The available literature contains several experiments with hydrogen jet releases in the open, but limited information was available on the thermal exposure to surfaces that are impinged and engulfed by hydrogen jet fires.

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[66] Ustolin F, Scarponi GE, Iannaccone T, Cozzani V, Paltrinieri N. Cryogenic Hydrogen Storage Tanks Exposed to Fires: a CFD Study. Chem Eng Trans 2022;90:535–40.

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3.3.2 Jet fire experiments

Test setup

The test setup is designed to create a hydrogen gas jet flame with characteristics typical for a jet from a TPRD in a passenger car. When a hydrogen powered vehicle is exposed to a fire, the content of the high-pressure hydrogen storage tank will be released to prevent the tank from rupturing. When this occurs in an enclosed environment, the hydrogen jet flame will impinge on the surrounding surfaces and may completely engulf a volume. Relevant cases for such scenarios can be all enclosures that hydrogen vehicles can enter, like tunnels, garages, bus terminals, ro-ro ships, etc. To quantify the severity of such an enclosed hydrogen jet fire, the test setup is made to release a hydrogen jet fire onto panels representing varying degrees of enclosure and measure the thermal load to the exposed surfaces of the enclosure.

Figure 20: Enclosure configuration with 5 panels. Box with an open front face. The test shown is T16 (J45-5P) with the jet angled 45° down onto the floor panel approximately 1 second after ignition.

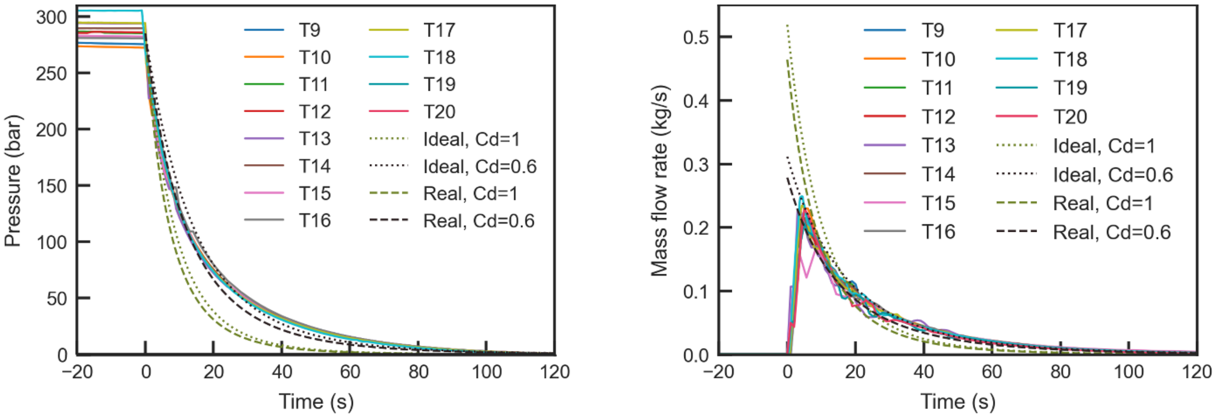
The jet is ignited and directed horizontally or 45° down onto 3 m × 3 m steel panels with embedded temperature measurements. Three different configurations of these steel panels are used, one panel on the ground, two panels: one on the ground and one rear wall, and finally five panels creating an enclosure with an open front (see Figure 20). The hydrogen is released freely from the tanks with a total of ~5.5 kg hydrogen at an initial pressure of ~280 barg through a 6 mm nozzle simulating a blow down with transient pressure and flow as the tanks are emptied. In total 21 jet fire experiments have been conducted, whereof 8 were used as pretests to develop the experimental setup, 12 where part of the main experimental campaign and 1 was conducted with propane as a reference experiment. All the 12 tests in the main experimental campaign were conducted with the same jet release configurations and measurements of pressure and flow show a good repeatability between the experiments as seen in Figure 21. The test matrix can be seen in Table 6.

Table 6: Test matrix

ID*	$T_{Ambient}$ (°C)	Relative humidity (%)	Wind speed (m/s)	Wind heading (from)	Jet direction (towards)	Jet position. x, y, z distance from origin (m)	Initial manifold pressure (barg)
T9 (J90-1p)	0	95	0.6	NW	N	1.5, 1, 0	275
T10 (J90-1p)	0	95	0.3	N	N	1.5, 1, 0	272
T11 (J45-1p)	8	63	0.6	W	E	1.5, 0.4, 0.4	285
T12 (J45-2p)	5	76	0.6	NE	E	1.5, 0.4, 0.4	286
T13 (J90-2p)	10	60	0.8	NE	N	1.5, 1, 0	293
T14 (J90-2p)	9	66	1.4	SW	N	1.5, 1, 0	290
T15 (J90-5p)**	13	84	0.6	SW	N	1.5, 1, 0	282
T16 (J45-5p)	10	81	0.6	SE	N	1.5, 1, 0	281
T17 (J45-2p)	5	62	0.6	E	N	1.5, 1, 0	Not measured
T18(J90-2p)	6	57	1.4	E/NE	N	1.5,1,0.7	294
T19 (J90-5p)	22	45	0.8	E/NE	N	1.5, 1, 0	Not measured
T20 (J45-5p)	24	38	1.1	NE	N	1.5, 1, 0	305
T21* (J90-5p)	27	35	0.6	E/NE	N	1.5,1,0	8

*Propane reference experiment.

**Although T15 (J90-5p) was conducted, only limited data were recorded due to the logger's malfunction. In addition, the insulation material was relatively damp, as clear water steam can be observed after the ignition of hydrogen. Therefore, only the manifold pressure and mass flow rate for T15 (J90-5p) was included in this study.



(a) (b)

Figure 21: Manifold (a) pressure and (b) flow rate measured in the experiments and compared to a tank blowdown model.

Flame characteristics

Although it has been widely believed that hydrogen burns with a nearly invisible pale blue flame, yellow flames were observed at different intensity in all conducted tests of hydrogen jet fires. Figure 22 shows the flame characteristics of the hydrogen flame in the test T10 (J90-1P). The test was performed at low ambient light conditions and the flame was clearly visible. The visible light and infrared images were both captured approximately 2.5 seconds from the start of the jet release.

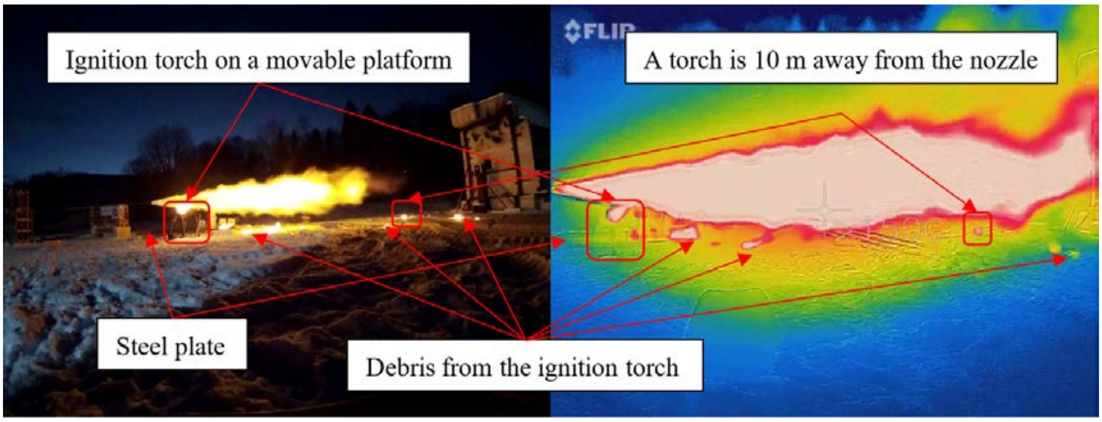


Figure 22: Visible light (left) and infrared (right) photos taken at around 2.5 s after the valve opening in the test T10 (J90-1P).

