Ignited releases of liquid hydrogen

Prepared by the Health and Safety Laboratory for the Health and Safety Executive 2014
In the long term the key to the development of a hydrogen economy is a full infrastructure to support it, which includes means for the delivery and storage of hydrogen at the point of use, eg at hydrogen refuelling stations for vehicles. As an interim measure to allow the development of refuelling stations and rapid implementation of hydrogen distribution to them, liquid hydrogen is considered the most efficient and cost effective means for transport and storage.

The Health and Safety Executive (HSE) have commissioned the Health and Safety Laboratory (HSL) to identify and address issues relating to bulk liquid hydrogen transport and storage and update/develop guidance for such facilities. The second phase of the project involved experiments on unignited (HSE RR986) and ignited releases of liquid hydrogen and computational modelling of the unignited releases (HSE RR985). This position paper determines the hazards and severity of a realistic ignited spill of LH2 focussing on; flammability limits of an LH2 vapour cloud, flame speeds through an LH2 vapour cloud and subsequent radiative heat and overpressures after ignition. The results of the experimentation will inform the wider hydrogen community and contribute to the development of more robust modelling tools. The results will also help to update and develop guidance for codes and standards.

This report and the work it describes were funded by the Health and Safety Executive. Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.
Acknowledgements

I would like to thank John Roach from BOC for his expertise and support through the experimental setup phase of the work. I would like to thank Mark Royle for his technical expertise and input as technical lead on the project until September 2011. I would also like to thank Peter Shelley for the blast modelling tool work in Air3D he performed and his pressure monitoring advice.
EXECUTIVE SUMMARY

If the hydrogen economy is to progress, more hydrogen fuelling stations are required. In the short term, in the absence of a hydrogen distribution network, these fuelling stations will have to be supplied by liquid hydrogen (LH2) road tanker. Such a development will increase the number of tanker offloading operations significantly and these may need to be performed in close proximity to the general public.

Several research projects have been undertaken already at HSL with the aim of identifying and addressing hazards relating to the storage and transport of bulk LH2 that are associated with hydrogen refuelling stations located in urban environments.

The first phase of the research was to produce a position paper on the hazards of LH2 (Pritchard and Rattigan 2009). This was published as an HSE research report RR769 in 2010.

The second phase developed an experimental and modelling strategy for issues associated with LH2 spills and was published as an internal report HSL XS/10/06. The subsequent experimental work is a direct implementation of that strategy.

LH2 was first investigated experimentally (Royle and Willoughby 2012, HSL XS/11/70) as large-scale spills of LH2 at a rate of 60 litres per minute. Measurements were made on un-ignited releases which included the concentration of hydrogen in air, thermal gradients in the concrete substrate, liquid pool formation and temperatures within the pool. Computational modelling on the un-ignited spills was also performed (Batt and Webber 2012, HSL MSU/12/01).

The experimental work on ignited releases of LH2 detailed in this report is a direct continuation of the work performed by Royle and Willoughby.

The aim of this work was to determine the hazards and severity of a realistic ignited spill of LH2 focussing on; flammability limits of an LH2 vapour cloud, flame speeds through an LH2 vapour cloud and subsequent radiative heat and overpressures after ignition. The results of the experimentation will inform the wider hydrogen community and contribute to the development of more robust modelling tools. The results will also help to update and develop guidance for codes and standards.
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1. INTRODUCTION

1.1 BACKGROUND

The 'Hydrogen Economy' is gathering pace internationally and now in the UK. Over the last year a number of vehicle related demonstration projects have appeared, linked into the 2012 Olympics. While in the long term, the key to the development of a hydrogen economy is a full infrastructure to support it, a short bridging option for Hydrogen Refuelling Stations particularly, is the bulk storage and transport of cryogenic hydrogen, referred to in industry as liquid hydrogen (LH2). LH2 storage and transport are the most efficient and cost effective means of rapidly implementing hydrogen distribution. This will result in moderately large inventory, local storage of LH2 e.g. the Olympic refuelling station. Although cryogenic liquid storage has been used safely for many years in secure and regulated industrial sites, its use in relatively congested highly populated urban areas presents a new set of problems in relation to security, safety and associated planning. There is previous work undertaken by NASA on LH2 relating to its spill behaviour, but this was performed in a low humidity desert environment. In addition, it does not cover issues around leakage and combustion behaviour thoroughly as these problems were managed by the controls that can be put in place in an isolated specialist facility on the large remote sites used.

Research is therefore needed to identify and address issues relating to bulk LH2 storage facilities associated with hydrogen refuelling stations located in urban environments. The existing guidance requires updating and developing for the new LH2 storage facilities that are beginning to appear in new challenging environments.

Issues in particular relating to LH2 include: its general combustion properties including flame speed, ignition behaviour as a cool/dense vapour and the complications of this associated with layering effects, LH2’s low boiling point and associated ability to condense out and even solidify oxygen from air to produce a hypergolic mixture of LH2 and liquid or solid oxygen.

1.2 UN-IGNITED RELEASES

During 2009-11 Royle and Willoughby performed experiments on large-scale un-ignited releases of liquid hydrogen (Royle, Willoughby 2012) with the aim to determine the range of hazards from a realistic release of LH2. A number of areas of spill behaviour were investigated:

- Hydrogen dispersion from un-ignited spills.
- On ground liquid pool formation.
- Spills into free air.
- Pool formation with respect to storage conditions.

The work plan involved releasing LH2 at a fixed rate of 60 litres per minute for differing durations. The release height and orientation were varied and the sensor positions were changed.
1.2.1 Experimental Measurements

- Hydrogen concentration – temperature measurements were taken at thirty positions in air at a range of heights and distances from the release point in line and downwind of the wind direction pool extent. The extent of the pool was measured using thermocouples and visual records.

- Thermal gradient in the ground – three thermocouples were embedded into the concrete substrate at depths of 10, 20 and 30 mm.

1.2.2 Discussion

A horizontal release along the ground can be seen in Figure 1.1. The visible cloud at Figure 1.1, observed two minutes into the release, extends approximately 10 m across and 8 m high.

![Figure 1.1: Visible cloud approximately 8m high](image)

Following the release, the extent of the pool formation is clearly visible on the surface of the concrete and measures approximately 3.6 m in length and 2 m across (Figure 1.2).

![Figure 1.2: Pool extent](image)

A contour graph (Figure 1.3) of a release onto the ground suggests that with a 3.0 m/s wind the hydrogen cloud stays relatively close to the ground. At around 4.5 m from the release point, the 4% boundary of hydrogen concentration is below the 2 m height level. Beyond 4.5 m from the release point, the hydrogen warms and rises such that at 7.5 m the 4% boundary is likely to be above 4 m in height. This would suggest a cloud with a flammable vertical cross-sectional area of 15 m² and a flammable volume of approximately 50 m³.
1.2.3 Conclusions

The conclusions from the un-ignited LH2 testing are as follows:

- The release of LH2 in contact with a concrete surface can give rise to pooling of liquid once the substrate is sufficiently cooled;
- Release of LH2 in close proximity to a concrete surface can result in sub-cooling due to vaporisation;
- The release of LH2 at a rate consistent with the failure of a 1 inch transfer line produces a flammable mixture at least nine metres downwind of the release point;
- The release of hydrogen in contact with a concrete surface produces a solid deposit of oxygen and nitrogen once the substrate is sufficiently cooled.

