HSE experimental work on large-scale LH_2 releases as part of the PRESLHY project

Safety of cryogenic hydrogen transfer technologies, workshop No. 2

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Introduction

The PRESLHY project:

PRESLHY was an EU FCH JU 2.0 co-funded research and innovation activity (Project ID 779613), addressing pre-normative work for the safe use of liquid (cryogenic) hydrogen LH_2 as an energy carrier

HSE carried out experimental work supported by co-funders Shell, Lloyd’s Register Foundation and Equinor

The experimental work was undertaken in the following work packages:

- WP3 – Release and mixing
- WP4 – Ignition
- WP5 – Combustion

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WP3 – Release and mixing

Aims:

The main aim of this series of experiments was to investigate the propensity for rainout to occur when LH_2 is released from elevated positions

The experiments also investigated:

- Vaporisation
- Characterisation of the flow at the point of release
- Dispersion of the gaseous hydrogen cloud (near and far field)
- Capacity for these releases to form pools

Experimental overview

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Dispersion

Release station and measurements

Storage

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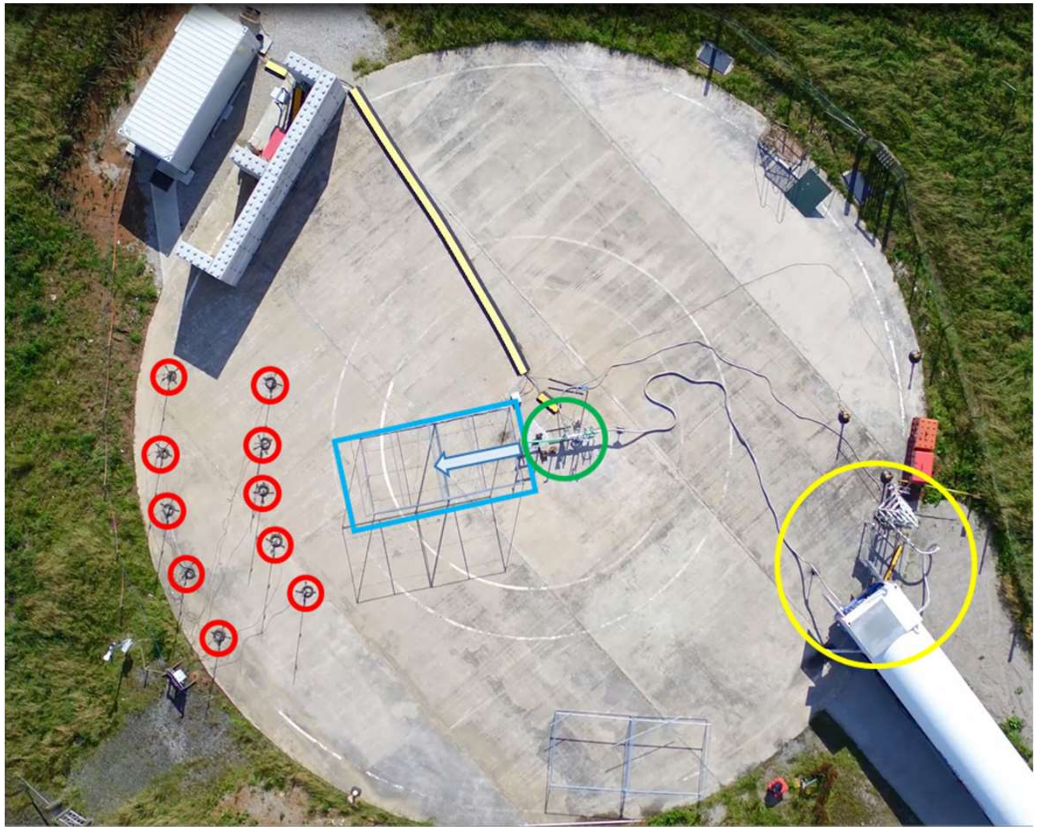
Experimental overview

- Green: LH_2 release station
- Yellow: tanker and vent stack
- Blue: the near-field array
- Red: far-field stands



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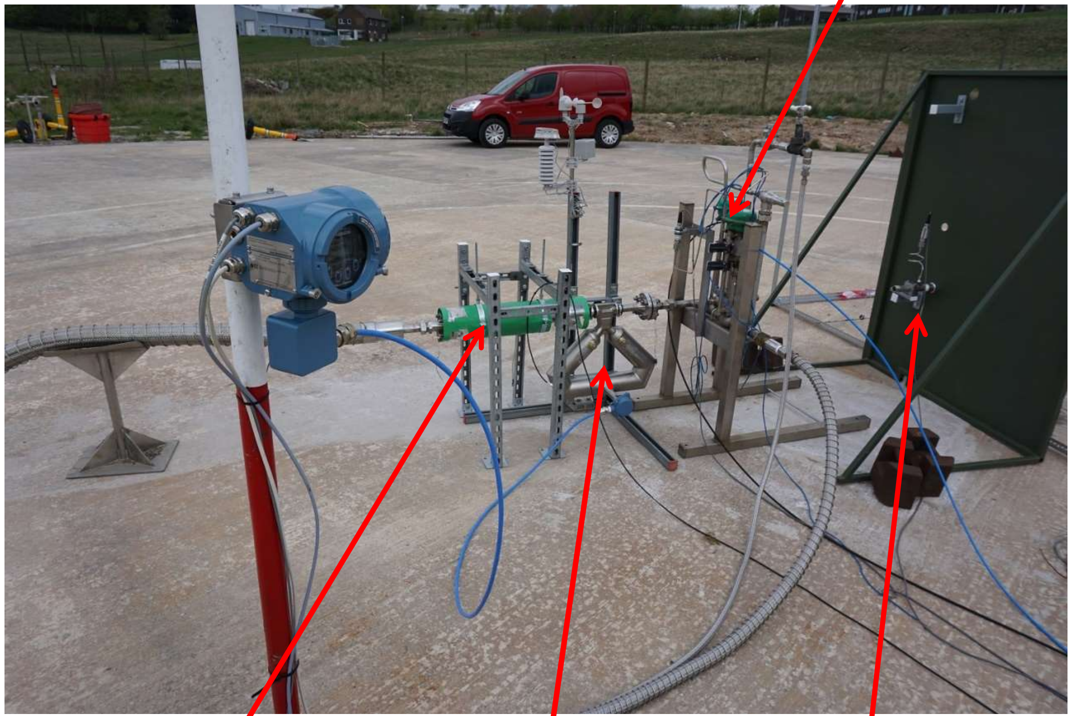
Release station

Release/recirculation valves



Electrically isolated section

Flowmeter

Shield (not used for dispersion tests)

