Project final report

Investigation of the impact of ignition of hydrogen and natural gas accumulations in spaces in dwellings – Phase 1

Kiwa 30875

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A report by Kiwa Ltd.

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Document control

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Contents

1 Executive summary

Gas escapes of methane and hydrogen into a domestic kitchen were simulated through the injection of fuel gas into Fire Investigation Boxes at the Fire Service College, Moreton in Marsh. Initially, the gas concentration reached at equilibrium conditions was measured and then a series of ignitions were carried out to simulate explosions in that environment. A 100m exclusion zone was established around the test area; overpressure was measured with fast response pressure sensors and high-speed video was recorded. Photos of the test area were also taken before and after ignition.

A range of injection rates between 4-100kW were investigated. A kW basis for measuring injection rate was chosen as it is known that methane and hydrogen escapes through an orifice (for instance, a damaged pipe) are roughly the same on an energy basis.

At low gas injection rates (16kW), damage seen with both methane and hydrogen was broadly similar. Most of the hot gases relieved through the windows or door. With higher gas injection rates (64kW), windows and doors were blown out and there was damage to plasterboard, again, with both methane and hydrogen.

There was evidence that hydrogen transitioned from a deflagration to a detonation-type explosion when the injection rate was around 64kW and hydrogen concentrations near the ignitor were above 20%. Localised structural damage and overpressures around three times higher than previous ignitions were observed. At increasing injection rates (100kW) where very large volumes of hydrogen were injected, and with hydrogen concentrations near the ignitor around 30%, there was severe damage.

It is recommended that techniques are developed to minimise the risk of high concentrations of hydrogen occurring. Further work is recommended to investigate the feasibility of installing automatic shut off valves and hydrogen detectors.

2 Introduction

A number of studies have concluded that providing hydrogen to domestic dwellings in place of natural gas may offer a cost-effective route to decarbonising heat supply [1, 2, 3, 4]. This raises the question of the impacts of leakage of hydrogen into a domestic building, and the damage that may be caused, relative to the damage caused by a natural gas leak. Developments of concentrations of hydrogen and methane due to sub-surface leaks from gas distribution were investigated through leak simulation in the HyHouse project [5]. Currently, investigations into the behaviour of leaks from distribution pipes are being undertaken for SGN under a separate project [6]. The overall objective for SGN is to hold sufficient information to enable quantitative risk assessment to be undertaken with regards to the supply of natural gas and of the supply of hydrogen through the gas distribution network.

The current expectation of the impact of natural gas explosions in domestic properties is that the property containing the seat of the explosion will be demolished by the impact of the blast and that attached properties will suffer significant damage and, in the extreme, may also collapse. This understanding is empirical, being based on the ~50 years of experience of supply and use of natural gas in the UK. However, it has not been formally demonstrated through experimental investigation. Hence, the relative likely impact of a hydrogen explosion cannot be determined through a programme of standard tests.

This programme of work is designed to address this knowledge gap and to provide the information needed to complete quantitative risk assessments for the supply of hydrogen through the gas distribution network to domestic users.

2.1 Technical background

There is some information available about the effect of deflagration/detonation explosions of flammable gases under certain conditions, generally vented explosions of lean hydrogen-air or stoichiometric concentrations in spaces such as spheres or cuboids. Under such conditions the resultant energy release, pressure excursions, etc. have been modelled using computational fluid dynamics (CFD) and then compared with experimental results [7, 8].

It was noted that although CFD simulations can be used to predict the effects of ignition with a reasonable degree of accuracy, there are also examples where the predictions are incorrect by more than an order of magnitude [7]. The accuracy of CFD modelling will also naturally diminish with more complex, multi variable scenarios.

To complicate matters further, the situations that might arise in dwellings are far more diverse. The concentrations of fuel gases that arise are very diverse, as demonstrated in the HyHouse project. The spaces inside domestic properties are complex. There are usually interconnecting spaces (rooms which may or may not be separated by doors which in turn can be of a range of strengths) and within each space there are items (furniture, appliances, etc).

These real situations are unlikely to be accurately modelled by CFD. There was therefore a need to generate information concerning the comparative impact of ignition of accumulations of fuel gases in spaces that are representative of those present in domestic dwellings.

3 Approach

The effects of known accumulations of gas in well-defined spaces were determined experimentally for a key set of configurations. The overall approach involved the creation of a simulated dwelling space. Fuel gas was injected into the space to achieve concentrations from defined leakage rates into spaces conforming to the tightest ventilation levels required by building regulations [9] (see Section 4.3). Such levels of ventilation represent a worst case in terms of gas accumulation.

The dwelling spaces were simulated using standard Fire Investigation Boxes (FIBs) provided by the Fire Service College (FSC) at Moreton in Marsh. These have been used extensively for simulating fires in dwelling spaces, are well defined and constructed in a reproducible manner. A kitchen was simulated as it represented the highest risk environment in terms both of likelihood of being the location of a gas leak and in terms of complexity and level of congestion (including arrangements of cabinets, appliances and tables and chairs).

A series of experiments were undertaken using separately, natural gas and hydrogen as the fuel gas. Release rates of gas were chosen to mimic potentially faulty appliances or internal pipework. These range from a leaking hob giving rise to a small release, to a damaged pipe giving rise to a potentially very large release. Measurements were made of conditions before, during, and after ignition of the gas accumulations, including gas concentrations, pressures, and visually (high speed video and stills).

The FSC were able to provide a suitable test location with space for the necessary safety exclusion zones as illustrated below.

Figure 1: Fire Service College, Moreton-in-Marsh. Test location, with circle of radius 100m overlaid.

4 Fire Investigation Boxes (FIBs)

Four Fire Investigation Boxes were used for the six ignition tests. The first two ignition tests did not cause any structural damage to the FIBs, so these (FIB1 and FIB2) were refurbished and refitted internally so that they could be reused for ignition tests 5 and 6.

4.1 Construction of FIBs

FIBs were constructed using standard shipping containers with steel sides, ends, roof. FIBs were modified to include openings for three windows (W, N, and E side) and door (E side), shown in Figure 2.

Figure 2: Construction and dimensions of the FIB (top);
view from south-west (bottom-left) and from south-east (bottom-right)

Suspended floor	12mm chipboard on steel cross members.
Ceiling and walls	12mm plasterboard on battens attached to the metal walls and roof.
Door	External fire door with wood frame, standard door latch and handles.
Windows	Single gazed with one fixed and one opening light in wooden frames, standard window furniture.

Table 1: Construction of FIBs

4.2 Installed in FIBs

Gas injection point	Under sink, 28mm copper pipe with ball valve.
Air sampling points	8 air sampling points for stage 1 (gas accumulation testing): • Under sink, attached to gas injector pipe. • Near ignitor position, at 1300mm height and 250mm from spark. • NW corner at 300mm and 2000mm heights (300mm from floor and ceiling), 300mm from W and N walls. • NE corner at 300mm and 2000mm heights (300mm from floor and ceiling), 300mm from N and E walls. • On centre line of S wall at 300mm and 2000mm heights (300mm from floor and ceiling), 300mm from S wall. 2 air sampling points for stages 2 and 3 (ignitions): • Under sink, attached to gas injector pipe. • Near to ignitor (at same height and 250mm from spark).
Ignitor	Standard boiler spark ignitor on wall near door at a height of 1300mm from floor.
Pressure measurement points	6 pressure measurement points: • Under sink, attached to gas injector pipe. • Near ignitor, at 1300mm height and 250mm from spark. • NW corner at 1300mm height, 200-300mm from W and N walls. • NE corner at 1300mm height, 200-300mm from N wall, 500mm from E wall. • Centre line of S wall at 300mm height, 200-300mm from S wall. • Centre line of S wall at 2000mm height (300mm from ceiling), 200-300mm from S wall.
Sink unit cupboard	Sealed to wall.
Table	Dining table positioned near N end of FIB
Assorted items	• Two standard 30kg dummies: ○ Positioned on chair at centre line of E wall. ○ Positioned on chair in SW corner. • Pig (tests 4 and 5), ~60kg pig positioned on chair in front of sink unit. • Six newspapers and two hard-backed books, spread out on table. • Crockery and saucepans, arranged in sink cupboard, on draining board and table. • Clothes – arranged on chair in SW corner of FIB: ○ Polyester tee-shirt. ○ Cotton tee-shirt.

Table 2: Installed in FIBs

4.3 Control and measurements

Gas Injection System	Gas was injected into a floor mounted sink cabinet via a 28mm diameter copper pipe.
Gas Concentration Measurement System	Automated multipoint sampling system and analysers for methane and hydrogen were installed to enable the volume concentration of fuel gases (%v/v) to be tracked and the stratification to be mapped. Dedicated software was created with Python [10] to control the sampling system and communicate was the gas analysers.
Gas Pressure Measurement System	High speed pressure transducers were mounted at several positions inside and outside the FIBs, positioned to enable the pressure rise and rise rate to be tracked at each location. A data logger capable of sampling at 20,000Hz was used to measure the output from high speed pressure transducers. The point of ignition was recorded which could later be matched to the appropriate time in the concentration measurements. The pressure measurements were digitally filtered (see Section 6.3.4) and graphed using a processing pipeline written using Python [10], NumPy [11], SciPy [12], Pandas [13] and Matplotlib [14].
Gas Ignition System	A spark igniter and remote activation system was installed in the FIB. The igniter was able to operate continuously and to be triggered at set times.
FIB Layout Recording	The general arrangement inside the FIBs was recorded by manual measurements and still photography.
Visual Recording Arrangements	High speed video of outside of FIBs was used so that the development of the explosions could be tracked in detail. This also provided a general record of the path and destination of debris. Stills record of conditions before and after tests both inside and outside the FIBs provided an accessible summary of the overall effect of each explosion. Distance markers were installed to assist in interpretation of the images collected.
Air Tightness	The development of fuel gas accumulations in spaces is moderated by air leakage from the building. The current standard for air leakage in domestic buildings is defined in Building Regulations Approved Document F [9] (for England and Wales) and Building Standards 3.14 [15] (for Scotland). These represent the most stringent constraint on the permitted air leakage. The lower the air leakage rate, the more rapidly gas accumulations will develop from a gas leak inside a space. So, the current requirements represent a 'worst case' for gas accumulation. In England and Wales the minimum ventilation rate is 0.3 l/s per m^2 internal floor area [9, p. 19; Table 5.1b], equivalent to 0.45 air changes/hour for a typical two-storey property. This in turn is equivalent to a flow rate of 9 $m^3/h/m^2$ envelope area at 50 Pa for an 'in use' property, i.e. with ventilation left unsealed [16, p. 11; §2.3]. The standards in Scotland are broadly similar, specifying trickle ventilation requirements for properties with infiltration rates of 5-10 $m^3/h/m^2$ at 50 Pa. Each FIB was pressure tested before gas injection, using the standard procedures for building pressure testing. The air flow required to hold the FIB at 50 Pa above or below atmospheric pressure was measured by a specialist subcontractor with UKAS accreditation. The initial air tightness of the FIBs was improved by sealing gaps around windows, door frames etc with expandable foam and tape. All FIBs were sealed so that the air requirement was 7-8 $m^3/h/m^2$ at 50 Pa.

Table 3: Controls and Measurements

5 Test programme

5.1 Stage 1: Rate and level of gas accumulation

The rate and level of gas accumulations was determined separately for defined gas leaks of methane and hydrogen. Concentrations were established based on field experience of the concentrations found in real world gas escapes inside buildings.

The leak rate of fuel gas from a particular orifice is dependent on the physical properties of the gas. These include the density, Wobbe Index and calorific value. Because of the large difference in density and calorific value of hydrogen and methane, the leak rate (l/minute) from a particular orifice will be significantly different for each gas, (hydrogen rate = almost 3 times methane rate). However, this results in a very similar rate in terms of energy flow. The release rates of hydrogen were further modified by the ratio of the Wobbe indices of the two gases.

The release rates chosen for the experimental work are shown in Table 4 below. To give context, these have been related to typical domestic appliance heat inputs.

Test set	Fuel gas	Release rate (kW)			
		Small	**Medium**	**Large**	**Very large**
A	CH_4 (G20)	4.0	16.0	64.0	—
B	H_2	—	14.6	58.3	100.2
Roughly equivalent to:		Consumption of: Hob (2x 2kW)	Consumption of: Hob (4x 2kW) Oven (3kW) Gas fire (6kW)	Consumption of: Hob (6x 2kW) Ovens (2x 3kW) Gas fires (2x 6kW) Boiler (30kW) i.e. the upper limit of any conceivable domestic use	Larger than any conceivable domestic use i.e. could only be due to damaged pipework (A hole in a pipe of ~8mm diameter would be required for a leak of this size at 20mbar)

Table 4: Injection rates

The results from this work provided a calibration for a FIB of gas concentration development and distribution with time. This information was required to enable the conditions for testing carried out in Stage 2 to be specified.

5.2 Stage 2: Ignition of gas accumulations

For these tests, the FIBs were configured with an ignition source (spark source located at a height equivalent to a light switch). A desk-based review of types of ignition source was carried out as part of this work, this is reported separately [17].

Based on the findings from Stage 1, injection rates were selected for each fuel gas. Injection was established and the conditions in the FIB measured and recorded, when the gas concentrations had reached the equilibrium measured in Stage 1, the igniter was activated, and the subsequent explosion was observed.

Tests were carried out for each fuel gas; five ignitions were completed.

5.3 Stage 3: Ignition of stoichiometric hydrogen

The most powerful explosion for a gas / air mixture occurs when the mixture is stoichiometric. The injection rates used in Stage 2 resulted in various fuel gas concentrations in the FIB, including a stoichiometric concentration of methane (~10%). However, to achieve the higher stoichiometric concentration of hydrogen (~30%), a much higher injection rate was required.

An injection of hydrogen was undertaken based on the calibrations produced by Stage 1, and ignition initiated at a stoichiometric concentration; one ignition was completed.

Conditions in the FIBs (pressure, rate of pressure change, flammable gas concentration) were measured prior to and after the ignition.

5.4 Safety

Due to the hazardous nature of the experimental work, safety was a prime consideration throughout the experimental programme. The work was carried out under the health and safety rules established by the FSC for similar types of testwork. In accordance with FSC requirements, fire crews were mobilised close to the FIB area during the explosion testing, ready to respond to any hazards.

5.4.1 Risk assessments for test programme

The execution of risk assessments for the proposed measurement equipment, test procedures and test matrices were implicit to the design processes for these. They included hazard identification and analysis with regards to the design and operation of the test equipment. Risk reduction measures were identified and applied including setting of safe working distances, monitoring of atmospheres, provision of warnings and barriers, and identification of PPE required.

This followed the principles set out in HAZOP Guide to Best Practice [18]. The knowledge and experience of the project technical specialists and the staff of the Fire Training College was applied to this.

The Risk Assessment is shown in Appendix A. Based on this risk assessment, a method statement and procedures for set up and testwork were developed. These are shown in Appendix B.

5.4.2 Personnel exclusion zone

Whilst flammable gas was being injected, a personnel exclusion zone was established around the FIB.

The size of this zone was set based on calculations of the energy content of the gas / air mixtures within the FIB, compared with the explosive energy of TNT, and comparisons with other work. The rationale for the extent of the exclusion zone is shown in Appendix C. The zone was set at a radius of 100m.

Standard Fire Service College procedures were adopted to ensure that the exclusion zone was respected, including daily briefing of College Instructors and Personnel and the flying of red warning flags at the perimeter of the exclusion zone.

The control cabin, gas supplies, gas injection equipment, gas metering, and gas analysis equipment were all installed outside the exclusion zone. No 240V equipment was installed inside the zone, except for the ignitor unit. The controls for the ignitor were mounted in the control cabin and were locked off with a key system when not in use.

