Hy4Heat
demonstrating
hydrogen for heat

Department for
Business, Energy
& Industrial Strategy

## WORK PACKAGE 7

# Safety Assessment:
# Gas Ignition and Explosion Data Analysis

# WP7 SAFETY ASSESSMENT

The Hy4Heat Safety Assessment has focused on assessing the safe use of hydrogen gas in certain types of domestic properties and buildings. The evidence collected is presented in the reports listed below, all of which have been reviewed by the HSE.

The summary reports (the Precis and the Safety Assessment Conclusions Report) bring together all the findings of the work and should be looked to for context by all readers. The technical reports should be read in conjunction with the summary reports. While the summary reports are made as accessible as possible for general readers, the technical reports may be most accessible for readers with a degree of technical subject matter understanding.

**Safety Assessment:**

### Precis

An overview of the Safety Assessment work undertaken as part of the Hy4Heat programme.

**Safety Assessment:**

### Conclusions Report

(incorporating Quantitative Risk Assessment)

A comparative risk assessment of natural gas versus hydrogen gas, including a quantitative risk assessment; and identification of control measures to reduce risk and manage hydrogen gas safety for a community demonstration.

**Safety Assessment:**

### Consequence Modelling Assessment

A comparative modelling assessment of the consequences in the event of a gas leak and ignition event for natural gas and hydrogen gas.

**Safety Assessment:**

### Gas Ignition and Explosion Data Analysis

A review of experimental data focusing on natural gas and hydrogen gas ignition behaviour and a comparison of observed methane and hydrogen deflagrations.

**Safety Assessment:**

### Gas Dispersion Modelling Assessment

A modelling assessment of how natural gas and hydrogen gas disperses and accumulates within an enclosure (e.g. in the event of a gas leak in a building).

**Safety Assessment:**

### Gas Dispersion Data Analysis

A review of experimental data focusing on how natural gas and hydrogen gas disperses and accumulates within an enclosure (e.g. in the event of a gas leak in a building).

**Safety Assessment:**

### Gas Escape Frequency and Magnitude Assessment

An assessment of the different causes of existing natural gas leaks and the frequency of such events; and a review of the relevance of this to a hydrogen gas network.

**Safety Assessment:**

### Experimental Testing - Domestic Pipework Leakage

Comparison of leak rates for hydrogen and methane gas from various domestic gas joints and fittings seen in typical domestic gas installations

# WP7 SAFETY ASSESSMENT

**Safety Assessment:**

### Experimental Testing – Commercial Pipework Leakage

Comparison of hydrogen and methane leak rates on a commercial gas pipework system, specifically the gas meter and equipment contained within the Plant Room of a MOD site.

**Safety Assessment:**

### Experimental Testing - Cupboard Level Leakage and Accumulation

Comparison of the movement and accumulation of leaked hydrogen vs. methane gas within cupboard spaces in a typical domestic property.

**Safety Assessment:**

### Experimental Testing - Property Level Leakage and Accumulation

Comparison of the movement and accumulation of leaked hydrogen vs. methane gas within a typical domestic property.

**Safety Assessment:**

### Experimental Testing - Ignition Potential

Investigation of the ignition potential of hydrogen-air mixtures by household electrical items and a comparison with the ignition potential of methane-air mixtures.

# Hy4Heat

# Gas Ignition and Explosion Data Analysis

1.0 | 1 May 2021

**Department for Business, Energy & Industrial Strategy**

# Hy4Heat

# Gas Ignition and Explosion Data Analysis

KIW-WP7-GEN-REP-0003

1.0 | 1 May 2021

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## Contents

# 1 Executive summary

This gas ignition and explosion assessment report forms part of the Hy4Heat safety assessment suit of reports. It covers a contextual setting for understanding how gas ignitions behave. It is a review of experimental data and other literature relating to deflagrations of flammable mixtures of hydrogen and methane. It provides qualitative assurance to the consequence assessment and the QRA.