Local weather

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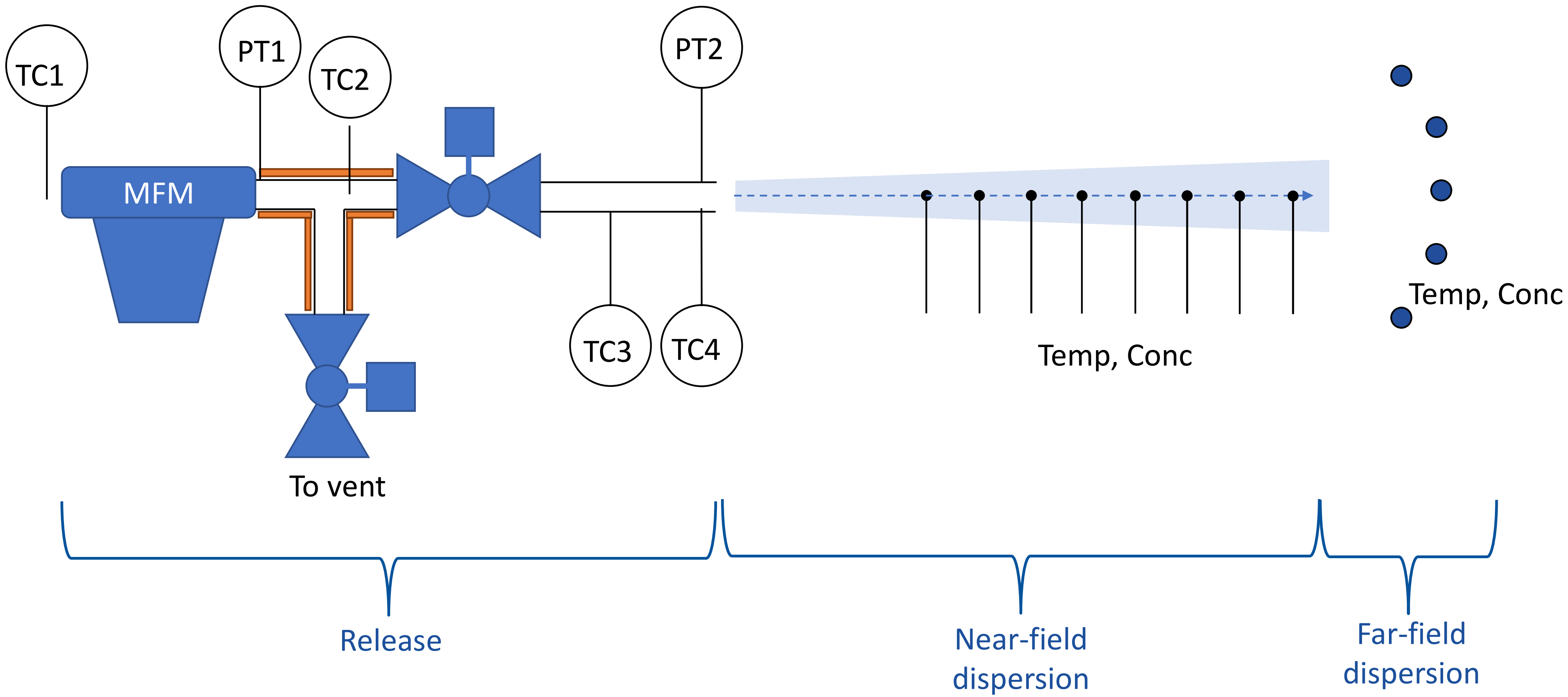
Instrumentation



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Experiment list

Test No	Release Orientation	Release Height Above Ground (m)	Orifice Diameter (mm)	Pressure (barg)
3.5.1	Horizontal	0.5	25.4	1
3.5.2	Horizontal	0.5	12	1
3.5.3	Horizontal	0.5	6	1
3.5.4	Horizontal	1.5	25.4	1
3.5.5	Horizontal	1.5	12	1
3.5.6	Horizontal	1.5	6	1
3.5.7	Vertical Up	0.5	12	1
3.5.8	Vertical Down	0.5	12	1
3.5.9	Horizontal + obstruction	0.5	12	1
3.5.10	Horizontal	0.5	25.4	5
3.5.11	Horizontal	0.5	12	5
3.5.12	Horizontal	0.5	6	5
3.5.13	Horizontal	1.5	25.4	5
3.5.14	Horizontal	1.5	12	5
3.5.15	Horizontal	1.5	6	5
3.5.16	Vertical Up	0.5	12	5
3.5.17	Vertical Down	0.5	12	5
3.5.18	Horizontal + obstruction	0.5	12	5

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Data acquisition and processing

- Clean and synchronise the data to a common time base, convert to meaningful units:
  - Pipework pressures & temperatures
  - Near field concentration & temperatures
    - 31 hydrogen sensors, 24 thermocouples
  - Far-field concentration & temperatures
    - 30 hydrogen sensors, 30 thermocouples
  - Flow meter
  - Weather stations
  - Current & resistance
- Video
  - Drone, thermal & high speed

Sensor	Manufacturer	Model	Range	Accuracy
Pipework thermocouples	TC Direct	1.5 mm Type T Mineral insulated	−200 to 350°C	±1.5% of Reading
Near-field thermocouples	TC Direct	1.5 mm Type T Mineral insulated	−200 to 350°C	±1.5% of Reading
Far-field thermocouples	TC Direct	1.5 mm Type T Grounded Chamfered tip	−200 to 350°C	±1.5% of Reading
Pressure	Wika	IS-3	0-10 barg	±0.5% of Full Scale
Tank Pressure	N/A	Dial gauge	0-15 barg	Visual
Mass flow	Emerson	Micro Motion Coriolis meter	0-7.5 kg/s	±3% of Reading*
H2 concentration	Xensor	XEN-5320	0-100 Vol %	±3% of Full Scale
H2 concentration	Dräger	Xam 5000 XXSH2 HC	0-4 Vol %	±2% of Reading
H2 concentration	Dräger	Xam 5000 Cat-Ex 125	0-100% LEL	±1% of Reading
H2 PPM	Dräger	Xam 5000 XXS H2	0-2000 ppm	±1% of Reading
O2 depletion	Dräger	Xam 5000 XXS O2	0-25 Vol %	±1% of Reading
Near-field weather station	PCE Instruments	PCE-FWS-20	0-240 km/h 10-90 % humidity	Indicator
Far-field wind sensor	Gill Instruments	Windsonic	0-60 m/s 0-359°	±3% of Reading ±2°
Far-field humidity sensor	Skye Instruments	SKH 2053	0-100 % -20 to 70°C	±2% ±0.05°

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Experiment procedure

- Condition LH_2 in tank
  - Flatten the fluid by venting gaseous H_2 from the tanker
  - Allow LH_2 into the heat exchanger until the desired pressure is reached
- Purge the pipework with N_2 then warm H_2
- Initiate recording and prepare triggers
- Implement safety zones and open manual release valve
- Operate remote release valves
- Stop release and complete post-test tasks

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Release system measurements

- Temperatures
  - "Warm" temperatures logged as cold junction compensated temperature
  - "Cold" temperatures (pipework, near-field array) logged as voltage
- Voltage converted to temperature using cold junction measurement and lookup table
  - Thermocouples in pipework not indicating BP for LH_2
- Post-test investigation of thermocouples conducted using LN_2:
  - low temperature error found on thermocouples in pipework (TC1-5 only)
  - error increases as temperature decreases, and
  - investigation reported in D3.6

Release system measurements

Mass flow meter

- Extensively modified to help cope with the conditions
- Mass flow output based on factory calibration for expected temperatures
- Drive gain (excitation power) provides useful information
- Density can be derived from measurement of tube frequency (not in two phase flow cases)

$$\omega \propto 2\pi\sqrt{\frac{m}{k}}$$

tube mass (volume, density, temperature)

tube period

tube stiffness (temperature)

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Flow rate calculation

Mass flow rate calculations completed and reported:

- Mass flow rates derived from a combination of flow meter and calculations based on pressure data
- Results included in deliverable 3.6