5.5 Monitoring equipment and materials

The equipment defined in Section 4 and associated consumable materials and equipment necessary for execution of the test programme were procured. This included sufficient fuel gases to carry out all the tests defined. The equipment layout is shown in Figure 3. Photographs of the equipment are shown in Figures 4-7.

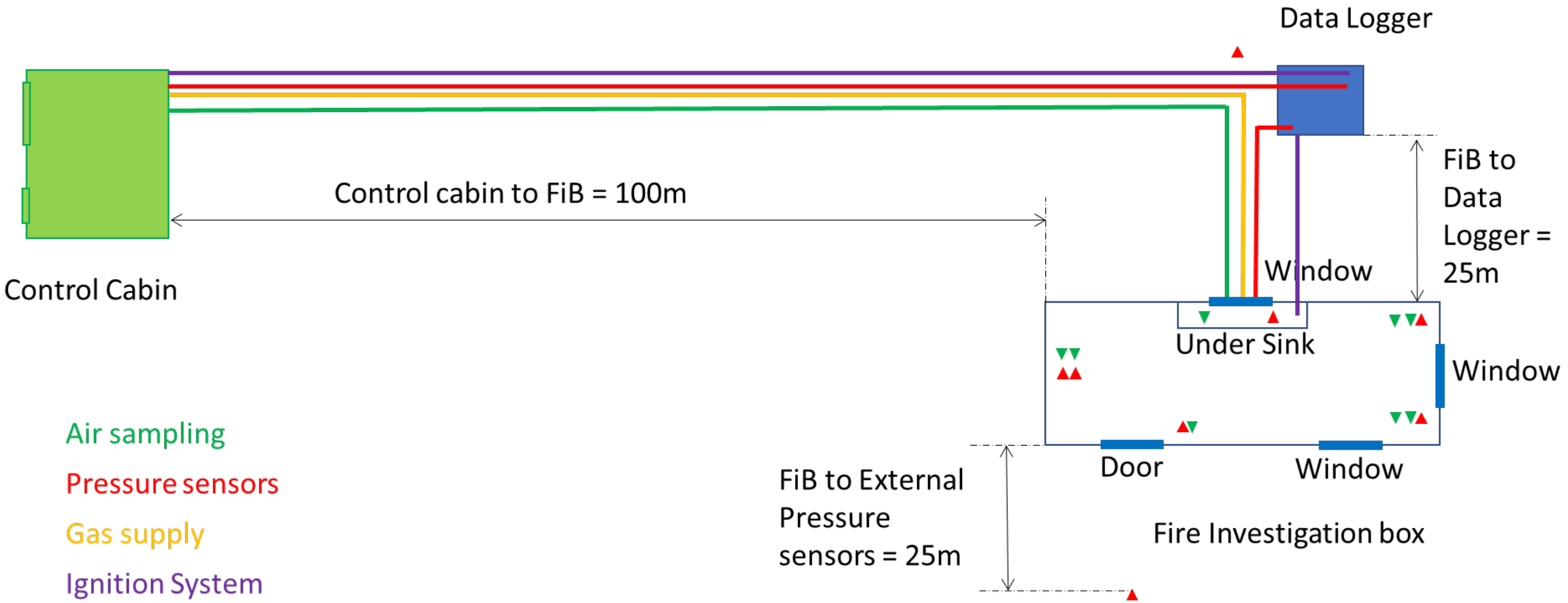

Figure 3: General layout of equipment

Figure 4: Fire Investigation Box (viewed from near control cabin)

Figure 5: Inside FIB

Figure 6: Control cabin and gas supplies

Figure 7: Inside control cabin

5.5.1 Data logging arrangements

A key element of the data collection was to ensure that the data collected was coherent, i.e. the values recorded for the various parameters could be related in time. The gas concentrations, ignition times and pressure development profiles needed to be interpreted together. Data logging arrangements were set up to ensure that this was achieved:

- Dedicated software was created to control the gas concentration logging system, including the timed switching of solenoid valves on each of the sampling lines and communication was the gas analysers.
- A data logger capable of sampling at 20,000Hz was used to measure the output from high speed pressure transducers. The point of ignition was recorded which could later be matched to the appropriate time in the concentration measurements.
- The pressure measurements were digitally filtered (see Section 6.3.4) and graphed using an automated processing pipeline (see Section 4.3).

5.5.2 Gas injection systems

The gas injection system was designed and constructed to enable injection of fuel gases to be controlled remotely. The system allowed the supply to be switched between gases and the rate of injection to be controlled. In the first stage of testing, the system design needed to ensure that there was no risk of causing ignition of the fuel gases. In the second and third stages of testing, it needed to be able to withstand the likely impacts (overpressures) of igniting the gas accumulations in the FIBs.

6 Results and discussion

6.1 Air tightness

In total, four FIBs were used during the testing. FIB 1 was used for Stage 1 and all four FIBs were used for Stages 2 and 3. The first two FIBs used for the smaller ignitions were refurbished and used again in the later ignitions.

Before testing, each FIB was pressure tested by an approved testing company to determine air permeability. The results of the pressure testing work are shown in Table 5 below.

Fire Investigation Box Number	FIB Volume, m^3	Air requirement to achieve 50Pa, ($m^3/h/m^2$)	Uncertainty	FIB used for Ignition Number
FIB 1	29.7	7.50	±1.2%	1
FIB 2	29.6	7.89	±1.1%	2
FIB 3	29.5	7.07	±2.2%	3
FIB 4	29.5	7.46	±1.4%	4
FIB 1R (refurbished)	29.7	7.16	±1.2%	6
FIB 2R (refurbished)	29.7	7.08	±1.9%	5

Table 5: Air pressurisation test results

The current standard for air leakage in domestic buildings is defined in Building Regulations and is equivalent to 9 $m^3/h/m^2$ at 50 Pa 'in use' (see Section 4.3). This represents the most stringent constraint on the permitted air leakage. The lower the air leakage rate, the more rapidly gas accumulations will develop from a gas leak inside a space. So, the current requirements represent a 'worst case' for gas accumulation. These air tightness measurements of 7-8 $m^3/h/m^2$ at 50 Pa show that the FIBs were sealed to a permeability equivalent to a modern building.

6.2 Stage 1: Rate and level of gas accumulation

In this section, the equilibrium flammable gas concentrations in the FIB will be shown at high, middle and low elevations in the box (300mm, 1150mm and 2000mm from floor level, respectively – see Section 4.2), along with the average concentration.

Gas was injected into the FIB at slightly different rates for methane and hydrogen, to mimic their different leak rates through an orifice (see Section 5.1). The actual gas escape rates were measured and are related to the target escape rates in Table 6.

Gas		Methane, CH_4			Hydrogen, H_2		
Target escape rate	kW	4.0	16.0	64.0	14.6	58.3	58.3
Actual escape rate	kW	4.0	17.3	62.1	14.6	58.6	55.5

Table 6: Actual escape rates of hydrogen and methane

The equilibrium gas concentrations measured at each injection rate are summarised in Figure 8 and the equilibrium concentrations in the sink cupboard are shown in Figure 9. The development of gas concentration measured at each gas injection rate is shown in full in Appendix E.

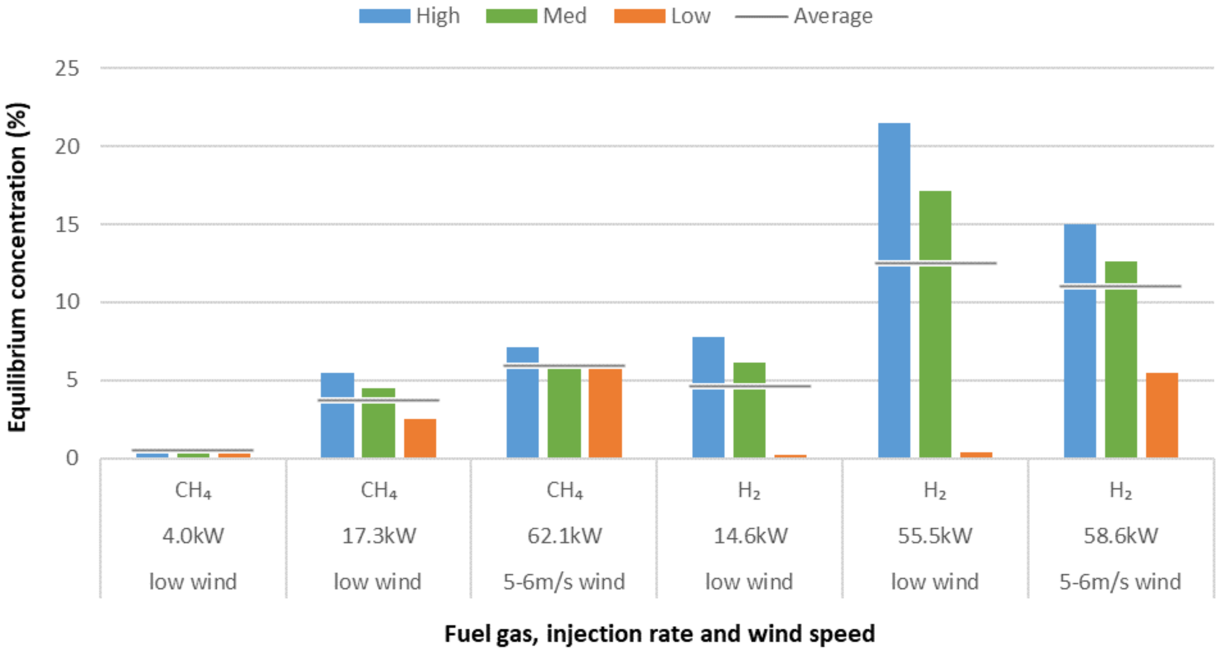

Figure 8: Summary of equilibrium gas concentrations in the room for each fuel gas injection (low wind means there was generally little or no wind, and not enough to make a representative measurement)

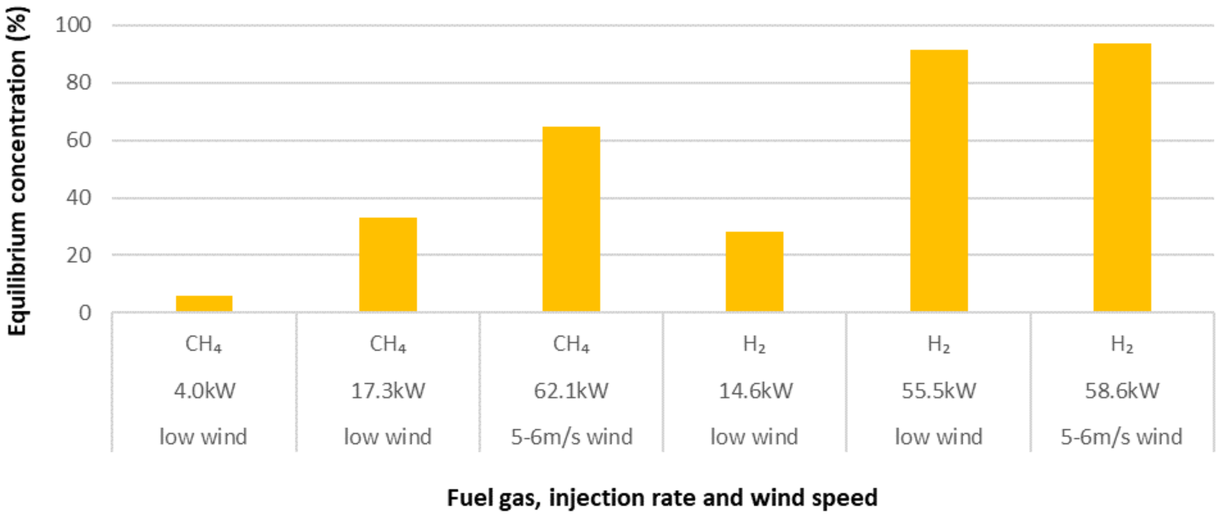

Figure 9: Sink cupboard gas concentrations for each fuel gas injection (low wind means there was generally little or no wind, and not enough to make a representative measurement)

A 4kW rate of injection of methane was insufficient to build up concentrations which approached the LEL (5%). Using a 17kW rate of injection of methane, the average concentration in the FIB reached equilibrium at around 4%. This is still below the LEL, however the methane was stratified in the FIB, with concentrations just above the LEL at high level and much lower concentrations found near the floor. At a 62kW rate of injection of methane, the average methane concentration reached equilibrium at around 5.5% to 6%.

At 15kW rate of injection of hydrogen, the average hydrogen concentration was 4.5% to 5% at equilibrium. This is just below the LEL for hydrogen (4.8%[1]). Using a 60-64kW rate of injection, the average concentration reached equilibrium at approximately 11-13%. This is above the LEL for hydrogen.

6.2.1 Comparison between data and models

The equilibrium gas concentrations measured in the FIB for the various fuel gas injection rates were compared with a buoyancy model. The model considered the buoyancy effect of both the fuel gases which are lighter than air, and the resulting pressure difference between the inside and the outside of the FIB at ceiling level. This pressure difference causes an air flow through gaps and holes in the building fabric (of which the air tightness is known), which draws in fresh air at low level, which dilutes the overall concentration of gas in the FIB.

The model is similar to the one described in the HyHouse report [5] and predicts that hydrogen concentrations will reach 1.7 times that of methane, for the same kW injection rate of fuel gas. This is lower than would be expected by considering air changes in the FIB alone. A comparison between the data collected and the concentrations predicted by the model is shown in Figure 10. A more detailed description of the model is given in Appendix D.

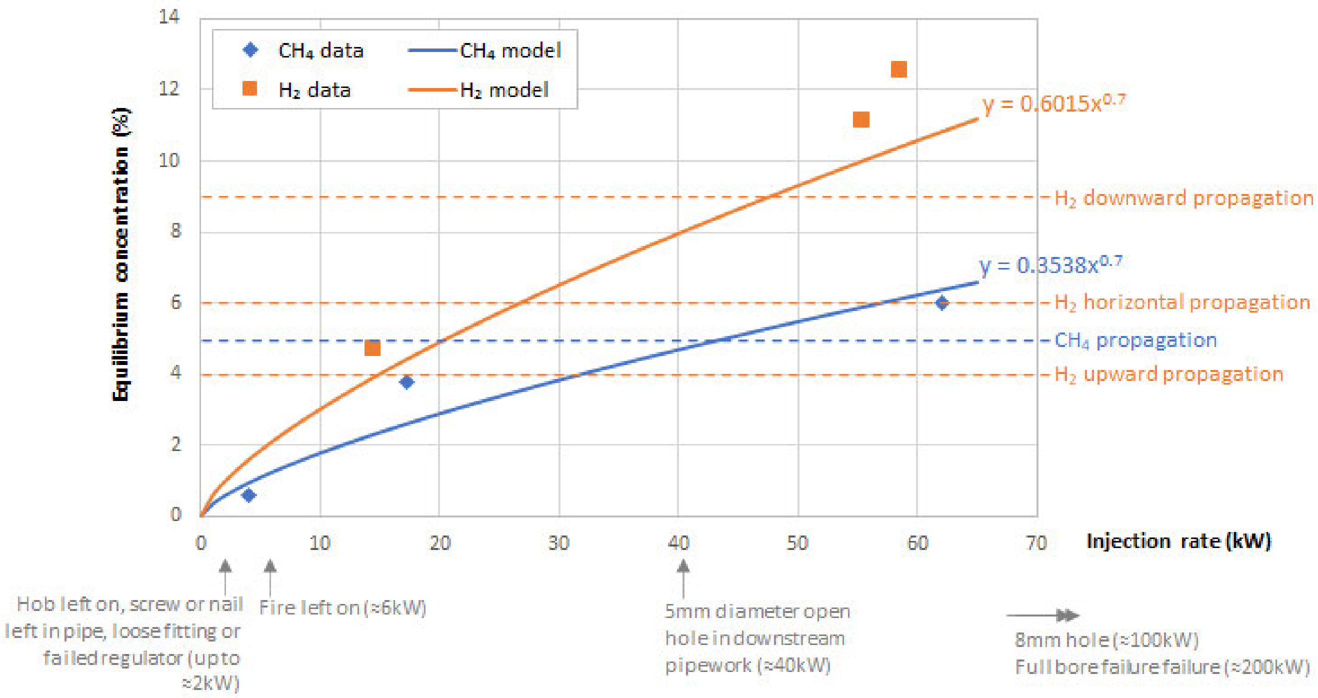

Figure 10: Average gas concentration in the room at equilibrium (points) compared with gas concentrations predicted by buoyancy models (solid lines). Minimum concentrations for hydrogen flame propagation are shown (dotted lines) along with nominal values for some escapes (arrows along x-axis)

The data points collected (although few in number) are broadly consistent with the model. A similar relationship was also shown at HyHouse, and the data collected here are also consistent with the patterns shown in that work.