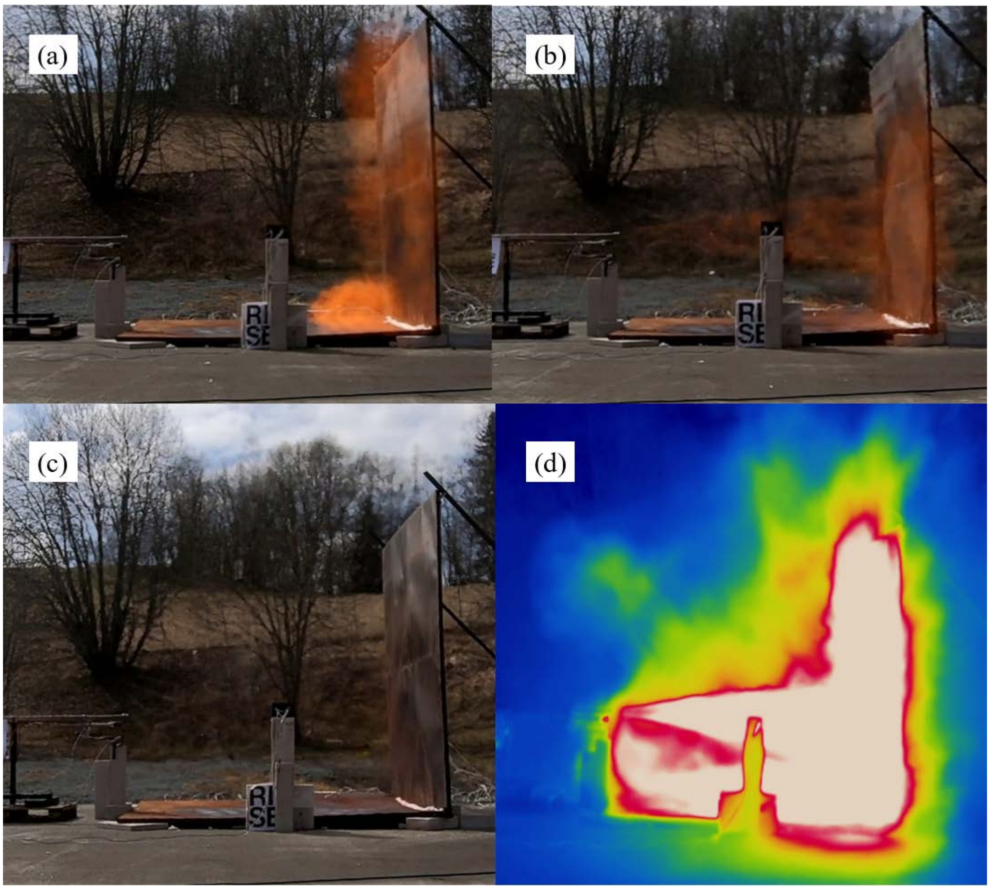


Figure 23: Visible light photos taken at the beginning of the experiment (a), at around 2 s after the valve opening (b), at around 10 s after the valve opening (c), and infrared photos taken at around 10 s after the valve opening (d) in the test T13 (J90-2P).

Figure 23 shows the flame characteristics of the hydrogen flame in the test T13 (J90-2P). Visible flames can be observed from Figure 23 (a) and Figure 23 (b) at the very beginning of the test. Such visible flames were most likely caused by the dust on the surface of the steel plates. After all the dust has been blown away, the flame started to become invisible as shown in Figure 23 (c), which was taken at around 10 s after the valve opening during the test. Such observation has also been reported before by Willoughby and Royle in the large-scale tests[68], in which hydrogen flames were nearly invisible before hitting objects or close to the ground under daylight conditions. Figure 23 (d) shows an infrared image of the flame at the same time as the picture in Figure 23 (c) illustrating the large difference in signature in the infrared and visible light spectrum.

Comparison between impinging and confined jet fires

The measured temperatures during T13, T14, and T19 are shown in Figure 24. Figure 24 (left) shows the maximum steel temperature caused by a horizontal jet fire impinging onto the rear wall of a target consisting of two steel panels (T13 and T14) and a target consisting of five steel panels (T19). The time from release start to the maximum steel temperature is shown on the right-hand side of Figure 24. Each of the "small" squares in the contour plots represents a single thermocouple measurement. Note, white squares represent locations that have not been logged. Furthermore, it can be seen that some of the measurements are apparently wrong, for example, the top left corner of the rear wall in T19. This is because some of the thermocouples lost contact with the backside of the steel panels after multiple experiments that caused the steel panels to buckle. The buckling of the steel panels was also the reason for changing the floor (i.e., bottom panel) with a new one after T16. Experiment T14 is a repetition of T13. It can be seen that the resulting steel temperatures for these two experiments are similar. Note, two thermocouples on the rear wall were broken after T13.

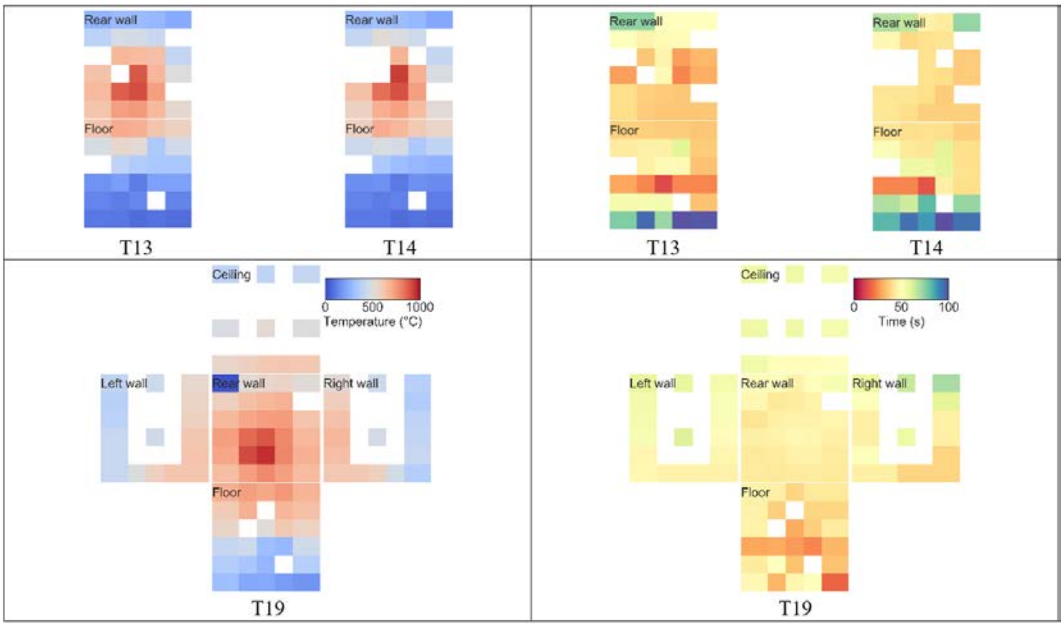


Figure 24: Maximum temperature measured locally, each square representing one thermocouple, during the experiment (left). Time from the start of the release until the maximum temperature is measured (right). The experiments T13 (J90-2p), T14 (J90-2p) and T19 (J90-5p) are shown.

Both configurations, two panels and five panels, led to a similar maximum temperature of 900 °C-960 °C, reached after 40-50 seconds at the rear wall. The main difference between the impinging in the confined jet fire is the extent of the high-temperature region. The entire rear wall as well as more than half of the bottom plate, exceed 500 °C for the confined jet fire, while only approximately 1/3 of the bottom plate exceeds 500 °C for the impinging jet fire. It can also be seen in T13 and T14 that it takes around 75 seconds and more to reach the local maximum temperature in the regions furthest away from the impingement area, which indicates that this temperature increase is caused by the heat conduction within the steel panels, as the hydrogen mass flow rate is already significantly reduced at this point (see Figure 21).

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[68] D. B. Willoughby and M. Royle, "The interaction of hydrogen jet releases with walls and barriers," International Journal of Hydrogen Energy, vol. 36, no. 3, pp. 2455–2461, Feb. 2011.

Comparison between hydrogen and propane jet fires

Figure 25 shows a comparison between a hydrogen jet fire and a propane jet fire. Both jet fires are impinging horizontally onto the rear wall of the 5-panel confinement. The top figures show the maximum local temperature (left) and time to reach the maximum for the hydrogen fire (right). The hydrogen fire is based on a blowdown scenario (see Figure 21), while the propane jet fire is based on the ISO 22899-1 standard[69] jet fire with a constant propane mass flow rate of 0.3 kg/s. Hence, it is not possible to directly compare the two scenarios. However, the reference fire test with propane makes the 5-panel target used in this study comparable to well-known jet fire tests. Furthermore, it is possible to inspect some of the differences between the two different scenarios by selecting specific times during the propane experiment. After 50 seconds, the chemical energy of the released propane is comparable to the total chemical energy stored in the hydrogen reservoir. A time of 50 seconds is furthermore comparable to the time when the local maximum temperatures in the hydrogen experiment are reached. The local maximum steel temperatures for T21 at this time are shown in Figure 25, bottom left. Notably, the temperature distribution is comparable between the propane and hydrogen fire in most areas. However, the high-temperature region in the impinging zone that is visible for T19 is not present for T21.

