

THE LATEST VOYAGE OF DISCOVERY – QUANTIFYING THE CONSEQUENCES OF LH2 RELEASES FOR THE MARINE INDUSTRY

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ABSTRACT

Following a desktop study undertaken in 2021 to identify hazard scenarios associated with the use of liquid and compressed hydrogen on commercial shipping, Shell has started a programme of large-scale experiments on the consequences of a release of liquid hydrogen. This work will compliment on-going research Shell has sponsored within several joint industry projects but will also address immediate concerns that the maritime industry has for the transportation of liquid hydrogen (LH2). This paper will describe the first phase of experiments involving the release of LH2 onto various substrates as well as dispersion across an instrumented test pad. These results will be used to address the following uncertainties in risk assessments within the hydrogen economy, such as (1) Quantify the impact of low wind speed and high humidity on the buoyancy of both a passive and momentum jet dispersion cloud, (2) Gather additional data on liquid hydrogen jet fires (3) Understand the likelihood for the formation of a sustained pool of hydrogen (4) Characterise materials, especially passive fire protective coatings, that are exposed to LH2. Not only will these experiments generate validation data to provide confidence in the Shell consequence tool FRED, but they will also be used by Shell to support updates and new regulations developed by the International Maritime Organisation as it seeks to reduce CO2 intensity in the maritime industry.

1.0 INTRODUCTION

There is an increasing desire to utilise liquid hydrogen (LH2) as a source of energy during the energy transition as an alternative to hydrocarbons. It is envisaged that LH2 could be used directly to fuel engines as a direct replacement to hydrocarbons, such as in the maritime industry and for heavy-duty vehicles. In addition, several designs propose using LH2 as a vector to store and deliver energy from locations where electricity can be generated more cheaply. In these scenarios, such as proposed for the H2Sines.Rdam project [1], hydrogen is generated from renewable energy using electrolysis and then liquified to allow hydrogen to be transported and used in other parts of the World. It is therefore necessary for the maritime industry to establish appropriate guidance and standards for the storage and use of LH2 on maritime vessels.

The International Maritime Organisation (IMO) released its greenhouse gas strategy in 2018 where it acknowledged the importance of reducing greenhouse gas emissions and had set the challenge of reducing emissions by at least 40% by 2030 and 70% by 2050 compared with 2008 [2]. To meet these targets, the shipping industry needs to transition from hydrocarbon-based fuels, typically heavy fuel oil and now also Liquefied Natural Gas (LNG), to alternative, such as hydrogen. This ambition aligns with Shell's powering progress strategy and Shell International Trading and Shipping Company Limited (STASCO) has a stated aim to be at the forefront of decarbonised shipping.

Hydrogen is considered a promising future fuel, partly due to the high efficiencies achieved when using hydrogen in a fuel cell and zero toxicity compared with other alternatives. However, while there is an appreciation of the specific properties of hydrogen from its use in gaseous form by industry for many years, such as its significant explosion potential, several new safety challenges are anticipated when using LH2 within a marine environment. These challenges require further quantification of the major hazards to identify and understand gaps in understanding to enable the development of practicable solutions that are commercially viable. Consequently, it is important to quantify the hazards and de-risk the transportation of hydrogen by sea and so influence maritime standards that are starting to be written, such as the MarHySafe project, where a consortium of leading companies and associations, including Shell, worked on a handbook for hydrogen-fuelled vessels [3].

The lack of data to quantify the major hazards of LH2 has been recognised by academia and industry working within the field and so a number of Joint Industry Projects (JIPs) have been running over the last few years. The most relevant was the PRESLHY (Pre-normative research for safe use of liquid hydrogen) JIP, that was partially funded by the European Union [4][5]. This project covered several areas, including the formation of small liquid pools onto different substrates and the release of LH2 across a test pad, both of which could be useful to quantify the hazards of using LH2 in the marine environment. A second JIP to investigate “Safe Hydrogen Fuel Handling and Use for Efficient Implementation” (SH₂IFT) was partially funded by the Research Council of Norway [6]. Amongst other research, this JIP conducted research on the Rapid Phase Transition (RPT) phenomena and through both an experimental programme and theoretical analysis showed that the severity of hydrogen RPTs would be less than that demonstrated for LNG releases onto water [7].