The experiments concerned ignitions within structures constructed from varying types of material such as glass, wood, block and metal. Nearly all structures had some means by which the deflagration could be vented. Some experiments contained obstruction within the enclosure.

Pressure traces were extracted from reports, digitised and plotted on iso-damage charts to provide a visual comparison between the consequences of methane and hydrogen deflagrations, within different concentration bands. The relevance of each experimental set-up to a domestic situation was considered and the dataset refined to provide a range of possible damage outcomes that might occur to a property from an ignition of methane and hydrogen.

The key findings were:

- Data from experiments representative of a domestic property showed that for concentrations of around 10% methane and 15-20% hydrogen the consequence of an ignition would be roughly comparable. Towards the higher end of this concentration band the hydrogen ignition starts to become more severe than methane
- Beyond 20% (up to around 40%) the consequence of a hydrogen ignition gets progressively much more severe
- The presence of obstruction within the combustion zone can cause turbulence of flammable gas mixtures leading to increased peak overpressure for both hydrogen and methane
- There was no evidence of hydrogen exhibiting a general transition from deflagration to detonation in a pseudo domestic environment. A general detonation was only achieved using chemical detonators
- Local detonation can occur with hydrogen where the flame is heavily constrained (e.g. within steel compartments of a vehicle in a hydrogen filled garage). Where local detonation was observed it was confined to the compartment in which it happened and there was no evidence that it led to bulk detonation of the gas surrounding the compartment. It should be noted that in all experiments where local Deflagration to Detonation Transition (DDT) in a compartment was observed, the deflagration had been initiated outside the compartment. It is unclear whether a deflagration that is initiated within the compartment that then leads to localised DDT could lead to bulk detonation of the gas surrounding the compartment. Further experimental work would be required to understand this risk
- Work carried out in response to the Ronan Point disaster suggested that the behaviour of a deflagration in a domestic property is influenced by the layout of rooms and how and when various parts of the property's structure fails. Further experimental work would be required to better understand the behaviour of deflagrations in real properties as well as to further develop industry standards that currently only consider one room with one vent
- Domestic buildings fail progressively as a gaseous deflagration expands throughout a room. If a deflagration results in a high enough over pressure, the

relatively long nature of this type of deflagration (10s to 100s of milliseconds) means the pressure and impulse could be sufficient to cause failure of constructional components starting with the weakest first. This means that initially (for example) a window opens, then a door fails and then the ceiling lifts. General failure of the property only occurs when the pressure exceeds the failure pressure of a structural member. It is suggested that this sequential venting may result  in actual over-pressures observed in a domestic setting being less than those seen in many of the experiments reported here, where the deflagration occurs in strong steel or concrete rooms relieved only through the experimental vent. This tends to make results reported here conservative in terms of pressure, although local damage may be worse.

Further analysis and discussion was then carried out in the context of the King Report (a land mark UK Government report published in 1977 to compare the risks from Town Gas and Natural Gas);other data from Fire Research Notes published at Borehamwood in the 1960s and 1970s and SGN H100 Fire Investigation Box experiments

- Some Town Gas experiments using either artificially high levels of room obstruction or room interconnection could generate very high pressures, but by limiting the hydrogen release rate to <20m3/h it is unlikely that high concentrations can occur in more than one room.
- Further analysis of the videos of the SGN H100 FIB data was carried out on a millisecond by millisecond basis; this confirmed that hydrogen ignitions up stochiometric conditions were essentially similar, but faster versions of  natural gas fires i.e. they were relatively slow deflagrations extending to over 100ms. The weaker parts of the FIB (e.g. the windows and door) would fail sequentially as the pressure rose. This supports the above. With hydrogen at stochiometric conditions two wooden chairs were placed on the ground outside and 5m from the FIB. One was blown over but left essentially unmoved and one was displaced about 5m. This confirms that local external overpressures were generally low.
- Further estimations of overpressures within the FIB were carried out using a simple model published within Fire Research Notes (FRN) 0847 from the 1960s. This strongly supports the hypothesis that Natural Gas, Town Gas and Hydrogen deflagrations form a continuum with increasing flame speed. Furthermore, there was no obvious significant change in the incident rate of fires or deaths during the transition from Town Gas to Natural gas from 1968 to 1977 that did not have a clear mechanical cause. The King Report noted that whilst theoretical overpressures from Town Gas ignitions could be three times those of natural gas, observed overpressures (from real incidents) were only 20% higher. This can be rationalised by the sequential failure mode again described above. Combining these themes would indicate whilst hydrogen (up to 20-23%v.v) will readily produce higher overpressures, the resulting damage and injury rates were unlikely to materially change from more severe natural gas explosions. Whilst this is same conclusion as above, the analytical process is different. Such a twin track approach is always useful in a critical analysis.