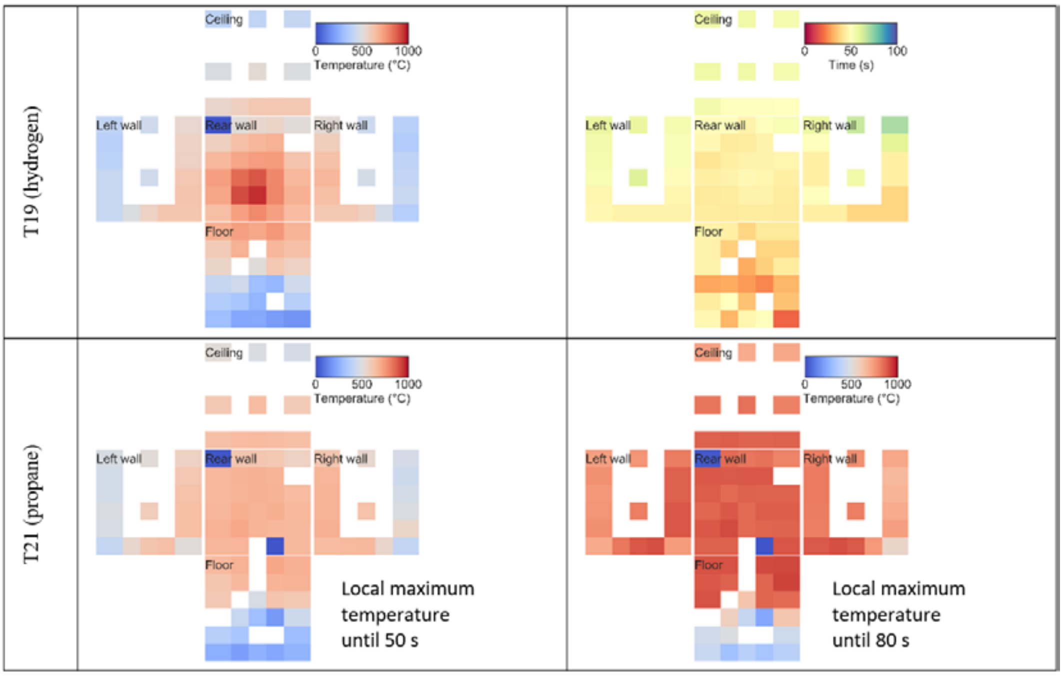

Figure 25: Maximum temperature measured locally, each square representing one thermocouple, during T19 (upper left) and T21 (until 50 s, lower left). Time from the start of the release until the maximum temperature is measured during T19 (upper right) and T21 (until 80 s, lower right).

After a release duration of approximately 80 seconds, the maximum steel temperature for T21 reaches similar values as the highest measured temperature in T19, which is around 960 °C. The highest temperatures in the T21 experiment are interestingly first reached in the corner region of the floor panel and not around the impinging point at the rear wall. This could point to a locally under-ventilated fire. It was noted during the experiment that parts of the flames burned outside of the confinement. The thermal radiation between the different panels may also be a contributing factor.

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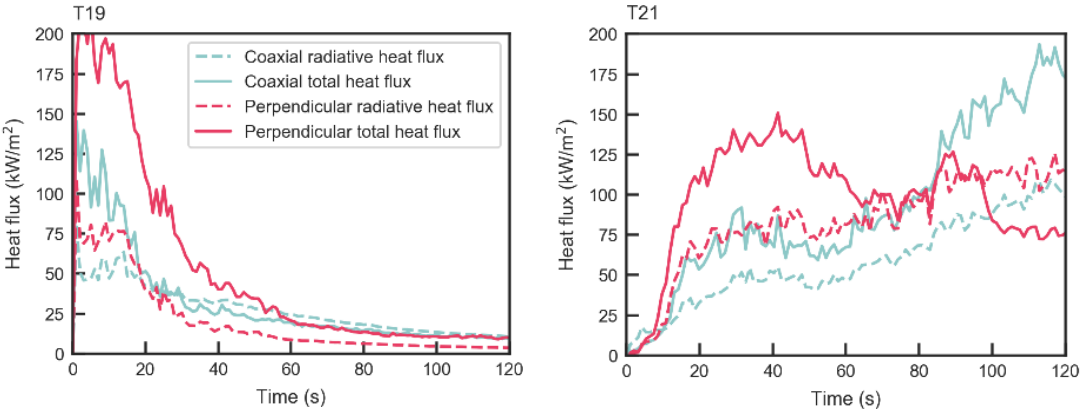
[69] ISO 22899-1:2007 Determination of the resistance to jet fires of passive fire protection materials. Part 1: General requirements. ISO Copyright office, 2007.

Figure 26 shows the total and radiative heat flux measured by heat flux meters facing in coaxial and heat flux meters facing perpendicular (90° to the right) direction relative to the jet release direction for the hydrogen (left) and the propane (right) jet fire. The hydrogen jet fire results immediately in a high heat flux exceeding the calibrated range of 200 kW/m^2 in the perpendicular direction. On the other hand, the propane experiment shows a much slower increase of the heat flux, which can be partially explained by a delay of ca. 10 seconds before the full propane flow rate is reached. The heat flux decreases following the decreasing release rate. Hence, the highest heat flux of 150 kW/m^2 and more, which is comparable to typical design heat fluxes used for hydrocarbon fuels, is limited to the first 20 seconds only. However, the total heat flux on the right wall is still above 20 kW/m^2 until 60 seconds, which can be critical in terms of fire spreading to some parts of adjacent vehicles[70]. More than half of the total heat flux to the site panel in T19 is contributed to convection at the beginning of the experiment and is considerably larger compared to the heat flux measured coaxial to the release direction. The heat fluxes decrease over time and reach a similar magnitude in both measurement locations after 20 seconds (for the radiation) to 60 seconds (for the total heat flux).



(a) (b)

Figure 26: Radiative and total heat flux measurements in coaxial (i.e., same as the jet release) and perpendicular (i.e., 90° to the right of the jet release) direction for (a) a hydrogen jet fire and (b) a propane jet fire (right).

The radiative heat flux seen from the heat flux meter at the sidewall was larger before the 20 second mark than the heat flux measured at the release location. This is the opposite after the 20 second mark. The heat flux meter located on the sidewall sees a larger flame cross section compared to the coaxially located flux meter, which sees more of the back wall. This means that when the radiative heat flux measured in the coaxial direction is larger than the heat flux at the sidewall, the thermal heat radiation from the hot back wall panel dominates the thermal radiation from the hydrogen flame. Note, this is a simplified view as all walls will exchange thermal radiation with each other, considering their individual viewing factors.

The measured heat flux for the propane experiment, on the other hand, is continuously increasing as the release rate is constant. This is with exception to the total heat flux measured perpendicular to the release at the right sidewall. The total heat flux and radiative heat flux are equal here, after approximately 60 seconds and the radiative heat flux is higher compared to the total heat flux after around 100 seconds. The cause for this is not known. However, it is believed the water cooling of the total heat flux meter might have been damaged during the experiment, which could have caused this behaviour. The experiments show that flame radiation seems to play a larger role in the propane jet fire, which is in line with other studies reported in the literature. However, it should be noted that the hydrogen fire in T19 was not completely invisible and showed a yellow/orange colour, which could have been caused by contaminations in the air (e.g., particles entrained from the ground and panels).

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[70] Fire spread in car parks, Report BD2552, Building Research Establishment, 2010.

3.3.3 Jet fire modelling

The main objective of jet fire consequence modelling is to calculate consequences such as flame lengths, trajectory, and heat fluxes for loss of containment events and identify possibly mitigating measures that could be taken to reduce consequences. In addition, modelling can help to understand relevant physical phenomena. In the SH2IFT project several aspects related to modelling hydrogen jet fires were investigated. This focused on three main aspects:

1. **Creation of a FLACS-CFD validation matrix/knowledge base:** A list of experimental cases available in the public domain was compiled, with detailed scenario descriptions. The new jet fire experiments conducted as part of the SH2IFT project were also added to the validation matrix.
2. **Refinement of modelling in FLACS-CFD:** Various approaches for improving the models in FLACS-CFD were investigated to improve predictive accuracy and getting more insight into hydrogen jet fire phenomena.
3. **Modelling and validation of the key cases in the validation matrix:** The most important cases in the validation matrix were identified, and these were modelled in various consequence modelling tools available in industry (incl. HYRAM and FLACS-CFD).

Validation matrix/knowledge base

Constitution of a validation matrix for consequence modelling of hydrogen gaseous fires (validation against experimental data and inter-comparison) is one of the knowledge gaps that had been identified in SH2IFT WP 3.1. A validation matrix was created in SH2IFT WP 3.2 including a number of relevant, well-documented experiments, to be able to evaluate various aspects of the physics of gaseous hydrogen fires. The matrix was built in a way so that simulations can be repeated efficiently to evaluate the effect of model changes during the development of the tool. The updated list of experiments for the validation matrix is presented in Table 7, where each campaign covers 2-12 individual experiments and includes the 12 SH2IFT jet fire experiments performed by RISE (SH2IFT WP 2.1).