Although Shell gained valuable insights by being involved with both JIPs, as well as other consortia related to hydrogen, the pace of research does not match the timeframe required by the IMO for the transition from hydrocarbon fuels. Therefore, following a review of the knowledge gaps in the safe handling of LH2, especially when applied to shipping and marine operations, it was decided to commission a bespoke test programme. This programme of work would speed up the development of new marine designs / projects within Shell and by working with relevant regulatory bodies, e.g. the UK HSE or the UK Maritime and Coastguard Agency (MCA) influence the development of marine standards. This paper is part of that programme of work to disseminate the outcome of the experimental programme. The first phase of work is focussed on the following areas:

- Dense gas dispersion and specifically to understand the impact of low wind speed and high humidity on the buoyancy of both passive and jet dispersion releases.
- Determine the credibility for the formation of a sustained pool of LH2 for typical release scenarios.
- Improve the characterisation of materials used for offshore and on topdecks of ships to understand if there could be charactrophic failure of steel and/or cold spill protective coatings.
- Gain further data on LH2 jet fires to improve the validation of existing jet fire models. Although seen as a lower priority for the marine environment, the application of hydrogen jet fire models is also applicable to other relevant markets, e.g. liquification.

2.0 EXPERIMENTAL SETUP

2.1 Test Site

The experimental campaign was commissioned at DNV’s Spadeadam test site. This site was chosen because they had the capability for large scale cryogenic releases from previous Shell test programmes on LNG [8], but also because they had managed an analogous series of LH2 release experiments, commissioned by the Norwegian Defence Research Establishment (Forsvarets forskningsinstitutt, FFI) [9]. The previous experimental campaign for FFI had released LH2 as a jet release horizontally and vertically downwards onto a concrete test pad and provided useful information to guide the experimental design.

2.2 Liquid Hydrogen supply

The LH2 was delivered to site by Air Liquide on a commercial road tanker. The tanker had a standard capacity of 40 m³ and consequently it could hold up to 3 tonnes of LH2. Rather than purchase a dedicated cryogenic storage vessel to hold the LH2 during the tests, the commercial vessel was hired, placed on the test pad and used throughout the test programme. This approach had been demonstrated during the test programme for FFI in 2019 and consequently it simplified the procurement and commissioning phases and reduced any boil-off required to cool a dedicated storage vessel.

The decision to use the commercial LH2 trailer necessitated a few compromises. First, there was no method to log data on the vessel in real-time during tests. In addition, there was no measurement of the

temperature and only an analogue pressure gauge. This meant that saturated conditions could only be inferred if the internal pressure remained constant. Second, to protect the vessel from a significant overpressure following ignition of a hydrogen cloud, it was necessary to place the tanker behind a double height row of iso-containers (which were bolted to the test pad) and position the release orifice 24 m from the tanker. A schematic drawing of the arrangement is shown in Figure 1. Not only did the long section of vacuum insulated pipework require more pre-cooling, but it also made it more likely that the liquid would start to flash before it was released from the orifice.

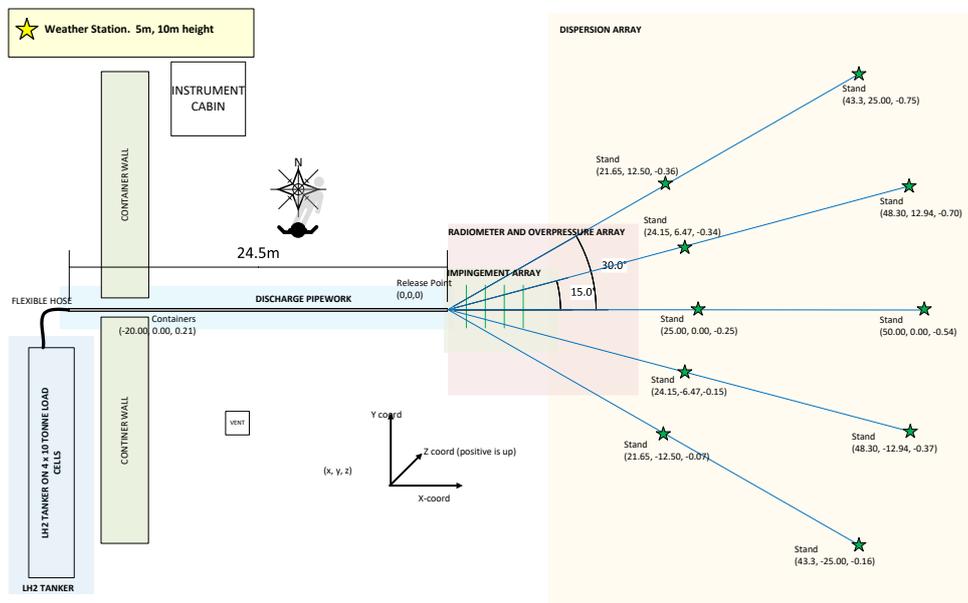


Figure 1: Schematic diagram of the experimental layout.