## 2 Introduction

The Hy4Heat programme aims to establish if it is technically possible to safely replace natural gas with hydrogen within the UK gas network. Work Pack 7 (WP7), specifically focusses on collating evidence to make the safety case for hydrogen and develop a Quantitative Risk Assessment (QRA) for use within the gas industry.

The primary risk from any flammable gas is formation of a flammable gas-in-air (GIA) mixture and the subsequent ignition of this mixture. Such an ignition can lead to an explosion (deflagration or detonation) which creates pressure or shock waves. These pressure/shock waves can act directly on a person near to the blast causing injury or death, or should the ignition occur within a building, exert force upon the elements of the building causing glass breakage and structural damage. Flying objects can cause secondary injury to people within, or close to, the property and people can sustain injury from being thrown against hard surfaces.

Both hydrogen and natural gas are flammable gases and therefore both offer this risk, plus the subsequent risk of fires causing further damage to people and buildings.

In order be able to quantify the relative risk of a hydrogen ignition it is important to understand the following,

1. The type and likelihood of events that can lead to build-up of flammable gas concentrations in buildings
2. The likely GIA concentrations that will be achieved through these events
3. The likelihood that these flammable mixtures will be ignited
4. The likely consequences of an ignition of these flammable concentrations

WP7 has produced two supporting reports that deal with the frequency and magnitude of gas escapes [1] and dispersion of gas within a property [2].

This report is limited to an assessment of the consequences of an ignition with reference to experimental results, academic studies and incident reports. It should be read in conjunction with the modelling report to assess the consequences of an ignition and two supporting reports. Conclusions from all these reports have informed the development of a QRA (which will include an assessment of the likelihood of a flammable gas ignition) to provide an estimation of the risk associated with these processes and to enable comparison between natural gas and hydrogen.

Understandably, there is a lack of data relating to the effect of real explosions of flammable gases in domestic situations, but many studies exist on the ignition of hydrogen, methane and other flammable gasses in laboratory situations as well as specially constructed enclosures.

This document aims to draw together the experimental data that exists relating to ignitions of natural gas and hydrogen and identify the factors that affect the severity of such an ignition. The relevance of the data to a domestic situation is discussed and based on the evidence available, a range of possible consequences for ignitions of different concentrations of hydrogen gas is suggested where possible making reference to an equivalent concentration of methane. Particular attention will be paid to the likelihood of detonation.

The objectives of this work were to:

- Carry out a literature review of experimental papers, studies and other evidence sources relating to the ignitions of hydrogen and methane mixtures
- Review literature for evidence relating to the consequences of ignitions, paying attention to:

  - the overpressures and impulses generated
  - any evidence of deflagration to detonation transitions
  - data relating to glass throw
- Extract available data and display graphically
- Summarise the key findings of the review and identify factors that affect the severity of an explosion
- Discuss the relevance of the findings in relation to domestic scenarios and provide a range of possible outcomes in the event of a hydrogen explosion.

# 3 Methodology

The overall methodology for this work consisted of a literature review, exploration of pressure and impulse data (including data extraction and selection of relevant data), and discussion of key findings and conclusions. Quality assurance checks were also performed.