Model improvements to FLACS-Fire

The detailed validation of previous generation of FLACS-Fire solver revealed inherent limitations in the modelling of large horizontal jet flames, in terms of the flame shape that appears to be more buoyant than in the experiments. To improve the performance of the FLACS-Fire solver for these types of scenarios two main approaches were identified:

1. Improve the source term model to better match the velocity,
2. Change the turbulence model, to reduce buoyancy for these scenarios.

With both approaches, it was important to ensure that not only the performance for horizontal hydrogen jet fires was improved, but that the performance on vertical and included releases was not negatively impacted.

This work presents assessment of implemented two alternative source term models. It was shown that the Ewan-Moodie source term model improved results significantly and was later added to FLACS-Fire as default model.

Table 7: List of experiments for validation matrix for hydrogen jet fires

	Campaign name	**Key campaign characteristics**	**Reference**
1	GL Large-scale horizontal hydrogen jet fires	Large scale horizontal jet fires (1-7.4 kg/s)	Ekoto et al. (2014) [71]
2	Cryogenic Hydrogen jet Fires	Medium scale (0.33 – 0.63 kg/s) incl. low temperatures (64 K and higher)	Cirrone et al. (2019) [72]
3	INERIS Horizontal Hydrogen jet fire	Medium scale hydrogen/methane mixtures. Release inside a channel with cross section of 12 m^2	Studer et al. (2009) [73]
4	SRI Large Release jet fire Experiment	Large scale vertical jet fires	Groethe et al. (2007)[74]
5	HSL impinging jet fires	Medium scale horizontal, impinging on vertical and inclined walls	Willoughby et al. (2011) [75]
6	NATURALHY jet fires	Large scale horizontal jet fires (3 – 20 kg/s) with mixtures of 24 % hydrogen in natural gas	Lowesmith et. al. (2012) [76]
7	NATURALHY Pipe rupture	Large scale jet fire from a pipeline crater for mixture of 22.3 % hydrogen in natural gas	Lowesmith et. al. (2013) [77]
8	SH2IFT jet fires	Medium scale horizontal jet fires with varying geometry behind jet fire (free jet, wall, and chamber)	SH2IFT WP2 reports (2019-2022)

Secondly this work presents detailed sensitivity studies to understand effect of second turbulence coefficient ($C_{\varepsilon 2}$) on flame length, trajectory, and radiative heat flux. For a limited set of the large-scale horizontal jet flames, the results shown in Figure 27 seemed to suggest that the second turbulence coefficient of 1.8 gives better estimation of all three output variables for a limited number of large-scale horizontal jet flames. However, further sensitivity work outside the SH2IFT project showed that for a wider range of scenarios unfortunately it was not better overall, and it was decided to not implement these changes in the commercial version of FLACS-CFD. Despite it not being better overall, this investigation has given us useful new insight and helped identify future approaches to improving the model, including improving the way chemical time scales are modelled and potentially evaluating other commonly used k-epsilon turbulence models variation such as RNG and realizable.

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[71] I.W. Ekoto, A.J. Ruggles, L.W. Creitz, J.X. Li, Updated jet flame radiation modeling with buoyancy corrections, International Journal of Hydrogen Energy, Volume 39, Issue 35, 3 December 2014, Pages 20570-20577.

[72] D.M.C. Cirrone, D. Makarov, V. Molkov, Thermal radiation from cryogenic hydrogen jet fires, International Journal of Hydrogen Energy, Volume 44, Issue 17, 2 April 2019, Pages 8874-8885.

[73] Studer, E., Jamois, D., Jallais, S., Leroy, G., Hebrard, J., Blanchetière, V., Properties of large-scale methane/hydrogen jet fires, Int. J. Hydrogen Energy, 34, (2009), 9611-9619.

[74] Groethe, M., Merilo, E., Colton, J., Chiba, S., Sato, Y., Iwabuchi, H., "Large-scale hydrogen deflagration and detonation", International Journal of Hydrogen Energy v.32, 2007, pp. 2125 – 2133.

[75] D. B. Willoughby and M. Royle, "The interaction of hydrogen jet releases with walls and barriers," International Journal of Hydrogen Energy, vol. 36, no. 3, pp. 2455–2461, Feb. 2011.

[76] Lowesmith, B.J., Hankinson, G., 2012., Large-scale high-pressure jet fires involving natural gas and natural gas/hydrogen mixtures. Trans. IChemE Part B: Process Safety Environ. Protect. 90, 108–120.

[77] Lowesmith B.J., Hankinson G., Large scale experiments to study fires following the rupture of high-pressure pipelines conveying natural gas and natural gas/hydrogen mixtures, Process Safety and Environmental Protection, 91, 2013.

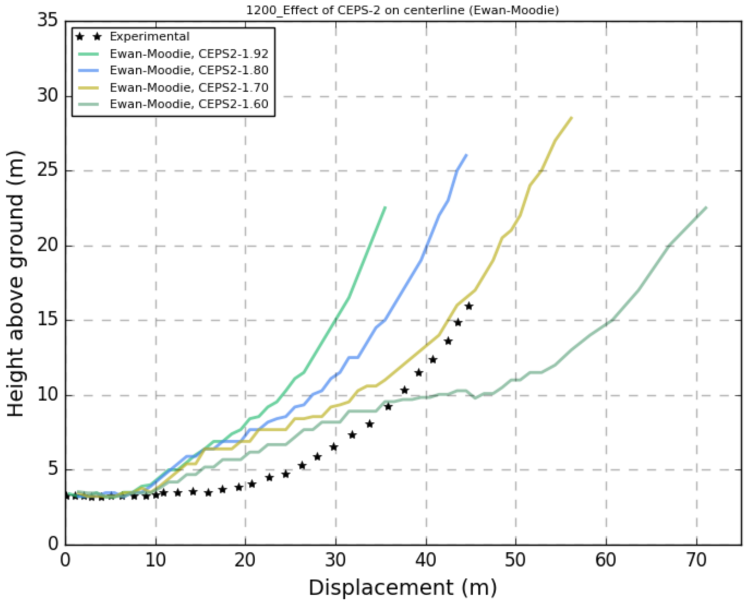


Figure 27: FLACS-Fire Flame centreline trajectories vs GL Test 2 experiment for various CEPS2 values

Modelling and validation key scenarios in validation matrix

The main objective of the validation is to verify that consequence models predict relevant consequences values and trends over a wide range of scenarios with acceptable accuracy and identify where models perform less well, to allow users to use the models with confidence for other types of scenarios.

Comparisons were made between the experimental data and FLACS-CFD simulations. As an example, some of the SH2IFT cases are presented here. As there were some inconsistencies in the experimental total heat flux measurements (e.g., lower than radiative heat flux, which is unphysical), only results for heat radiation will be shown. In Figure 28, the geometry configurations, with grid, for the SH2IFT jet fire experimental cases are shown.

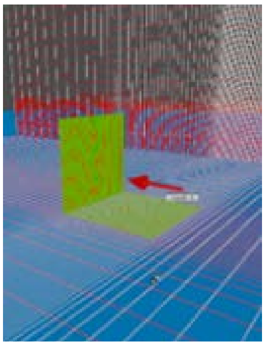


Figure 28: FLACS-CFD geometry and grid setup for SH2IFT jet fire experiments for the three different geometry configurations.

Subsequently these cases were added to the proprietary FLACS-CFD validation framework so the validation can be repeated efficiently to evaluate the effect of model changes during the development of the tool and for future versions.