1.3 AIMS OF IGNITED RELEASES

This series of experiments follows on from the un-ignited experimental results (summarised above) to establish the severity of an ignition from a release of LH2 with comparable spill rates, consistent with a transfer hose operation.

A number of distinct areas relating to an ignition were investigated:

- Flammability limits of a vapour cloud;
- Flame speeds through a vapour cloud;
- Radiative heat levels generated during ignition;
Overpressure measurements encountered during ignition.

1.4 THIS REPORT

This report is a factual record of the tests undertaken and of the measurements recorded.
2. IMPLICATIONS

This project follows on directly from the un-ignited releases of LH2 performed (Royle and Willoughby 2012, HSL XS/11/70) to establish the severity of an unintentional failure of a one-inch LH2 transfer hose and its subsequent ignition.

The findings of this work should help to identify phenomena associated with a spill and its subsequent ignition as well as providing data on the potential risks to enable future mitigation measures for use within the hydrogen economy.
3. METHODOLOGY

3.1 TEST FACILITY

The facility was situated at the Frith Valley site at the Health and Safety Laboratory in Buxton (Figures 3.1 and 3.2). A P&ID of the release facility is shown in Figure 3.3.

![Figure 3.1: Spill area and release facility](image1)

![Figure 3.2: Test area and surrounding terrain](image2)
The facility included:

- Concrete pad, measuring 32 m in diameter;
- LH2 tanker containing up to 2.5 tonnes of hydrogen;
- 20-metre long vacuum insulated flexible liquid hose;
- Liquid bypass hose to vent stack;
- Nitrogen and hydrogen packs for system purging;
- Local instrumentation cabin containing the signal conditioning units, data logging system and control plc;
- Remote control room (300 m from the firing pad) with video displays of the trials area and the networked control system.

Figure 3.3: P&ID of the release facility
3.1.1 LH2 tanker

The tanker was an ISO tank container provided by BOC; it contained up to 2.5 tonnes of LH2 in a vacuum insulated internal tank surrounded by an outer jacket containing liquid nitrogen (Figure 3.4).

The tanker was equipped with vent valves such that the pressure within the tanker could be lowered. It was also provided with a LH2/air heat exchanger such that the pressure in the tanker could be raised. The tanker was fitted with a bursting disc rated at 12 bar to protect against over pressurisation.

Figure 3.4: Liquid hydrogen (LH2) tanker

3.1.2 Release rig

The LH2 release system comprised the 2.5 tonne capacity LH2 tanker, 20 metres of vacuum insulated hose, a release valve station with bypass purge and release valves, a LH2 bypass hose and a 6 m high vent stack to vent excess hydrogen.

On receipt of delivery, the hydrogen within the tanker was normally at around 4 bar pressure and as such it was super-heated relative to its atmospheric boiling point of 20K. In order to achieve a liquid spill of the contents at atmospheric pressure without excessive flash vaporisation, the tanker was first depressurised to atmospheric pressure by venting hydrogen from the vapour space above the liquid, thereby cooling the remaining LH2 within the tanker to its atmospheric boiling point. Some LH2 was then allowed to flow into the hydrogen/air heat exchanger where it vaporised. This hydrogen vapour was fed to the top of the tanker in order to
re-pressurise the LH2 such that it would flow out of the tanker at a nominal flow rate (60l/min) when the release valve was opened.

During the ignited trials, a metal shield 1.26 m x 1.6 m was fitted to protect the release point from fire or overpressure damage, Figure 3.8. A 5 m radius was also drawn out to aid in the location of any interesting phenomena and flame speed measurement.

Photographs showing the release pipe work, vent stack and LH2 tanker can be seen in Figures 3.5 through to 3.8.

*Figure 3.5: Connection to LH2 trailer*
Figure 3.6: 20 m of 1” vacuum line (release pipe work)

Figure 3.7: Remotely operated valves to deliver hydrogen to the release point
3.1.3 Test protocol

After purging all of the LH2 pipe-work with nitrogen and then warm hydrogen, the manual valve on the tanker was opened fully, the actuated valve on the tanker was then opened and the connection between the tanker and the vacuum hose was checked for leaks. The bypass valve to the vent stack was opened and when the pipe-work had cooled sufficiently (as evidenced by liquid air running off the surfaces of the un-insulated portions of the pipe), the release valve was opened allowing LH2 to flow out of the pipe onto the concrete pad.
3.2 INSTRUMENTATION AND DATA PROCESSING

This section provides information regarding sensor details, modes of operation and locations.

3.2.1 Visual records

Video cameras at normal video speed of 25 frames per second were used to monitor and record selected trials. Two cameras were used: one to give a crosswind view and one to give an alternative view at 90° to the first camera.

A FLIR infra-red (IR) camera was used at 25 frames per second. The camera was not calibrated for the high temperatures associated with hydrogen flame temperatures but gave an indication of flammable cloud extent and subsequent flame propagation, allowing for approximate flame speed measurements to be made.

A modified Nikon D200 was used with a lens filter converted for IR light only. This gave high quality images and a means of comparing the images from the FLIR IR camera.

High-speed video was also used at 500 frames per second as a more accurate measure of flame speed and to provide a clearer picture of the ignition characteristics involved.

3.2.2 Meteorological monitoring

The wind speed and direction was recorded at close proximity to the release point using an ultra-sonic anemometer. Air temperature, relative humidity, wind speed and direction were also measured at the edge of the release pad by a Vector Instruments weather station.

3.2.3 Data logging

The weather station outputs were logged on a laptop connected via the USB port to a Datashuttle USB56, manufactured by Iotech Inc. This system is capable of measuring up to 28 channels at a resolution of up to 22 bits. During the trials the computer was programmed to record data at a frequency of 0.5 Hz. Multipliers and offsets were programmed into the data collection software such that the recorded sensors read in engineering units.

The Kulite pressure transducers and radiometers were logged on laptops connected via the USB ports to two separate USB3005 Datashuttles, manufactured by Iotech Inc. This system is capable of measuring up to 32 differential channels at a resolution of up to 16 bits. During the trials the computer was programmed to record data from the transducers and radiometers at frequencies of 300 kHz and 100 Hz respectively. Multipliers and offsets were programmed into the data collection software such that the recorded sensors read in engineering units. In order to capture the over-pressure response from the pressure transducers, the logger was set to trigger off the positive up-slope of the event. This also included a pre-trigger of 4 seconds to capture the base line before the pressure pulse.
### 3.2.3.1 Data logger calibration

The data shuttles were purchased from new for the un-ignited release work and their use continued into this phase of the research. They were supplied with factory calibration certificates traceable to NIST standards.

### 3.2.4 Heat flux measurement

Heat flux measurements were made using fast response (50 ms) ellipsoidal radiometers, which measure only radiative heat. The range was 110 kW/m² with a 160° field of view. The sensors were mounted on poles at a height of 1.8 m (Figure 3.9).