The overpressure assessment was based upon previous experience at Spadeadam and although only a maximum overpressure of 30 mbar was recorded during the FFI test programme, DNV commented that significantly higher overpressures were recorded following the ignition of a gaseous hydrogen release that had a similar hydrogen mass to that expected during the proposed LH2 test programme.

2.3 Instrumentation

The mass flow rate of each release was determined using load cells to record the inventory loss in the tanker. The load cells were installed by lifting the tanker upon arrival and placing the tanker axial on four Novatech F327CFS0KN 10 tonne compression loadcells. Although the results were sensitive to external factors, such as wind loading, it was easy to visualise an inventory loss of more than 10 kg during a test release of 1 to 2 minutes and hence determine flow rates above 0.05 kg/s.

The discharge pipework was constructed from four lengths of 6 m vacuum jacketed pipes. These pipes had a 2" NB with a 4 mm thickness 316 stainless pipe welded onto Class 150 raised face flanges. Between the flanges were full stainless steel spiral wound Metaflax gaskets that allowed some flexibility. An additional flange was present at each connection, which was drilled with 3 mm holes and tapped for 1/4" fittings. In each case, the vertical hole was used for a pressure measurement and two horizontal holes were used for temperature measurements using Type T and Type N thermocouples as can be seen in Figure 2. Two types of thermocouples were used because measurements using Type N thermocouples had showed non-linearities at temperatures near the boiling point of hydrogen, resulting in a minimum temperature of -240 °C.



Figure 2: The image on the left shows the insulated pipework, spiral wound metaflex gasket and additional “flange” with temperature / pressure sensors. The image on the right shows the discharge line as it extends across the test pad from the iso-containers to the main valve and a 25 mm discharge orifice. A bypass valve is located to the left and before the final valve.

Each joint was insulated with several layers of 25 mm thick Kingspan Kooltherm© Phenolic pipe insulation and protective weatherproof PIB black rubber sheeting that was wrapped over the top and sealed by solvent welding with white spirits. The pipework was supported on a series of ‘goalpost’ pipe stands with holes drilled through to allow mounting at multiple heights and so allow the release height to be adjusted.

At the end of the discharge line, the pipework was connected to two valves; a 2” liquid hydrogen valve manufactured by Vinco and a ½” liquid hydrogen valve manufactured by Herose (shown in Figure 2). The ½” valve was used as a bypass value to cool the line and avoid pre-cooling the instrumentation downstream of the orifice on the test pad. The hydrogen was released from a 5, 10 or 25 mm orifice that was drilled into a class 150 blind flange that was replaced as required during testing.

The LH2 was initially released through an array of five Type N thermocouples arranged into a cross and aligned with the centre of the release point. This arrangement was repeated every metre to give four cross arrays that could be used to measure the temperature of the LH2 core as it vapourised.

The dispersion of the released fluid was also detected in the far field on a dispersion array as shown in Figure 1 and Figure 3.



Figure 3: The instrument array installed along two arcs of five stands and at three heights. The box contains the oxygen depletion sensor and a Type T thermocouple is mounted on the front.

The instruments were located on ten stands and arranged into two arcs at 25 m and 50 m distance from the release point. Both arcs were centred on the release axis and stands were placed along the release axis and at $\pm 15^\circ$ and $\pm 30^\circ$. Each stand had three measurement positions at which a single Type T thermocouple and a VIAMED R-22AVG oxygen cell were located; in these experiments the hydrogen concentration was measured indirectly through determining the depletion of oxygen. Each oxygen cell was placed in a small enclosure to protect it from the ambient temperature as can be seen in Figure 3 and so there was a small delay in the response time, which is nominally less than 6 s for 90% of the final value. The height of the detectors was 1, 3,5 and 6 m at 25 m and 1, 4.5 and 8 m at 50 m.