Pressure	Nozzle diameter	Mass flow
5 bar	6mm (¼ ”)	90-100 g/s
5 bar	12mm (½”)	265 g/s
5 bar	1” (open pipe)	298 g/s
1 bar	6mm (¼ ”)	Unknown
1 bar	12mm (½”)	104-107 g/s
1 bar	1” (open pipe)	135-144 g/s

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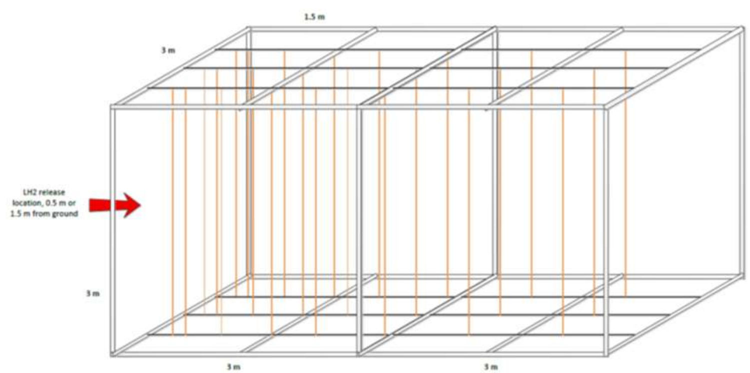
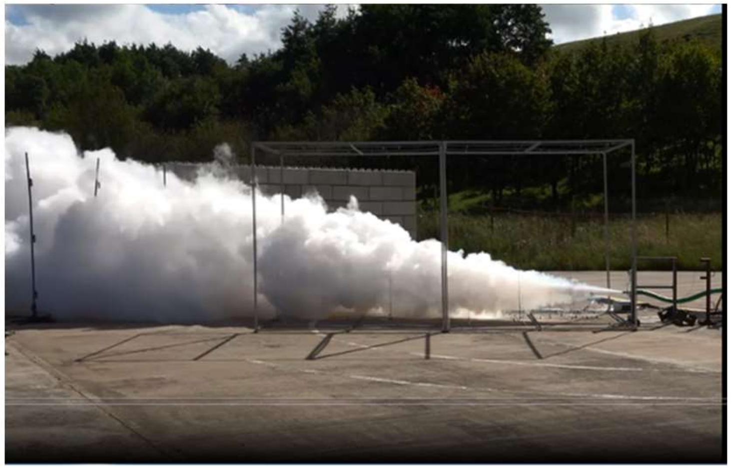
Near-field dispersion

- Collaboration with National Renewable Energy Laboratory (NREL) for near-field concentration measurements
- System of pumped sampling tubes and remote sensors
- Up to 32 detectors based on thermal conductivity
- Up to 12 co-located TCs
- Deployment of NREL's system for measurements in the jet





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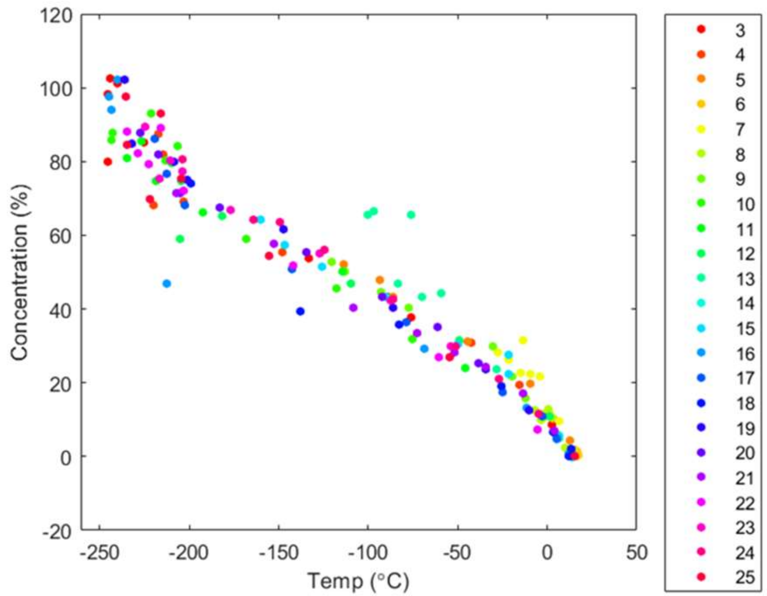
Near-field dispersion

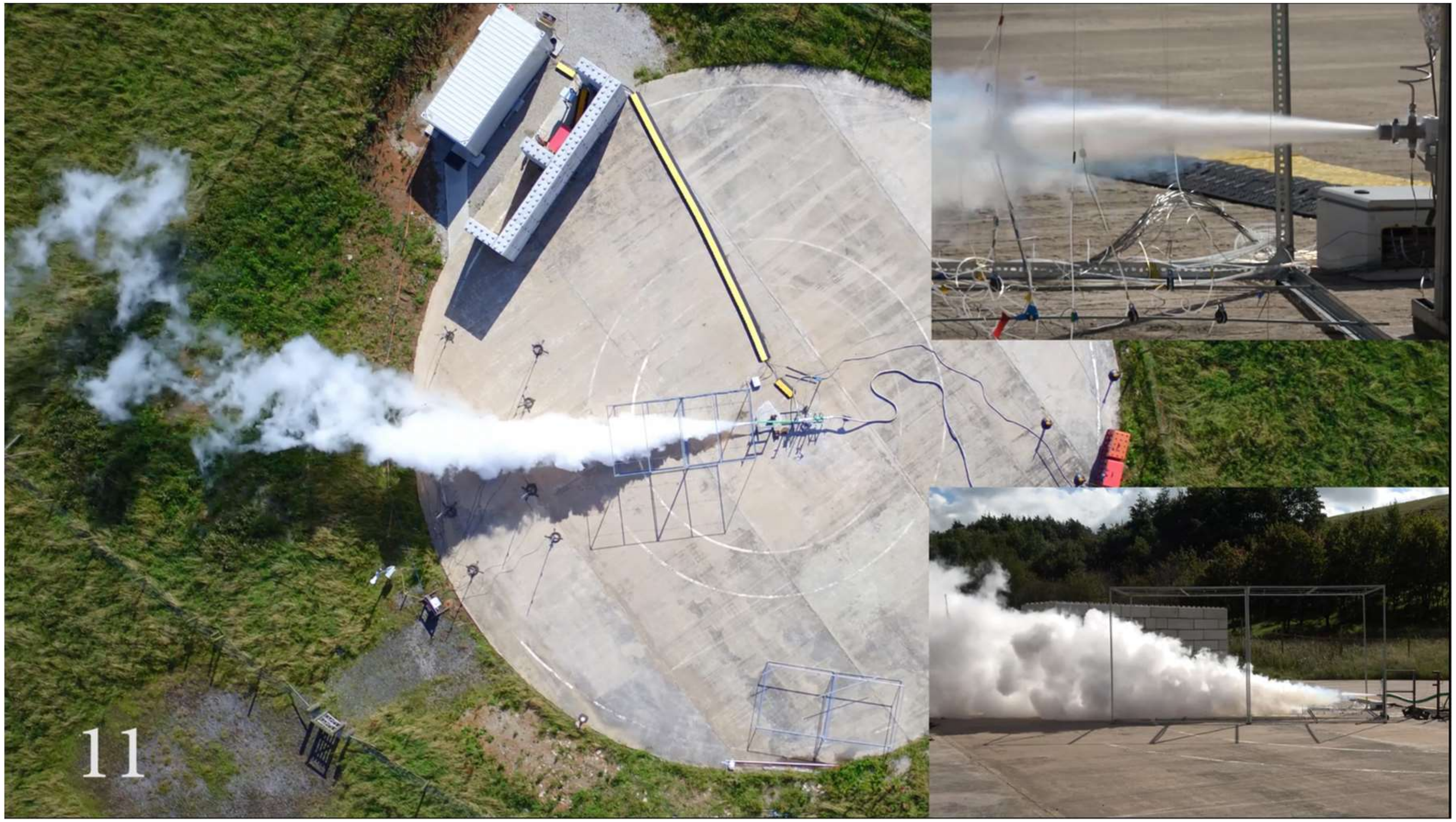
- In some tests, solid material accumulated on the sampling point and caused horizontal displacement of the location and possibly interfered with sampling
- Generally, good correlation of temperature and concentration was observed across all tests