The heat flux sensors were purchased from new for the un-ignited release work and their use continued into this phase of the research. They were supplied with factory calibration certificates traceable to NIST standards.

Six heat flux sensors were located downwind and parallel with the release point, separated by 2 m intervals (Figure 3.10). For the purposes of identification the heat flux, sensors are subsequently referred to as HF1-6, with HF1 being closest to the release and HF6 furthest away.

![Radiometer mounted on pole](image)
3.2.5 Over-pressure measurement

Kulite ETS-IA-375M 17 bar absolute piezo-resistive sensors were used to measure the incident over-pressure from the ignitions (Test 7 onwards).

The transducers have an operating range of 17 bar and were set with the data-logging amplification for a 4 bar range. The sensors were factory fitted with an ablative coating to protect them against heat and flash light. All the piezo-resistive sensors were mounted, pointing upwards, in specially made streamlined blocks. The sensors were fixed into short lengths of scaffolding, which were securely bolted to the ground (Figure 3.11).
The three transducers were positioned 7, 10 and 13 m from the release point, 45° from the normal; the positions are shown in Figure 3.12.
3.3 **TEST PROGRAMME AND PARAMETERS**

The work plan involved releases of LH2 at a fixed rate of 60 litres per minute for different durations. The liquid was released onto the ground horizontally in an approximate North Easterly direction. A minimal number of scoping tests were performed, as the un-ignited trials had already served to validate operating procedures, check instrumentation location and function and to train personnel in the operation of the facility. These tests do not form part of this report.

### 3.3.1 Igniter Positions

To ignite the hydrogen vapour cloud 1kJ Sobbe chemical igniters were used at varying positions on the test pad (Figure 3.13). The optimum positions for the igniters were established using concentration data taken from previous un-ignited tests (Figure 1.3). Four independently operated igniters were used to allow the firing officer to fire any given igniter when the cloud passed over. This was essential due to the highly variable wind conditions at the test site. The igniters were mounted on stands at a height of 1.5 m facing towards the release point. The firing officer during the trials was located 250m away in a building and used a spotter and video displays to time ignition based on the water vapour cloud location.

![Igniter Positions Diagram](image)

*Figure 3.13: Igniter positions on test pad*
3.3.2 Test Parameters

The nominal storage pressure was measured immediately upstream of the release valve with the tanker valve open and the release valve closed. The nominal release pressure was measured immediately upstream of the release valve with the release valve open. The release rate, nominal storage pressure and release pressure for all the tests are given below in Table 3.A.

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<th>Release rate (l/m)</th>
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3.3.3 Weather Conditions

The weather conditions at the time of the release for each test were recorded; see Section 4 – Results, Table 4.B. The wind direction and speed were measured at two locations. One was at the edge of the pad 2.5 m from the ground (shed) and the other (ultrasonic array) at close proximity to the release 86 cm from the ground. The wind direction was recorded relative to North (0°).
4. RESULTS

Fourteen tests were performed in total. Table 4.A shows an overview of the data and footage gathered from each test. Tests that are greyed out in the table represent non-ignitions and are not considered in this report. The reasons for the non-ignitions are discussed later in the report. All flame speeds quoted are derived from video footage of the tests.

Radiometer plots for tests which are not shown in this section are located in Appendix 7.1. The meteorological data and release duration for each ignited test (except the scoping tests) are shown in Table 4.B. Table 4.C shows maximum heat flux against release duration for each ignited test.

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Table 4.A: Test overview

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<th>Test Number</th>
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<th>Av. Wind Speed (m/s)</th>
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<th>Av. Humidity (%)</th>
<th>Av. Ambient Temperature (deg C)</th>
<th>Release Duration Pre Ignition (secs)</th>
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Table 4.B: Meteorological data and release duration from tests with ignitions

Data Missing
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<th>Test Number</th>
<th>Maximum Heat Flux (kW/m²) from 'burn back' phase</th>
<th>Maximum Heat Flux (kW/m²) from secondary explosion</th>
<th>Release Duration pre-ignition (secs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>40.33</td>
<td>NA</td>
<td>140</td>
</tr>
<tr>
<td>6</td>
<td>57.82</td>
<td>120.14</td>
<td>260</td>
</tr>
<tr>
<td>7</td>
<td>75.64</td>
<td>NA</td>
<td>75</td>
</tr>
<tr>
<td>9</td>
<td>38.26</td>
<td>NA</td>
<td>150</td>
</tr>
<tr>
<td>10</td>
<td>53.97</td>
<td>NA</td>
<td>197</td>
</tr>
<tr>
<td>11</td>
<td>35.12</td>
<td>NA</td>
<td>274</td>
</tr>
<tr>
<td>13</td>
<td>26.92</td>
<td>NA</td>
<td>326</td>
</tr>
</tbody>
</table>

### 4.1 TESTS 1 – 3

Tests 1-3 were performed on 10-03-11 and were used primarily as scoping tests for the instrumentation and cameras. Only a limited number of scoping tests were required, as the earlier un-ignited tests provided a good indicator as to what the vapour cloud might do as well as liquid/solid material build ups.

In all three tests, ignitions of the vapour cloud were made. Standard video footage of the tests was taken from two locations.

### 4.2 TEST 4

Ignition occurred from igniter no.3 and propagated back through the horizontal cloud towards the release point. The flame front accelerated up to speeds of 50 m/s and began to lift upwards once momentum was lost (Figure 4.1[a-f]). A jet of flame continued to burn from the release point after the vapour cloud had been consumed until the release was stopped.
The maximum heat flux generated during ignition of the cloud measured 40.33 kW/m² at radiometer position no. 2, a distance of 7.6 m from the release point. This maximum is shown in Figure 4.2 as an initial peak due to the burning back of the cloud; following this, a steady state burning of the LH2 is evident as it is fed into the existing fire.
4.3 TEST 6

Ignition occurred from igniter no.3 and propagated back through the horizontal cloud towards the release point. The flame front accelerated up to speeds of 50 m/s and began to lift upwards once momentum was lost. A jet of flame continued to burn from the release point after the vapour cloud had been consumed as in test 4. However, approximately 3.6 seconds after the initial cloud ignition, a secondary explosion occurred emanating from the liquid/solid pool location. This is shown in Figure 4.3, images f – h.
This secondary explosion created an 8 m diameter hemispherical fireball around the solid/liquid pool location and created a noise level audible from over a mile away. Unfortunately no sound or over-pressure measurements were taken during the test and so a clear quantitative value was not obtained. The flame speed can only be approximated to >75 m/s as the IR camera footage was taken at 25 fps. A clear second peak in radiated heat can be seen in Figure 4.4 denoting the secondary explosion. The maximum heat flux measured was 120.14 kW/m² from radiometer no. 2, at a distance of 7.1 m from the release point during the secondary explosion. This heat flux is greater than the calibrated range of the radiometer; however, the signal shows no sign of over-
ranging. The initial deflagration created a maximum heat flux (first peak in figure 4.4) of 57.82 kW/m² from radiometer no. 1, a distance of 7.6 m from the release point.