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[1] The combustion properties of hydrogen are unique in that the classic %LEL is not representative of a general deflagration in a room. In such a large space hydrogen deflagration will not occur horizontally until about 6% and not generally until about 8.8%.

However, at the higher injection rates of hydrogen into the FIB, it appears that the concentration was higher than predicted. It is believed this is because the FIB was becoming pressurised by the large volume of fuel gas being injected (approaching 300 litres/minute). In order to ventilate the FIB at this rate, there would be a pressure drop across the gaps and holes in the building fabric which would become an appreciable fraction (~10%) of the buoyancy force driving the ventilation. This resulted in a slightly increased pressure inside the FIB which resisted the inflow of dilution air and led to slightly higher (~1.04 times) gas concentrations in the FIB.

A house clearly has much larger volume (hundreds of m^3) than the FIB (only $29m^3$) and would have a higher overall ventilation rate, so it might be expected that this pressurisation effect could be neglected. However, in the cases where doors between rooms are closed (and especially if those doors form a good seal) there may be a localised pressurisation effect for gas escapes at 64kW and above. These points therefore represent a worst-case scenario.

The buoyancy model shows two things:

1. The general behaviour of the (gas in air) equilibrium concentration of a fuel gas as the injection rate is increased.
2. A prediction of the precise equilibrium concentrations that will be reached at various injection rates.

It should be noted that although the general behaviour of the fuel gas is well predicted, the actual precise concentrations are very sensitive to the input parameters to the model. This means that small changes to the input parameters can result in large variation in the predictions. This reiterates the finding in [7] that computer simulation can be incorrect by more than an order of magnitude and emphasises the importance of practical testing work to allow comparison with modelling, as opposed to modelling alone.

6.2.2 Stratification of gas concentration

The degree of stratification of gases within the FIB is shown by the relative heights of the bars in Figure 8. The stratification of gas concentration was more pronounced with hydrogen than with the methane injections.

This is shown more clearly in Figure 11, where the ratios of gas concentration at high level to the concentration at low level are calculated. The stratification of hydrogen in particular was dependent on windspeed, with the injection on a day with higher windspeed resulting in significantly less stratification of the hydrogen in the FIB than on a day with lower windspeed (although the overall room average concentration of hydrogen was not significantly different).

The fuel gas concentration at high level was 1.1-1.8 times that of the room average in each test (shown in Figure 12). However, on days with low wind the floor level concentration of hydrogen was almost zero.

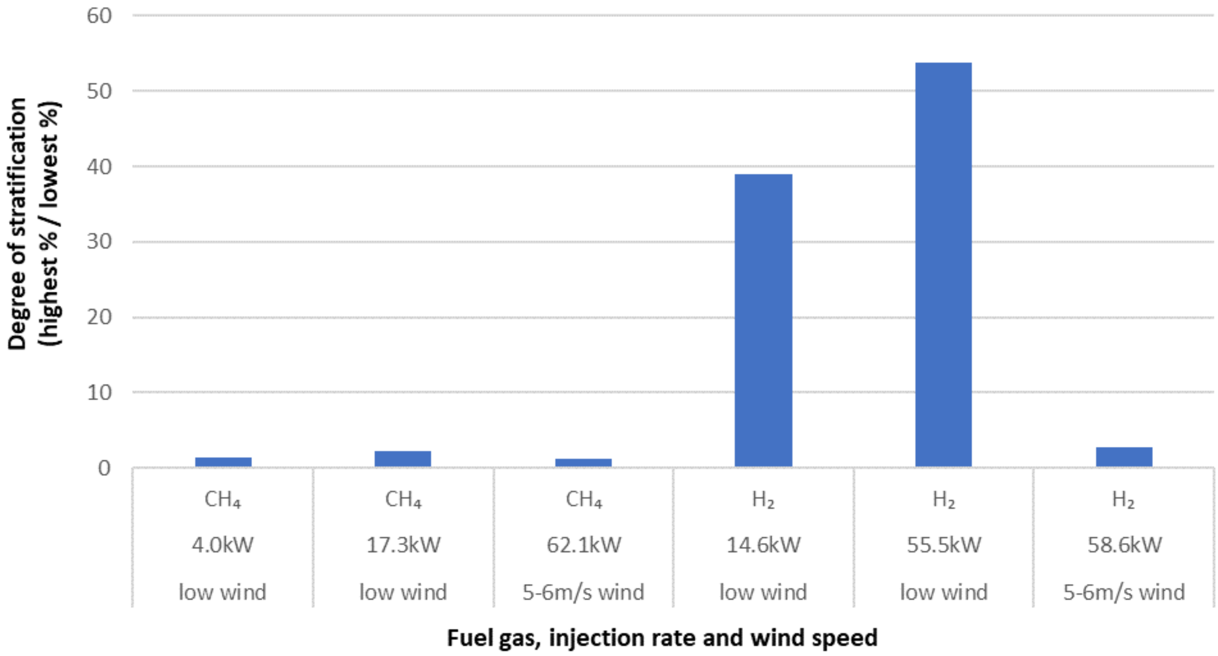

Figure 11: Degree of stratification for gas concentration (the ratio of gas concentration at high level to the concentration at low level) for each fuel gas injection (low wind means there was generally little or no wind, and not enough to make a representative measurement)

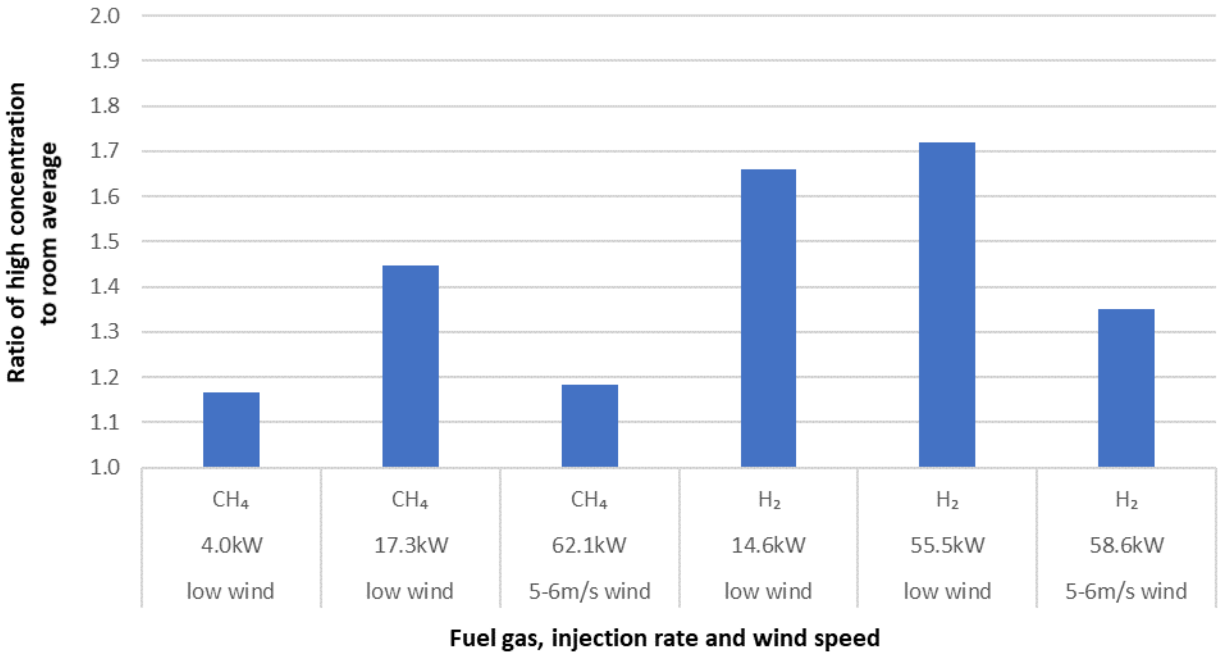

Figure 12: Ratio of high level gas concentration to room average for each fuel gas injection (low wind means there was generally little or no wind, and not enough to make a representative measurement)

6.3 Stage 2: Ignition of gas accumulations

In Stage 2, flammable gases were injected until the average concentration in the FIB (i.e. the measured concentration close to the ignitor) reached the required value. High speed video recording was then started, and the gas / air mixture was ignited. Any resulting fire was extinguished and the resulting damage from the overpressure was recorded.

The results of the testing are summarised in the tables below. More detailed descriptions of damage are provided in Appendix F and photographs are provided in Appendix H. Slow motion videos of the ignition tests and a full photo library accompany this report.

A description of the ignitions carried out and the gas concentrations at the ignitor before ignition is shown in Table 7.

Fuel gas injected		CH_4		H_2		
Ignition Number		1	5	2	3	4
Nominal gas injection rate	kW	~16	~64	~16	~64	~64
Gas concentration at ignitor (mid-level)	%	6.5	9.8	9.0	17.8	20.1

Table 7: Ignitions carried out and the gas concentrations at the ignitor

6.3.1 Pressure relief

The primary mechanism for pressure relief in the explosions was through the windows and in some cases through the door shown in Figures 13-14.

Figure 13: Outside view of FIB showing window above sink with detached frame and glass fallen out after ignition 1 (16kW methane)

Figure 14: Blown out door and door surround
Left: ignition 5 (64kW methane); Right: ignition 4 (64kW hydrogen with detonation)

Table 8 summaries the damage that was observed. In the smallest methane and hydrogen ignitions, the window frames were damaged and the windows opened, but the peak pressure was not sufficient to break the glass. In the larger ignitions for each of the gases, the glass was broken and the door was blown off its hinges. Ignition 4 (~64kW hydrogen) was sufficient to blow the entire door a distance of 25m.

Fuel gas injected		CH_4		H_2		
Ignition Number		1	5	2	3	4
Window damage		Frames opened (glass did not break)	Glass broken	Frames opened (glass did not break)	Glass broken	Glass broken
Number of windows damaged		2	3	1	3	3
Maximum distance to window debris	m	10	15	10	20	40
Damage to door		None	Door blown off hinges	None	Door blown off hinges	Door blown off hinges
Maximum distance to door debris	m	—	2	—	5	25

Table 8: Damage caused by pressure relief through windows and door

6.3.2 Damage to building contents

The damage to the FIB contents was surveyed after each ignition and the findings are shown in Table 9. In the methane ignitions, the sink cupboard did not open and the gas inside was not ignited, whereas in the hydrogen ignitions the door was knocked opened sufficiently to cause ignition of the gas inside the cupboard and then the collapse of the cupboard (Figure 15).

Figure 15: Close-up of sink damage after ignition 2 (16kW hydrogen)
Crockery was only damaged by landing on floor after collapse of cupboard and not by ignition itself

It is of note that concentrations of fuel gas around or above the LEL were detected in the cupboard after the ignition. This is of relevance to emergency services personnel who may find flammable accumulations of gas remain in some places even after an explosion.

Fuel gas injected		CH_4		H_2		
Ignition Number		1	5	2	3	4
Gas under sink ignited		No	No	Yes	Yes	Yes
Sink damage		None	None	Collapse	Blown apart	Blown apart (more severely)
Dummies moved on chairs		No	Chairs moved	No	No	Chairs moved
Effect on pig *		—	Scorched, did not move	—	—	Scorched, did not move

Table 9: Damage to the building contents (a slaughtered pig was placed in the FIB for ignitions 4 and 5 – the findings are reported in Section 6.3.6)*

6.3.3 Damage to building fabric

Damage to the building fabric was minimal in the ignitions at lower concentrations. At higher concentrations there was damage to the plasterboard in the FIB (this would have allowed additional pressure relief) and in ignition 4 there was structural damage to the metal skin of the FIB (Figure 16). Table 10 summarises the observations.

Figure 16: Damage to FIB wall near sink cupboard after ignition 4 (64kW hydrogen with detonation)

Fuel gas injected		CH_4		H_2		
Ignition Number		1	5	2	3	4
Damage to walls and ceiling		Minimal	Ceiling plasterboard collapsed	Minimal	Plasterboard pushed outwards at low level	Plasterboard pushed outwards at low level
Damage to structure		None	None	None	None	Bowed out; split welds on 2 sides

Table 10: Damage to building fabric

6.3.4 Pressure measurements

Fast acting pressure transducers were installed in and around the FIBs as shown in Figure 3. These were connected to a data logger to record pressure changes during the ignition process. The results of the measurements are summarised in Table 11 and Figure 17. An example of the data collected during an ignition is shown in Figure 18. The detailed time plots for the pressure measurements are shown in Appendix G.

The pressure measurements were sampled at 20,000Hz and were then digitally filtered in two stages:

1. The frequency spectrum of the data was inspected as noise components were removed. These were predominantly from mains noise and were at multiples of 25Hz, 50Hz, 150Hz, etc. Additional noise components falling in the range 1kHz-10kHz were also removed.
2. A median filter was then applied to the data with kernel size = 41.

The time taken to reach peak pressure was much lower for the hydrogen ignitions and the entire duration of the overpressure was generally shorter than the methane ignitions. The damage caused by an overpressure also depends on the duration of the overall event, i.e. large overpressures – if short in duration – can effectively pass by a person without there being time to cause severe injury as the impulse is small [19, 20, 21, 22] (see Appendix I).

