CONSEQEUNCES OF CATASTROPHIC RELEASES OF IGNITED AND UNIGNITED HYDROGEN JET RELEASES

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ABSTRACT

The possibility of using a risk based approach for the safe installation and siting of stationary fuel cell systems depends upon the availability of normative data and guidance on potential hazards and the probabilities of their occurrence. Such guidance data is readily available for most common hydrocarbon fuels. For hydrogen however data is still required on the hazards associated with different release scenarios. This data can then be (related) linked to the probability of different types of scenarios (from historical fault data) to allow safety distances to be defined and controlled using different techniques. Some data on releases has started to appear but this data generally relates to hydrogen vehicle refuelling systems that are designed for larger throughput, higher pressures and generally the use of larger pipe diameters than are likely to be used for small fuel cell systems.

The aim of this paper is to report on work that is providing data for informing safety distances for high-pressure components / fuel cell systems and associated fuel storage. Using high-pressure release scenarios, the extent of the clouds, jets and, following ignition, fires, and explosions were investigated.

The work was primarily focused on compressed H_2 storage for stationary fuel cell systems, which may be physically separated from a fuel cell system or could be on board such a system.

The flammability envelope, flame size and blast overpressure for different release geometries, pressures and dimensional envelopes were investigated.

The main objective was to obtain data for realistic release scenarios based on different release levels including emergency relief operation and potential leak scenarios. This included investigating the effects of leak/release size, ignition position, ignition timing and leak orientation to establish release dimensions, jet flame size and associated radiation hazard. All experiments carried out were to simulate a leak from two 50 litre hydrogen cylinders at 200 bar, which, after discussion with fuel cell manufacturers and users was determined to be a realistic cylinder storage arrangement used with back-up power systems.

1.0 INTRODUCTION

The European project HyPer (1) - Full title, Installation Permitting Guidance for Hydrogen and Fuel Cells Stationary Applications - started on 1 November 2006 and ended in February 2009. The project had 15 partners from Europe, the US and Russia (2). The work programme of the project was structured around the development of the Installation Permitting Guide for small stationary fuel cells (IPG), which is now available on the internet (see reference 2).

The aim of the project was to produce a generic guide for small fuel cell installation which incorporated best practice, covered issues such as design, installation, operation, maintenance, hazards, risk assessment and permitting route. To do this the project drew on previously available data and guidance, but incorporated data obtained from experiments and modeling carried out as part of HyPer.

As part of their contribution to the project (which included technical coordination of the project) HSL performed experimental risk evaluation studies to investigate fire and explosion phenomena from catastrophic releases of hydrogen. This paper presents new data acquired from over 40 hydrogen jet releases where parameters including orifice size, ignition delay and ignition position were varied. Maximum overpressures were measured and Schlieren video taken on selected tests. The results were analysed and the effects on overpressure of varying the ignition delay and position were determined.

The aim of this work was to provide data for informing safety distances for high-pressure components of fuel cell systems and associated fuel storage. The work was primarily focused on compressed H_2 on site storage and compression, which may be physically separated from a fuel cell system, or could be on board such a system

2.0 TEST FACILITY AND SET-UP

2.1 Test facility

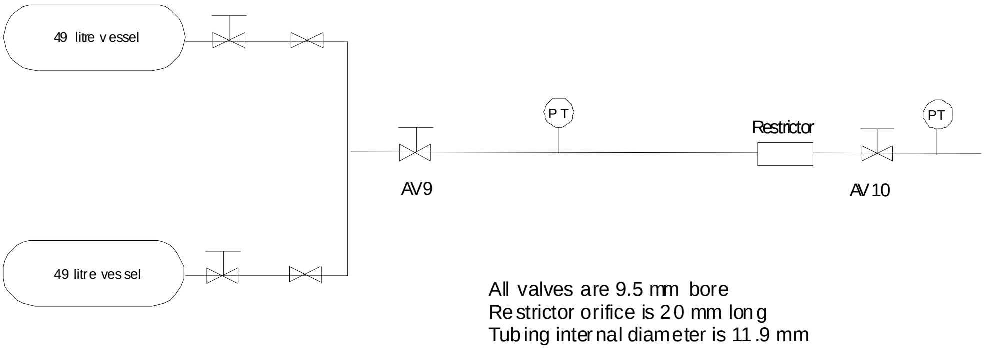
The main test facility comprises a:

- Purpose-built concrete pad, measuring some 10 m x 10 m inset in a 24 m x 18 m tarmac pad
- Screw air compressor and associated air drying equipment
- Air operated gas booster to compress hydrogen
- Two 50 litre storage vessels capable of storing hydrogen at pressure up to 1000 bar
- Pipe work and remotely operated valves to deliver hydrogen to the release point
- Local instrument (15 m from the firing pad) cabin containing the signal conditioning units and 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.
- The release point situated at 1.2 m above the ground and the ignition point located between 2 m and 10 m from the release point depending on the experiment taking place. The release area is illustrated in Figure 1.