Each experiment was recorded using video cameras located on top of the iso-container and pointing along the discharge line, perpendicular to the release to record a lateral view of the release and just up-stream of the release orifice to monitor the conditions immediately following release. An IR camera was also positioned on the test field near the radiometers to record the thermal radiation during ignited tests.

2.4 Release procedure

To ensure that the LH2 could both be released safely and to limit any flashing in the discharge line, a series of inerting and pre-cooling stages were implemented. The initial cooling was achieved by connecting the discharge line to a supply of liquid nitrogen (LIN) and allowing it to flow out of the bypass valve. When the pipework was sufficiently cold, gaseous helium was used to remove all traces of nitrogen, to avoid it freezing valves when hydrogen was introduced. The line was then cooled further by cold hydrogen gas from the vapour space of the tanker before LH2 was introduced. During this process the temperature (and pressure) within the line was carefully monitored to ensure that liquid was released from the by-pass valve. Once the necessary start conditions had been achieved, the instruments were triggered, and the main valve was opened.

At the end of the test and once the LH2 supply from the trailer had been switched off, the discharge line was again purged with helium gas to ensure that all traces of hydrogen were removed.

When the tanker arrived at the test site, the pressure on the head space was <0.5 barg. This was lower than expected based upon previous experience during the experimental campaign for FFI [9]. In addition the pressure did not significantly increase over a period of 18 days and there was no loss of hydrogen due to boil-off. This was because the LH2 trailer was insulated with a LIN jacket, unlike the previous campaign where trailer was only insulated with conventional insulating material and vacuum. This improved thermal insulation on the tanker was vital, because the typical westerly weather conditions expected by the Spadeadam site were not present during the initial testing period.

When a higher pressure was required, the pressure in the headspace was increased using a vaporiser to achieve 3-4 bar above the required value and the pressure of the whole vessel allowed to rise slowly. This process was repeated several times over a period of a few days. The resultant pressure appeared to be steady and did not decrease significantly either overnight or during a release. Although no direct measurements of the liquid temperature within the trailer was possible, it is believed that the hydrogen liquid and gas was in thermodynamic equilibrium at the elevated pressure and so at or close to saturation conditions.

3.0 RESULTS

3.1 Formation of LH2 Pool

The formation of a LH2 pool following a release has been demonstrated previously. For instance, by the UK HSE following the release of LH2 from a 1" hose [10], or in the FFI test releases at Spadeadam [9]. However, in both these cases a sustained pool, e.g., a pool that persists after the release has stopped, was not achieved. These tests, therefore, did not demonstrate whether bunding would have any benefit in realistic scenarios and also complicated the source term for dense gas dispersion experiments.

A sustained pool of hydrogen was reported as part of the PRESLHY JIP [11], which showed that it is possible to fill an enclosure, but as the bund size was relatively small, 0.25 m², then it may not represent a typical scenario and in these tests no dispersion measurements were made. Finally, in 1980, NASA reported the formation of pools following the release of 5.7 m³ LH2 within approximately 35 s [12]. These results clearly showed that a pool of LH2 was formed and measurements of the subsequent dispersion were made. The limitation of these experiments was that the release was onto a sand substrate and steady state boiling was unlikely to have occurred, resulting in a transient source term for the subsequent dispersion.

In this experimental programme, it was decided to standardise on a bund size of 1.5 x 0.75 m. This would give an internal surface area of 1.11 m², which was believed to be a good compromise to achieve a quiescent pool based upon the two equivalent programmes by Spadeadam [9] and UK HSE [10]. More importantly it matched the internal dimensions of half of the test specimen as defined in ISO 22899-1 and hence allow Fire Protective and Cold Spill Protection (CSP) materials to be exposed to LH2 and then subsequently tested in a conventional jet fire following the test procedure in ISO 22899-1 and ISO 20088-1. To support this aspect of the experimental programme, a separate contract was signed with AkzoNobel, who were also looking to characterise their Chartek CSP material at LH2 temperatures and hence verify their commercial products for the application in marine and offshore deck applications.

The initial pool experiment was carried out using the standard iso box that was assembled by AkzoNobel with a coating of one of their commercial grades of Chartek CSP (consisting of epoxy passive fire protection with a universal prime). This box was situated below the release orifice, which had an elbow and additional extension pipework to allow the LH2 to be discharged 20 mm above the surface of the Chartek CSP; to inhibit mixing of the fluid with air and suppress splashing. This is shown in the left-hand image of Figure 4, which shows the two sides of the iso box separated by a central partition (webbing) with height of 250 mm that is part of the ISO 22899-1 design. The area on the right, has two circular pots containing thermocouples at heights of 2, 10 and 50 mm above the surface. The outside surface of the box was covered with Kingspan wall insulation to reduce the boil-off rate.