Fuel gas injected		CH_4		H_2		
Ignition Number		1	5	2	3	4
Number of peaks observed		1	1	1	3/4	2
Maximum overpressure observed	mbar	40	60	40	90	280
Approx. time from initial increase in pressure to peak	s	0.4	0.3	0.1	0.1	0.1
Approx. duration of event	s	0.5	1.0	0.5	0.6	0.5
Approx. increase in room T *	°C	7-22	8-19	4-16	6-15	9-22

Table 11: Results of pressure measurements (temperature increase inferred from pressure sensor zero point)*

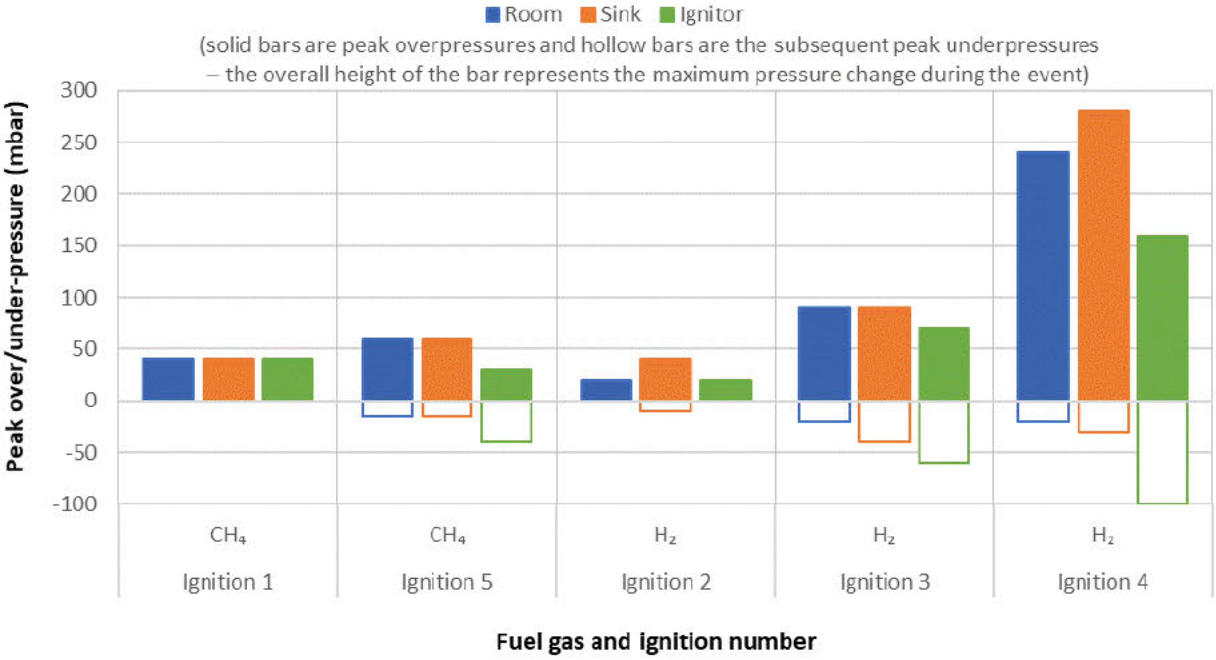

Figure 17: Peak over- and under-pressures observed after ignition

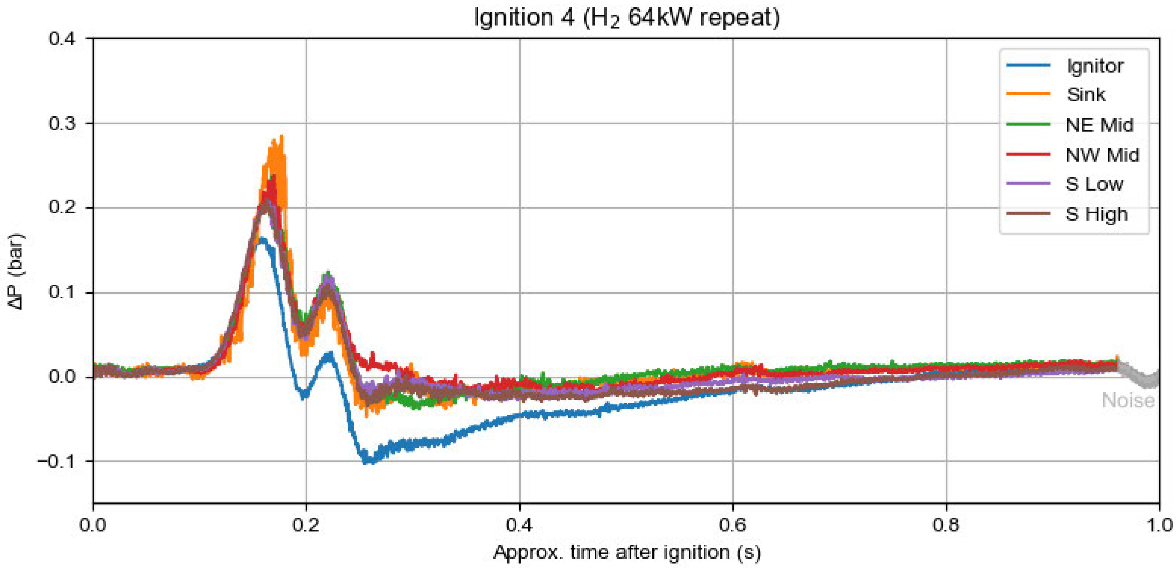

Figure 18: Example of pressure data collected from ignition 4 (20% H_2 at ignitor)

The pressure measurements are consistent with those reported in other studies [7, 8]. Figure 19 shows the data collected in the hydrogen ignitions plotted against reference data from ignitions on the rear wall and centre of a vented enclosure. The overpressures measured are consistent with the exponential pattern identified in the other studies.

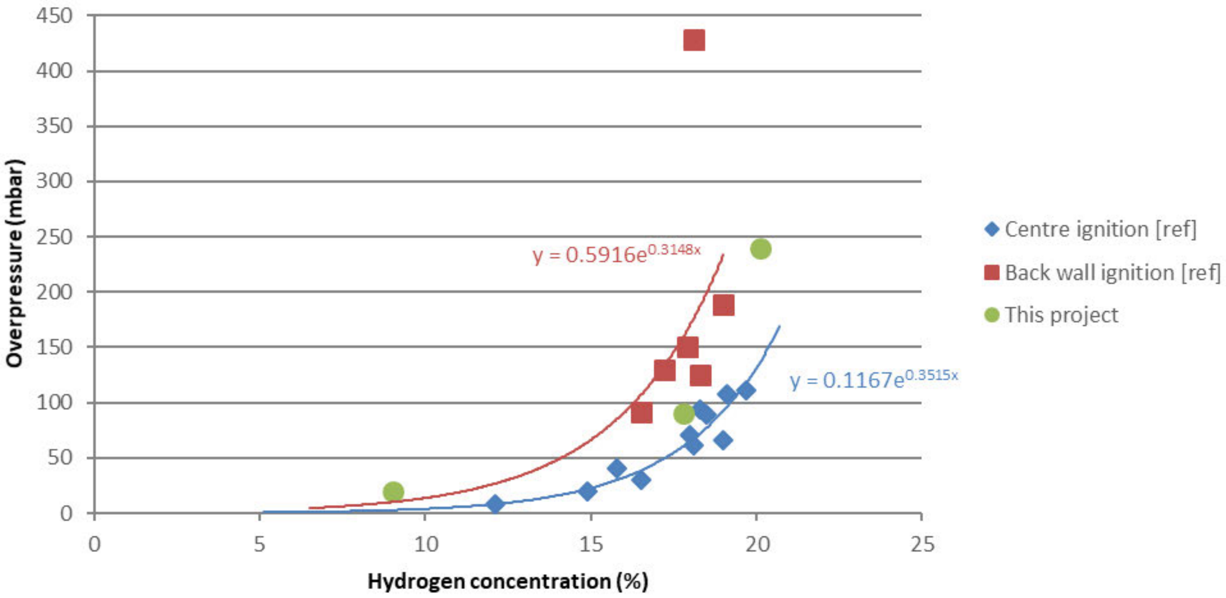

Figure 19: Comparison between hydrogen overpressure data collected in this project and reference data from other studies [7, 8]

The double pressure peak may either be caused by a double-ignition, or may be an artefact of the vented explosion. Such double-peaks (with a higher first peak and lower second peak) were observed in hydrogen ignitions where the ignition source was on the back wall of a vented enclosure [7].

The overpressure at the ignitor (by the door) was generally lower in all ignitions, however the sum of the overpressure and underpressure were similar.

Data on damage to building windows, structures and occupants has been collated from various sources [23, 24, 25, 26] and is shown in Appendix I. These reference overpressures are consistent with the data collected. They also show that in ignitions 1, 2, 3, and 5, the overpressures were modest:

- The glass windows were only broken at or above 60mbar overpressure in the room.
- There was minor damage to the structure in ignitions 1 and 2 and it is likely the house would have been at most temporarily uninhabitable after ignitions 3 and 5 (but there would not have been extensive damage to brickwork).
- The probability of death to occupants would have been low and injuries were more likely to be caused by flying debris and possibly heat rather than peak overpressure.

In ignition 4, the peak overpressures were much larger than the other ignitions:

- It is likely there would have been significant damage to brickwork, however this would have also provided another mechanism for pressure relief.
- In the overpressures measured, occupants of the house would probably have been seriously injured and possibly killed.

However, it should be noted that to fully consider the damage done by an overpressure, the speed and duration of the overpressure should also be taken into account.

6.3.5 Other observations

Various other qualitative observations were made (summarised in Table 12). Coupled with the evidence above, it was suspected that the two bangs heard in the hydrogen ignitions were at first the gas in the room igniting, then the gas in the cupboard igniting.

However, from the damage observed in ignition 4, it is believed that hydrogen transitioned from deflagration to detonation. This would explain the order-of-magnitude increase is overpressure and additional damage caused.

In the methane ignitions, the plastics in the room (for example, duct tape and hardback books) were damaged more than in the hydrogen ignitions. The temperature increase in the FIB was also higher in the methane ignitions (see Table 11). This reflects the fact that there is increased radiation in methane ignitions compared with hydrogen ignitions.

Fuel gas injected		CH_4		H_2		
Ignition Number		1	5	2	3	4
Description of bang in control box (120m from FIB)		Not heard in control box	Audible	Audible	Loud thud	Loud thud
Bang heard in offices (700m+ distance from FIB)		No	No	No	Yes (loud 700m away)	Yes (loud 1km away)
Other observations		None	One ignition seen on video	Two bangs heard, 2s apart	Two bangs heard, 0.1s apart	Two ignitions seen on video
Ignition type		Suspect deflagration	Suspect deflagration	Suspect deflagration	Suspect deflagration	Suspect detonation*

Table 12: Additional qualitative observations (additional metal pans were placed in the sink cupboard for this ignition)*

6.3.6 Exposure of pig carcasses

For ignitions 4 and 5, pig carcasses were positioned in the FIB to see whether there were as any differences in damage caused during a methane or hydrogen explosion.

- Pig A was exposed in the ~64kW hydrogen ignition (ignition 4)
- Pig B was exposed in the ~64kW methane ignition (ignition 5)

Following exposure, the carcasses were sent for post-mortem examination at the Department of Veterinary Medicine at the University of Cambridge. A detailed report is attached in Appendix J.

The results of the examinations showed that both pigs had only superficial damage, and that there was very little difference between each pig. This is despite the suspected detonation in ignition 4. The pigs had been scalded after slaughtering to remove hairs, so it was not possible to deduce if the ignition would have burnt the skin.

6.4 Stage 3: Ignition of stoichiometric hydrogen

The ignitions in Stage 2 did not include one at stoichiometric concentrations of hydrogen in the room. In Stage 3, one further ignition of ~30% hydrogen was carried out. Measurements were made as in Stage 2, with the exception of pressure measurements (as the equipment was damaged by the ignition itself).

The results of the work are summarised below. More detailed descriptions of damage are provided in Appendix F and photographs are provided in Appendix H. Slow motion videos of the ignition tests and a full photo library accompany this report. A description of the ignition carried out and the gas concentration at the ignitor before ignition is shown in Table 13.

Fuel gas injected		H_2
Ignition Number		6
Nominal gas injection rate	kW	~100
Gas concentration at ignitor (mid-level)	%	30.3

Table 13: Stoichiometric hydrogen ignition

The FIB suffered severe damage in the ignition and the sides of the metal container were blown apart (Figure 26). Debris was spread over a wide area, with window fragments found up to 70m away and door fragments 25-30m away. The metal shutters of the FIB were also thrown around 25-30m, some of which damaged the tarmac of the test area in the process.

Inside the FIB there was also severe damage. All the furniture was destroyed, and the metal sink was misshapen. The dummies were knocked to the floor and covered in debris (Figure 27).

Figure 20: View of end wall of FIB after ignition 6 (100kW hydrogen)
The FIB's metal doors have been torn apart from FIB frame during the explosion.
Debris from inside FIB is visible on the ground outside.

Figure 21: Close up of damage inside FIB showing collapsed ceiling, walls and floor, and 30kg dummy and broken chairs

The bang from the ignition was heard very loudly around 1km away from the FIB and there were complaints from properties on the edge of the town surrounding the testing area. From the high speed video recording, it appears there were two ignitions and it is suspected the hydrogen in the FIB transitioned to a detonation explosion.

Four points are noted:

- A gas injection rate of over 100kW to was required in a fairly well sealed room of $30m^3$ to obtain a 30% concentration of hydrogen at the ignitor. This is a very high injection rate (see Table 4).
- The energy content in either methane at 10% or hydrogen at 30% are approximately equal. The TNT equivalent[2] of the FIB at these concentrations would be about 3kg, which is very modest compared to most munitions.
- Whilst undoubtedly the ignitions of hydrogen were more destructive within and immediately around the room, the overpressure from an explosion falls with the cube of the distance from the explosion. Thus, at medium and large distances the overpressure damage is likely to be similar to that of methane (although there would still be flying debris which again may be more serious in the case of hydrogen).
- Despite the severe damage that the metal container suffered, a domestic property constructed from brick may well have behaved differently. The brickwork would have failed at a lower pressure than the steel and therefore the overall overpressure could have been lower. It is therefore believed this is a worst-case scenario in terms of overpressure. This subject is further analysed in Phase 3 [27].

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[2] At 10% destructive yield (N.B. calculations of TNT equivalent always contain gross assumptions).

7 Conclusions and recommendations

At injection rates below 64kW, the average hydrogen concentration in the room was around 1.7 times that of methane for the equivalent kW injection rate. Methane was well-mixed with the bulk air of the room, at all external wind speeds, however hydrogen was stratified at low external wind speeds and only well-mixed at high external wind speeds. The stratification was most notable at the lowest external windspeeds, when the concentration at the top of the room was around 1.7 times the room average and there was almost no hydrogen at floor level. These findings are broadly consistent with the results of the HyHouse project [5].

Injection rates of approximately 18kW (39 l/min) for methane, and 14kW (70 l/min) for hydrogen were required to reach the LEL of fuel gases at the ignitor, which was at light switch level (in the upper half of the room). At high injection rates of around 64kW, the gas concentration at the ignitor was at most 10% (for methane) and 20% (for hydrogen). This is the upper limit of any conceivable domestic use, being equivalent to around six hob rings, two ovens, two fires and a combi boiler at hire fire (see Table 4).

At very high (above 64kW), large volumes of hydrogen were injected into the FIB. It is thought this led to a slight pressurisation effect, which would have reduced the amount of dilution air entering the FIB. This would have led to higher equilibrium concentrations of hydrogen gas in the FIB for a given injection rate. A house will be much larger than the FIB and have a higher overall ventilation rate, so it might be expected that this pressurisation effect could be neglected. However, in the cases where doors between rooms are closed (and especially if those doors form a good seal) there may be a localised pressurisation effect for gas escapes at 64kW and above.

In the ignitions of methane and hydrogen in Stage 2, the primary mechanism for pressure relief in the explosions was through the windows and in some cases through the door. In some cases, the sink cupboard was still intact after the ignition and concentrations of fuel gas around or above the LEL remained inside. This is of relevance to emergency services personnel who may encounter such situations even after an explosion.

The time taken to reach peak pressure was much lower for the hydrogen ignitions and the entire duration of the overpressure was generally shorter than the methane ignitions. To fully consider the damage done by an overpressure, the speed **and** duration of the overpressure should be taken into account.

In ignitions 1, 2, 3 and 5, the overpressures were modest and only resulted in broken windows / glass, minor structural damage. The probability of death to occupants would have been low and injuries were more likely to be caused by flying debris and possibly heat. However, in ignition 4 (hydrogen 20%) the peak overpressures were much larger than the other ignitions. It is likely there would have been significant damage to brickwork, and occupants of the house would probably have been severely injured.

Based on the damage observed in ignition 4, it is believed that hydrogen transitioned from deflagration to detonation. The higher flame speeds in a detonation do not allow enough time for pressure relief and therefore resulted in much higher overpressures. Ignition 6 (stoichiometric - hydrogen 30%) was severely damaging and represents the worst case scenario in terms of overpressure, with little pressure relief.