Figure 4.4: Radiometer readings from ignited release (Test 6) exhibiting a secondary explosion

4.4 TEST 7

The vapour cloud formed during this test was observed to rise more vertically than in previous tests where the wind speeds were higher. Ignition occurred from igniter no.2 and propagated spherically outwards consuming the cloud at flame speeds up to 25 m/s. The wind speed during this test was relatively low: 0.5 m/s South Westerly.

High-speed colour footage of the test was taken in low light conditions at 500 fps.

4.5 TEST 9

Ignition occurred from igniter no.1 and propagated upwards through the vapour plume. The flame front accelerated upwards through the cloud up to speeds of 25 m/s and lifted upwards after the initial ignition. A jet of flame continued to burn from the release point after the vapour cloud had been consumed as in Test 4.

4.6 TEST 10

Following the secondary explosion seen in Test 6, further tests were performed to try to replicate this phenomenon. However, the meteorological conditions during Test 10 and onwards were more like Test 7 than Test 6.
The resultant fireball was comparable to Test 9, despite increasing the release duration from 150 secs to 197 secs. Ignition of the cloud was obtained from igniter no. 1 with no secondary explosion. The fireball after ignition from the vapour cloud can be seen in Figure 4.5, which shows a stills image from the video footage of Test no.1, 240 ms after ignition.

![Figure 4.5: Ignition of the vapour cloud during Test 10 during low wind conditions](image)

4.7 TEST 11

The meteorological conditions and resultant fireball were again comparable to tests 9 and 10, despite increasing the release duration further to 274 secs. Ignition was obtained from igniter no. 3. Figure 4.6 shows stills of the ignited cloud 300 ms and 2000 ms after ignition.
4.8 TEST 13

An ignition was produced in test 13 from igniter no. 2, which consumed the vapour cloud, but did not produce a secondary explosion of the solid/liquid pool. Igniter no. 4 was then fired onto the remaining solid/liquid pool, which caught fire but did not explode.

4.9 SOLID DEPOSIT IGNITION TEST

Following the results of Tests 1-3 and the observation of the solid/liquid pool, an ignition test was performed on an isolated sample of solid/liquid created during a LH2 release.

The sample was collected using a polystyrene container of dimensions 0.5 m x 0.5 m x 0.8 m. The container quickly created the same solid/liquid seen in the releases onto concrete in both the un-ignited and ignited trials (Figure 4.7). The appearance of the solid is like a ‘snow’, presumed to be solid nitrogen/oxygen composition, which appears to sublime very quickly. There is also
liquid present within the solid, which is again presumed to be liquid air and possibly LH2 for a short time after release.

The mixture was ignited using a match head (1 joule) igniter. The solid/liquid appeared to burn with a small partially visible flame emanating from the solid. No audible explosion was heard on ignition or thereafter. The solid/liquid quickly burnt/vaporised leaving no residue within the container.

Figure 4.7: Solid/liquid deposit during un-ignited trials
5. DISCUSSION

The un-ignited trials (D. Willoughby, M. Royle 2012) and the ignited scoping tests 1-3 revealed that there were two distinctly different release scenarios: firstly a low wind speed condition in which the buoyant effects of the hydrogen cloud would be dominant resulting in a vertical plume of hydrogen and water vapour on account of the cryogenic temperature of the gas, and secondly, a high wind speed condition where plume is driven from the release point and carried downwind.

A number of ignited releases were performed with varying parameters. The release rate and pressure were the same as for the un-ignited releases. All the ignited releases performed to date have been made with the hydrogen released horizontally along the ground at ground level. A number of releases were made at night to enable the flame to be more easily visualised.

5.1 NON-IGNITIONS

It should be noted that the clouds of hydrogen produced by the release of LH2 could not be ignited on four separate occasions (Tests 5, 8, 12 and 14); four pyrotechnic igniters were fired within the cloud with no resulting ignition of the hydrogen gas. The reason for this is not clear; it may be that the gas cloud was under or over-rich in hydrogen at the point that the igniters were fired due to differing dispersion and wind effects, or a quenching effect was created by the water vapour created by the cold hydrogen cloud.

5.2 TYPICAL BURNING BEHAVIOUR

The first ignited release was performed with the ignition timed immediately after the release had stabilised and before any pool or solid had accumulated on the ground. On ignition there was a soft report followed by a low rumble and then a gentle jet flame as the hydrogen issuing from the release pipe burned. The ignition was approximately 9 m from the release point and at 1 metre high. The flame speed was measured from the high-speed video and found to develop up to 25 m/s.

Later releases (Test 4 onwards) were performed with delayed ignitions varying between 75 and 326 seconds after the start of the releases. These delayed ignitions allowed for a larger build-up of flammable cloud and also reproduced the liquid/solid pooling phenomena first seen during the un-ignited releases of LH2 work (XS/11/70, Royle and Willoughby, 2011). The burning characteristics of the cloud were found to be the same as for releases with a short ignition delay with the flame reaching speeds of approximately 50 m/s. The extent of the flammable cloud appeared to be congruent with the visible extent of the water vapour cloud created by the very cold hydrogen cloud when IR footage was compared with visible footage.

On one occasion (Test 6 – Figure 4.3) the burning characteristics changed as the cloud was ignited; it burnt back to source creating a jet-fire and then a secondary explosion appeared to emanate from the liquid/solid pool location. This event is discussed further in Section 5.6 – Secondary Explosion.
5.3 **WIND SPEED**

Tests were performed during various wind conditions; low wind speeds were considered to be $<0.6$ m/s and high wind speeds $>0.6$ m/s. This enabled a comparison to be made with almost entirely buoyancy driven cloud dispersions (low wind speeds) and momentum dominated cloud dispersions (high wind speeds).

![Figure 5.1: Maximum heat flux plotted against average wind speed during each test](image)

From Figure 5.1 it is clear that there is no strong correlation between the creation of high heat fluxes at distances greater than 7 m and wind speed. Due to that fact that the radiometer positions were constant throughout the different wind speed tests, it is not possible to comment on whether heat fluxes would be higher at distances closer than 7 m (the first radiometer position). One possible reason for the variable results is that the wind direction and release duration are not constant throughout the tests.

5.3.1 **Low wind speed ignitions (<0.6 m/s), vertical release plume**

The tests with low speed conditions were: Tests 7, 9, 10 and 11. It was observed that in all the tests with low wind speeds, the hydrogen cloud dispersion remains dominated by buoyancy rather than the momentum provided by the release jet. This leads to a flammable cloud, which extends approximately 5 m in diameter and mushrooms upwards to nearly 30 m with flame speeds up to 25 m/s.

5.3.2 **High wind speed (>0.6 m/s), horizontal release plume**

The tests with high-speed conditions were: Tests 4, 6, and 13. It was observed that in all the tests with high wind speeds, the hydrogen cloud dispersion was predominantly momentum...
driven from the release jet. This momentum-dominated plume travelled up to 15 m along the ground with a 2.5 m radius cylindrical dispersion pattern before a transition to the buoyancy driven behaviour seen in low wind speed cases and rapid dispersion. Ignition of the momentum influenced plume caused flame acceleration up to speeds of 50 m/s back towards the source of the release. Some deflagration away from the release source was seen but this did not extend for more than 1 m.