Figure 1. Release area

2.2 Gas supply

A gas booster was used to charge the two storage vessels with hydrogen to the required release pressure. The hydrogen delivery to the release point is via stainless steel tubing having an internal diameter of 11.9 mm. A series of ball valves used to control the release; these valves had an internal bore of 9.5 mm. The final release valve was fitted with a modified pneumatic actuator to provide rapid opening and closing of the valve. A simplified schematic of the release system is shown in Figure .2.



All valves are 9.5 mm bore
Restrictor orifice is 20 mm long
Tubing internal diameter is 11.9 mm

Figure 2. Simplified schematic of the release system

2.3 Release configuration

Releases of hydrogen were made both with and without flow restrictors in place. The flow restrictors were simple orifices having diameters of 6.4, 3.2 and 1.5 mm. The flow restrictors consisted of a stainless steel insert 12 mm long with various bores, the 1.5 mm restrictor is shown in Figure 3 (a) and (b), these were inserted within a modified fitting immediately upstream of the final release valve. All of the release functions were controlled remotely.

Figure 3 (a) In-line restrictor (upstream view)

Figure 3 (b) In-line restrictor (downstream view)

2.4 Ignition systems

Initial tests were conducted using an electrical ignition system (single spark aircraft gas turbine igniter unit). Examination of Schlieren images showed significant disturbance in the flow field due to the bulk of the device hence the ignition source was switched to less bulky pyrotechnic. This system consisted of a match head igniter, which contained a small amount of pyrotechnic material. Both systems were automatically triggered at a predetermined times during the releases by the control system PLC.

3.0 EXPERIMENTAL MEASUREMENTS

The following experimental measurements were made:

Overpressure measurement -Two types of pressure sensors were deployed:

Kulite ETL-345F-375M Series 40 bara piezo-resistive transducers were used to measure the ‘higher’ reflected overpressures in the wall, and Kulite ETS-IA-375M 17 bara piezo-resistive sensors were used to measure all other overpressures.

The high-pressure Kulite gauges were 40 bar gauges with the data logging amplification set for a 16 bar range with a measurement error of ± 8 mbar. They were factory fitted with shields to protect the sensors against heat and flash optical radiation. The lower pressure Kulite gauges were 17 bar gauges with the data-logging amplification set for a 4 bar range. The 17 bar Kulite sensors were factory fitted with an ablative coating to protect the sensors against heat and flash optical radiation. All the piezo-resistive sensors were mounted, pointing upwards (except for the wall mounted sensors), in specially made streamlined blocks. Sensors were mounted on blocks fixed into a short length of scaffolding, which were bolted into a standard floor fitting fixed to the ground. Sensors were mounted on blocks fixed into the wall.

Flame length measurements - made using a combination of low light and infra-red video.

Visual records -Video records were made at 25 frames per second.

Background orientated Schlieren - BOS (1000 frames per second) was performed on selected tests by Fraunhofer ICT (3).

High speed infra red - measurements were made at four different wavelengths at 100 frames per second. These were performed on selected tests by Fraunhofer ICT.

Storage system measurements – the temperature and pressure of the storage vessels were recorded

Meteorological measurements - The air temperature, relative humidity, wind speed and direction were measured at the instrument cabin 10m from the pad using an FT Technologies ultra-sonic anemometer and a Vector Instruments weather station. This comprised wind speed; wind direction, temperature and humidity measurement mounted 3.5 m above the ground.

4.0 RELEASE SEQUENCE OPERATION

The valve and ignition timing were performed in an automated release sequence by the PLC. The following variables can be set on the system:

Release duration – This is the length of time the valve open signal is present at the output and can be set between 0 and 60 000 ms

Ignition delay - This is the time at which the ignition pulse occurs relative to the valve open signal, i.e. a delay of 0 ms will result in the valve open signal and the ignition pulse occurring at the same time. This can be set between minus 10 000 and plus 60 000 ms.

5.0 TEST VARIATIONS

A number of release scenarios were investigated to provide data on the effects of varying; orifice size (restrictor), ignition delay, ignition position, and jet attachment.