Figure 4: The image on the left shows an iso box used as a bund area for the LH2 pool; a coating of Chartek CSP has been applied to the inside of the box. The image on the right shows vapour dispersion from a quiescent pool of LH2 after filling has stopped.

In this experiment, the LH2 was released through a 25 mm orifice at 0.3 barg, resulting in an average mass flow rate of 0.15 kg/s. The thermocouples registered temperatures below -240°C almost immediately (see Figure 5) and so the fill level was determined by a real-time video of the rig. After approximately 700 s the LH2 started overflowing the webbing into the right-hand side of the box and the fill was stopped. The resultant quiescent LH2 pool is shown in the right-hand image in Figure 4.



Figure 5: The temperature of the LH2 pool recorded by thermocouples at 2, 10 and 50 mm above the floor of the bund with a Chartek CSP system. The bund was filled at 625 s and then refilled at 2150 s.

As can be seen in Figure 5, the LH2 appears to have evaporated at approximately 2150 s and so more LH2 was released to refill the pool to the top of the webbing. This second fill period lasted 200 s and, allowing for 3 kg lost due to quiescent boil-off, it is estimated that approximately 75% of the released LH2 contributed to refilling the pool. The two quiescent time periods, seen in Figure 5, have durations of approximately 1150 and 1380 s and therefore this gives an average regression rate of 0.014 kg/m²/s.

It should be noted that this boil-off rate does not consider the liquification or solidification of either nitrogen or oxygen from air, which has been reported previously [10], [11]. In fact, a careful inspection of Figure 5 shows stable periods of -196°C, indicating the presence of LIN as the pool warms up and also some indication for solid O₂ and solid N₂ at -218°C and -210°C respectively.

This test was repeated for a second iso box, which had a thinner application of Chartek CSP. This test showed a faster rate of cooling through the Chartek CSP as would be expected for the reduced thickness of protective coating. In this test the quiescent pool duration was only 840 s, resulting in a slightly bigger regression rate of 0.021 kg/m²/s.

Two pool experiments were also carried out using a concrete bund with a similar area (1.13 m²) and volume (0.28 m³). The concrete bund was created using C40 concrete with a wall thickness of 200 mm and Type N thermocouples were embedded at nominal depths from the exposed surface at 20 mm, 50 mm and 100 mm to understand the temperature response of the concrete when exposed to LH2 temperatures. The first experiment using the concrete bund had similar release conditions to the CSP bunds and was filled with the same pipe extension and 25 mm orifice, albeit with a slightly higher mass flow rate of 0.18 kg/s. The fill period lasted approximately ten minutes. The thermocouples placed in the pots started to warm up after 280 s, resulting in a calculated regression rate of 0.064 kg/m²/s.

Images from the second test using the concrete bund are shown in Figure 6 and was setup to simulate a more realistic release scenario at 1 barg, resulting in a mass flow rate of 0.53 kg/s from the 25 mm orifice. In addition, the downpipe was removed so that the LH2 was released from a height of 570 mm above the bottom of the concrete bund. Even though the resultant release was more violent, with significantly more splashing, a pool of LH2 was still formed and overtopped the bund wall after filling for just three minutes. With the increased flow rate, this experiment required approximately 1.5× the mass of hydrogen compared to the low pressure and zero splashing regime tested previously.



Figure 6: LH2 released into a concrete bund at 1.0 barg and from a height of 570 mm at the start of the experiment (left) and after all liquid H2 has evaporated showing a formation of solidied air (right).

It was not possible to calculate a regression rate for this test, because the thermocouples did not register a temperature lower than -210 to -220°C . This indicated that solid air had started to form almost immediately. This was also apparent in the video images at the end of the test, as can be clearly seen in Figure 6. This result indicates that solid air is likely to form for any realistic elevated release as the jet of LH2 will entrains air.