5.4 WIND DIRECTION

During testing there were two dominant wind directions, South Westerly and Easterly. Tests 4, 6 and 7 were performed with a South Westerly wind and Tests 9, 10, 11 and 13 with an Easterly wind.

Ignoring other potential variables, Figure 5.2 shows that there is a trend that maximum heat flux levels appear to be greater when the wind was South Westerly. This wind direction was also prevalent when the secondary explosion occurred in Test 6. One hypothesis for the increased heat flux levels is that the 1.6 m high protective plate behind the release point acted as a baffle causing an increase in turbulence as it faces perpendicular to a South Westerly wind. This increase in turbulence would serve to increase the flame propagation speed during the deflagration stage. The plate may have also acted as a windshield to the solid/liquid deposit area, reducing evaporation and dissemination of the hydrogen/oxygen in the region. This may explain why after the initial ‘burn back’, enough oxygen was able to build-up and allow the necessary oxygen enrichment required for an explosion of the magnitude seen in Test 6.

Another explanation for increased heat flux readings with a South Westerly wind (Tests 4, 6, 7) is that this wind direction would blow the flammable cloud closer to the radiometers. This is a far simpler explanation, which combined with the baffle effect caused by the protective plate mentioned above may help explain the increase in deflagration heat flux levels for a given wind direction.
Figure 5.2: Chart of average wind direction against maximum heat flux (test numbers shown in brackets)

Test 4 appears to be anomalous in Figure 5.2 as it is reading considerably lower than Tests 6 and 7 which also share a South Westerly wind direction. Test 4 also exhibited the highest wind speeds recorded during any of the tests at 2.28 m/s on the shed anemometer.

5.5 RELEASE DURATION (IGNITION DELAY)

Ignoring all buoyancy effects and meteorological differences it would be expected that the longer the release duration or ‘ignition delay’, the greater the potential for a higher maximum heat flux. This is because there is a greater volume of released hydrogen that is available to burn when ignited.

Figure 5.3 shows a graph for the ignited tests of release duration against maximum heat flux of the initial deflagration (the peak for Test 6 has been ignored for this graph). During initial testing (Tests 1-9), the release duration varied greatly based on the time taken for conditions to be favourable for ignition of the hydrogen cloud due to wind variance. During Test 10-13, the
release duration was based on the size of the forming solid/liquid pool, rather than cloud ignition specifically.

Figure 5.3 shows that conversely, a weak correlation can be found to suggest that the longer the release duration, the lower the maximum heat flux. This contradicts what would normally be expected although several other variables may influence the results of these tests. A reason for this abnormal trend may be due to the liquefaction and solidification of the oxygen in the surrounding air preferentially to nitrogen due to its higher boiling point. This would create an inerting effect as more oxygen is stripped from the air lowering the available combustion reactants. Therefore, the longer the test duration, the colder the substrate and surrounding air gets, leading to an increase in nitrogen concentration.

Furthermore, a secondary effect of this increased substrate cooling is that the hydrogen itself may also increasingly remain as a liquid. It is known from previous testing that this phenomenon can happen readily and that the substrate can cool sufficiently for this to happen. This increase in liquefied hydrogen would serve to lower the hydrogen cloud concentration and lower the heat flux levels from subsequent ignition.

5.6 SECONDARY EXPLOSION

In one experiment there was evidence of a secondary explosion occurring close to the release point after LH2 had been released at ground level, during windy conditions, for 4.3 minutes (258 s). The explosion occurred after the hydrogen cloud had been ignited, burned back to the release point and then burned steadily for 3.6 seconds. The radiometer trace from this
 experiment is shown in Section 4, Figure 4.3; the second peak, corresponding to the secondary explosion, is evident.

From IR video footage, the explosion was estimated to be of a hemispherical profile and approximately 8 m in diameter, emanating 2.5 m from the release point, corresponding with the location of the solid/liquid pool seen prior to ignition.

Several attempts were made to reproduce the phenomenon without success, although the conditions on those occasions were far less windy with the wind in the opposite direction than when the explosion occurred. It is possible that oxygen enrichment of the condensed air may have occurred due to oxygen (-183°C) having a higher boiling temperature than nitrogen (-196°C), an effect that was more evident during the windy conditions. It is postulated that the explosion was either a gas phase explosion resulting from a sudden release of oxygen from the solid due to a rapid phase change, or even a rapid reaction within the condensed slurry of solidified air and LH2 if the oxygen concentration were high enough Cassutt, 1964.

The explosion was sufficiently energetic to be heard over a kilometre away. Unfortunately, at the time of the explosion no pressure measurements were being made. Therefore, it was necessary to estimate the “size” of the explosion by other means.

5.7 BLAST MODELLING

As no over-pressure measurements were made at the time of secondary explosion, an estimate of the TNT equivalent energy can be used to determine the magnitude of the explosion over-pressure. A blast-modelling program can then process this TNT equivalent to provide a visual representation of the pressure, but it must first be estimated in one of two ways:

5.7.1 Method 1 - Pressure effects

The explosion witnessed failed to break the Perspex windows in the small shed approximately 20 m from the centre of the explosion. Knowing the material composition of the window (Perspex) and the distance from the epicentre, it is possible to input this data into Hazl to model the TNT equivalent required to break a window of comparable dimensions. The modelling program used does not contain data for Perspex specifically; however, an assessment can be made for annealed glass, which can be considered weaker than Perspex and for Polycarbonate, which is stronger than Perspex.

The program calculated that the minimum required TNT equivalent was 2.7 kg for annealed glass and 4.01 kg for Polycarbonate. From these estimates a TNT equivalent of <4 kg can be assumed for the explosion seen in Test 6. At 100% equivalence this would equate to less than approximately 100 g of hydrogen.

5.7.2 Method 2 - Radiative fraction

Another method of estimating the size of the secondary explosion is to use the radiometer data and relate it to the radiative fraction.
The fraction of potential heat release that is emitted in the form of radiation is referred to as the radiative fraction, \( \chi \), and is defined in Equation 1.

\[
(1) \quad Q_r = \chi M \Delta H_c
\]

where:
- \( Q_r \) = Heat radiated (kW)
- \( \chi \) = Radiative fraction (between 0 and 1)
- \( M \) = Mass rate of fuel combustion (kg/s)
- \( \Delta H_c \) = Heat of combustion of the fuel (kW/kg)

The radiative fraction depends upon the fuel type and whether contaminants are present within the burning cloud. Hydrogen flames typically radiate less than flames from the combustion of hydrocarbon gases. The radiative fraction was estimated for the steady burning periods of the LH2 release experiments, that is when the initial cloud had burned back and the hydrogen was being consumed as it was released and evaporated.