Three different size restrictors were used in the release system 1.5, 3.2, and 6.4. Releases were also made at 9.5 mm (full bore). Tests using different ignition timings (e.g. very early ignition, early ignition) were performed with a single ignition position. Tests using a fixed ignition time were performed with varying ignition positions. The effects of jet attachment were evaluated by comparing jets released at 1.2 m height from the ground with jets released along the ground.

5.1 Tests Performed

All the tests were performed with hydrogen released at 200 bar into free air. Over forty tests were conducted with a range of orifices, different ignition positions and different ignition delays. Initial tests used the electrical ignition system (tests 1 – 11); subsequent tests were performed with the pyrotechnic system.

5.1.1 Sensor positions

The pressure sensor positions are shown in figure 4.

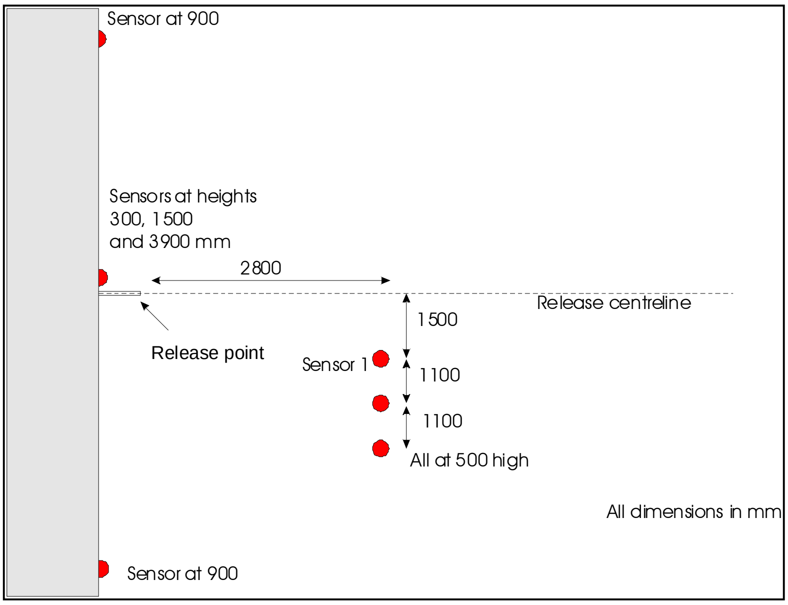


Figure 4. Pressure sensor positions

6.0 RESULTS

The results of varying orifice diameter, ignition delay, ignition position and flame lengths are given in sections 5.1.

6.1 Effect on overpressures of varying the orifice diameter

Table 1 below gives the maximum overpressures recorded for the tests conducted with a range of orifices and with early (800 ms) and very early (400 ms) ignition delays.
The tests involving the very early ignition delays were undertaken to correspond with the timing of the high-speed video used for the Schlieren.
The maximum overpressures for all tests were recorded on sensor 1 which was located 2.8 m from release point and 1.5 m from centre line of jet (see Figure 4). The release height for all tests was 1.2 m.

Table 1: Maximum Overpressure.

Test No	**Release pressure (bar)**	**Orifice diameter (mm)**	**Ignition delay (ms)**	**Max overpressure (bar)**
12	205	1.5	800	NR *
21	205	1.5	400	NR *
13	205	3.2	800	0.035
20	205	3.2	400	0.021
14	205	6.4	800	0.152
19	205	6.4	400	0.027
22	205	6.4	400	0.037
15	205	9.5	800	0.165
16	205	9.5	400	0.049
18	205	9.5	400	0.054
23	205	9.5	400	0.033

* Not recordable

The pressure versus time traces (maximum overpressure) for the 3.2, 6.4 and 9.5 restrictor can be seen at figures 5(a) and 5(b).