3.2 Characterisation of Chartek CSP

The Chartek CSP coating on the two iso boxes showed no obvious indication that it had been exposed to LH2 temperatures for over 50 mins for the thicker coating and about 25 mins for the thinner coating. This was demonstrated by the lack of disbondment or visible defects immediately after testing, but also from Type K thermocouples that were installed under the box as per the ISO 22899-1 and ISO 20088-1 standards. These thermocouples all showed a uniform temperature change as the Chartek CSP surface cooled, indicating no microcracks in the structure.

The ISO standard requires that the iso box is subjected to a jet fire immediately, but this was not possible due to safety concerns in case hydrogen was still present. However, equivalent testing on the specific Chartek CSP surface exposed to LIN by AkzoNobel has previously shown that the test is not impacted if there is a delay in performing the jet fire test. The outcome of testing one of the Chartek CSP coated boxes is shown in Figure 7, which shows the Chartek CSP surface after exposure to LH2 and then subsequently after the jet fire test. No adverse effects were seen following the jet fire test and AkzoNobel subsequently verified that the extra thickness of Chartek CSP required to provide protection from jet fires following cryogenic exposure is similar to that required when testing the same system using LIN.



Figure 7: The Chartek CSP surface after exposure to LH2 (left) and following jet fire testing (right).

3.3. Pool Dispersion

The experimental programme has only recently concluded and therefore only an initial analysis of the dispersion from the pool experiments was possible for this paper. These tests and their ambient conditions are listed in Table 1.

Table 1: Environmental conditions during pool tests (unless stated the release was at 0.3 barg through a 25 mm orifice and at a height of 20 mm above the bund surface).

Test #	Test description	Ambient Temp (°C)	Relative humidity (%)	Wind speed (m/s)	Time of day
7	Thicker Chartek CSP coating	0	66%	1.5 – 2.0	Sunset
8	Thinner Chartek CSP coating	4	53%	2.0 – 2.5	Sunset
9	Concrete bund	-3	100%	3.0 – 4.0	Sunrise
13	Concrete bund at 1.0 barg & release height of 570 mm	4	96%	3.5 – 5.5	Sunrise

This information was used to qualitatively compare the buoyancy of the dispersing plume by analysing the profiles of the plume using video footage recorded during each test. Although short periods of higher buoyancy were identified, these were very localised and could not be correlated with the recorded meteorological data for that specific time, for example at a lower wind speed. In addition, no obvious trends were observed when comparing the plume shape between Tests 7 and 8, which were recorded during periods of lower relative humidity and reduced wind speed compared to Tests 9 and 13. Although, since the ambient temperature was close to 0°C for all four tests, then the difference in humidity may not have had much impact. In addition, these environmental differences may have been masked by the higher emission rate for Tests 9 and 13. Overall the video analysis generally showed the condensation cloud passing through the arc of detectors at 25 m below the height of the stands, but did exceed 10 m if it passed the detector array at 50 m. This is illustrated in Figure 8, which shows a typical snapshot during the dispersion from a quiescent pool in Test 13.



Figure 8: Dense gas dispersion from a quiescent pool of LH2 during Test 13.

Unfortunately, the dispersion measurements of hydrogen, from the oxygen depletion sensors were inconclusive for the two bunds coated in Chartek CSP in Tests 7 and 8 for several reasons. In Test 8 the wind changed direction after filling started and the bulk of the dispersion cloud passed to the left of the detector array. While the baseline concentration recorded by the detectors drifted due to changes in ambient temperature over the longer duration of these pool tests. Allowing for these experimental complications, the maximum hydrogen concentration seen during a quiescent pool was less than 0.5% and it was not possible to discern a trend regarding average plume height.

The dispersion results from the concrete bund tests were better and some indication of average cloud height could be found at 25 m. These results are shown in Figure 9 and Figure 10 for Tests 9 and 13 respectively. As is normal for dispersion experiments, the plume centreline meandered over time as the wind direction changed and so to simplify the presentation of the results the concentration shown in the graphs is the maximum value recorded for any of the five detector stands for the given height. By plotting the data in this way, the maximum concentration at each height can be seen more easily. It should also be noted that the majority of the time periods shown are during the filling period, but hydrogen was also detected after filling had stopped and during a period when the pool was quiescent.