Key recommendation: The greatest damage was done with hydrogen escapes at or above 64kW, which led to accumulations of hydrogen above 10% (room average) and around 20% (at ignitor level). Such flow rates are greater than the upper limit of any conceivable domestic gas use. It is therefore recommended that domestic houses converted to hydrogen should be fitted with a 64kW excess flow valve at the meter that would automatically switch off the gas should the flow rate exceed this level.

This could also be included within the technology of intelligent meters, allowing for further safety checks in the meter, for example:

- up to three manual resets could be allowed before the gas supply company would be required to reactivate the supply,
- regular gas tightness checks using daily periods of no-flow,

- use of wireless link to shut off gas if a hydrogen detector mounted (e.g.) at top of stairs detected hydrogen at high ppm levels, or
- an automatic call out if the hydrogen concentration continued to rise substantially for more than (e.g.) 15 minutes.

Recommended further work: It is recommended that the feasibility of such a hydrogen detector is investigated, in addition to the risk posed by low-level escapes inside confined spaces such as cupboards and meter boxes. Further investigation is also required to support emergency services personnel responding to house fires, to determine whether existing pipe fitting methods are suitably heat resistant, or whether escapes similar to those investigated in this project will arise.

This will enable on-site actions for emergency personnel to be reviewed. Differences between methane and hydrogen may mean that the procedure for approaching a suspected gas escape safely may need to be revised, including the concentrations at which approach is considered safe or unsafe.

This project and other studies have noted that in computer simulations of both gas concentration and explosion overpressure, the models are very sensitive to the input parameters. This means that small changes to the input parameters can result in large variation in the predictions, which emphasises the importance of practical measurement work and not just modelling alone.

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Appendices

Appendix A: Risk assessment

General				
Number	**Hazard or Critical Issue**	**Possible Consequence**	**Existing Safeguards**	**Reducing Risk**
1	Thunderstorm during gas injection causes unscheduled explosion	Unexpected explosion, people and / or equipment too close to FIB, possible damage or injury	Exclusion zone around FIB during gas injection Instruction to stop gas injection during thunderstorms	
2	Cold or wet weather causes Slip and falls	Cuts, bruises, etc	Common Sense Footwear with suitable tread to be worn	
3	Hot, cold, or wet weather causes equipment malfunction	Unreliable test results	Lean-to to protect gas supply area Heater in control cabin Heaters on regulators	
4	Poor weather during installation or breakdown impacts health	Illness	Suitable PPE provided	
5	Electric shock during set up or breakdown	Injury	Only use qualified electrician Lock off electric supply during works Electrical systems protected by trip in consumer unit in Control Room	
6	Sound of explosion causes alarm to local population or livestock	Complaints	Notification of ignition times to be sent to FSC on day before	
7	Material in FIB (disturbed by explosion) hazardous to health, e.g. asbestos	Damage to health	No hazardous material present in FIB	FSC to clarify that no hazardous material present in FIB
8	Other incidents / injuries / problems eg first aid requirement, lone working, etc	Minor injuries	All staff go through site safety induction and have FSC Safety passport All staff sign in / out at gate List of phone numbers in Control Room Site radio Lone working not permitted, at least 2 staff (Kiwa or FSC) present at all times	Investigate need for permit to work

Site Activities				
Number	**Hazard or Critical Issue**	**Possible Consequence**	**Existing Safeguards**	**Reducing Risk**
9	Other activites on site put Kiwa staff or equipment at risk	Injury or equipment damage	Send daily operations plan to FSC	
			Approved escape/evacuation route in case of emergency (to be advised daily by FSC in case of other work nearby)	
10	Vehicles cause damage to equipment	Injury or equipment damage	Cone off area and prohibit vehicles	
			Daily visual inspection of pipes and connections	
			Weekly soundness check of sample lines	
11	Movement of gas cylinders (MCPs or individual cylinders) causes injury	Injury	Use forklifts etc (FSC will operate)	
			Manual handling training	
12	Unauthorised use of or tampering with equipment	Fire or other safety risk	The Fire Service College is a secure site	
			The equipment is in exclusion area	
			Equipment to be locked away if possible	

Explosion				
Number	**Hazard or Critical Issue**	**Possible Consequence**	**Existing Safeguards**	**Reducing Risk**
13	Staff cause unscheduled explosion (flying debris or pressure wave)	Injury or equipment damage	Check gas concentration with analysers before approaching; don't approach FIB with high concs (>20%LEL) Personal gas alarms Anti-static clothing Open FIB doors/windows from outside with waxed rope to ventilate and disperse gases in FIB Procedure for locking off gas and electric supply during work in FIB Pipework, cabling, data acquisition systems protected from shock	Investigate opening door and isolating gas remotely
14	Flying debris from planned explosion	Injury or equipment damage	Exclusion zone marked with flags during testwork Warning sound before ignition Pipework, cabling, data acquisition systems protected from shock particularly near the FIB	
15	Pressure wave from planned explosion	Injury or equipment damage to Control cabin (esp. window) or gas cylinders (e.g. knocks over)	Exclusion zone marked with flags during testwork Warning sound before ignition PPE especially ear protection Pipework, cabling, data acquisition systems protected from shock particularly near the FIB Doors/windows of FIB and control cabin oriented away from each other MCP cylinders sheltered behind control cabin Span gases secured in cage	
16	Staff approaching datalogger to perform reset procedure are in close proximity to FIB and at risk if there is unscheduled explosion	Injury	Check gas concentration with analysers before approaching; don't approach FIB with high concs (>20%LEL)	
17	Thermocouples in FIB cause unscheduled explosion	Injury or equipment damage		Needs further investigation

Fire				
Number	**Hazard or Critical Issue**	**Possible Consequence**	**Existing Safeguards**	**Reducing Risk**
18	Fire following gas explosion	Injury or equipment damage	Valve to isolate gas supply at Control Cabin Qualified fire fighters on standby to combat and extinguish any fire following explosions	
19	Large flammable gas release from gas supply pipe	Damage to gas supply pipe due to explosion or vehicle impact	Valve to isolate gas supply at Control Cabin Pipework, cabling, data acquisition systems protected from shock particularly near the FIB Qualified fire fighters on standby to combat and extinguish any fire following explosions	Investigate isolating gas pipe at FIB remotely
20	Flashback down sample pipes following explosion	Damage to sample pipes due to explosion or vehicle impact	Valves to isolate sample lines at Control Cabin Pipework, cabling, data acquisition systems protected from shock particularly near the FIB Qualified fire fighters on standby to combat and extinguish any fire following explosions	Investigate additional flashback arrestors
21	Fire in control cabin due to electrical fault	Injury or equipment damage	Only use qualified electrician Electrical systems protected by trip in consumer unit in Control Room	
22	Inappropriate transport of gases results in vehicle fire	Vehicle fire	Flammable gases transported by cylinder supply company Fuel gases transported by cylinder supply company; cylinders fastened securely	
23	Sampling lines or span gases leak inside control cabin	Fire risk	Span gas cylinders located outside Control Cabin Anaylsers and sampling lines vented outside Control Cabin Personal gas alarm in Control Cabin Training of staff in spanning procedures	

Appendix B: Method statement

Fire Service College: Explosion Testing Method Statement

Prepared by	Kiwa Ltd
Date	10th December 2017

Introduction

Kiwa have been contracted to carry out some experimental testwork to provide input data for a Quantified Risk Assessment on the relative severity of natural gas and hydrogen explosions in the home. The work will be carried out at the Fire Service College (FSC) due to the facilities and infrastructure available there.

The overall set up comprises:

- Portable Control Room (PCR)
- Gas injection system
- Gas supply
- Ignition system
- Detection equipment
- Data collection system
- Fire Investigation Box (FIB) supplied by the FSC

Pre-test visits

The testwork will be preceded by a series of pre-test visits to the FSC. During these visits Kiwa staff will:

1. Undertake a risk assessment for the proposed test work, to be reviewed at the start of each day of testing.
2. Determine whether the testing requirements can be met.
3. Formulate plans for the work to be carried out, including:
    a) Site for Fire Investigation Boxes
    b) Site for Portable Control Room (PCR) and associated equipment
    c) Electricity supply to PCR
    d) Gas supply, air sampling, and pressure sensor pipe and cable runs
    e) Exclusion zones to be observed before and during testing.
4. Explain to the site contacts the requirements for the test programme, with particular emphasis on the requirements during the explosion testing.
5. Check that all areas to which the monitoring staff will need access are safe provided that they adhere to the precautions identified in the risk assessment completed for the work.
6. Check access arrangements to ensure that the measurement equipment can be easily transported to and from the sampling locations.
7. Carry out air tightness checks on all the FIBs and seal joints etc to ensure that all FIBs can be considered to have similar levels of air tightness.

Installation

The procedures for installation of the equipment are detailed in a separate document “Hydrogen 100 Consequence testing for SGN: Procedures: Equipment and deployment”.

Test visits

Set-up

On arrival, Kiwa staff will notify the site contact and record their presence on site by signing in to the site at Reception.

Any necessary inductions will be taken by Kiwa staff. The site contact shall identify available staff facilities and explain any site emergency procedures to be followed in case of incidents, including injury or illness to staff. In the absence of specific procedures, as a minimum, a means of alerting the emergency services is required.

Kiwa staff will conform to site rules and regulations and will obtain any necessary permits to work.

Kiwa staff will re-evaluate their existing risk assessment (from the pre-visit) and if necessary update it. This will be repeated at the beginning of each day of work. The risk assessment will identify the required PPE to wear. As a minimum, Kiwa require staff to wear safety boots and high-vis clothing.

Test equipment will be set up tidily and in consultation with the site contact. As the test work spans multiple days, overnight storage for test equipment will be required and this will be inside the PCR.

Before test work commences, Kiwa staff will perform checks on the test equipment to ensure it is functioning correctly. Kiwa staff will brief any site personnel involved as to their required activities.

Testwork

Gas injection tests

The gas analysis equipment requires an extended period for warm-up and calibration – usually around 2 hours. During this period, Kiwa staff will liaise with the FSC staff to check the timetable for that day's testing and other planned activities near to the test ground.

Gas will be injected into the FIB using the gas pressure and flow regulation equipment at the PCR. The air inside the FIB will be continuously sampled and analysed using the gas analysers in the PCR. Data will be recorded throughout the whole test period from the start of gas injection to the concentrations falling to background levels. Once the gas flow rates required by the test programme have been set, Kiwa staff will monitor the concentrations of flammable gas inside the FIB. Once these concentrations have stabilised, ie the system has reached steady state, gas injection will be stopped and the gas supply pipe will be manually isolated at the PCR. Kiwa staff will monitor the concentrations of flammable gas inside the FIB, until it falls to close to background levels. When all concentrations have fallen to below the LEL, the FIB can be ventilated by opening the door and windows.

Typically, there will be several different test periods throughout the day, each of 2 to 3 hours duration. At the end of each day Kiwa staff will record the time of their departure from site by notifying the site contact and signing out on the entry log.

Explosion tests

FSC fire fighting staff will be on standby throughout the explosion testing. Kiwa and FSC staff will liaise to ensure that the exclusion zone around the FIB is respected.

The explosion tests will follow the same pattern as the gas injection tests. Gas will be injected into the FIB using the gas pressure and flow regulation equipment at the PCR. The air inside the FIB will be continuously sampled and analysed using the gas analysers in the PCR. Data (including gas concentrations, pressures and temperatures inside the FIB and site weather conditions) will be recorded throughout the whole test period from the start of gas injection to the concentrations falling to background levels. Once the gas flow rates required by the test programme have been set, Kiwa staff will monitor the concentrations of flammable gas inside the FIB. Once these concentrations have stabilised, ie the system has reached steady state, gas injection will be stopped and the gas supply pipe will be manually isolated at the PCR. High speed video recording will be started and Kiwa staff will then actuate the ignition system.

If an explosion occurs, the situation will be monitored and any fire will be extinguished by FSC fire fighting staff.

If explosion does not occur, Kiwa staff will monitor the concentrations of flammable gas inside the FIB, until it falls to close to background levels. When all concentrations have fallen to below the LEL, the FIB can be ventilated by opening the door and windows.

The FIB will then be prepared for the next test.

Typically, only one explosion will be carried out on each testing day.

System shutdown

At the end of each testing day, the equipment will be shut down and packed away. Gas analysers and heaters in the PCR will be left operating overnight.

Kiwa staff will meet with the site contact to sign out of the site and return any permits to work, site passes, etc.

Breakdown

At the end of the testing, the equipment will be shut down, packed away and removed.

The areas where Kiwa staff have worked will be checked to ensure that they are clear of equipment and materials brought by them. Kiwa staff will meet with the site contact to sign out of the site and return any permits to work, site passes, etc.

Appendix C: Rationale for exclusion zone

Rational for Exclusion Zone Distance at Fire Service College

Prepared by	Kiwa Ltd
Date	11th December 2017

Approach 1 - TNT equivalent

Vol room	33
%	30%
Density	0.084
CV	141000
kJ	117255.6
Yield	10%
kJ	11726
kg TNT	2.8

Notes

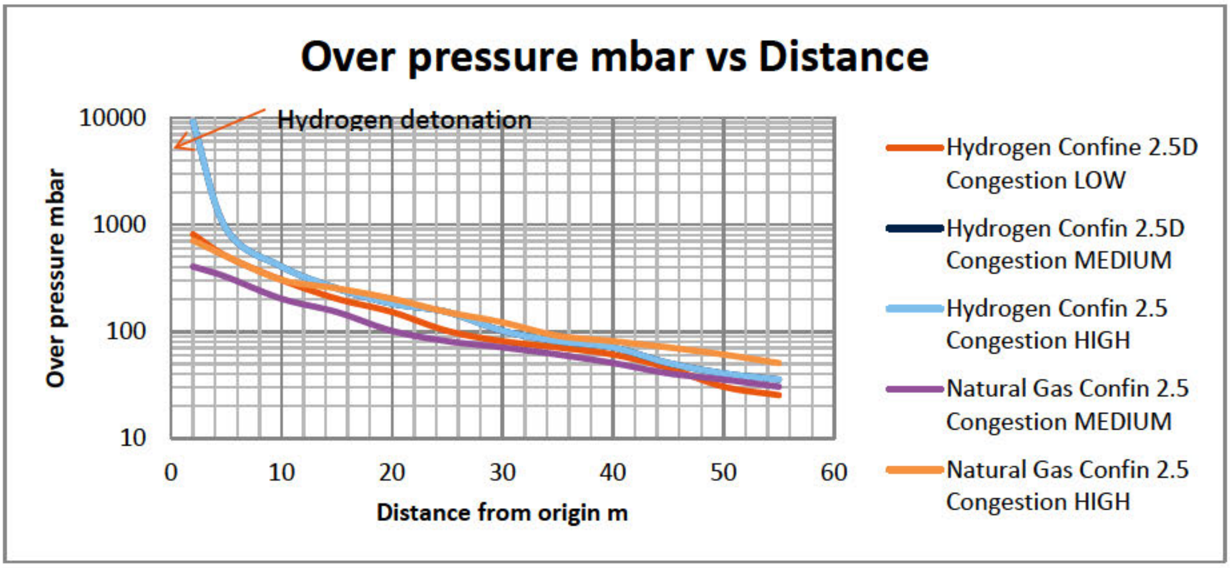
- The 10% is high. 5% is more normal
- Extremely unlikely to be 30% average. Concentrations at floor level known to be low.