The methodology is summarised in Figure 1.

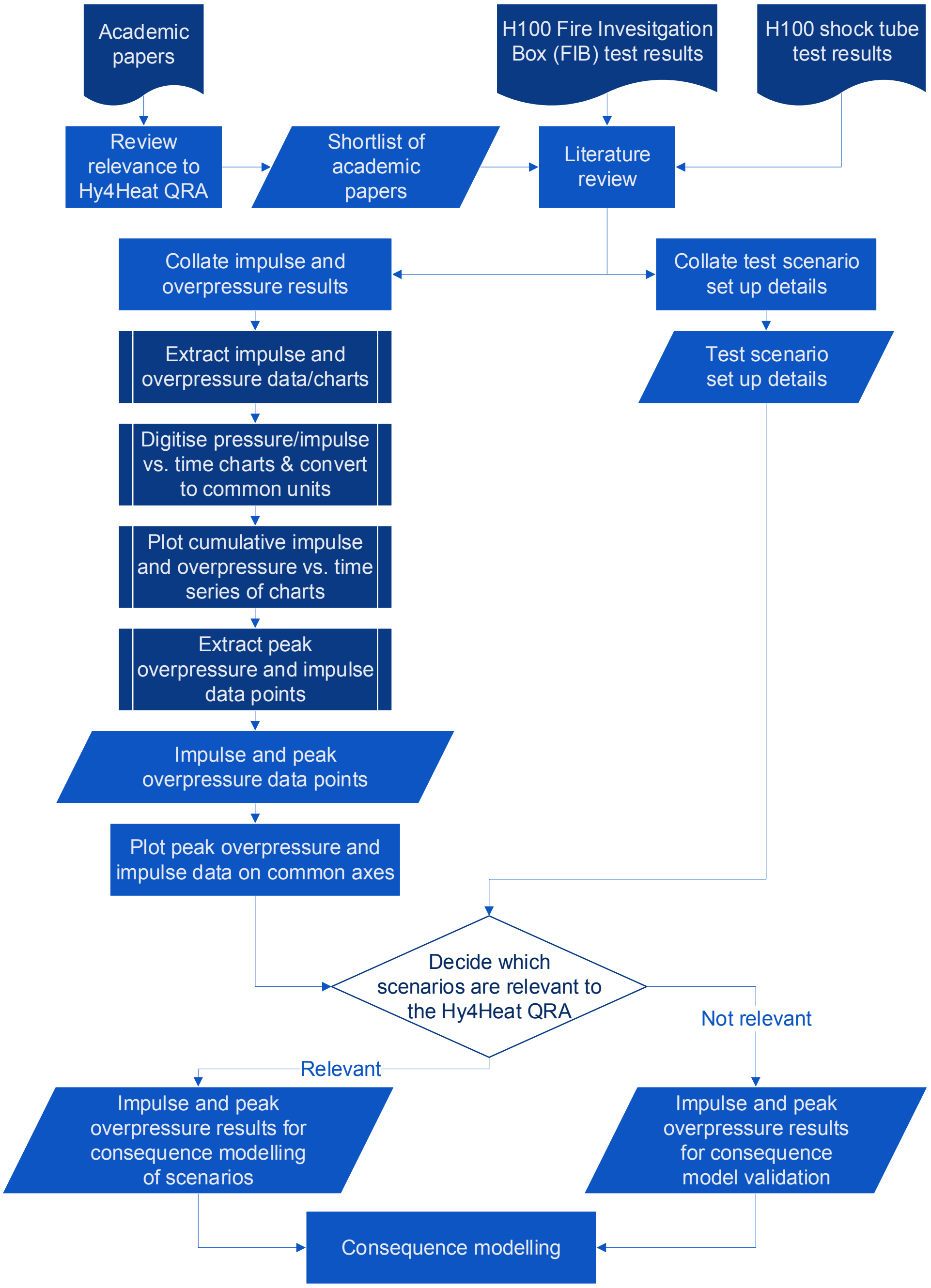


**Figure 1: Methodology**

## 3.1 Literature review

A list of papers, studies and reports involving the ignition of flammable gases was obtained through consultation with experts and searches of literature. Recent experimental work on flammable gas ignitions carried out by Kiwa for SGN under the H100 programme was also reviewed.