Far-field dispersion

- 30 Dräger X-am 5000 units mounted at three heights on stands in the far field, 0.5, 1.5 and 2.5 m
- Each instrument contained:
  - PPM H_2 sensor
  - LEL H_2 sensor
  - O_2 sensor
- Each instrument co-located with a thermocouple

Images from dispersion video



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Dispersion – some observations

- Rainout did not occur during the established flow of these releases, some dripping seen after valve closure (probably liquid air)
- Solid deposits formed around the release point and on impingements with 6/12 mm nozzles, thought to be solidified air
- Pools can form with vertically downward releases
- Flow meter was only effective at higher pressures and smaller nozzle sizes (i.e. void fraction is low)
- Heat gains due to the flow meter and additional pipework reduced effectiveness of the meter (two phase flow)
- Transient pockets with an H_2 concentration above LEL were measured at 14 m distance from LH_2 release point for 12 mm or 25.4 mm or larger holes
- Following the initial jet dispersion region, approximately 1.5 m for the 1 bar releases and 3 to 6 m for the 5 bar releases, the dispersion of the hydrogen cloud was heavily dependent of the wind, including transient localised gusts

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WP4 – Ignition

Aims

To help understand the propensity for an electrostatic charge capable of igniting a hydrogen cloud to be generated during a release, or accidental spill scenario. The experimental programme measured:

- Charge within a dispersing LH_2 plume
    - In the free-field and using a Faraday cage
- Charge within a section of electrically isolated pipework

Experimental overview

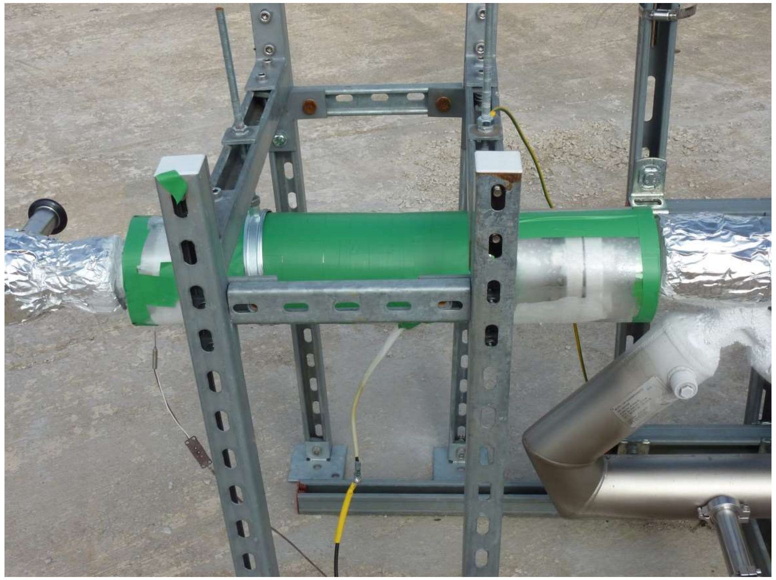
Plume charge measurement (7 trials):

Field meter, faraday cage

Faraday cage and field meter

Wall current (30 trials):

Isolated pipe section, electrometer



Isolated pipework

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Results – Plume measurements

- Seven trials in total
- No positive charge results on the majority of trials

Trial No	Test No	Field meter configuration	Orifice Diameter	Pressure	Results
1	4.3.2	Free-field layout 1	6 mm	5 Bar	No significant charge measurements
2	4.3.2	Free-field layout 1	6 mm	5 Bar	No significant charge measurements
3	4.3.2	Free-field layout 2	6 mm	1 bar	No significant charge measurements
4	4.3.4	Free-field layout 2	12 mm	1 bar	No significant charge measurements.
5	4.3.6	Free-field layout 2	25.4 mm	1 bar	Initial & mid-flow peaks
6	4.3.3	Faraday cage	12 mm	1 bar	No significant charge measurements
7	4.3.5	Faraday cage	6 mm	5 bar	Initial peak

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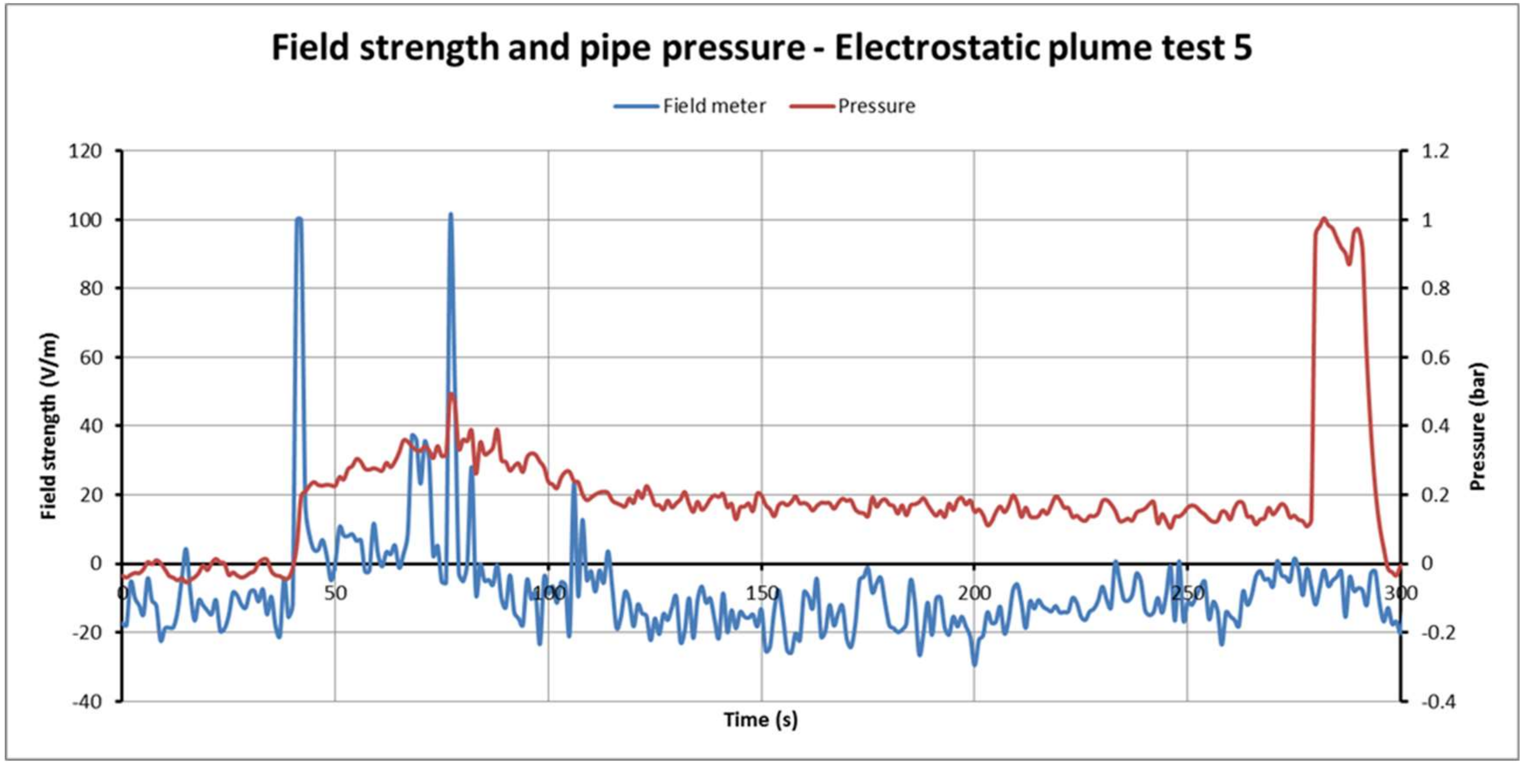
Results – Plume measurements