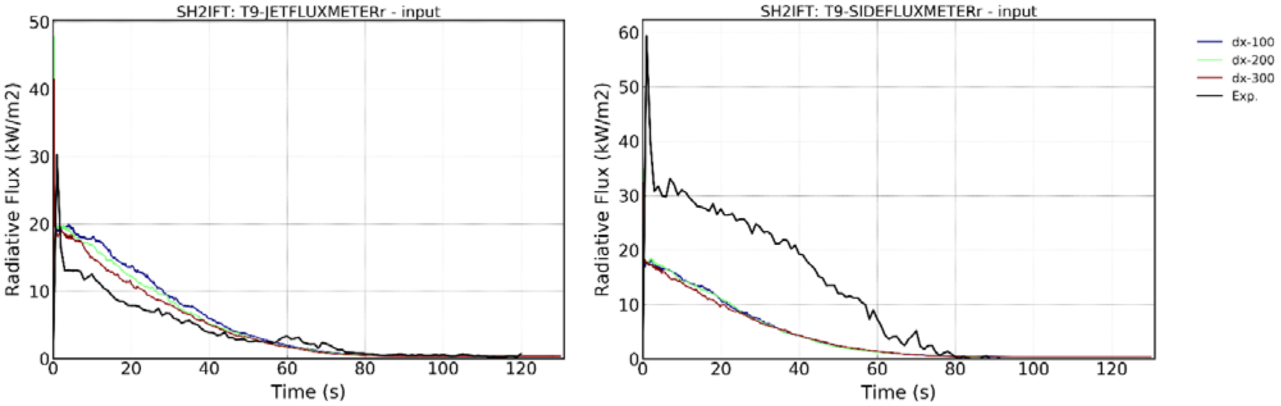


Figure 29: FLACS-CFD simulated radiative flux (with 3 different grid resolutions) vs. measured for jet fires

Overall, the validation work shows that for the FLACS-CFD simulation the flame shape, flame length and radiative heat fluxes from small to medium-scale hydrogen jet flames (< 15 m) compare favorably to experimental measurements. FLACS-CFD overpredicts the buoyancy effect at the far end of large-scale hydrogen jet fires. However, it was shown that the proposed turbulence constants allow for a possible future route to improving the model. The validation work for the empirical/integral tools (HYRAM, EFFECTS and FRED) was carried out on a more limited number of cases, but also show excellent agreement for flame lengths and reasonable to good agreement for heat radiation especially for the smaller leak sizes.

Conclusions on jet fire modelling

A validation matrix with relevant and well-documented hydrogen jet fire experiments (both from the new SH2IFT jet fire experiments and the previously conducted experiments in the public domain), was compiled, to address an identified knowledge gap. This matrix is valuable to the entire industry as it can be used to evaluate any type of consequence modelling tool in future. All the cases in the validation matrix were modelled and validated for FLACS-CFD and a limited subset of the cases were also modelled in other consequence modelling tools (EFFECTS, FRED and HYRAM). FLACS-CFD perform well for heat flux, flame length and flame trajectory for small to medium-scale hydrogen jet flames (< 15 m). FLACS-CFD still overpredicts the buoyancy effect at the far end of large-scale hydrogen jet fires and is an area that can be further improved in future. The empirical/integral tools (HYRAM, EFFECTS and FRED) showed excellent agreement for flame lengths and reasonable to good agreement for heat radiation especially for the smaller leak sizes. This work also presented parametric studies to investigate various approaches to further improving the performance for horizontal hydrogen jet fires. Two approaches were considered

- The pseudo source models in FLACS-CFD (Jet utility and Ewan-Moodie) are varied to study its effect on the flame length and flame profile. The results show the FLACS-CFD with Ewan-Moodie pseudo source model perform best compared to others.
- The effect of turbulence constants on flame trajectory and flame length. The objective of this sensitivity study is to find a set of optimum k-epsilon turbulence model constants which works well for different type of jet fires.

Useful insights into the phenomena were gained from the FLACS-CFD modelling:

- In the FLACS-CFD simulations with enclosed geometry, surfaces that were not directly impinged by the jet flame underpredicted heat fluxes. This can be explained by the panel-to-panel radiation that was not included in the FLACS-CFD simulations. In future FLACS-CFD modelling this effect should be included.
- When the jet nozzle was close to the impinging surface, simulations showed a relatively cold spot on the surface at the impinging center consistent with previous GH2 and hydrocarbon experiments in literature. However, this was not observed in the SH2IFT experiments, most likely due to the coarse resolution of the measurements.

3.4 Societal concerns

The interest in hydrogen fuel has risen in recent years as a low/zero-emission alternative to fossil fuels in the transport sector. Despite continued advances in hydrogen and fuel cell technologies, societal barriers to mainstream adoption remain. This work package explores these societal barriers and focuses on public perception through the dimensions of awareness, perceived sustainability, and perceived risk to identify potential drivers and barriers to hydrogen fuel adoption.

3.4.1 Hydrogen and the Norwegian transport system

The Norwegian transport sector is a good case country for investigating societal barriers for several reasons: (1) Norway has a long history of large-scale production of hydrogen, through both electrolysis and gas reformation. (2) Norway has also been a major exporter of oil and gas for decades. As the recognition of the negative effects of fossil fuel use gains traction in Norway and internationally, large-scale hydrogen production through natural gas reformation represents an opportunity to continue energy exports by building on the foundation of existing actors, networks and institutions in the oil and gas sector. (3) Almost all electric power in Norway is generated from renewable resources. Hydrogen production through electrolysis can be carried out anywhere one has access to water and the electric grid. (4) Norway is a country of first adopters when it comes to transitioning away from fossil fuels in transport. As electric vehicles (EVs) account for an increasing share of vehicles and vessels, hydrogen can serve as a complement in those areas that are not best suited for battery solutions. (5) Norway's geography poses challenges for battery electrification, and complementary opportunities for hydrogen, with respect to long distances between destinations and the prevalence of hard to electrify segments like ferries and aviation. (6) The 2019 explosion at a hydrogen refueling station outside of Oslo presents a unique and relevant empirical case for the study of public perception of safety in the aftermath of a real-world incident.

The use of hydrogen fuel in Norwegian transport is currently in the phase of piloting with limited efforts at commercialization. The passenger vehicle segment is increasingly dominated by battery electric vehicles (BEVs). The market share of BEVs for new vehicle sales crossed 50 % in 2020 and is nearly 80 % for 2022 (OFV, 2022). As older petrol and diesel vehicles are phased out, it is expected that a majority of the Norwegian passenger vehicle fleet will be electric before the end of the decade. Unlike BEVs, hydrogen cars were not able to benefit from an already existing energy infrastructure (i.e., the electric grid) and parallel innovations in other sectors (e.g., lithium-ion advances in consumer electronics). Sales figures of hydrogen passenger vehicles were small but growing right up until the 2019 hydrogen refueling station (HRS) explosion, in the aftermath of which sales never recovered. Since the HRS incident, efforts to introduce hydrogen fuel are increasingly focused on heavy-duty land and maritime transport.

In the bus and ferry segments, public tendering and piloting have been a key tool for the introduction of new technology – it can also serve as an effective way to avoid the 'chicken and egg' problem hereby infrastructure will not get built until a proven market is evident, and a market will not develop until the infrastructure is in place. A fleet of five urban public transit buses were in operation in Oslo from 2012 to 2020. Efforts by Ruter, the public transit authority, to upscale with a larger fully commercial ten bus tender in 2019 failed to attract any successful bids. Tenders, like all introduction efforts, must involve sufficient scale to attract market entry from actors along the value chain. The ferry segment has less of a problem with scale because one ferry represents enough demand to justify the expenditures for new infrastructure, at least in the piloting phase. There is currently one hydrogen passenger ferry in operation in the west-coast county of Rogaland with three more expected to be introduced in the coming years.

Coordination among actors can also serve to articulate the demand required to jump-start a market. The H2Truck initiative seeks to facilitate such coordination among actors along the entire value chain to articulate demand prior to the procurement of heavy-duty vehicles and the building of necessary infrastructure. There are currently four heavy-duty trucks operating as part of a pilot project by ASKO, a grocery wholesaler, with plans for an additional two in the coming years.

A segment that warrants further attention is taxis, where dozens of hydrogen cars have been introduced over the past year in the Oslo area. Whereas the private passenger car market has yet to show signs of recovery, and other segments continue with pilot projects, taxis represent the first commercial transportation service efforts that have seen vehicles in operation.

3.4.2 Survey on Public Perception

With the help of a survey company (Kantar), a nationally representative survey was carried out in February 2021, which yielded a sample 2,117 respondents and a response rate of 38 percent. Although hydrogen was the central topic to be explored in the survey, it was designed as a general survey on a range of fuels and powertrains. This was done to ensure that we did not lead the respondents to draw connections between a fuel (e.g., hydrogen) and an attribute (e.g., risk). The main topics covered in the survey included general awareness, perceived sustainability, and perceived safety/risk.