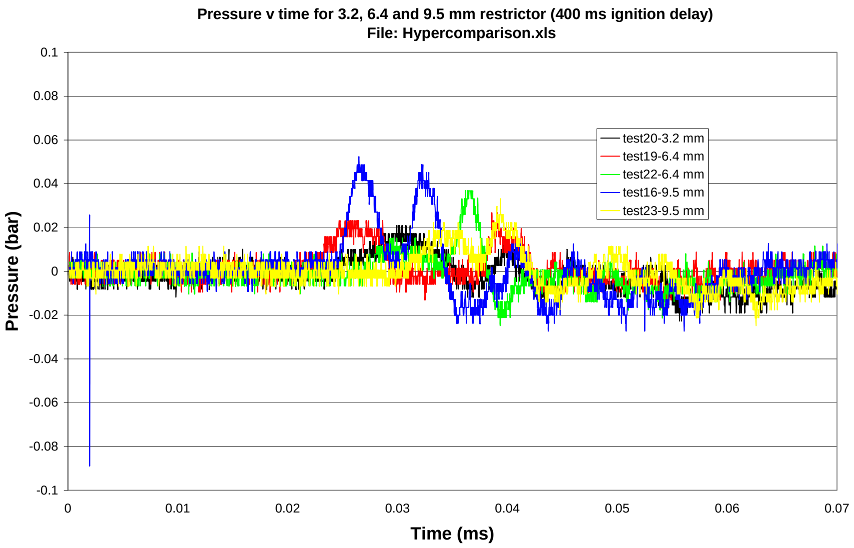


Figure 5(a) Pressure v time for 3.2, 6.4 and 9.5 mm restrictor (800 ms ignition delay).

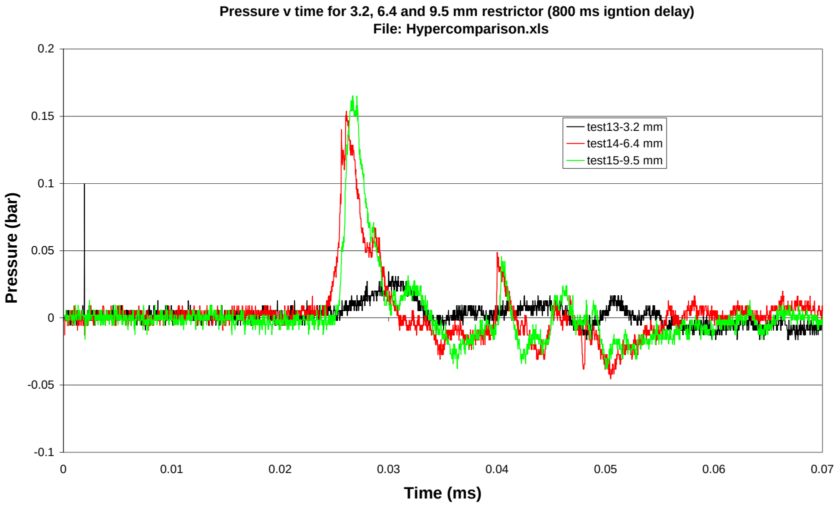
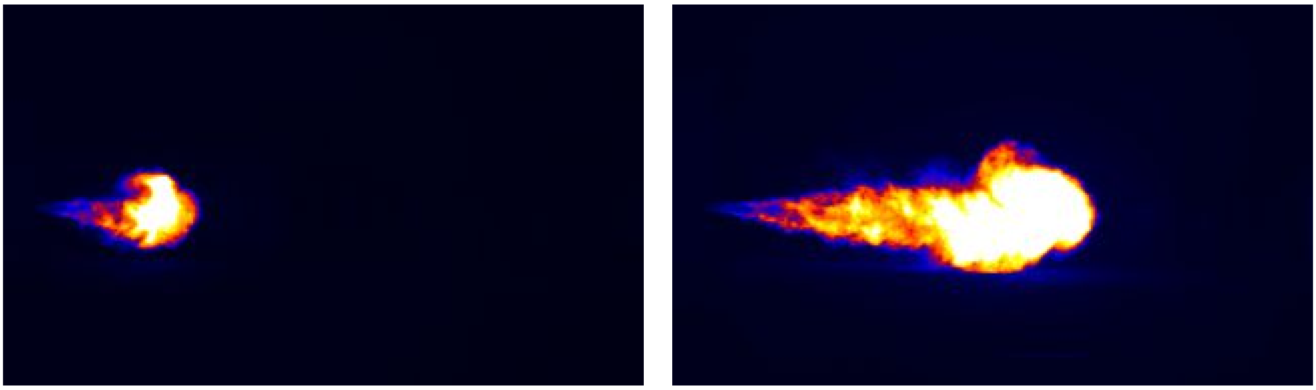


Figure 5(b) Pressure v time for 3.2, 6.4 and 9.5 mm restrictor (400 ms ignition delay).