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Results – Isolated pipe section

- Wall current measurements taken in a total of 30 trials
- Positive results on 12 trials, shown below

Work Package	Trial No.	Orifice Size (mm)	Pressure (bar)	Wall Current peak	Range	Resistance (Ω^2)
3.5	2	25.4	1	3.8 (nA)*	-2 to 2 nA	1.06×10^7
3.5	**3**	**25.4**	**1**	**230 (nA)***	**-200 to 200 nA**	$\mathbf{1.02 \times 10^6}$
3.5	**5**	**6**	**1**	**240 (nA)***	**-200 to 200 nA**	$\mathbf{2.48 \times 10^6}$
3.5	6	12	1	-9.6 (nA)	-2 to 2 μA	
3.5	7	12	1	-9.6 (nA)	-2 to 2 μA	
3.5	**8**	**12**	**1**	**2.8 (μA)***	**-2 to 2 μA**	$\mathbf{2.07 \times 10^7}$
3.5	**10**	**25.4**	**5**	**0.16 (μA)**	**-200 to 200 μA**	$\mathbf{2.67 \times 10^4}$
3.5	18	6	1	-0.27 (nA)	-200 to 200 nA	
3.5	23	12	4.5	-0.25 (nA)	-200 to 200 nA	
3.5	25	25.4	4.5	-0.99 (nA)	-200 to 200 nA	1.03×10^7
4.3	**3**	**6**	**1**	**0.20 (μA)**	**-200 to 200 μA**	$\mathbf{6.06 \times 10^4}$
4.3	5	25.4	1	-0.35 (nA)	-200 to 200 nA	

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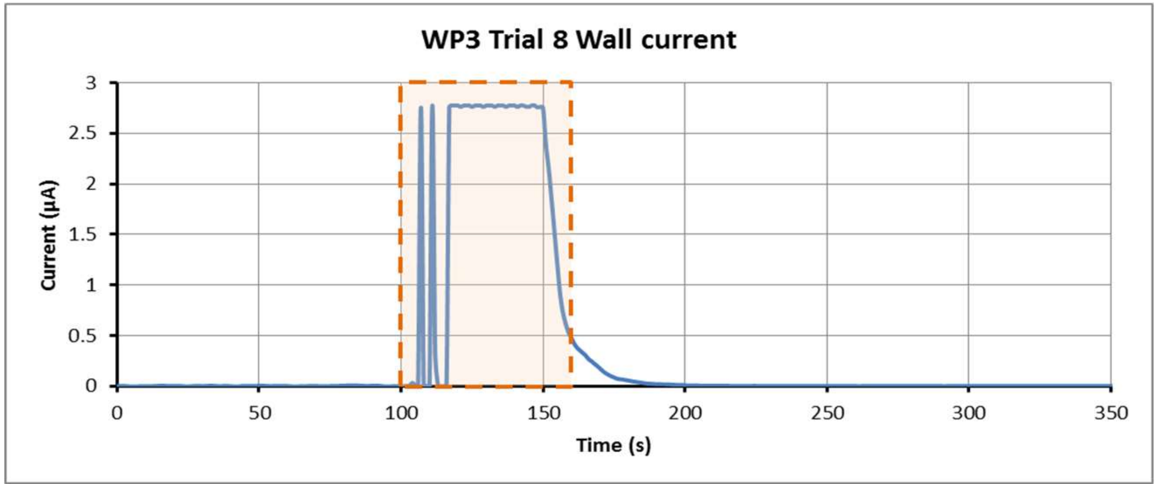
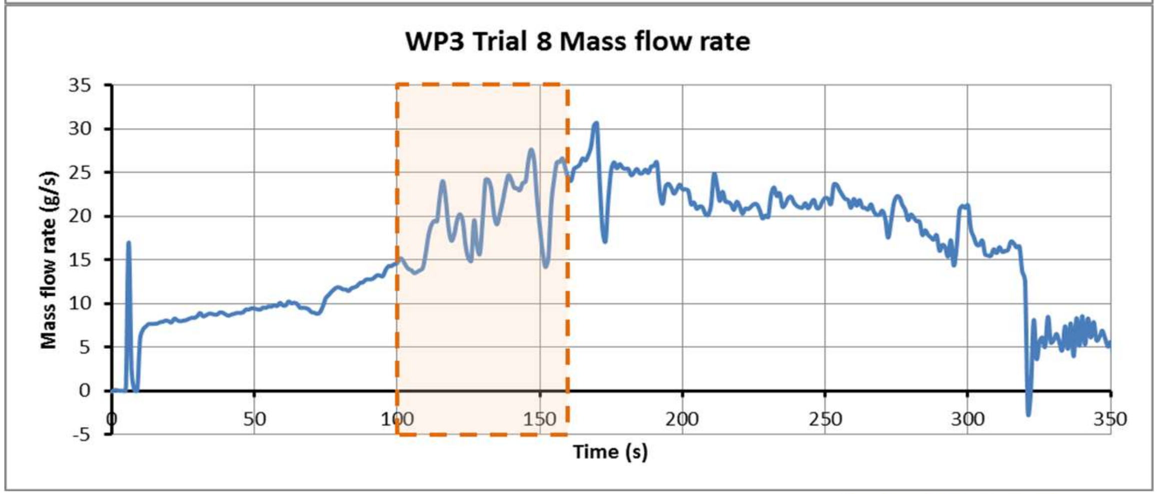
Results – Isolated pipe section





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Ignition – some observations

- Hydrogen did not hold a significant charge in these tests
- Multiphase hydrogen flow can generate a current in isolated steel pipework
- Occasional charge spikes have been identified, possibly caused by ice breaking off the nozzle or air being ejected from un-purged pipework

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WP5 – Combustion

Aim:

The aim of this experimental campaign was to determine the effect of differing levels of congestion upon the ignition behaviour of a cryogenic hydrogen plume