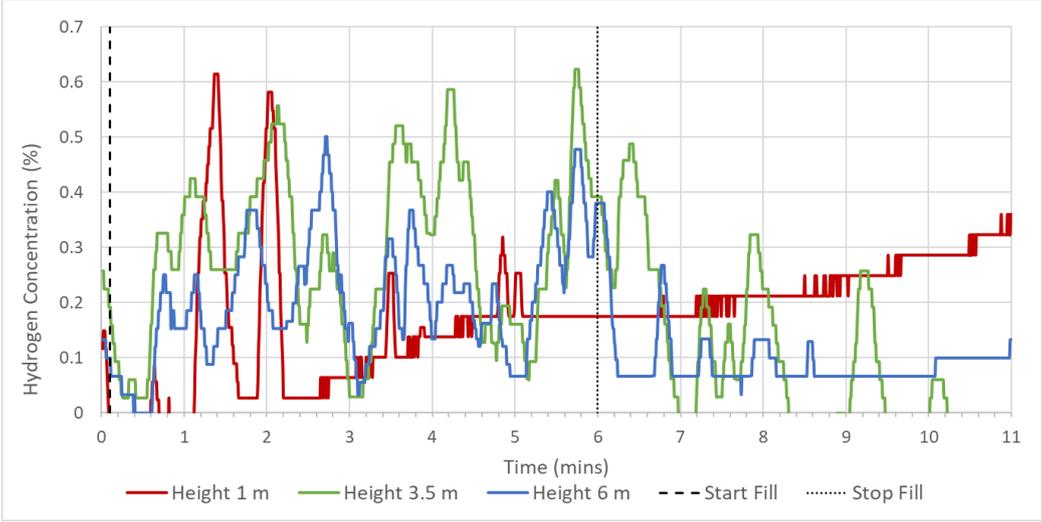


Figure 9: Measurements of hydrogen concentration for three heights at a distance of 25 m for Test 9 during filling and afterwards as the pool boiled dry.

The results in Figure 9 for Test 9 show a peak concentration of 0.6% while the bund is filled, and this subsequently reduces after 6 minutes when the filling has stopped. In this test no hydrogen is detected at ground level after the initial filling period, although the detector did show some drift 3 minutes after the start of the experiment. Overall the results for this test indicate that the average height appears to be around or just above 3.5 m at a distance of 25 m.

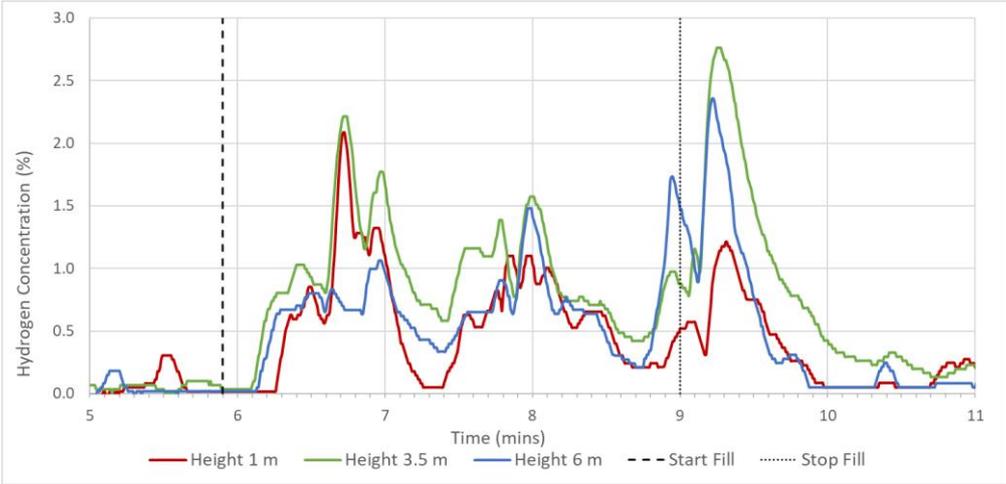


Figure 10: Measurements of hydrogen concentration for three heights at a distance of 25 m for Test 13 during filling and afterwards as the pool boiled dry.

The results in Figure 10 for Test 13 are clearer and show a hydrogen concentration of over 2.5 %. Interestingly the highest concentration peak occurred immediately after filling, although unlike Test 9,

shown in Figure 9, the maximum hydrogen concentration decayed more quickly, with no indication of hydrogen 1.5 minutes after filling stopped. Along with the higher measured concentrations, this suggests a higher regression rate than the other concrete bund test, although a reduced volume of LH2 in the bund due to the formation of more solid air in the bund will also explain the shorter period after filling stopped. Similar to the previous concrete test, the average plume height appears to be just above 3.5 m, because the measurements indicate that the concentration at 1 m is generally below that measured at both 3.5 m and 6 m.