Some literature was not considered for further review, either in parts or in its entirety if it:

- did not contain the results of actual experiments (some papers related to modelling or simulation work)
- was of insufficient quality for data to be extracted

The review considered the rationale behind the experiment, the experimental set-up and a summary of the key findings relevant to this report (i.e. regarding the consequences of an ignition of flammable gas). The key findings from the review were then summarised.

## 3.2 Exploration of pressure and impulse data

The damage to a structure is related to the force that is applied to it as well as the duration over which the force is applied. The key metrics to consider when quantifying the consequences of igniting a flammable gas/air mixture are overpressure and impulse.

The overpressure is a measured value that varies with time and the peak overpressure is the highest (usually positive) value reached.

The impulse is an integration of overpressure with respect to time, which reaches a maximum (peak impulse) usually at the end of the positive phase of the deflagration.

Plotting maximum overpressure and peak impulse data on a graph and adding experimentally-derived lines [3] [4] showing regions of known levels of damage (so-called ‘iso-damage lines’), provides a way of visually comparing the severity of different explosions in terms of structural and glass damage to a building.

The actual consequence of an ignition event will depend on the materials used for construction of the various elements of the building/enclosure and the structural properties of these when combined in a building (e.g. a brick wall in tension behaves differently to a brick wall in compression and walls, windows and doors have different failure characteristics).

Work by BRE [5] in the early 1990’s showed that gas deflagrations generally occur over a period of 10’s to 100’s of milliseconds (mS) compared to the potential demolition time of a brick or re-enforced concrete wall (when subjected to a constant overpressure) of <5mS. This comparison shows that, for the majority of gas deflagrations, the failure of structural components provides some relief to the build-up of overpressure within a building and prevents theoretical overpressures derived from vented room models being achieved in practice.

Where possible, data was extracted from the literature either directly, or was calculated from figures of pressure curves by the procedure detailed below. For ease of visualisation, the data was then separated into five concentration bands and plotted on the same set of axes.

### 3.2.1 Data extraction process

Peak overpressure and impulse data were extracted from several of the papers. Where the test results were reported as a pressure/time transient the following procedure was used to obtain the peak overpressure and impulse for the tests.

1. **Digitisation of pressure history graphs**

   - Images of figures were opened in the graph-visualising software WebPlotDigitizer [6].
   - The curve was identified by distinguishing the colour of the curve from the background.
   - A series of data points spaced equally along the curve was created – the granularity of the points was manually adjusted to ensure the peaks were captured.
   - The data was exported in CSV format.
2. **Converting to common units**
   - The time values were converted to seconds and the pressure to millibar (if original data was in other units).
3. **Calculating the cumulative impulse**
   - The cumulative impulse data series was created, by approximating the area under the pressure/time curve with trapeziums
4. **Extraction of peak overpressure and maximum impulse**
   - The pressure and impulse series were plotted, and the peak overpressure and maximum impulse taken from the graph. Maximum impulse was usually taken from the time where the initial positive overpressure phase finished.

### 3.2.2 Selection of relevant data

The literature review identified tests that simulated the consequence of flammable gas ignitions in a range of situations. It was necessary to identify which experimental set-ups were relevant to a domestic situation. For the purposes of this report a domestic space was conceptually defined as a wholly enclosed room of cuboid geometry with at least one of the walls having a window and/or door.

Data was plotted on iso-damage curves, split into concentration bands, to demonstrate the extent of the consequences obtained from the experimental data studied. Some data points were identified as “not relevant” to a domestic situation due to the nature of the experimental set-up, and these have been acknowledged on the graphs. These data points have not been used to inform the discussion around the consequence of a hydrogen ignition in a domestic situation. Further detail regarding relevance is included in section 5.1.3.