It is common to approximate the radiative fraction of a flame based on radiometer readings taken at a significant distance from the flame such that an inverse square law can be reasonably applied. However, in this case the flame was elongated along the line of the radiometers and was generally close to the ground. It can be seen that the readings of the first three radiometers are very similar to each other. This would be expected from the flame shape observed on the video recordings. For this reason, a semi-cylindrical radiating heat source was assumed for the purposes of estimating the radiative fraction and the total radiated heat estimated using Equation 2.

\[
(2) \quad Q_r = (1 + \alpha) \pi d L q_r \frac{L}{2}
\]

where:
- \( Q_r \) = Heat radiated (kW)
- \( d \) = Distance to radiometer (m)
- \( L \) = Length of flame (m)
- \( q_r \) = Heat flux at radiometer (kW/m²)
- \( \alpha \) = Reflection coefficient of concrete surface below the flame

Data from two of the ignited releases were analysed in this way, assuming a reflection coefficient for the concrete of 0.55 from Markvart, Castalzer 2003, giving an estimate of the radiative fraction as 0.054. This estimate compares reasonably well with previously reported values for gaseous and LH2 hydrogen releases in Studer 2009, Friedrich 2011.

Using the radiative fraction above and the radiometer response during the explosion (that is the area under the second peak which represents the total energy per m² received at the radiometer), another estimate for secondary explosion size can be made. Since the explosion almost engulfed the nearest radiometers, the estimate is based on the furthest radiometer and a hemispherical heat flux. It was also assumed that the radiative fraction during the explosion was similar to that during steady burning. On this basis the quantity of hydrogen rapidly burned in
the explosion was estimated as 675 g, yielding approximately 82 MJ or a TNT equivalent of 18 kg. This value of 18 kg of TNT is clearly very high, although it assumes all of the energy available behaves like TNT. A value of 10% of the TNT equivalent for vapour cloud explosions is a better estimate of the energy involved in this case, which gives a TNT equivalent of 1.8 kg, a value far closer to the estimate made from the pressure effects in method 1.

5.7.3 Modelling the blast

The use of Polycarbonate (4 kg) in method one appears overly conservative as method two accounts for the worst case in terms of combustion (1.8 kg) and appears more closely matched with the results from annealed glass (2.7 kg). Therefore, 2.7 kg of TNT was taken as the input condition for the modelling based on the anecdotal evidence described.

Air3D was used to model the secondary explosion. Air3D is an open source code developed to simulate three dimensional air-flows in a heterogeneous, anisotropic zone. Figure 5.4 shows the blast wave propagating across the test pad, emanating from a position at which the solid/liquid builds up. The wave strikes firstly the protective shield on the release point and then the sheds at the edge of the pad.
Figure 5.4 (a-i): Air3D blast wave model prediction for the secondary explosion experienced during Test 6 after ignition of the LH2 cloud.
Using the Air3D model it was possible to predict the overpressures at the three Kulite pressure transducer positions installed after Test 6. Figure 5.5 shows the predicted over-pressure against time for transducer no. 3, 7 m from the source of the blast. The first peak on the graph represents the primary blast wave; the following smaller peaks and troughs are indicative of reflections from the surroundings, in this case, the protective plate and sheds.

Figure 5.5: Over-pressure against time from source blast at transducer no. 3 (7m from source)

The predicted maximum over-pressures for transducers 1, 2 and 3 are 160 mbar (13 m from source), 280 mbar (10 m) and 730 mbar (7 m) respectively.

5.8 THERMAL DOSE

The safety distances from an ignited LH2 release can be formulated by considering the levels of harm caused by thermal radiation. The level of harm caused by thermal radiation is expressed by considering the level of radiation experienced and the period of time for which this radiation level is tolerated. This is expressed in ‘thermal dose units’ (TDUs), shown in Equation 3:

$$\text{TDU} = I^{4/3} \times t$$

where:

- $\text{TDU}$ = thermal dose units
- $I$ = thermal radiation intensity (kW/m$^2$)
- $t$ = duration for which the radiation is experienced (secs)

By taking the heat flux data from the radiometers used during testing it is possible to assess the potential thermal dose caused by an ignition of LH2. This includes: the initial deflagration of the cloud, the resultant jet-fire and any secondary explosion which may occur. The radiometers measure radiation from the IR region and thus IR burn data have been used for comparison. Table 5.A shows the thermal dose levels for several harm (burn) criteria.
Table 5.A: Burn severity vs. thermal dose relationship

<table>
<thead>
<tr>
<th>Harm Caused</th>
<th>IR radiation thermal dose (TDU) (kW/m²)</th>
<th>Mean</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pain</td>
<td></td>
<td>92</td>
<td>86-103</td>
</tr>
<tr>
<td>Threshold – 1st degree burn</td>
<td></td>
<td>105</td>
<td>80-130</td>
</tr>
<tr>
<td>Threshold – 2nd degree burn</td>
<td></td>
<td>290</td>
<td>240-350</td>
</tr>
<tr>
<td>Threshold – 3rd degree burn</td>
<td></td>
<td>1000</td>
<td>860-2600</td>
</tr>
</tbody>
</table>

See References, Table 8.A for burn data references

It is of note that the burning of hydrogen releases significant quantities of ultra-violet (UV) radiation compared with hydrocarbon-based fires of a similar size. However, Tsao and Perry 1979 found that the dosage of UV radiation must be more than twice the IR dosage to cause similar injury levels. Therefore UV radiation has been excluded and IR radiation assumed to be the dominant cause of harm.

By applying the average dose levels for the different ‘harm’ levels (shown in Table 5.A) to the heat flux data measured experimentally by the radiometers, it is possible to determine the time taken to reach a given harm threshold at a given distance. This technique can be applied to infer approximate safety distances for the four main phenomena seen during testing:

1. A steady state jet-fire during high wind speed conditions >0.6 m/s.
2. A steady state jet-fire during low wind speed conditions <0.6 m/s.
3. The initial deflagration or ‘burn back’ of the release cloud to source.
4. The secondary explosion seen after the initial deflagration has occurred.

Due to the nature of the phenomena above, they can be grouped further. Both the initial deflagration and the secondary explosion are events that occur within a known, comparatively short (milliseconds) timeframe. This is in comparison with the high and low wind speed jet-fires, which can be approximated to a continuous event, which can last for long periods (minutes). Therefore, the deflagration and explosion are reviewed separately from the jet-fires.

The following assessment of safety distances is purely for radiative heat and does not consider any potential pressure effects.

5.8.1 Jet-Fire Safety Distances

A ‘no harm’ criterion for jet-fires has been established at 1.6 kW/m² EIGA DOC 75/07/E. This is the heat flux level at which no discomfort will be felt regardless of exposure time. The document also suggests a ‘no harm’ level of 37.5 kW/m² for equipment that is not insulated.
In order to find the base heat radiation level for a hydrogen jet–fire, the initial peak due to burn back was discounted until a steady state level was achieved. This steady state level was then averaged for the individual radiometers to create heat fluxes at known distances from the flame extent (extrapolated from radiometer positions and video footage). Figure 5.6 shows the jet-fire flame extent compared with radiometer position. The flame extent was equated to a 5 m long, hemi-cylindrical shape emanating from the LH2 release point.