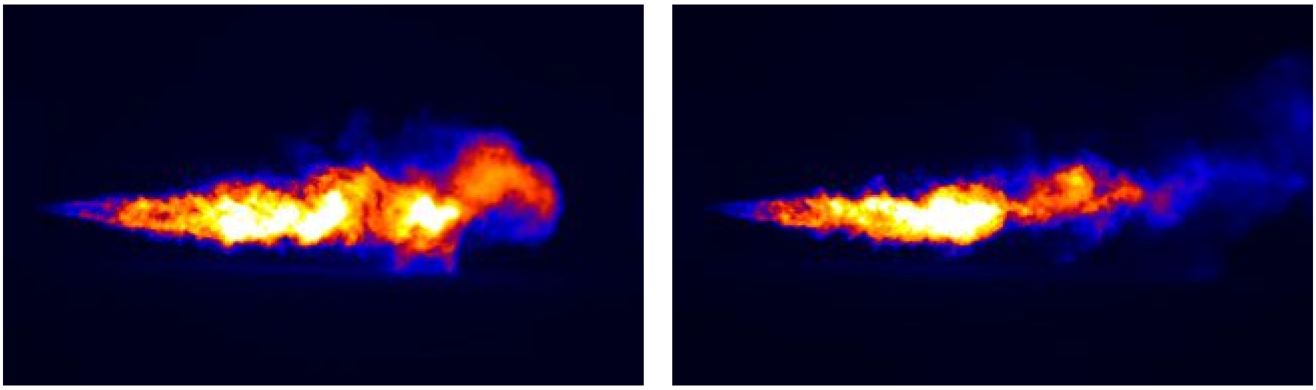
6.2 Infra red imaging

Images of the thermal radiation of the jet 60ms, 300ms, 540ms and 900ms into the release (release from 9.5 mm orifice) can be seen at Figure 6



60ms into release

300ms into release



540ms into release

900ms into release

Figure 6. Infra-red images

6.3 Background Oriented Schlieren (BOS)

BOS was performed using a 6 m x 2.4 m background approximately 3 m behind the jet. Images were recorded at 1000 fps using phantom F9 camera. The BOS images obtained showed good jet definition and gave detail of the ignition of the jet together with visualisation of shock waves produced by some tests. Example images are shown in figures 7(a) and 7(b).

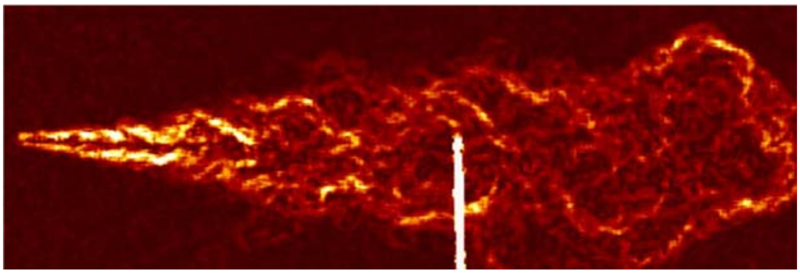


Figure 7(a) Un-ignited jet from 3.2mm restrictor 200ms into release

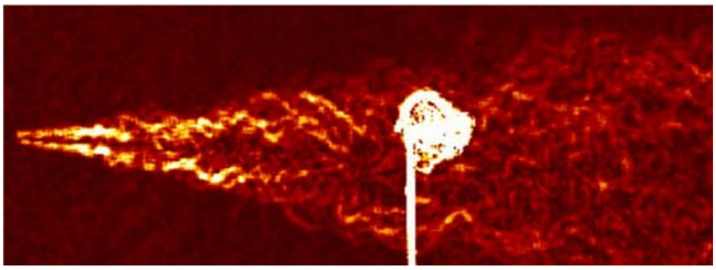


Figure 7(b) Ignited jet from 3.2mm restrictor 4ms after ignition

6.4 Effect on overpressures of varying the ignition delay

A single orifice (6.4 mm) was chosen along with a fixed release pressure of 205 bar. A fixed ignition position at a height of 1.2 m, 2 m from the release point was selected. The ignition delay varied from 400 ms to 2000 ms, seven tests were conducted in total and the maximum over pressures recorded. The maximum pressures were seen on sensor 1 (2.8 m from release point and 1.5 m from centre line of jet).

Table 2: Overpressures recorded for varying ignition delay

Test No	**Release pressure (bar)**	**Orifice diameter (mm)**	**Ignition delay (ms)**	**Max overpressure (bar)**
22	205	6.4	400	0.037
08*	205	6.4	500	0.184
25	205	6.4	600	0.194
14	205	6.4	800	0.152
26	205	6.4	1000	0.117
27	205	6.4	1200	0.125
09*	205	6.4	2000	0.095

*Denotes tests ignited by the electrical system

The pressures versus time traces (maximum overpressure) for varying ignition delay can be seen at figure 8.