## 3.3 Discussion of key findings and conclusions

Factors affecting the severity of an ignition of a flammable gas in air mixture were identified and are discussed in the context of a typical domestic situation. Conclusions are made as to the likely severity of an ignition of a build-up of hydrogen in a domestic property based upon the available experimental data.

## 3.4 Quality assurance

This study involved a considerable amount of digitising and processing of data from a variety of different sources. The areas of greatest potential error were identified as:

- Determining the relevance of each experimental scenario.
- The manual reading of scales during the digitisation of figures to determine peak overpressures and impulses.

As part of the methodology, several internal reviews and cross-checks on data extraction were performed, including a visual cross-check of the impulse data (the area under the positive phase on a pressure/time graph) by approximating this area to a triangle.

# 4 Literature review

The following pieces of literature were reviewed. A summary of the test conditions and key findings are provided for each study.

## 4.1 Limits of flammability of gases and vapours

Coward and Jones [7] investigated certain chemical and physical factors connected with the initiation and propagation of flame in different flammable gases under various conditions. The study was carried out to understand and reduce the likelihood of gas explosions and fires in the mining, metallurgical, petroleum, gas manufacturing and related industries.

The study included experimental work to determine the upper and lower limits of flammability for many different gases in the downwards, upwards and horizontal directions. To determine the limits, tests were carried out in open spaces, open and partially closed tubes as well as spherical vessels.

Key findings:

- Hydrogen has a wide general range of flammability, but the flammability range differs with flame direction
- Flames can only propagate in all directions within specific concentration ranges (Table 1).

**Table 1: Flammability range for hydrogen-air mixtures saturated with water vapour, for different flame propagation directions**

| Propagation direction | Upwards | | Horizontally | | Downwards | |
|---|---|---|---|---|---|---|
| **Concentration limit** | Minimum | Maximum | Minimum | Maximum | Minimum | Maximum |
| | 4.1% | 74% | 6.0% | Not specified | 9.0% | 74% |

## 4.2 Fundamentals of hydrogen safety engineering

This book by Molkov [8] was written to inform stakeholders about hydrogen safety engineering and safe engineering use of hydrogen. It covers theory on risks posed by hydrogen as well as fundamental properties of hydrogen gas. Molkov references Coward and Jones [7] and summarises the flammability limits of hydrogen (Table 2).

**Table 2: Flammability range for hydrogen-air mixtures, for different flame propagation directions [8]**

| Propagation direction | Upwards | | Horizontally | | Downwards | |
|---|---|---|---|---|---|---|
| **Concentration limit** | Minimum | Maximum | Minimum | Maximum | Minimum | Maximum |
| | 3.9–5.1% | 67.9–75% | 6.0–7.15% | 65.7–71.4% | 8.5–9.45% | 68–74.5% |

## 4.3 Dynamics of vented hydrogen-air deflagrations in an open ended $10m^3$ vessel

Daubech et al. [9] conducted experiments on vented hydrogen explosions in industrial sized containers. A series of ignition tests using hydrogen concentrations of 10–30% GIA were performed in two vented chambers ($1m^3$ and $10m^3$ in volume).

Overpressures were measured inside the chambers and outside along the axis of discharge form the vent.

A typical pressure trace for 23% hydrogen (Figure 2) shows an initial peak pressure of around 170mbar followed by a secondary peak after the flame has left the vessel. Daubech et al. postulated that the exit of the flame from the vessel ignited unburned gas outside, which stopped burnt gasses inside the vessel from leaving the vessel, causing the pressure to rise again. A similar phenomenon was seen by Kasmani [10]. There are no pressure spikes indicating detonation.