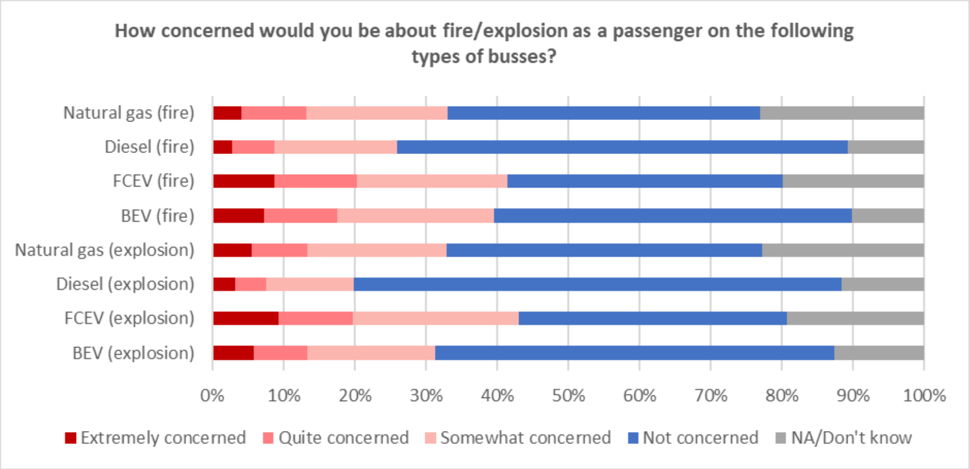


Figure 30: Fear of fire and explosion by powertrain as a hypothetical bus passenger.

As shown in Figure 30, in scenarios measuring fear of fire and explosion as a hypothetical passenger on a bus, respondents expressed more fear for hydrogen than other fuels and powertrains. Similarly, they expressed more fear of living next to a hydrogen refueling station (HRS) or parking garage with many hydrogen cars, as compared with other fuels and power trains.

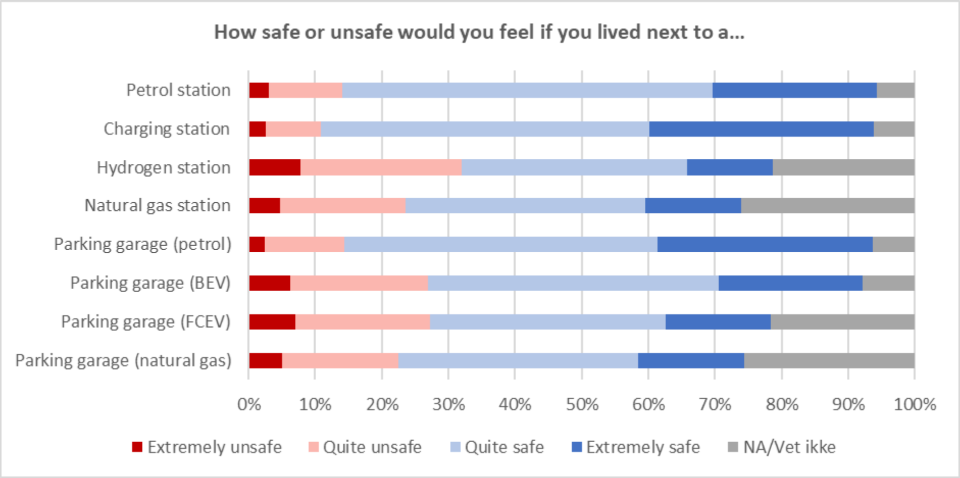
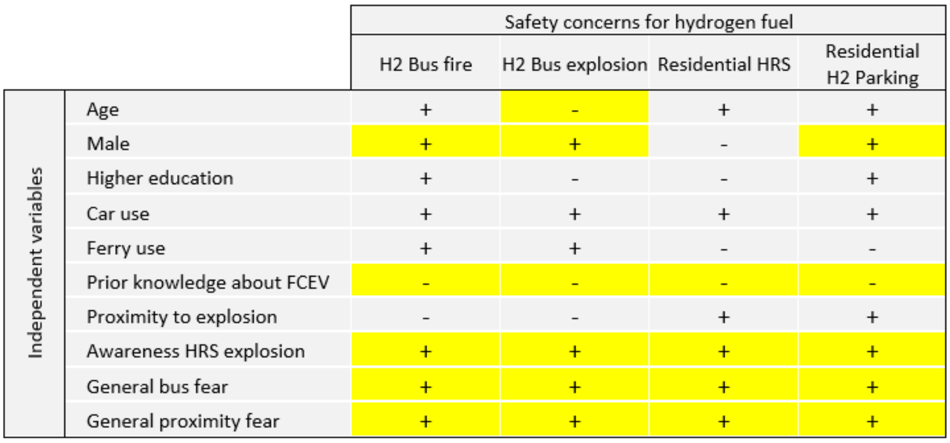


Figure 31: Fear of residential proximity to different vehicle infrastructures

Based on a binary logistic regression analysis of the survey results, a number of significant relationships related to fear were identified. Importantly, awareness of the 2019 HRS explosion is positively and significantly correlated with perceived safety concerns for hydrogen fuel across all four fear variables. However, the opposite is the case with prior knowledge about hydrogen vehicles, which is negatively and significantly correlated with the four fear variables. Simply put, those who know more about hydrogen are less scared of it. Furthermore, the four variables measuring fear of hydrogen were positively and significantly correlated with general fear variables for bus and residential proximity. Most surprisingly, there was no significant relationship between proximity to (the 2019 HRS) explosion and any of the hydrogen fear variables; we had expected the residents of the municipalities of and near to the incident to exhibit greater levels of fear than the rest of the country.



		Safety concerns for hydrogen fuel			
		H2 Bus fire	H2 Bus explosion	Residential HRS	Residential H2 Parking
Independent variables	Age	+	-	+	+
	Male	+	+	-	+
	Higher education	+	-	-	+
	Car use	+	+	+	+
	Ferry use	+	+	-	-
	Prior knowledge about FCEV	-	-	-	-
	Proximity to explosion	-	-	+	+
	Awareness HRS explosion	+	+	+	+
	General bus fear	+	+	+	+
	General proximity fear	+	+	+	+

Figure 32: Summary of results from binary logistic regressions (+/- refers to the direction of correlation and yellow indicates significant relationships).

In terms of awareness, overall, public perception is characterized by low levels of familiarity and knowledge, which is consistent with findings from prior studies, and is subject to change with increased demonstration activities and market rollout. This is supported by the high levels of "NA/Don't know" responses for questions related to hydrogen safety and sustainability.

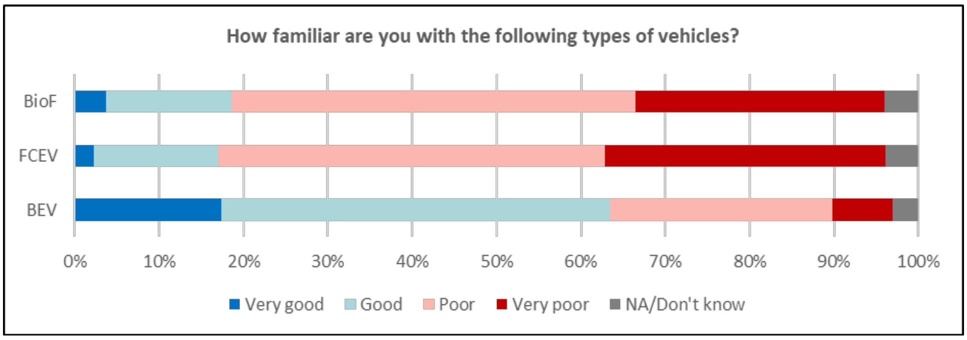


Figure 33: Prior familiarity with hydrogen, battery, and biofuel vehicles.

In terms of perceived sustainability, 50 % of respondents found hydrogen cars to be more environmentally friendly than petrol for use in cars, somewhat less than for BEVs and PHEVs. However, a greater number of respondents found BEVs and PHEVs to be worse than petrol cars, as compared with hydrogen.

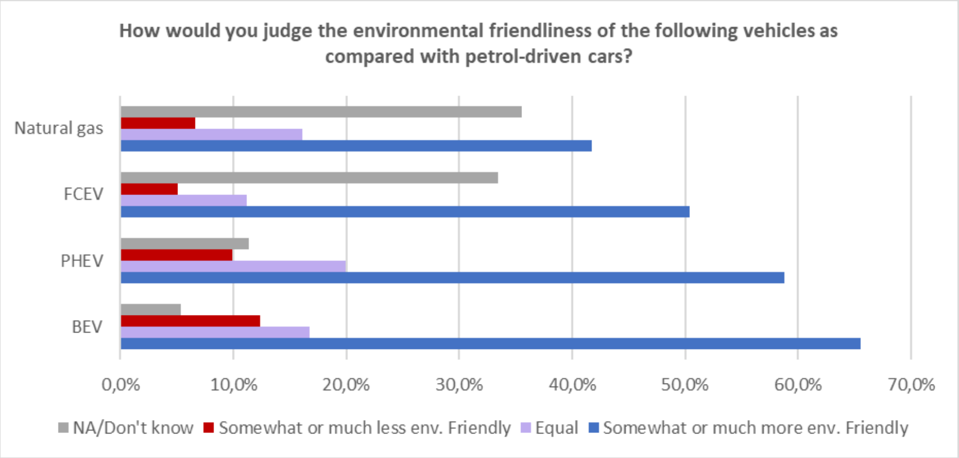


Figure 34: Perceived environmental friendliness of different vehicle powertrains.