![Diagram](image)

**Figure 5.6: Flame extent for LH2 jet-fires including radiometer positions**

Two tests were chosen to compare jet-fires in high and low wind conditions: Tests 4 and 7 respectively. These particular tests were chosen as they had good data sets at extremes of wind condition (Test 4: 2.15 m/s, Test 7: 0.59 m/s); the wind direction was the same (South Westerly) and the release duration was similar (Test 4: 140 secs, Test 7: 75 secs). Radiometers 1-3 were considered as being at the same distance from the heat, and were grouped and averaged. From the experimental results of Test 4 (high wind conditions), Figure 5.7 shows thermal dose against exposure time at a range of distances from the flames with various harm levels overlaid.
For the experimental results of Test 7 (low wind conditions), Figure 5.8 shows thermal dose against exposure time at a range of distances from the flames with various harm levels overlaid.

From Figures 5.7 and 5.8, it is clear that during high wind speed conditions the exposure time to reach harmful levels of heat radiation is lower than for low wind speeds. This is highlighted in
Table 5.B, which shows that to reach the lowest harm level, i.e. ‘pain’, requires exposure for 6 seconds at 6.5 m (distance from flame) in high wind speeds, compared with up to 13 seconds for low wind speed conditions.

**Table 5.B: Time to reach harm levels for LH2 jet-fires**

<table>
<thead>
<tr>
<th>Distance from flame (m)</th>
<th>Exposure time to reach (secs):</th>
<th>‘Pain’</th>
<th>1st degree burns</th>
<th>2nd degree burns</th>
<th>3rd degree burns</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5</td>
<td>Indicates Test 4: high wind speed conditions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.6</td>
<td>Indicates Test 7: low wind speed conditions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.7</td>
<td></td>
<td>28</td>
<td>44</td>
<td>32</td>
<td>50</td>
</tr>
<tr>
<td>10.1</td>
<td></td>
<td>185</td>
<td>648</td>
<td>205</td>
<td>740</td>
</tr>
</tbody>
</table>

Distances: 8.7m (radiometer 5) and 10.1m (radiometer 6) have been omitted as the heat flux measures from these locations falls below the ‘no harm’ criterion.

Taking the ‘worst-case’ scenario, i.e. high wind conditions (Test 4), Figure 5.9 shows the exposure time taken for a normally clothed person to reach the ‘pain’ threshold for a given flame separation distance.

![Figure 5.9: Separation distance against time to reach ‘Pain’ threshold – Test 4](image-url)
5.8.2 Initial Deflagration/Secondary Explosion Safety Distances

In order to approximate the distance of the radiometers from the heat source (event location), the ignited cloud must be mapped against the radiometer positions. Figure 5.10 shows the flammable cloud profile for Test 6 with respect to the radiometer positions. Test 6 is being used, as it is the only data set that contains both an initial deflagration and then a secondary explosion. The flammable cloud extent and epicentre of the secondary explosion have been estimated from IR video footage and simplified accordingly.

The flame extent for the secondary explosion was equated to an 8 m diameter hemisphere (dashed blue circle in Figure 5.10) emanating from a point source 2.5 m from the release point on a centreline in line with the release. The equivalent stand-off distance for each radiometer is marked with blue arrows in Figure 5.10.

The flame extent for the ‘burn-back’ was equated to a 9 m long, hemi-cylindrical shape (long dashed orange cylinder, Figure 5.10) emanating from the LH2 release point, although this profile does not truly represent the measured burning pattern over the 2.5 second initial burn-back time. From IR footage of Test 6, it is clear that the greatest intensity of burning occurs when the flame approaches the source at a distance of approximately 3 m (close to the secondary explosion source). Therefore, it is preferable to assume a smaller flame extent (short dashed orange cylinder, Figure 5.10) to take into account the lower intensity of flame seen at distances between 3 and 9 m. This means that radiometers 1 and 2 are measuring parallel with the new flame front and radiometers 3 to 6 are effectively measuring from a point at the front of this new 3 m flame extent. The equivalent stand-off distance for each radiometer is marked in orange in Figure 5.10.
As the initial deflagration and secondary explosion are finite and relatively short events in comparison with a continuous jet-fire, the thermal dose for these phenomena can be plotted as a function of distance from the flame extent. The assumption is made that a person would be unable to escape the event and would experience the total heat flux from the phenomena at a given distance instantly. A plot of heat flux against distance (Figure 5.11) is given for Test 6, as this is the only test in which the initial deflagration is followed by a secondary explosion.
6. CONCLUSIONS

6.1 IGNITED RELEASE REGIMES

From experimentation, four separate regimes have been found to occur when a full bore failure of a 1-inch liquid (60 l/min) hydrogen tanker transfer hose is ignited:

- An initial deflagration of the cloud back to source at speeds up to 50 m/s.
- A possible secondary explosion emanating from the solid deposit generated after the initial deflagration of the release cloud due to oxygen enrichment. This was estimated to have an equivalent energy of up to 4 kg of TNT.
- A buoyancy driven jet-fire when wind conditions are minimal (wind speeds <0.6 m/s).
- A momentum dominated jet-fire when wind conditions are high (wind speeds >0.6 m/s).

During testing, several factors were found to affect the maximum heat flux generated by igniting releases:

- Increasing the release duration of the spill lowered the maximum heat flux from the initial deflagration although, it is of note that the secondary explosion occurred during a test of relatively long duration.
- Wind direction appears to affect the heat flux generated by an ignition, with the worst being South Westerly. This direction effect is most likely due to the protective plate affecting local turbulence levels.
- High wind speeds (>0.6 m/s) rather than low wind speeds (<0.6 m/s) were found to create worse case conditions during a jet-fire. No strong correlation was found between wind speed and heat flux during the initial deflagration phase, but an increase in ‘burn-back’ speed from 25 m/s to 50 m/s was seen between low and high wind speeds.

The solid/liquid deposit, first described in the un-ignited phase of this project (Royle and Willoughby 2011, HSL XS/70/11), was again created during each test. This solid/liquid was ignited separately and found to burn with a partially visible flame until the solid/liquid was consumed/evaporated.

6.2 SAFETY DISTANCES

From radiometer data recorded during testing, it has been possible to estimate safety distances for the different release phenomena associated with a full bore failure of a LH2 refuelling hose. In order to do this, different assumptions have been made for the different phenomena based on visual information from the testing and previous work on harm criteria and TDU levels. It must be pointed out that the safety distances described below are for IR radiation only and do not consider any potential pressure effects.
6.2.1 Initial deflagration or ‘burn back’ of release cloud to source

The assumptions used with this phenomenon are that it is an instantaneous event with the greatest intensity of burning occurring at a distance of 3 m from the release point, burning in a hemi-cylindrical pattern in line with the release direction.

The worst-case separation distance from source as given in Table 6.A was calculated by the addition of the maximum flame extent in any direction from the release point and the distances at which a person would experience pain/burns found from Figure 5.11.

The worst-case distance at which 3rd degree burns would be suffered is 7 m from the release point and ‘pain’ would be felt as far away as 11.1 m from the release point.

6.2.2 Secondary explosion seen after initial deflagration has occurred

This phenomenon only occurred once during the fourteen tests but must be considered despite its low frequency. The assumptions with the secondary explosion are that it can be considered an instantaneous event that expands to an 8 m hemisphere from a point source 2.5 m from and in line with the release point.

The worst-case separation distance from source as given in Table 6.A is calculated by the addition of the maximum flame extent in any direction from the epicentre of the explosion, the distance between the epicentre and the release point and the distances at which a person would experience pain/burns found from Figure 5.11.