It was also possible to obtain good dispersion results for the detector arc at 50 m for Test 13 and these measurements are shown in Figure 11. These results clearly show that the plume height has risen as it has travelled downwind, and the majority of the hydrogen was detected at 8 m. It is therefore possible that at 50 m, the plume centre line has risen above 8 m during this test.

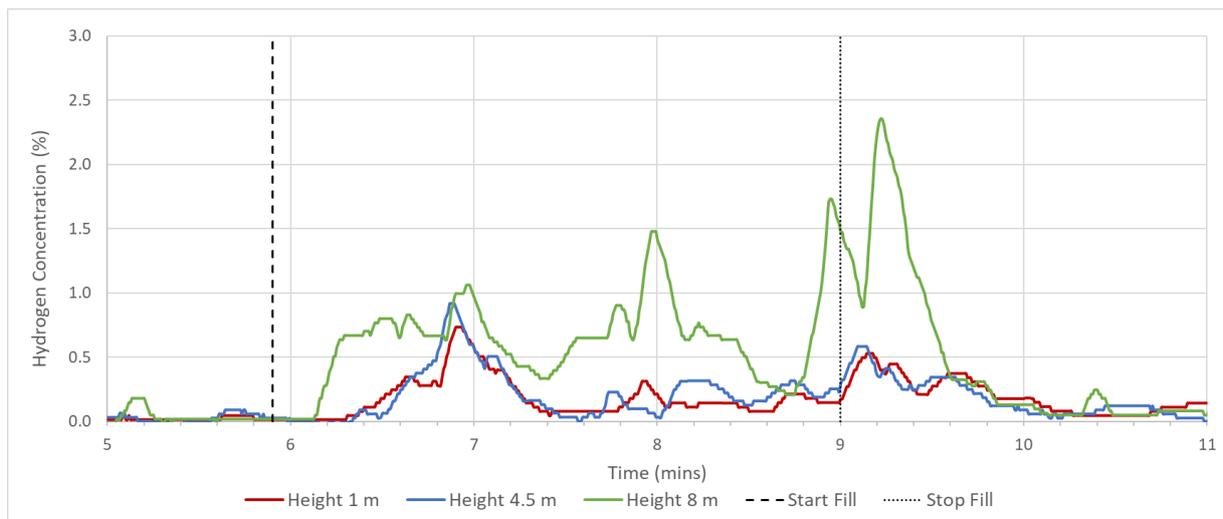


Figure 11: Measurements of hydrogen concentration for three heights at a distance of 50 m for Test 13 during filling and afterwards as the pool boiled dry.

4.0 Conclusions

This paper describes some of the results that have been obtained from an experimental campaign commissioned by Shell to obtain data on liquid hydrogen releases for its marine business. Unfortunately, the experimental programme was delayed; the first LH2 release was only at the start of March and the programme had completed by the time this paper was written. Consequently, it was not possible to analyse the results as fully as had originally been planned for this paper. Nevertheless, the results obtained so far have provided excellent data to quantify the some of the areas of uncertainty regarding the major hazards following a release of LH2 and good insights into experimental programmes. The main conclusions that can be drawn are

- A sustained pool of LH2 could be generated from a downwards release at a height of 0.5 m and pressure of 1.0 barg.
- A regression rate of 0.064 kg/m²/s was measured for a LH2 pool on a surface constructed using C40 concrete.
- A Chartek CSP coating used for marine / offshore deck applications from AkzoNobel showed no adverse effects following exposure to a pool of LH2 for time periods up to 50 minutes and subsequent ISO 22899-1 jet fire testing exceeding 2 hours.
- Concentration measurements were obtained following dense gas dispersion from a LH2 pool, which showed the height of the plume as a function of distance.

It was not possible to present the results of the jet dispersion and jet fire experiments that have also been obtained in this experimental campaign. These results will be presented in a subsequent publication work once the data has been fully analysed.

Additional phases of work are also being planned. These phases will focus on extensions to the explosion testing already planned in the CostFX II JIP and applying the results obtained in this first phase to credible release scenarios in the marine industry. For instance, to quantify the consequences from a failure of a ship loading arm and subsequent release of LH2 between the jetty and ship's hull; does LH2 reach the sea surface and what impact does this channel on the subsequent dispersion?

Acknowledgements

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