Additionally, 44 % expressed are in favor of government incentives to support hydrogen fuel vehicles. As with the previous question, one must consider the significant share of responses that were “NA/Don’t know” suggesting a dynamic situation in terms of perception and opportunities for information and outreach.

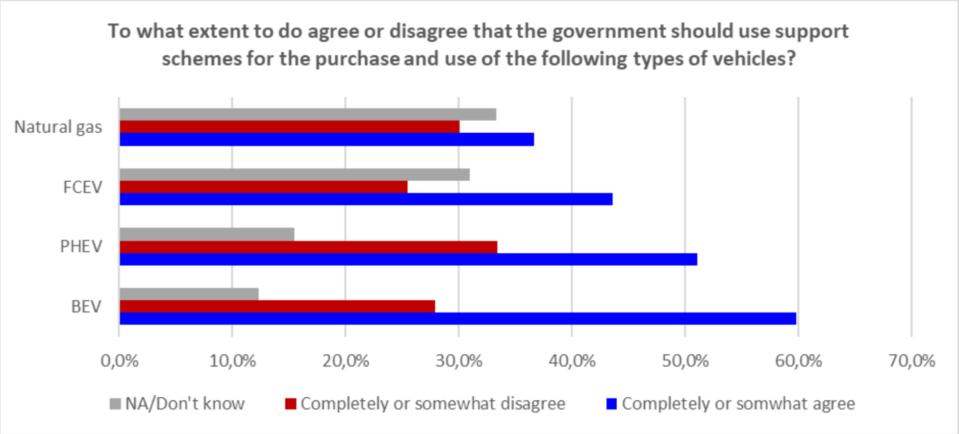


Figure 35: Support for government programs that promote different vehicle powertrains.

As pilot projects continue and commercialization efforts take hold, it is reasonable to assume that this "NA/Don't know" share of the general public would decline. Active campaigns to boost familiarity and knowledge of hydrogen fuel at this early stage should be considered for bridging any gaps between public perception and adoption.

4 Conclusions and main messages

Based on the performed work and results gained from both experimental and modelling activities, the following main messages have been summarised for each phenomenon

4.1 Rapid phase transition

RPT resulting from LH2 spills onto or into water is *not* found to be a major issue for safe implementation of LH2 technologies. There are no records in the literature for such a phenomenon, and it was not observed in previous tests where LH2 was spilled onto a pool of water, or where an LH2 release was sprayed with water. Furthermore, no RPTs were observed during the 75 release tests conducted in SH2IFT, where high momentum jets were released onto or into a pool of water. These observations are supported by the theoretical assessment concluding that the known pathways to RPT are impossible or very unlikely for LH2. It was estimated by thermodynamic modelling that the theoretical consequences of an LH2 RPT is significantly lower than of on LNG RPT. It should be noted, however, that any spill of hydrogen should be avoided to prevent the occurrence of other issues such as the risk of ignition, evaporation and spreading of gas cloud, and cryogenic hazards. Moreover, it was noticed during the SH2IFT experimental campaign that high momentum releases of LH2 onto and into water may cause ignition of the evaporated gas cloud in free air. This represents a safety concern, and the mechanisms and consequences of this phenomenon must be studied further. New research questions arise from these findings: What is the source of ignition? What are the realistic release scenarios that could lead to such ignition? Is there a correlation between the momentum of the released LH2 and the probability of ignition?

4.2 Boiling Liquid Expanding Vapour Explosion

Critical indications on the behaviour of LH2 tanks engulfed in a propane fire were provided thanks to the experimental and modelling activities during the SH2IFT project. All three double walled vacuum insulated LH2 vessels withstood the propane fire for more than one hour despite the safety relief valve being kept blocked during the tests. This outcome indicates that there is a long available evacuation time if an LH2 vessel is caught in a fire, which would allow for emergency response. Only the vessel with MLI insulation failed catastrophically after exceeding the design burst pressure and exploded suggesting that perlite performs better as an insulation material when this type of tanks is engulfed in a fire over a long period. Further studies would be beneficial to better understand the heat transfer in the LH2 vessel and consequent pressure build-up during this accident scenario as well as issues related to scaling up tank size. Moreover, the insulation performance must be investigated further to understand how the catastrophic rupture of the vessel can be avoided, especially in case of MLI. This information is critical for the model validation activity. Furthermore, a larger number of experiments is necessary for a statistically sound investigation of the BLEVE consequences. Additional instrumentation and measurements are needed to measure fluid state, phase, temperature, pressure, which are critical parameters considered by the models used to simulate the BLEVE. Therefore, the models proposed in the project must be developed further to accurately estimate fluid state, stratification, and heat flux to increase understanding of what causes burst, as well as the blast wave intensity, fragments, and fireball consequences when the BLEVE occurs. Although the vessels were able to withstand a fire over a long period of time, additional work on the development of safety barriers is recommended.

4.3 Gaseous hydrogen jet fire

The hydrogen jet fire experiments conducted in this project are mainly relevant for blowdown scenarios leading to high initial release rates. The 6 mm diameter nozzle that was used in the experiments is larger than typical valves for hydrogen cars, which is usually around 3 mm, but comparable to the size of the ones adopted for hydrogen buses. The larger diameter nozzle was also intended to compensate for the lower initial pressure in the tests (300 barg) compared to the maximum pressure in cars (700 barg). Therefore, the experiment resembles leak duration and total amount released from a car. Furthermore, using a larger hole size in the experiments in addition to a horizontal release direction makes the results more relevant for accidental releases in other situations where a horizontal release can occur. Earlier experiments have mostly been performed with horizontal release. Moreover, the effect of the confinement shown in the experiment is considered as a “worst case” due to the relatively small steel confinement compared to for example a tunnel structure, where larger dimension and more reinforced concrete is expected. The experimental data were exploited for model validation and upgrade during the projects. The same data allow other researchers to validate and improve their models. This is critical since there is a limited number of impinging/confined hydrogen jet fire experiments available in literature.

From the research activity carried out on the hydrogen jet fires, it was reaffirmed that the safety management for hydrogen should consider the scenario for both visible and invisible flames because the invisible flames can be challenging for emergency response. Both visible and invisible flames were observed during the experiments, where low ambient light conditions and the presence of other substances than hydrogen are suspected to cause visible flames. It was also noted that the thermal heat flux to the surroundings caused by a hydrogen jet fire is more directional compared to hydrocarbon jet fires. A larger fraction of the heat is transferred by convection of the hot gases than by radiation in hydrogen jet fires than in hydrocarbon jet fires. This information can be utilized for the design of facilities and their safety barriers. For instance, there is a reduced risk of impairment to escape routes due to lower thermal radiation in the far field. On the other hand, local high heat flux and large momentum of the hydrogen jet may be challenging for existing passive fire protection designed for hydrocarbon fires and should therefore be further investigated.

4.4 Societal concerns

The project findings related to the societal concerns are here reported distinguishing between public perception and transport system.

Public perception

A nationally representative survey (N=2117) on alternative fuels for transport was carried out in February 2021. The main topics of the survey were perceived safety, general awareness, and perceived sustainability, and the response was 38 %. Regarding the perceived safety topic, the respondents expressed more fear for hydrogen than other fuels and powertrains in hypothetical scenarios measuring fear of fire and explosion on a bus and living near refuelling/charging stations and vehicles. The perceived safety concerns for hydrogen fuel use are significantly correlated with the awareness of the 2019 hydrogen station explosion in Norway. Active campaigns to boost familiarity with hydrogen fuel can help to increase the perceived safety. The results of the awareness show that the public perception is overall characterized by low familiarity and knowledge, which is consistent with the findings from prior studies, and is subject to change with increased demonstration activities and market rollout. Finally, from the questions on perceived sustainability 50 % of respondents perceived hydrogen fuel to be more environmentally friendly than fossil fuels for use in cars and busses, and 44 % expressed are in favour for government incentives to support hydrogen fuel.

Transport system

For the transport system, the document analysis and event participation were used to identify drivers, barriers, and trends for hydrogen fuel adoption in Norwegian transport within a sustainability transitions context. The Norwegian passenger vehicle segment is increasingly dominated by battery electric vehicles, whereas efforts to introduce hydrogen fuel are increasingly focused on the heavy-duty land and maritime transport. The public procurement and tendering for transport services are effective means of introducing hydrogen fuel, and sufficient attention must be given to demand articulation. Moreover, adequate consideration must be given to coordination of actors along the entire value chain. The ongoing introduction activities for busses, trucks and ferries show promise. Finally, it was identified that Norway is positioned to take a leading role internationally in the introduction and use of hydrogen technology in the maritime segments.