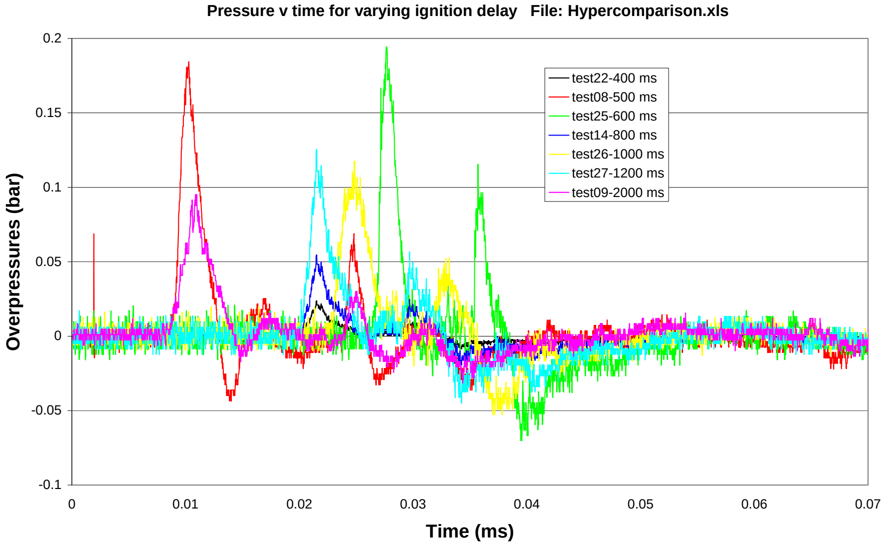


Figure 8. Pressure versus time for varying ignition delay

6.5 Effect on overpressures of varying the ignition position

A single orifice (6.4 mm) was chosen with a fixed release pressure of 205 bar and a fixed ignition delay of 800 ms. The ignition position (pyrotechnic system) was varied from 3 m to 10 m, the ignition height was fixed at 1.2 m.

Six tests were conducted in total and the maximum over pressures recorded. The maximum pressures were seen on sensor 1 (2.8 m from release point and 1.5 m from centre line of jet).

Table 3: Overpressure recorded for varying ignition position.

Test No	**Release pressure (bar)**	**Orifice diameter (mm)**	**Ignition position (m)**	**Max overpressure (bar)**
28	205	6.4	3	0.050
29	205	6.4	4	0.021
30	205	6.4	5	0.021
31	205	6.4	6	NR
32	205	6.4	8	NR
33	205	6.4	10	No ignition

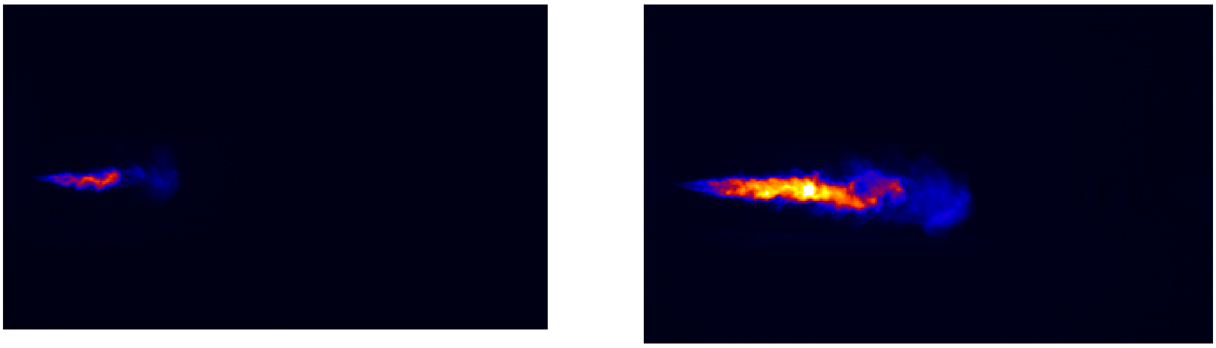
6.6 Effects of attachment on jet length

For this series of tests a fixed pressure of 205 bar along with a fixed ignition delay of 800 ms was used. The ignition position was set at the height of the release point and 2 m downstream from the release point. All four orifices were used. The attached jets were released along the ground at a height of 110 mm; the unattached jets were released at a height of 1.2 m. The flame lengths were measured. Flame lengths of attached and unattached jets are given in table 4.

Table 4. Flame lengths of unattached and attached jets.