Table 1 Hazard Type 1 explosive in a brick-built mounded store

	Distance in metres to protected works and/or buildings of							
Quantity of explosives (kg)	**Class A** Footpath, lightly used road	**Class B** Minor road, railway	**Class C** Major road, place of public resort	**Class D** Buildings	**Class E** Vulnerable building	**Class F** On-site buildings	**Class G** On-site stores	**Class H** On-site manufacture & processing
0.1–25	33	50	100	100	100	50	9	18

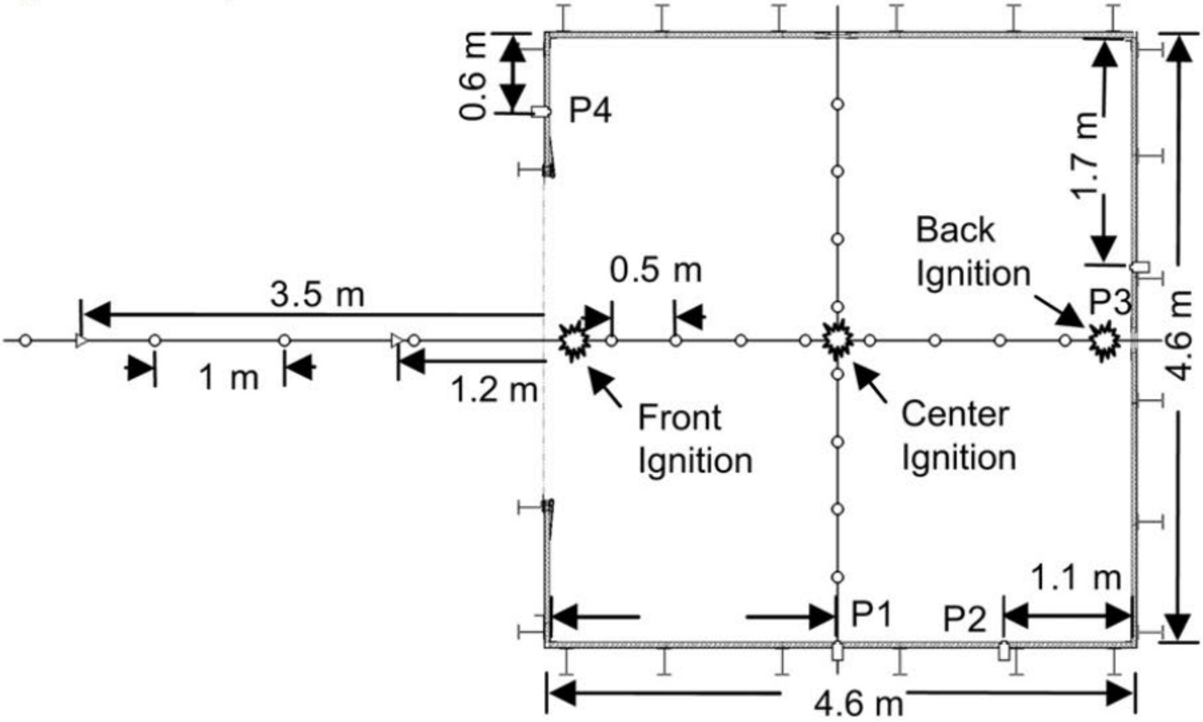
From above 50m is adequate. 100m is twice this.

Approach 2 - BST curve



The pressures shown above (ie 2-5kPa) at 50m are less than any of the injury pressures shown below. (ie 6.9 to 8kPa). By 100m the risk will be even less.

Approach 3 - Extrapolation of US data 63m^3 box with window



Pressure sensor located at P1 ie within the chamber Note units are kPa.

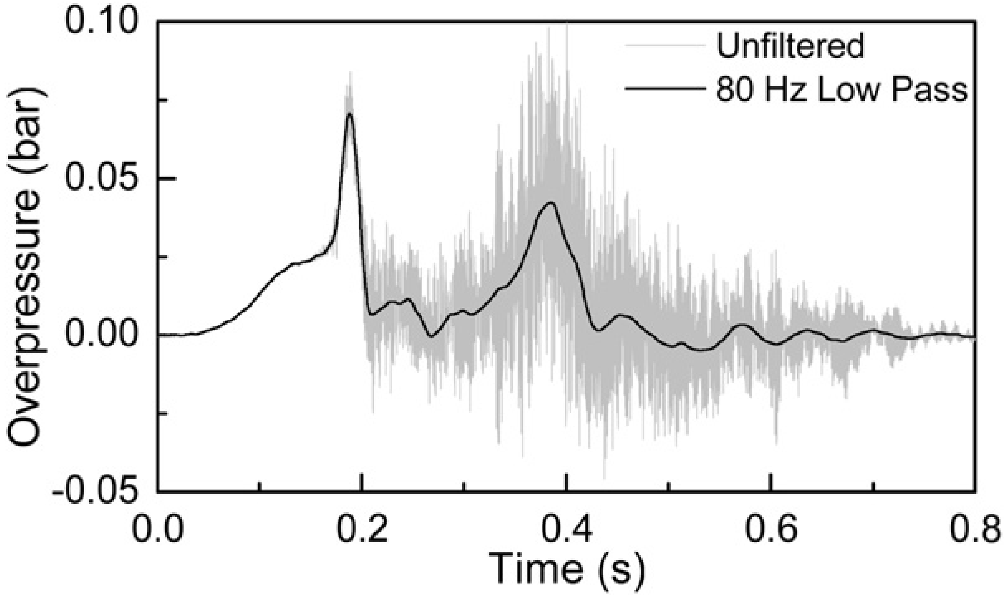


Fig. 3 e Filtered and unfiltered pressure time history for an
18% hydrogen-air mixture ignited with central ignition
and a 5.4m2 vent.

Over-pressure (kPa)	**Physiological Response**
6.9 – 8	Minor injuries to people in the open.
10 – 21	Serious injuries to people inside, with some fatalities.
30	Increased risk of fatality inside.
34 – 105	Ear drums rupture, potential limitation on evacuation.
54	Fatal head injuries occur.
560	Severe lung damage occurs.
910	50% mortality rate inside, 15% in the open.
1400	100% mortality rate inside.

Being within the FIB would be highly likely to be injurious to health.
The pressures observed very close to the source, ie within the box were about 10% of those calculated by the BST curve. This is not unexpected.

Approach 4 - Extrapolation from US garage tests

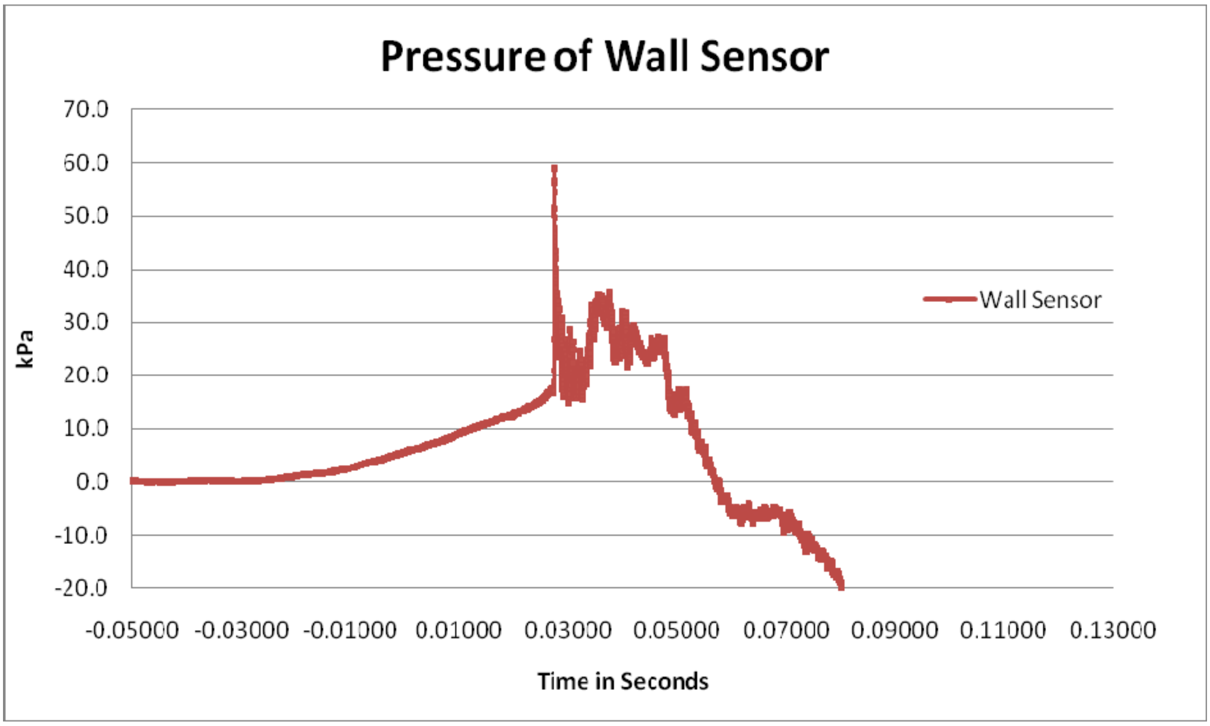


Figure 27. Pressure Sensor Results for the Wall PT for Test # 10/1/09, 28.8 %-1.

Again furthest object was thrown 43m. Staff will be at 100m and inside control cabin.

Conclusion
No evidence of significant hazard beyond 50m

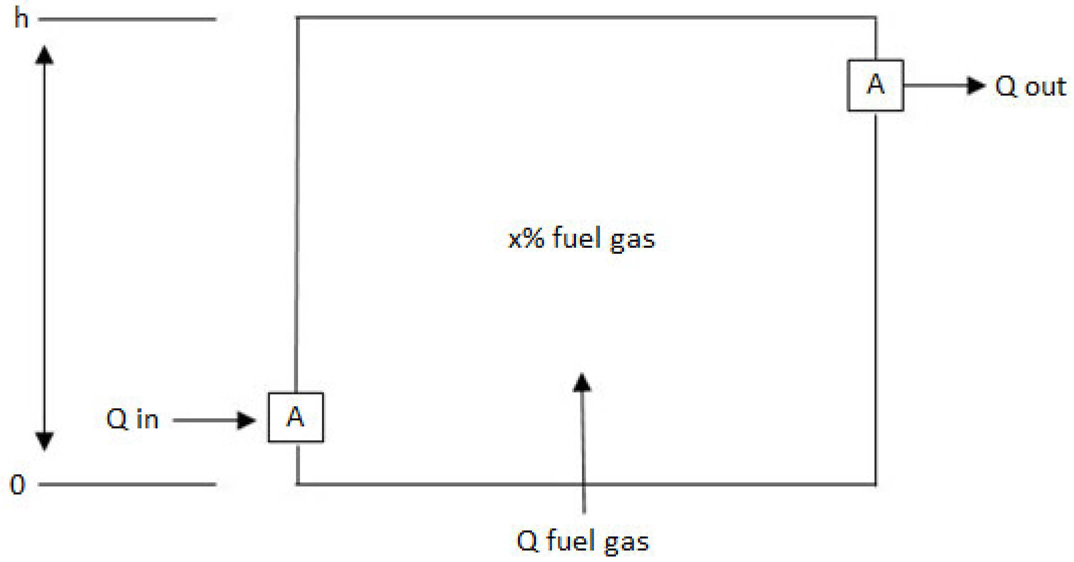
Recommendation
Make exclusion zone radius 100m.

Appendix D: Buoyancy model for equilibrium gas concentration

To allow comparison between theoretical and actual results, a density (buoyancy) model was used to estimate the concentrations that would be achieved within the FIB.

This theory used a simple vented box (as shown below) with known vent sizes to calculate the concentrations that would remain within the space during fuel gas injection. The vent sizes were chosen to be consistent with the ait tightness testing results.

The model assumes the gas within the space is well mixed and at steady state.

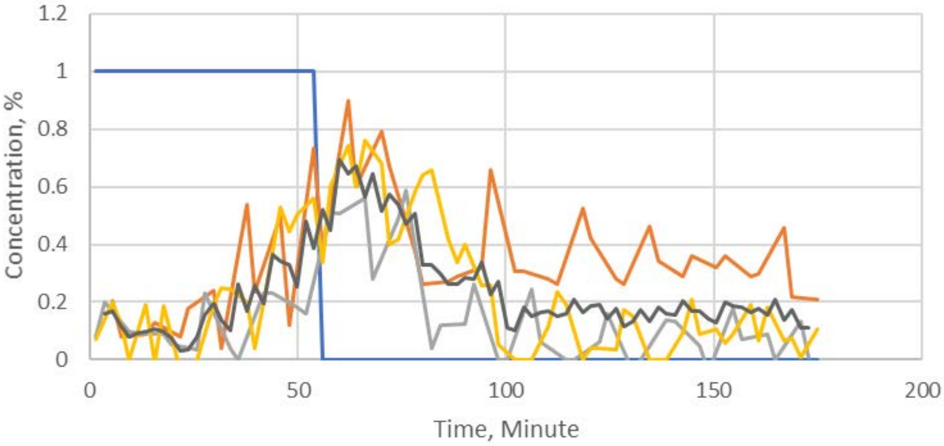


The model uses the following steps:

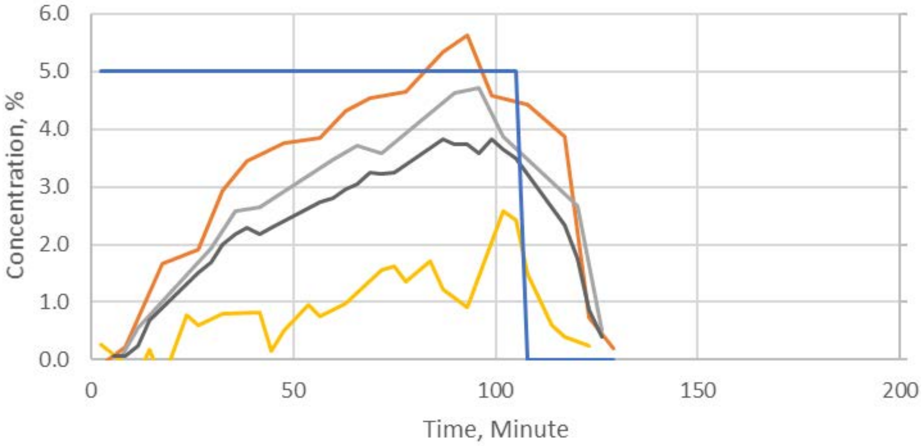
1. An initial concentration of fuel gas (x%) is chosen.
2. The density of the air gas mixture inside the box is calculated.
3. Assuming a linear decrease in air pressure with increasing height (h), the difference in pressure between the inside and outside at the top of the box can be calculated.
4. The pressure difference, vent area and chosen fuel gas concentration are used to calculate the velocities and flow rates of the air in (Q in), and air/gas out of the box (Q out).
5. The flow rates are used to estimate a new % fuel gas concentration within the box and the disagreement of the original chosen fuel gas concentration is calculated.
6. The model then varies the initial fuel gas concentration chosen until the disagreement is minimised.
7. This figure is the % concentration assumed within the box at steady state.