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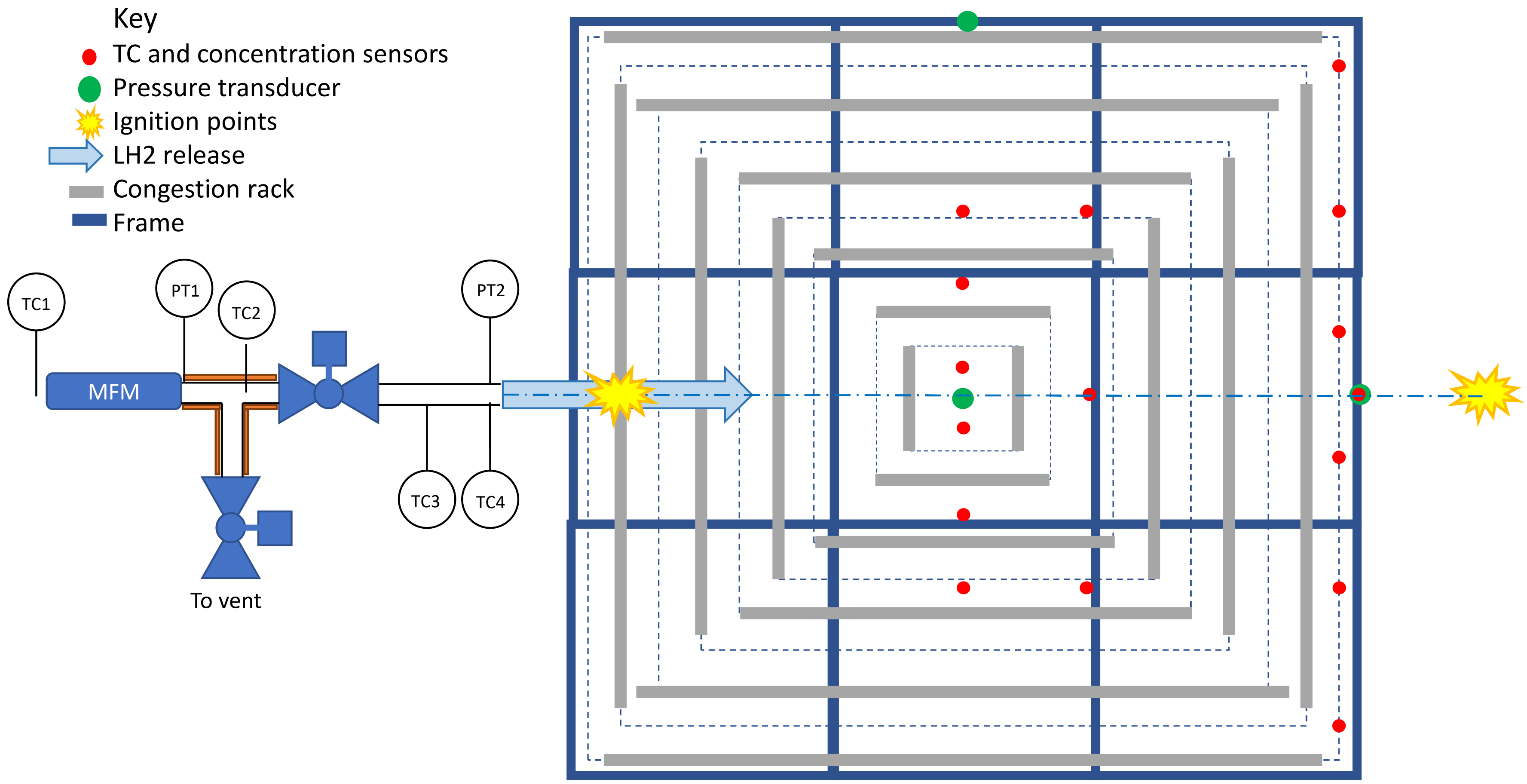
Facility

- Release pipework as WP3 dispersion trials
  - In-flow temperature, pressure and mass flow measurements
- Congestion provided by congestion rig
  - “High” congestion provided by additional 99 scaffold poles

Experimental setup – plan view



Congestion levels

	Bottom half area blockage ration (m^2/m^3)	Top half area blockage ration (m^2/m^3)	Bottom half volume blockage ratio (%)	Top half volume blockage ration (%)
Low congestion	0.80	1.00	1.54	1.93
High congestion	1.53	1.33	4.20	4.60

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Instrumentation

- Pressure, temperature & concentration sensors
- Video including high speed & thermal
- Far-field sound meters
- Pyrotechnic ignition source

Experiment matrix

Trial No	Test No	Orifice Diameter	Pressure	Ignition point	Congestion level	Noise
1	5.5.1	1/4"	1 bar	Front	Low	
2	5.5.2	1/2"	1 bar	Front	Low	
3	5.5.3	1"	1 bar	Front	Low	
4	5.5.2	1/2"	1 bar	Front	Low	123 dB
5	5.5.3	1"	1 bar	Front	Low	117 dB
6	5.5.2	1/2"	1 bar	Front	Low	125 dB
7	5.5.3	1"	1 bar	Front	Low	114 dB
8	5.5.2	1/2"	1 bar	Rear	Low	
9	5.5.2	1/2"	1 bar	Rear	Low	123 dB
10	5.5.3	1"	1 bar	Rear	Low	108 dB
11	5.5.1	1/4"	5 bar	Front	Low	122 dB
12	5.5.2	1/2"	5 bar	Rear	Low	132 dB
13	5.5.2	1/2"	5 bar	Front	Low	131 dB
14	5.5.2	1/2"	5 bar	Rear	Low	127 dB
15	5.5.2	1/2"	5 bar	Front	Low	132 dB
16	5.5.2	1/2"	5 bar	Rear	Low	134 dB
17	5.5.2	1/2"	5 bar	Front	Low	129 dB
18	5.5.3	1"	5 bar	Front	Low	120 dB
19	5.5.3	1"	5 bar	Rear	Low	137 dB
20	5.5.4	1/4"	1 bar	Front	High	
21	5.5.5	1/2"	1 bar	Front	High	134 dB
22	5.5.5	1/2"	1 bar	Front	High	132 dB
23	5.5.5	1/2"	1 bar	Front	High	145 dB