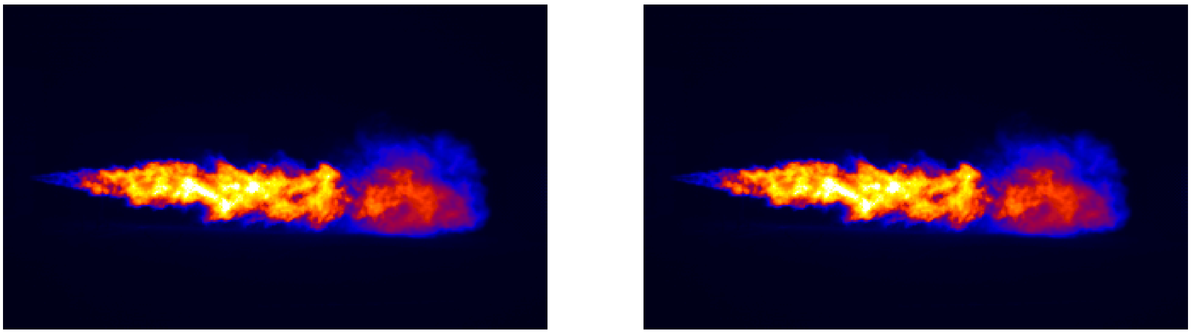
Release pressure (bar)	**Orifice diameter (mm)**	**Ignition delay (ms)**	**Flame length (m) Attached jets**	**Flame length (m) Unattached jets**
205	1.5	800	5.5	3
205	3.2	800	9	6
205	6.4	800	11	9
205	9.5	800	13	11

Infra red images for unattached jets (at the maximum extent of the radiation) with each restrictor are shown in Figure 9.



1.5 mm restrictor

3.2 mm restrictor



6.4 mm restrictor

9.5 mm restrictor

Figure 9. Infra –red images of jets

6.7 Weather data

Weather data (temperature, wind speed, wind direction and humidity) was collated for each release. This data was used to provide information for modeling purposes and I.R transmission and is not included in this report.

7 DISCUSSION

7.1 Overpressures v orifice size (restriction)

Larger overpressures were observed with the larger orifices as would be expected with an increase in the amount of hydrogen released. This indicates that when planning installations consideration should be given to the fitting of flow restrictors as close as possible to the source of hydrogen. Fitting of a restrictor could reduce the safety distances required.

7.2 Overpressures v ignition delay

Seven tests were performed on free jets with a fixed ignition position and a variable ignition delay. The ignition delay is referenced from the final release valve open signal. The valve takes approximately 260 ms to go from fully closed to fully open and the hydrogen jet takes a further 140 ms to reach the 2 m distant ignition position. This means the shortest ignition delay possible with this configuration is 400 ms.

The overpressures measured for a 400 ms delay were lower than those measured for a 800 ms delay. This is probably due to ignition occurring at the edge of the approaching hydrogen cloud i.e. the ignition is in a weak part of the hydrogen/air mixture see Figure 10 (a).

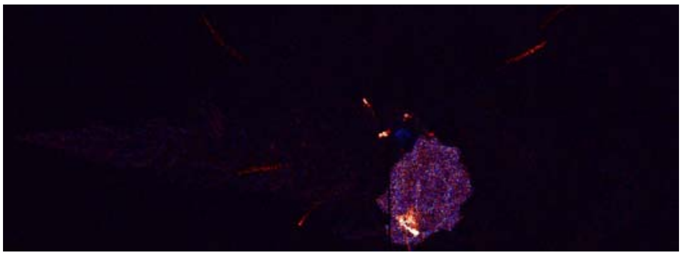


Figure 10 (a) BOS image of 3.2 mm restrictor release showing edge ignition (400 ms delay)

The overpressures recorded reach a maximum with an ignition delay of 600 ms, this corresponds with ignition in the centre of the turbulent region in the front portion of the jet see Figure 10(b). Further increases in the ignition delay result in corresponding decreases in recorded overpressures. This is probably due to a combination of the ignition occurring in a poorly mixed portion of the jet and a reduction in turbulence. As the storage pressure decreases (for later ignitions) the jet becomes less turbulent.