Appendix E: Development of equilibrium gas concentrations

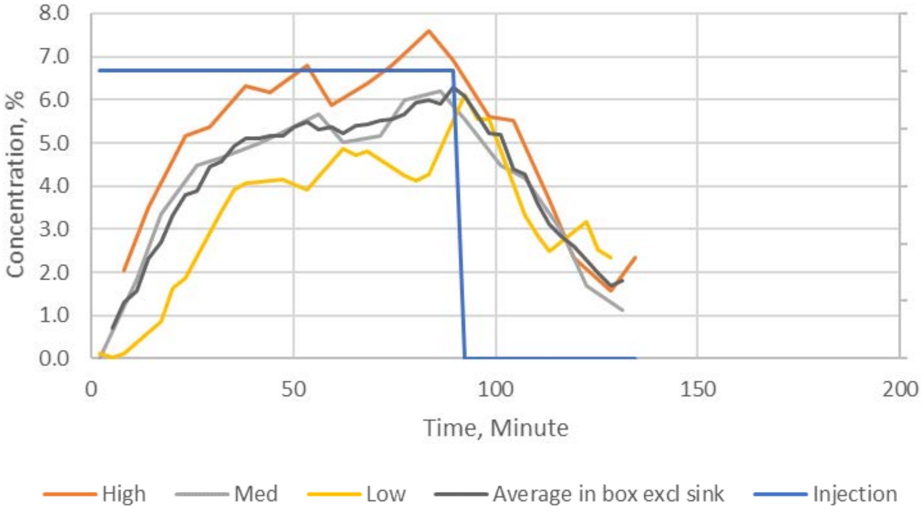
CH_4 injection, ~4kW



CH_4 injection, ~17kW

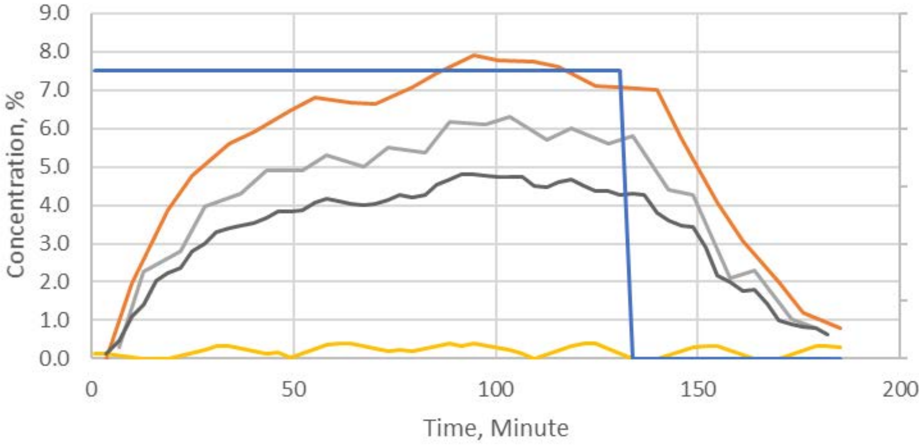


CH_4 Injection, ~62kW



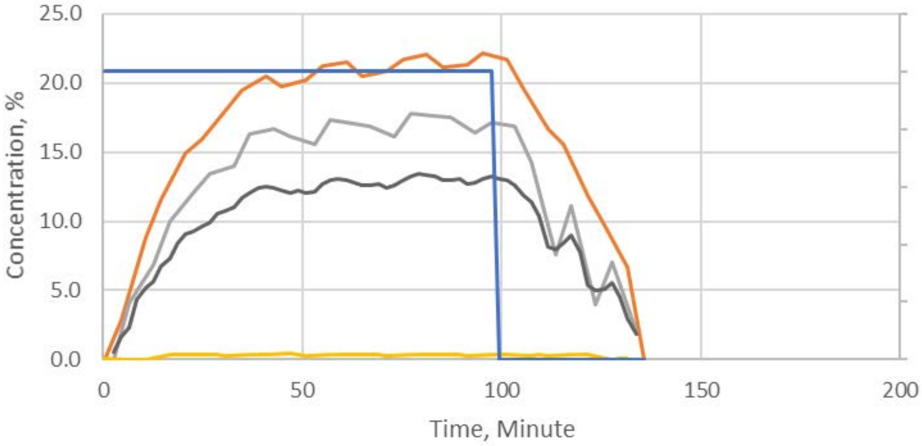
H_2 injection, ~15kW

(equivalent to a similar escape of ~16kW methane)



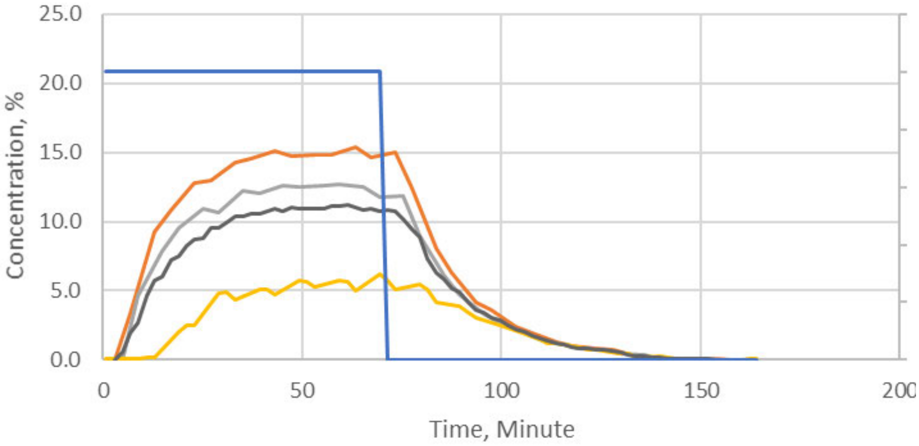
H_2 Injection, ~59kW

(equivalent to a similar escape of ~64kW methane)



H_2 Injection, ~56kW repeat at higher windspeed

(equivalent to a similar escape of ~61kW methane)



Appendix F: Damage after ignitions

Ignition 1

Conditions

- FIB 1
- 16 January 2018
- CH_4 – 5.5% near ignitor, 63% under sink
- ~16kW

Damage seen

- West window blown open debris thrown up to 10m
- East window blown open debris thrown up to 10m
- North window intact
- Door intact
- Foam around windows caught fire but then extinguished on its own
- Newspapers caught fire, extinguished by Fire Crew
- Cabinet intact, gas detector showed gas inside
- Dummies still in place on chairs
- Crockery intact
- Ignitor in position, slightly melted on top / front
- Pressure transducers in position

Ignition 2

Conditions

- FIB 2
- 18 January 2018
- H_2 – 9% near ignitor, 86% under sink
- ~16kW

Damage seen

- West window intact
- East window blown open debris thrown up to 10m
- North window intact
- Door blown open but still attached to frame
- Foam around windows scorched but then extinguished on its own
- Newspapers caught fire, extinguished by Fire Crew
- Cabinet blown apart
- Dummies still in place on chairs
- Crockery intact, apart from plates dislodged which broke on floor
- Ignitor in position, no further melting
- Pressure transducers and gas sample lines in position
- Appeared to be a double ignition:
    - First gas in FIB ignited, approximately 2s delay
    - Then gas in cabinet – causing damage to cabinet, and audible bang

Ignition 3

Conditions

- FIB 3
- 22 January 2018
- H_2 – 17% near ignitor, 75% under sink
- ~64kW

Damage seen

- West window blown out debris thrown up to 20m
- East window blown out debris thrown up to 20m
- North window blown out debris thrown up to 20m
- Door blown off hinges debris thrown 5m, door openers destroyed
- Plasterboard pushed outwards at low level
- Foam around windows scorched but then extinguished on its own
- Newspapers caught fire, extinguished by Fire Crew
- Cabinet blown apart, worse damage than ignition 2
- Dummies still in place on chairs
- Crockery intact, apart from plates dislodged which broke on floor
- Ignitor blown off wall, no further melting
- Pressure transducers and gas sample lines in position
- Appeared to be a double ignition:
    - First gas in FIB ignited, approximately 0.1s delay
    - Then gas in cabinet – causing damage to cabinet, and very audible bang (heard in reception and offices ~700m away)

Ignition 4

Conditions

- FIB 4
- 24 January 2018
- H_2 – 21% near ignitor, 90% under sink
- ~64W

Damage seen

- West window blown out debris thrown up to 40m
- East window blown out debris thrown up to 40m
- North window blown out debris thrown up to 40m
- Door blown off hinges debris thrown 25m
- Foam around windows scorched but then extinguished on its own
- Newspapers slightly singed
- Cabinet blown apart, worse damage than ignition 3
- Dummies still in place on chairs, chairs moved
- Pig still in place, slightly scorched
- Crockery intact, apart from plates dislodged which broke on floor
- Ignitor blown off wall, no further melting

- Pressure transducers and gas sample lines in position, except for under sink which had all come apart.
- FIB distorted - bowed out on both sides, split welds at bottom on W side, and split on S side W corner.
- From video, appeared to be a double ignition:
    - First gas in FIB ignited, very short delay
    - Then gas in cabinet – causing damage to cabinet, and very audible bang (heard in reception and offices ~1000m away). Louder bang than Ignition 3.
    - Consensus that this was a detonation, all others were deflagrations.

Ignition 5

Conditions

- FIB 2R
- 26 January 2018
- CH_4 – 9.8% near ignitor, 45% under sink
- ~64kW

Damage seen

- West window blown out debris thrown up to 15m
- East window blown out debris thrown up to 15m
- North window blown out debris thrown up to 15m
- Door blown off hinges debris thrown 2m
- Ceiling plasterboard collapsed
- Foam around windows scorched but then extinguished on its own
- Newspapers caught fire, extinguished by Fire Crew
- Cabinet intact
- Dummies still in place on chairs, chairs moved
- Pig still in place, slightly scorched
- Crockery intact, no plates dislodged
- Ignitor blown off wall, some further melting
- Pressure transducers and gas sample lines in position
- FIB metal body intact
- Audible bang, louder than ignition 1, about the same as ignition 2
- From video, appeared to be a single ignition

Ignition 6

Conditions

- FIB 1R
- 30 January 2018
- H_2 – 30% near ignitor, 85% under sink
- ~100kW

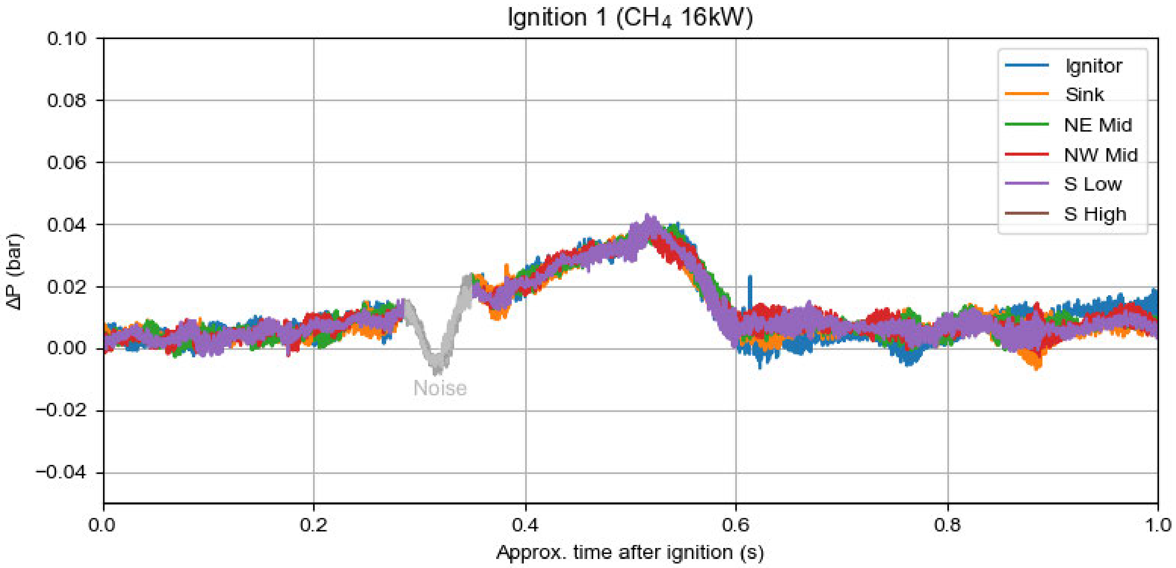
Damage seen

- West window blown out debris thrown up to 70m
- East window blown out debris thrown up to 40m

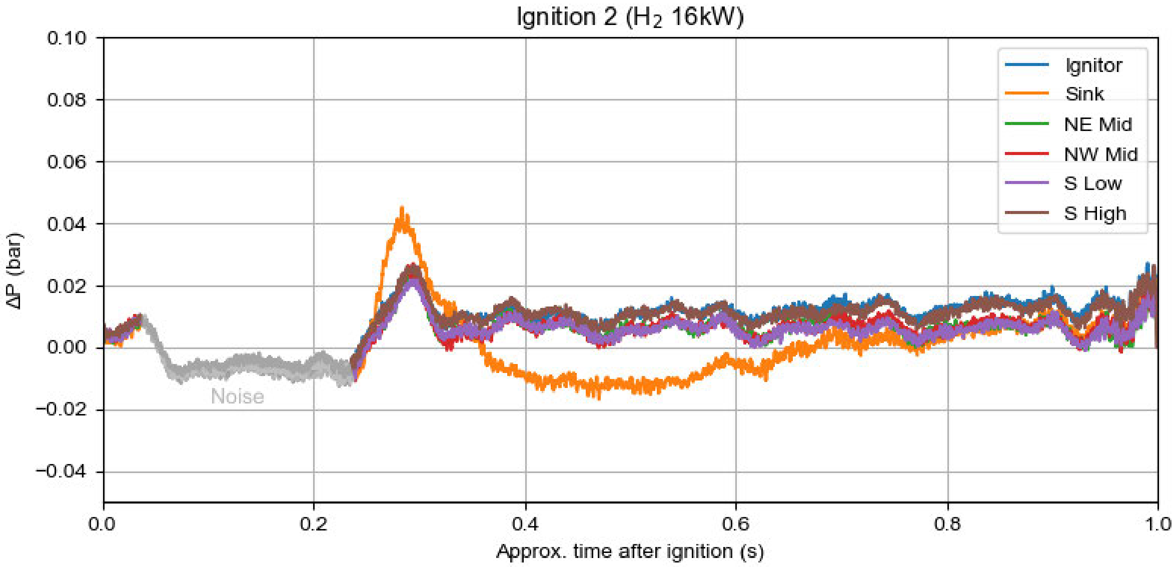
- North window blown out debris thrown up to 70m
- Door blown off debris thrown 25m+
- Foam around windows scorched but then extinguished on its own
- Newspapers burned
- Cabinet blown apart, worse damage than ignition 4
- Dummies knocked to floor, chairs moved, chair backs separated from supports
- Plates broken, several plates dislodged which broke on floor
- Ignitor blown off wall, casing smashed
- Pressure transducers and gas sample lines in position, but the stands had moved, under sink had all come apart.
- FIB distorted and significantly damaged --bowed out on both sides, floor blown out, foof blown off. Split welds on both E and W side, and split on W, S and E. End doors (S side) blown off – one door thrown25m
- From video, appeared to be a double ignition:
    - First gas in FIB ignited, very short delay
    - Then gas in cabinet – causing damage to cabinet, and very audible bang (heard in reception and offices ~1000m away). Louder bang than Ignition 4.Several complaints from local neighbours.
    - Consensus that this (and 4) was a detonation, all others were deflagrations.