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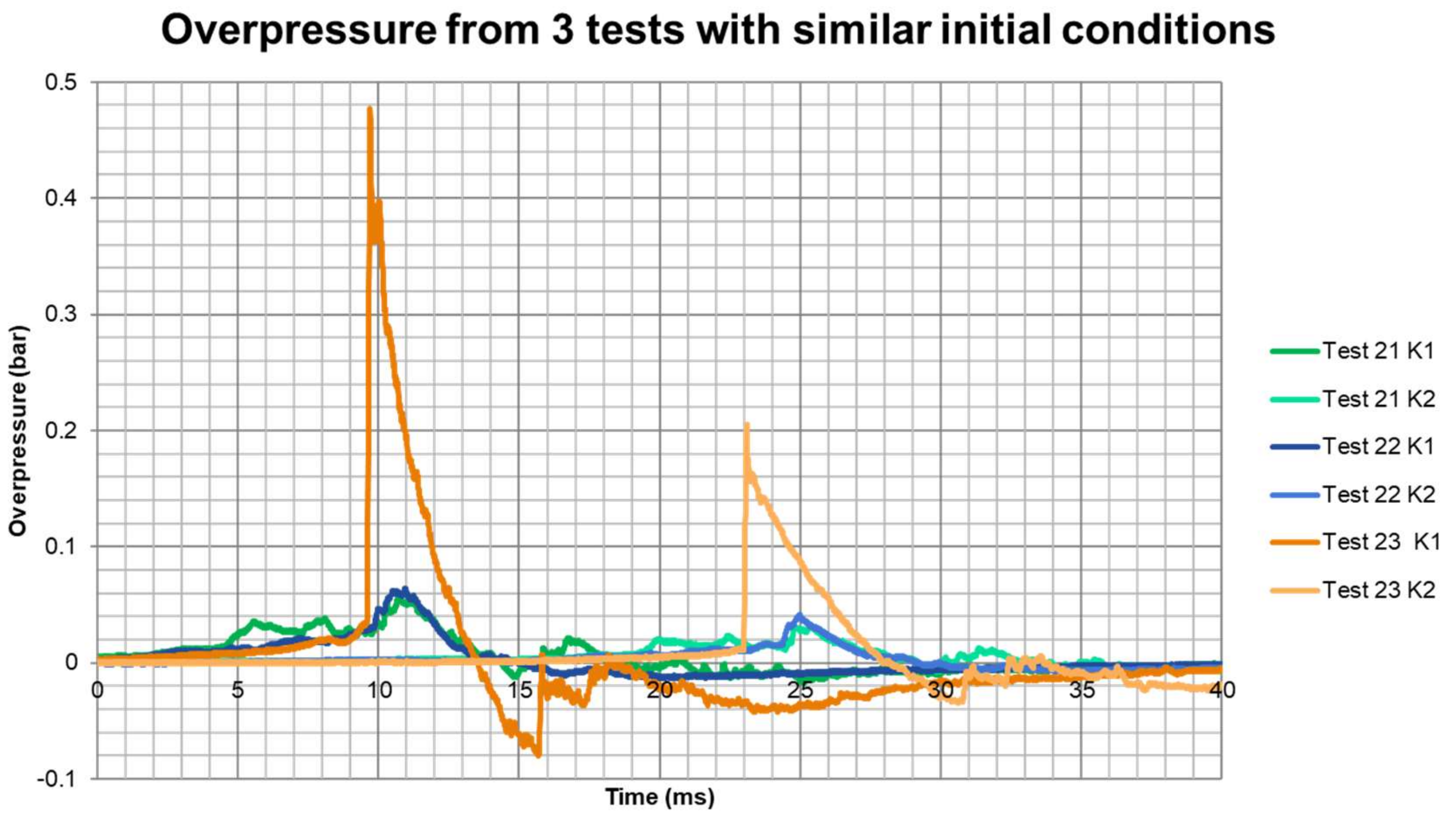
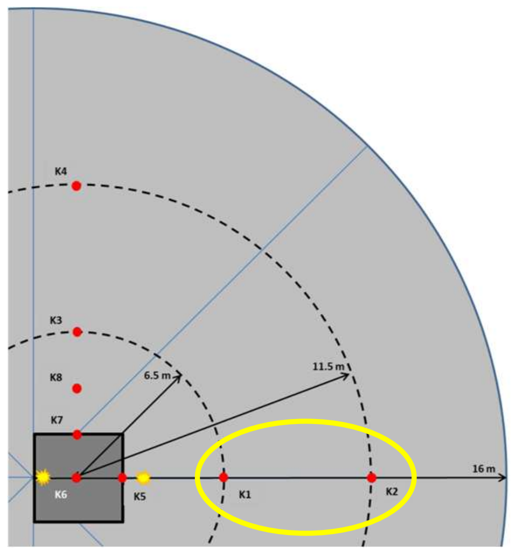
Comparison of repeated tests





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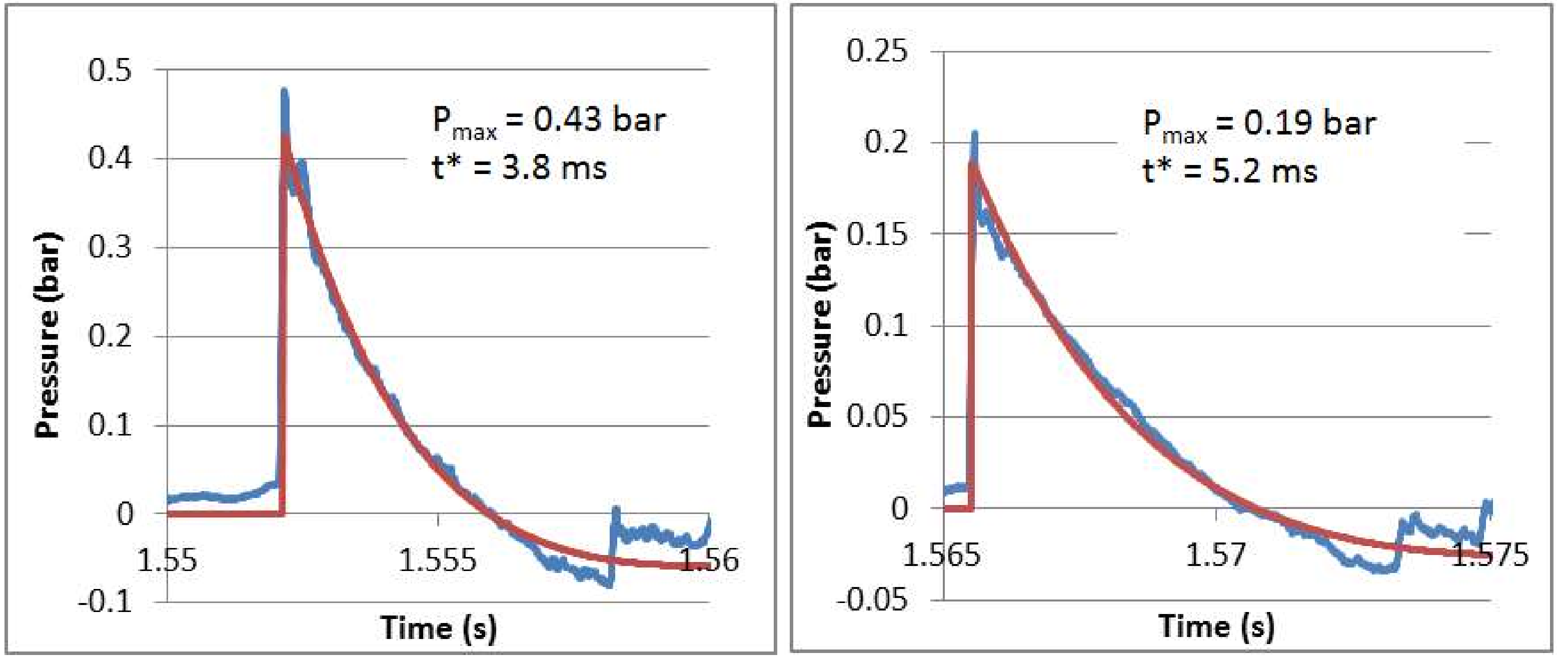
Friedlander waveform



Test 23 – Friedlander curve fitting of pressure gauges response K1: 6.5 m (left figure) and K2: 11.5 m (right figure) distance from centre along jet axis.