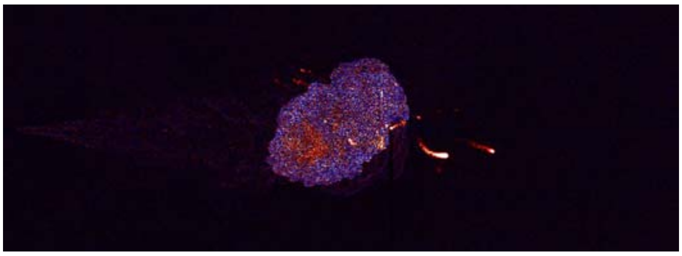


Figure 10 (b) BOS image of 3.2 mm restrictor release showing ignition in turbulent region of jet (600 ms delay)

7.3 Overpressures v ignition position

As the ignition position was moved outwards from the release point the overpressures reduced, this is probably due to lower initial flame speeds in weak hydrogen air mixtures. Ignition in the weak area of the jet results in relatively slow burning of a weak hydrogen / air mixture thereby consuming a large quantity of the released hydrogen without producing a large pressure wave.

7.4 General observations

From both the background oriented Schlieren and the high-speed infra red images it is apparent that there is very little buoyancy associated with these horizontal 200 bar hydrogen releases. The figures below show Schlieren images of releases through a 1.5mm orifice shortly after ignition occurs and 94 ms later.

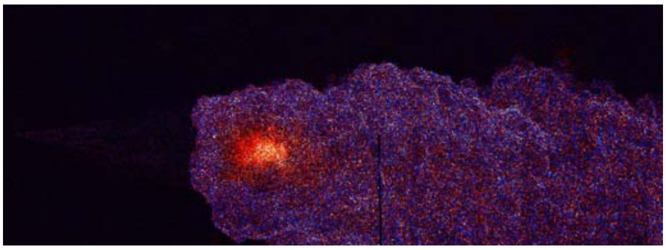


Figure 11(a) Schlieren image of hydrogen jet 296 ms after ignition

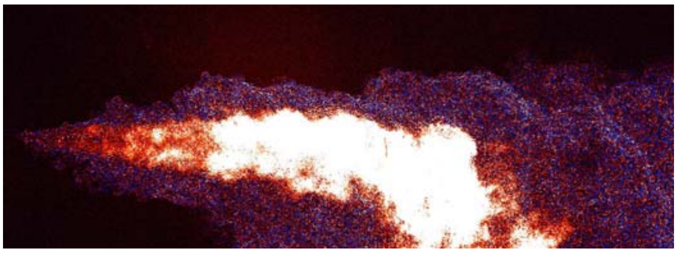


Figure 11(b) Schlieren image of hydrogen jet 390 ms after ignition

The infra-red image shown in figure 11 (c) again shows little evidence of buoyancy after ignition.

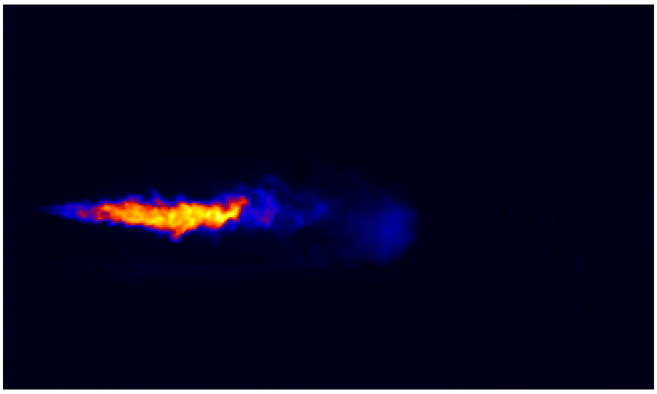


Figure 11(c) Infra-red image of ignited hydrogen jet 32 ms after ignition

7.5 Jet lengths

These results indicate that the length of a hydrogen jet is enhanced slightly if it is released in proximity to an object along which it can flow. The effects of attachment are most evident with releases from smaller orifices. Attachment effects are probably enhanced with the smaller orifice releases because turbulence is reduced relative to that produced by the larger orifice releases.

The so-called attached jets have only been investigated with flow along the ground and only at one distance from the ground. It is likely that there is some optimum distance (from the ground) for each diameter jet, which gives the maximum attachment effect.

8. CONCLUSIONS

(1) The inclusion of flow restrictors in hydrogen supply line reduces the flame lengths observed, therefore reducing safety distances required.

(2) From the experiments carried out it is apparent that jets from hydrogen storage at 200 bar are predominantly momentum driven, i.e. the cloud is relatively non-buoyant within the flammable range.

(3) When a release is orientated such that attachment to a surface can occur the jet length may be enhanced.

(4) Ignition in a weak region of the jet cloud results in a relatively slow burn and hence a small overpressure.

(5) Maximum overpressures were observed when the jet was ignited at a time, which coincided with the area of maximum turbulence within the front portion of the jet, reaching the ignition point.

9. ACKNOWLEDGEMENTS

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10. REFERENCES

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