Appendix G: Pressure measurements during ignitions

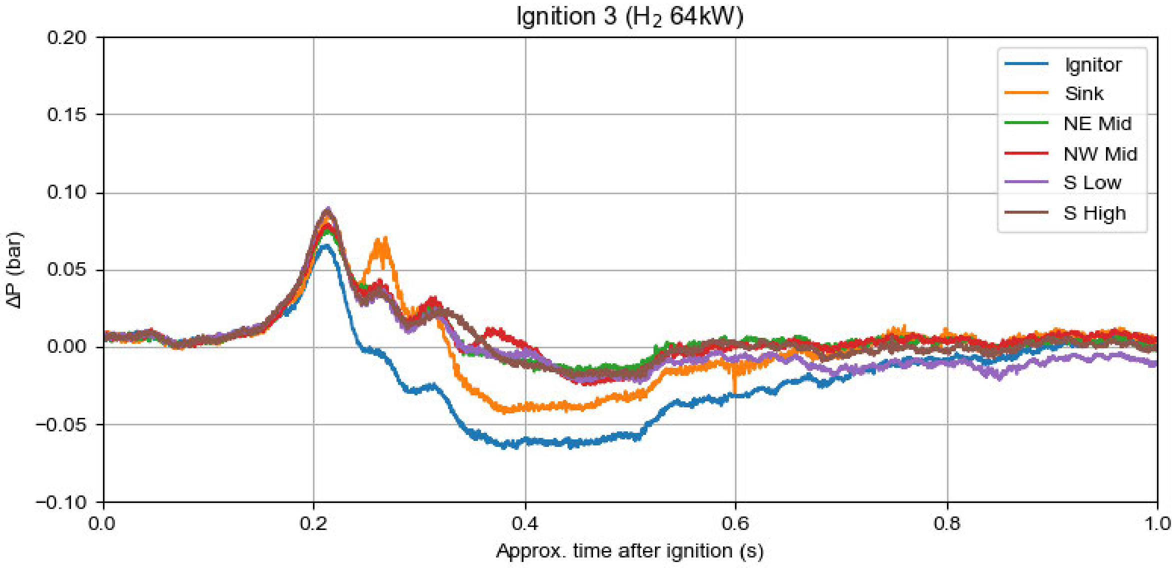
Ignition 1



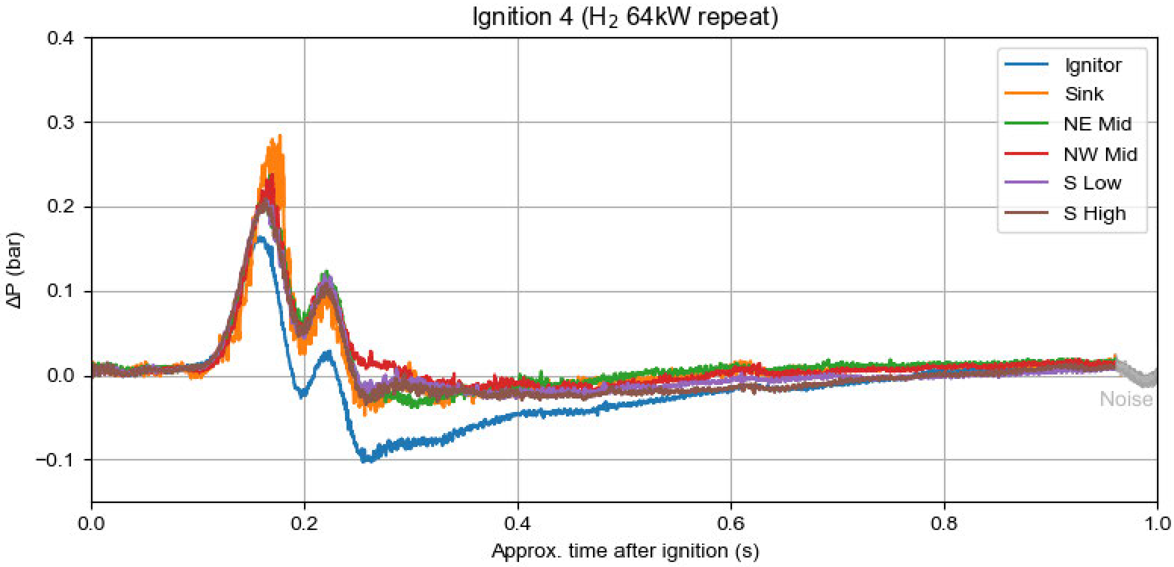
Ignition 2



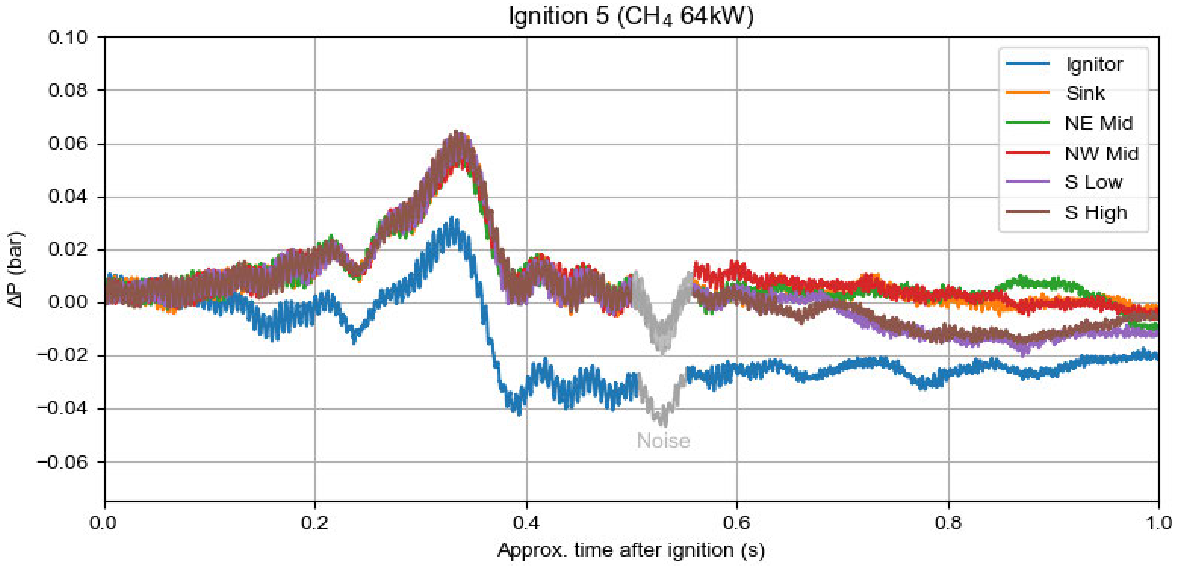
Ignition 3



Ignition 4



Ignition 5


Ignition 5 (CH_4 64kW)
ΔP (bar)
0.10
0.08
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
0.0
0.2
0.4
0.6
0.8
1.0
Approx. time after ignition (s)
Ignitor
Sink
NE Mid
NW Mid
S Low
S High
Noise

Appendix H: Photographs

Before ignition

Figure 22: FIB in situ on runway (before ignition)

Figure 23: Door to FIB – Left: view from outside showing closing mechanism; Right: view through door showing 30 kg dummy

Figure 24: View inside looking out of open door, showing ignitor at light switch-height and 3x pressure sensors secured to the floor – one at light switch and two (low/high) next to door

Figure 25: View inside from doorway, showing sink (closed, ready for ignition), table with assorted items and 30 kg dummy. One pressure sensor (next to light switch) in foreground and two pressure sensors in background (left/right of far window)

Figure 26: Close-up of cupboard, showing plates on top and plates inside. Gas injection point and pressure sensor are mounted at mid-height in the cupboard (in later the two final H_2 tests, additional saucepans were placed in the cupboard)

After ignition 1 (6.5% CH_4 at ignitor)

Figure 27: Outside view of FIB showing window above sink with detached frame and glass fallen out. Flames from newspaper on fire on table top just visible through window

Figure 28: Side window at table end of FIB, showing furthest distance to glass fragment. Remaining glass fell out of frame and smashed on ground

Figure 29: Inside view of FIB showing newspapers on fire on table top. Scorch marks visible around windows are from non-fire retardant insulating foam

Figure 30: Close-up of books and newspapers on table top

Ignition 1 - CH4 16kW
2018-01-16

Figure 31: View of sink (undamaged) and blown out window frame

After ignition 2 (9.0% H_2 at ignitor)

Figure 32: Outside view of FIB showing window above sink (undamaged but with condensation). Flames from newspaper on fire on table top just visible through window

Figure 33: View of door with broken frame (but not completely blown out) and broken frame of side window

Figure 34: Inside view showing newspaper on fire and damaged sink cupboard

Figure 35: Close-up of sink damage (crockery was only damaged by landing on floor after collapse of cupboard and not by ignition itself)

After ignition 3 (17.8% H_2 at ignitor)

Figure 36: View of sink window showing blown out glass in both windows

Figure 37: View of blown out door and side window frame (door was restricted from moving any further due to door opening mechanism)

Figure 38: View through blown out end windows showing newspapers on table top

Figure 39: Inside view through doorway, showing blown out sink window and damage to sink cupboard (crockery was only damaged by landing on floor after collapse of cupboard and not by ignition itself)

Figure 40: View of blown out sink window frame, approx. 10m from FIB

Figure 41: Damaged plasterboard at floor-level (approx. 30cm from ground and 2m long), indicating some pressure-relief was through the walls

After ignition 4 (20.1% H_2 at ignitor)

Figure 42: View of blown out sink window showing damage to FIB wall near sink cupboard

Figure 43: Side view of damaged FIB wall and damage to paint at bottom of end wall (caused by pressure-relief)

Figure 44: Close-up of damage to FIB wall showing 10-20cm gap in weld

Figure 45: Close-up of damaged sink cupboard and damage to FIB wall

Figure 46: Outside view of damage to FIB shape on opposite side to sink cupboard, also showing blown out window

Figure 47: Blown out door approx. 25m from doorway

After ignition 5 (9.8% CH_4 at ignitor)

Figure 48: View of sink window showing no damage

Figure 49: Blown out door and door surround (foreground)

Figure 50: Internal view of FIB showing collapsed ceiling

Figure 51: Collapsed ceiling in pig carcass

Figure 52: View of lit newspaper underneath damaged ceiling. Sink cupboard is in tact and gas inside did not ignite

Figure 53: View of door/window frame debris approx. 15m from FIB

After ignition 6 (30.3% H_2 at ignitor)

Figure 54: Wide view of severely damaged FIB and extent of debris on runway (approx. 25m in both directions)

Figure 55: View of end wall of FIB (doors have been torn apart from FIB frame during explosion). Debris from inside FIB visible on the ground outside, including pressure measurement stand (centre)

Figure 56: Close up of damage inside FIB showing collapsed ceiling, walls and floor, and 30kg dummy and broken chairs

Figure 57: Door debris approx. 30m from FIB

Figure 58: Window frame debris (background) and FIB debris (foreground) approx. 40-50m from FIB

Figure 59: Damage to tarmac approx. 10m from end wall of FIB

Appendix I: Direct blast effects

Table 14 shows the damage caused to buildings and occupants by various overpressures.

Damage caused to	Peak pressure (mbar)	Description of damage
Windows	35-70	Windows shatter
House structure	50	Minor damage to houses
	70	Houses uninhabitable
	140	Partial collapse of walls and roofs of houses
	170	50% brickwork destruction
	350	Collapse of most houses
Occupants	70	Slight injuries due to flying glass and fragments
	200	Many seriously injured and some killed
	250	Most seriously injured and many killed
	700	Most killed

Table 14: Reference overpressures and associated damage caused [23, 24, 25, 26]

The damage caused by an overpressure also depends on the duration of the overall event, i.e. large overpressures – if short in duration – can effectively pass by a person without there being time to cause severe injury as the impulse is small (Figure 60).

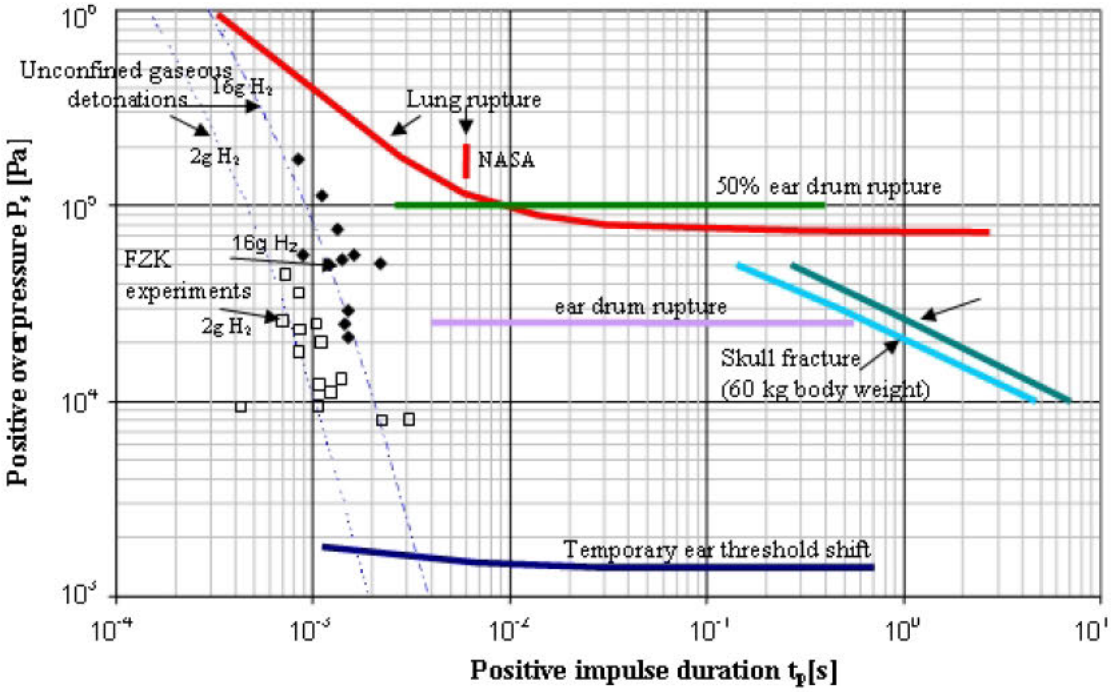


Figure 60: Damage caused by various durations of positive overpressure [19, 20, 21, 22]

Appendix J: Assessment of damage to pigs

Prof. [redacted]
Pathology

UNIVERSITY OF
CAMBRIDGE

Department of
Veterinary Medicine

[redacted]
Kiwa Gastec

28th March, 2018

Report on pathology inspection of two pig carcasses

Two pig carcasses were presented for examination. The pigs had been obtained from an abattoir and so had been bled out, scalded (to remove hair) and eviscerated. The pig carcasses were examined for evidence of pathology of skin, underlying fat and muscle, bones and joints.

Pig 1 (KIWA A): No blast-related lesions were detected of the skin surface. An area of mild subcutaneous and muscle oedema was present over the lateral aspect of the right shoulder (Fig. 1) and right stifle joint. These were interpreted as resulting from the carcass lying in lateral recumbency, right side down (rather than suspended from a hook). No other lesions were detected in limb, flank, paravertebral or head muscles. All limb bones, ribs and vertebrae were intact.

Fig 1.

Pig 1: oedema over right shoulder

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Fax: [redacted]
E-mail: [redacted]@cam.ac.uk

Pig 2 (KIWA B): The findings were broadly similar to those of pig 1; additional findings are given here.

A spattering of small (<1mm diameter) black particles was evident on the skin surface of the ventral abdomen, inner thighs (Fig 2) and right side of the neck/face. These were easily rubbed off and the underlying skin showed no scorch marking. These particles were interpreted as being carbon-based.

Fig 2.

Carbon particles on ventral abdomen and hindlimb

An area of skin of the ventral neck was (discoloured) (Fig. 3) and localized muscle at the incision made in the abattoir for evisceration was also discoloured (darker than expected). However but there was no pathology of deeper skin layers or of muscle tissue below the exposed muscle surface. This discoloration may be artefact (bleeding and bruising does not occur after death) or, in the case of the muscle, reflect exposure to heat.

Fig 3.

Discoloration of ventral neck skin of pig 2

As with pig 1, an area of mild subcutaneous and muscle oedema was present over the right shoulder and stifle. These were interpreted as related to the carcass lying in lateral recumbency (rather than suspended from a hook). No other lesions were detected in limb, flank, paravertebral or head muscles. All limb bones, ribs and vertebrae were intact.

Conclusion

Overall, with the exception of the (presumed) carbon particles mentioned above and possibly heat-related colour change of an exposed muscle surface, there were no significant lesions relating to gas explosions in either carcass.

[redacted]