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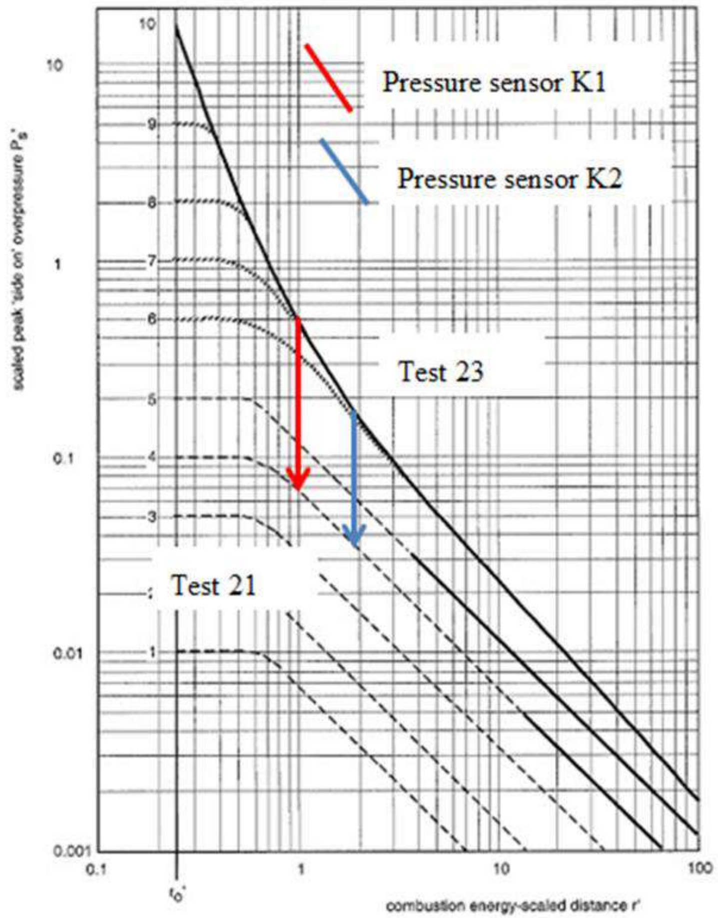
TNO Multi-Energy Method

- Using the pressure waves at 11.5 m from the centre, Test 23 energy is between 16 and 27 MJ
- Test 23 was a TNO level 8-10
- Test 21 was a TNO level 4



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TNT equivalence

- Difficulty expressing a single TNT equivalence
- Overpressure of 0.19 bar at 11.5 m is achieved by 2 kg TNT
- This is an explosive energy release of 9 MJ, about half of the energy from the Test 23 gas explosion
- There is uncertainty around DDT in Test 23. There were higher overpressures and characteristic shape, but flame speed was not as high as expected

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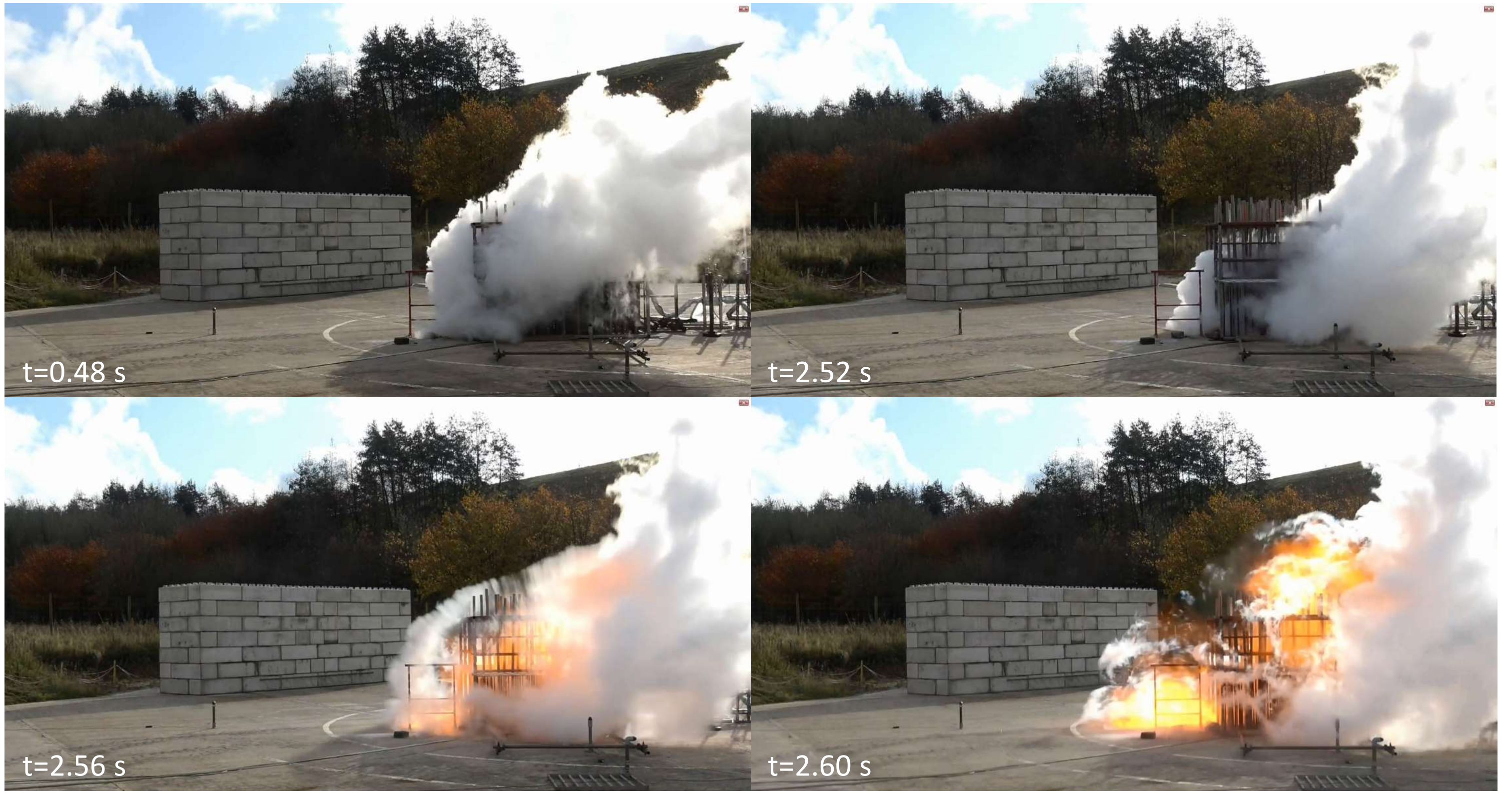
Wind effects



Combustion – some observations

- Significant variability when tests were repeated (Tests 21-23)
- Average concentrations in congestion rig slightly higher in Test 23 (2 %Vol.)
- Wind effects were noted on dispersion and hence overpressures generated
- For low congestion, TNO level 5 was a conservative assumption
- For high congestion, high level explosion and possibly DDT could occur

Publications related to the data

Giannissi, S.G., Venetsanos, A.G., Vyazmina, E., Jallais, S., Coldrick, S., Lyons, K., 2021. CFD simulations of large scale LH2 dispersion in open environment. 9th International Conference on Hydrogen Safety, September 19-22, Edinburgh, Scotland.

Venetsanos, A.G., Ustolin, F., Tolias, I.C., Giannissi, S.G., Momferatos, G., Coldrick, S., Atkinson, G., Lyons, K. and Jallais, S., 2021. Discharge Modelling of Large Scale LH2 Experiments with an Engineering Tool. 9th International Conference on Hydrogen Safety, September 19-22, Edinburgh, Scotland.

Palin, I., Lyons, K., Buttner, W., Coldrick, S., Hall, J., Atkinson, G., Thorson, J., Royle, M. 2023. Visualisation and quantification of wind-induced variability in hydrogen clouds following releases of liquid hydrogen. 10th International Conference on Hydrogen Safety, September 19-21, Québec, Canada.

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Thank you for your attention

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