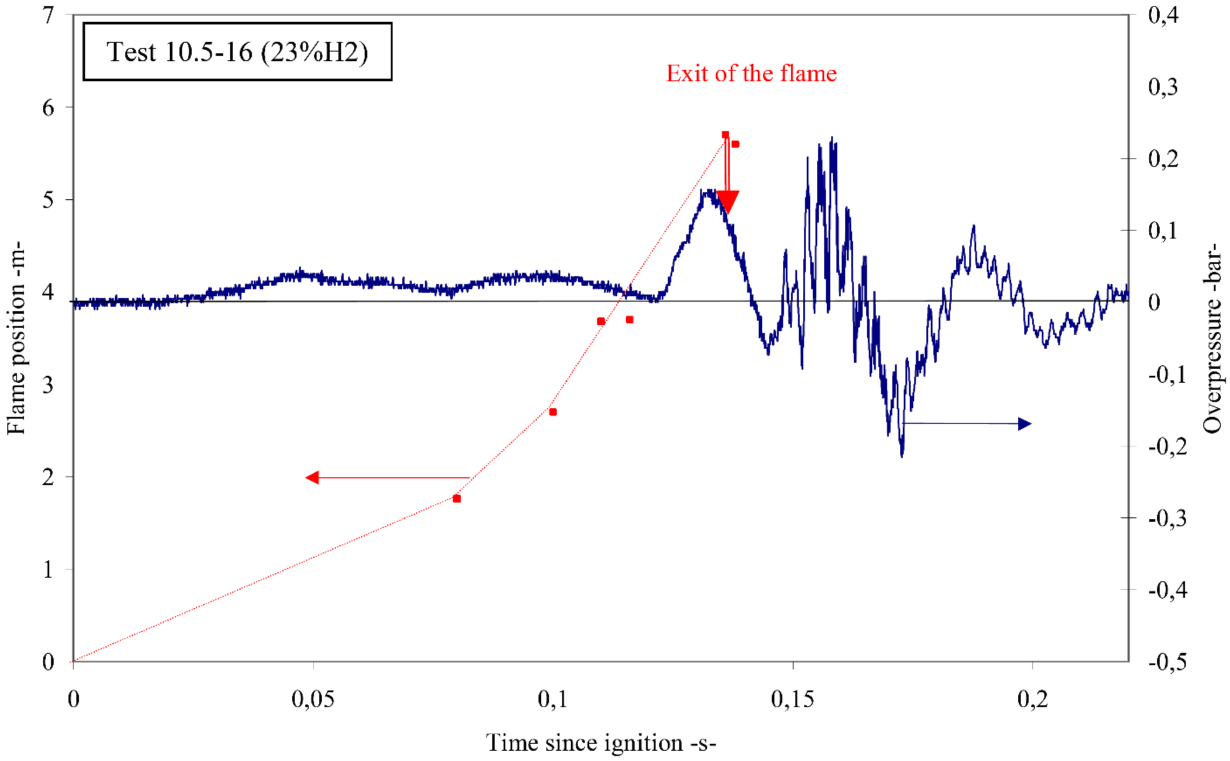


Figure 2: Flame position and overpressure, 10.5m$^3$ vessel, rear ignition, 2m$^3$ vent, 23 % $H_2$ [9]

## 4.4 The response of glass windows to explosion pressures

Harris et al. [11] investigated the hazard that is posed from flying glass in the event of a flammable gas ignition venting through a window.

Two test buildings were used, a concrete bunker and a building designed to represent the top three stories of a block of flats.

Different types of treated and untreated glass were installed in the open end of the bunker and within the windows of the building. Stoichiometric gas air mixtures initially contained in balloons within the bunker and building were ignited.

Key findings:

- The failure pressure of different types of treated and untreated glass was measured when installed and velocities of glass fragments and maximum distance of travel were measured (Figure 3).