The distance at which 3rd degree burns would be suffered is 7.6 m from the release point and ‘pain’ would be felt as far away as 11.3 m from the release point.

It is of note that if the estimated worst case of 4 kg of TNT is approaching reality, the pressure effects from the blast would be far more severe than the radiative heat output (at 11 m, the blast overpressure for 4 kg of TNT would approximate 24 kPa).

6.2.3 Steady state jet-fire during high and low wind speed conditions

High and low wind speed conditions are defined in this instance as >0.6 m/s and <0.6 m/s respectively. It is assumed that in the case of jet-fires the event is a continuous one and therefore exposure time becomes a factor. As with the initial deflagration, the burning pattern is simplified to a hemi-cylindrical pattern, which extends 5 m from and in line with the release point.

The worst-case separation distance from source as given in Table 6.A is calculated by the addition of the maximum flame extent in any direction from the release point and the distance to the closest radiometer as shown in Figure 5.6.

If an individual initially stood 11.5 m from the release point were not to move away from the jet-fire during the exposure, it would take 63 seconds and 133 seconds to receive 3rd degree burns during high and low wind speed conditions respectively. At the same distance it would only take 6 seconds and 13 seconds for the individual to experience ‘pain’ during high and low wind speed conditions respectively. It is clear therefore, that a jet-fire during high wind speed conditions represents the worst-case scenario.
Table 6.A provides a required separation distance guide based on the results of these ignited releases taking into account the various phenomena seen. The distances represent the minimum separation distance required for an individual to stand from the release point (refuelling point) to avoid feeling ‘pain’.

### Table 6.A: Separation distance guide for a 60l/min spill

<table>
<thead>
<tr>
<th>Phenomena</th>
<th>Initial cloud deflagration</th>
<th>Secondary explosion</th>
<th>Jet-fire (High wind)</th>
<th>Jet-fire (Low wind)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum separation distance from source to avoid ‘pain’</td>
<td>&gt;11.1 m</td>
<td>&gt;11.3 m</td>
<td>&gt;11.5 m (after 6 seconds exposure)</td>
<td>&gt;11.5 m (after 13 seconds exposure)</td>
</tr>
</tbody>
</table>

*Note: These values consider radiative heat only, not pressure effects*

Table 6.A indicates that the separation distance guide values for the four different phenomena are very similar (approx. 11m). This similarity in the case of the initial deflagration and secondary explosion is coincidental. The distance of 11.5m for the jet-fires is linked to the positioning of the instrumentation but is based on exposure time at that distance. These separation distances relate to the hydrogen flow rate of 60l/min and cannot be assumed or extrapolated for different flow rates.

### 6.3 FURTHER EXPERIMENTATION

From evaluating the data and witnessing the tests, one main area that would be of interest to explore and gain further understanding of is the secondary explosion phenomenon, which occurred during Test 6. This is directly linked with the lack of understanding of the composition and formation of the solid/liquid deposit formed after considerable cooling during a release.

It was unfortunately outside of the scope of the current project to look at this phenomenon, as it was not expected, hence explaining why pressure measurement devices were not set-up during the event. Some efforts were made to recreate the conditions in later testing, but a combination of lack of understanding of why the explosion occurred and difficulty in achieving repeat conditions due to the highly variable nature of the weather and combustion mechanics prevented the secondary explosion being recreated.

If further work were to be performed in this area, it would be recommended to look at the solid/liquid deposit formation in isolation on a laboratory scale due to the energetic nature of the event, the cost of large-scale releases and the greater degree of control of wind conditions a laboratory set up would bring.
7. APPENDIX

7.1 RADIOMETER DATA PLOTS

This section contains radiometer plots of heat flux for ignited tests that were not shown in Section 4.

7.1.1 Test 7

![Radiometer Readings - Test 7 diagram]
7.1.2 Test 9

Radiometer Readings - Test 9

7.1.3 Test 10

Radiometer Readings - Test 9
7.1.4  Test 11

Radiometer Readings - Test 11

7.1.5  Test 13

Radiometer Readings - Test 13
8. REFERENCES

8.1 TEXT REFERENCES


(6) EIGA (2007), Determination of Safety Distances, IGC Doc 75/07/E

8.2 BURN SEVERITY DATA REFERENCES

Table 8.A – References to data in Table 5.A in main report (Rew, 1996 and Hymes, 1994)

<table>
<thead>
<tr>
<th>Injury Type</th>
<th>Infra-red Radiation Thermal Dose (TDU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pain</td>
<td>86-103 Stoll and Green (1958)</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; degree</td>
<td>c. 80 Mehta et al (1973)</td>
</tr>
<tr>
<td></td>
<td>130 Tsao and Perry (1979)</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt; degree</td>
<td>240 Stoll and Green (1958)</td>
</tr>
<tr>
<td></td>
<td>270-410 Stoll and Green (1958)</td>
</tr>
<tr>
<td></td>
<td>c. 350 Mehta et al (1973)</td>
</tr>
<tr>
<td></td>
<td>290-540 Williams et al (1973)</td>
</tr>
<tr>
<td></td>
<td>730 Arnold et al (1973)</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt; degree</td>
<td>c. 500 Mehta et al (1973)</td>
</tr>
</tbody>
</table>

N.B. The 3<sup>rd</sup> degree burn data is inconsistent with some of the 2<sup>nd</sup> degree burn data; other sources have been used instead.
9. BIBLIOGRAPHY

(1) Willoughby D, Royle M (2010), Experimental / modelling strategy for issues associated with liquid hydrogen spills, HSL report XS/10/06

(2) Pritchard D K, Rattigan W M (2009), Hazards of liquid hydrogen: Position paper, HSL report XS/09/72


(6) Willoughby D, Royle M (2009), Hydrogen venting / flare study under variable flow conditions, HSL report XS_121_09

(7) EIGA (2006), Gaseous Hydrogen Stations, IGC Doc 15/06/E
Ignited releases of liquid hydrogen

In the long term the key to the development of a hydrogen economy is a full infrastructure to support it, which includes means for the delivery and storage of hydrogen at the point of use, eg at hydrogen refuelling stations for vehicles. As an interim measure to allow the development of refuelling stations and rapid implementation of hydrogen distribution to them, liquid hydrogen is considered the most efficient and cost effective means for transport and storage.

The Health and Safety Executive (HSE) have commissioned the Health and Safety Laboratory (HSL) to identify and address issues relating to bulk liquid hydrogen transport and storage and update/develop guidance for such facilities. The second phase of the project involved experiments on unignited (HSE RR986) and ignited releases of liquid hydrogen and computational modelling of the unignited releases (HSE RR985). This position paper determines the hazards and severity of a realistic ignited spill of LH2 focussing on; flammability limits of an LH2 vapour cloud, flame speeds through an LH2 vapour cloud and subsequent radiative heat and overpressures after ignition. The results of the experimentation will inform the wider hydrogen community and contribute to the development of more robust modelling tools. The results will also help to update and develop guidance for codes and standards.

This report and the work it describes were funded by the Health and Safety Executive. Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.