5 Dissemination activities

The following dissemination activities were held during the project period:

- **Hydrogen safety - liquid hydrogen workshop,** March 6th, 2019 in Bergen. The workshop was a joint initiative from HYSAFE and the PRESLHY and SH2IFT projects, focusing on hydrogen safety, with special emphasis on liquid hydrogen.
- **Hydrogensikkerhet - teori, praksis og samfunnsutfordringer (Hydrogen safety – theory, practice and societal challenges)**, December 5th, 2019 in Oslo. This event was a cooperation between the SH2IFT project and the Norwegian Hydrogen Forum.
- **Safe handling of gaseous and liquid hydrogen**, May 3rd-4th 2022 in Trondheim. The workshop was the final project workshop in SH2IFT, focussing on hydrogen safety, with special emphasis on liquid and gaseous hydrogen. The workshop was conducted in a hybrid format, and videos and presentations are available on the SH2IFT project website.

There were two PhD candidates connected with the project. One PhD was employed at TØI and was fully involved in WP1 on the societal concern of hydrogen utilization in the transport sector, while the other one was employed at NTNU and was working in WP4 on the modelling of accident scenarios from liquid hydrogen transport and use, namely BLEVE and RPT.

Thanks to the research activities carried out in the SH2IFT project, Federico Ustolin (PhD in WP4) received the Young Scientist Award 2021 by Hydrogen Europe Research. The poster titled “Evaluating the Mechanical and Chemical Energy of Liquid Hydrogen Tank Explosions”, with the results on the BLEVE research carried out during the SH2IFT project, was presented by Ustolin, Giannini, Pio, Salzano and Paltrinieri at the 10th International Seminar on Fire and Explosion Hazards in Oslo, Norway on May 22-27, 2022 and received the Best Poster Award. At the same conference, the paper “Experimental Investigation of Impinging and Confined Hydrogen Jet Fires”, presented by Meraner, Stølen and Li received one of two Best Paper Awards. The Best Paper Award was also given to the paper titled “Experimental investigation into the consequences of release of liquified hydrogen onto and under water” presented by Habib, Kluge, and van Wingerden (SH2IFT partners) at the 14th International Symposium on Hazards, Prevention, and Mitigation of Industrial Explosions held in Braunschweig, Germany on July 11-15, 2022.

Cyriac George (PhD in WP1) gave the following conference presentations during the project period: “Public sector drivers of innovation: Hydrogen fuel in Norwegian transport” at the Network for Early Career Researchers in Sustainability Transitions (NEST) Conference held digitally on May 7-8 2020; “Public perception and technology adoption: Alternative fuels in Norwegian transport” at the NEST Conference held digitally and in Sofia, Bulgaria on April 8-9, 2021; and “Inter-sectoral linkages and actor interests: hydrogen in Norwegian context(s)” at the International Sustainability Transitions Conference, held digitally and in Karlsruhe, Germany October 5-8, 2021.

Additionally, the following presentations were given during the SH2IFT project period:

- Anders Ødegård, "Safe hydrogen fuel handling and use - Norwegian KPN Project", H2FC 2018 Conference, May 2018, Trondheim, Norway.
- Anders Ødegård, "Safe hydrogen fuel handling and use", September 2019, International Conference on Hydrogen Safety Adelaide, Australia.
- Anders Ødegård, "Status på hydrogen, sikkerhet & forskning Norge og internasjonalt" (Status of hydrogen, safety and research, Norway and international), November 2019, Hydrogenkonferansen på Vestlandet (Western Norway Hydrogen Conference), Stavanger, Norway.
- Anders Ødegård, “Hydrogen safety-experiences from the SH2IFT project”, June 2020, Norwegian Hydrogen Conference, Oslo.
- Hans L. Skarsvåg, "Risk and Consequences of Rapid Phase Transition for Liquid Hydrogen", European Safety and Reliability Conference/Probabilistic Safety Assessment and Management Conference (ESREL2020-PSAM15), October 2020 held in Venice, Italy.
- Lars H. Odsæter, "Liquid hydrogen spills on water and risk of rapid phase transition", Fire and Blast Information Group (FABIG) lunchtime webinar, July 2022.

Owing to the success of the SH2IFT project, a follow-up project, SH2IFT-2, was proposed and was recently funded, mainly by the Research Council of Norway and other industrial partners. During the SH2IFT project, a collaboration with the European project “PRESLHY – Prenormative Research for Safe Use of Liquid Hydrogen” was established.

6 List of publications related to the project

1. Ustolin F, Tolias I, Giannissi S, Venetsanos A, Paltrinieri N, 2022. A CFD Analysis of Liquid Hydrogen Vessel Explosions Using the ADREA-HF Code. Process Safety Environmental Protection 159, 61–75.
2. Odsæter LH, Skarsvåg HL, Aursand E, Ustolin F, Reigstad GA, Paltrinieri N, 2021. Liquid Hydrogen Spills on Water—Risk and Consequences of Rapid Phase Transition. Energies 14, 4789.
3. Ustolin F, Paltrinieri N, Landucci G, 2020. An innovative and comprehensive approach for the consequence analysis of liquid hydrogen vessel explosions. Journal of Loss Prevention in the Process Industries 68, 104323.
4. Ustolin F, Paltrinieri N, Berto F, 2020. Loss of integrity of hydrogen technologies: A critical review. International Journal of Hydrogen Energy 45, 23809–23840.
5. Ustolin F, Scarponi GE, Iannaccone T, Cozzani V, Paltrinieri N, 2022. Cryogenic Hydrogen Storage Tanks Exposed to Fires: a CFD study. Chemical Engineering Transaction 90.
6. van Wingerden K, Kluge M, Habib AK, Ustolin F, Paltrinieri N, 2022. Medium-scale tests to investigate the possibility and effects of BLEVEs of storage vessels containing liquified hydrogen. Chemical Engineering Transaction 90.
7. van Wingerden K, Kluge M, Habib AK, Skarsvåg HL, Ustolin F, Paltrinieri N, Odsæter LH, 2022. Experimental investigation into the consequences of release of liquified hydrogen onto and under water. Chemical Engineering Transaction 90.
8. Ustolin F, Giannini L, Pio G, Salzano E, Paltrinieri N, 2022. On the mechanical energy involved in the catastrophic rupture of liquid hydrogen tanks. Chemical Engineering Transaction 91.
9. Ustolin F, Iannaccone T, Cozzani V, Jafarzadeh S, Paltrinieri N, 2021. Time to Failure Estimation of Cryogenic Liquefied Tanks Exposed to a Fire. Proceedings of the 31st European Safety and Reliability Conference.
10. Ustolin F, Paltrinieri N, 2020. Hydrogen fireball consequence analysis. Chemical Engineering Transaction 82, 211–216.
11. Ustolin F, Odsæter LH, Reigstad G, Skarsvåg HL, Paltrinieri N, 2020. Theories and Mechanism of Rapid Phase Transition. Chemical Engineering Transaction 82, 253–258.
12. Aursand E, Odsæter LH, Skarsvåg HL, Reigstad GA, Ustolin F, Paltrinieri N, 2020. Risk and Consequences of Rapid Phase Transition for Liquid Hydrogen. 30th European Safety and Reliability Conference 15th Probabilistic Safety Assessment & Management conference (ESREL2020 PSAM15).
13. Ustolin F, Salzano E, Landucci G, Paltrinieri N, 2020. Modelling Liquid Hydrogen BLEVEs: A Comparative Assessment with Hydrocarbon Fuels. 30th European Safety and Reliability Conference 15th Probabilistic Safety Assessment & Management conference (ESREL2020 PSAM15).
14. Ustolin F, Song G, Paltrinieri N, 2019. The influence of H2 safety research on relevant risk assessment. Chemical Engineering Transaction 74, 1393-1398.
15. PhD thesis titled “Modelling of Accident Scenarios from Liquid Hydrogen Transport and Use” Doctoral theses at NTNU;2021:241, ISBN 978-82-326-5575-5
16. Meraner C, Stølen R, Li T, 2022. Experimental Investigation of Impinging and Confined Hydrogen Jet Fires. The 10th International Seminar on Fire & Explosion Hazards (ISFEH10)
17. Meraner C, Stølen R, Skilbred E S, Li T, 2022. Large-scale experimental studies of impinging and confined hydrogen jet fires. Fire Safety Journal. (Pending review)

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Safe H2 Fuel Handling and Use for Efficient Implementation – SH2IFT