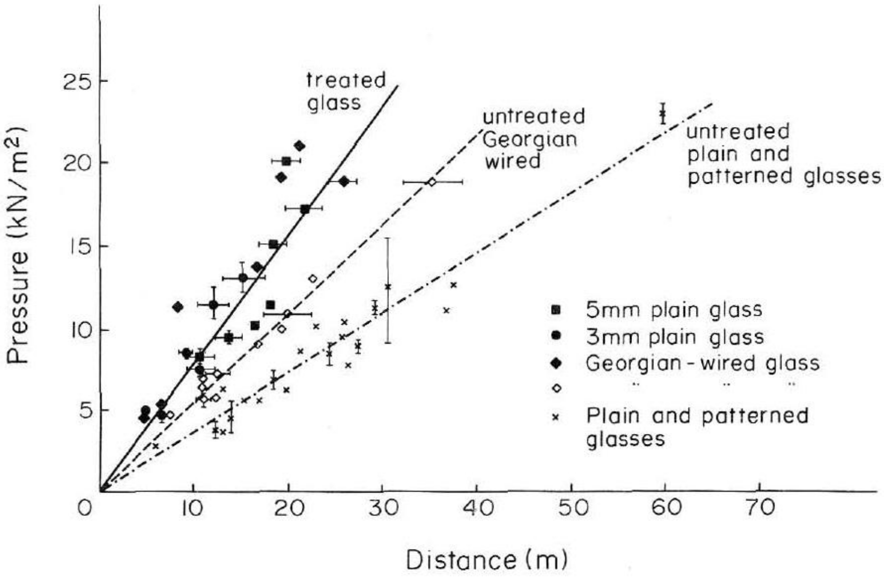


Figure 3: Glass throw vs. overpressure [11]

## 4.5 Ignitions in a Fire Investigation Box

Work by Kiwa during Phase 1 of the SGN H100 programme [12] involved a series of experiments simulating the effect of a flammable gas ignition in a room within a house (e.g. a kitchen).

A Fire Investigation Box (FIB) consisting of a 29.1m$^3$ ISO container containing a door and three windows was fitted out to represent a domestic kitchen. It was filled with a table, chairs, sink and under-sink cupboard containing pans and crockery. Two dummies were placed within it. The windows and doors were of approximate total area of 4m$^2$ giving a vent ratio (defined as the ratio of enclosure volume to the vent area, expressed as m$^3$/m$^2$) of approximately 7.3 m$^3$/m$^2$. Thermal damage to soft tissue was assessed by examining the effect of two ignitions on a pig carcass placed in the room.

Methane and hydrogen were injected into the FIB at different rates from 4–100 kW from a point located inside the under-sink cupboard. Pure gas was injected and dispersed within the enclosure until a steady state concentration was reached. Gas was sampled at five points in the room (including at the location of the ignitor) and under the sink cupboard. Gas concentrations at mid-level (ignitor level) in the room ranged from 6.5% to 20.1%.

Once the test concentration was reached, an attempt was made to ignite the flammable mixture from an ignitor located on the wall opposite the sink. The overpressure caused by the ignitions were measured by five fast acting pressure transducers located next to the gas sampling points.

Note, in this study, Kiwa compared similar energy release rates of hydrogen and methane and the consequences of subsequent ignition.

In these tests, hydrogen concentrations were stratified (to varying degrees depending on the wind conditions). So that the consequences of these ignitions could be compared with those of the other test in the paper, which used predominantly homogenous mixtures of gas, a nominal concentration had to be chosen, the choice of which is not obvious.

The Gas Dispersion Assessment report by the H100 project [2] showed that when hydrogen is released into a room from a point reasonably close to the ground it will tend to stratify into 2 layers, the boundary of which is around the height of the point of injection. Thus, taking the numerical average of each sampling point (which are distributed evenly along the vertical axis of the FIB) would not make sense. Choosing the largest concentration measured in the FIB would be likely to underestimate the consequence of an ignition of a uniform cloud of hydrogen at that concentration and taking the lowest value would be a large overestimate.

For the purposes of this report, concentrations at the ignitor have been used. The ignitor was purposefully placed at about mid height and adjacent to the door where the light switch might be.

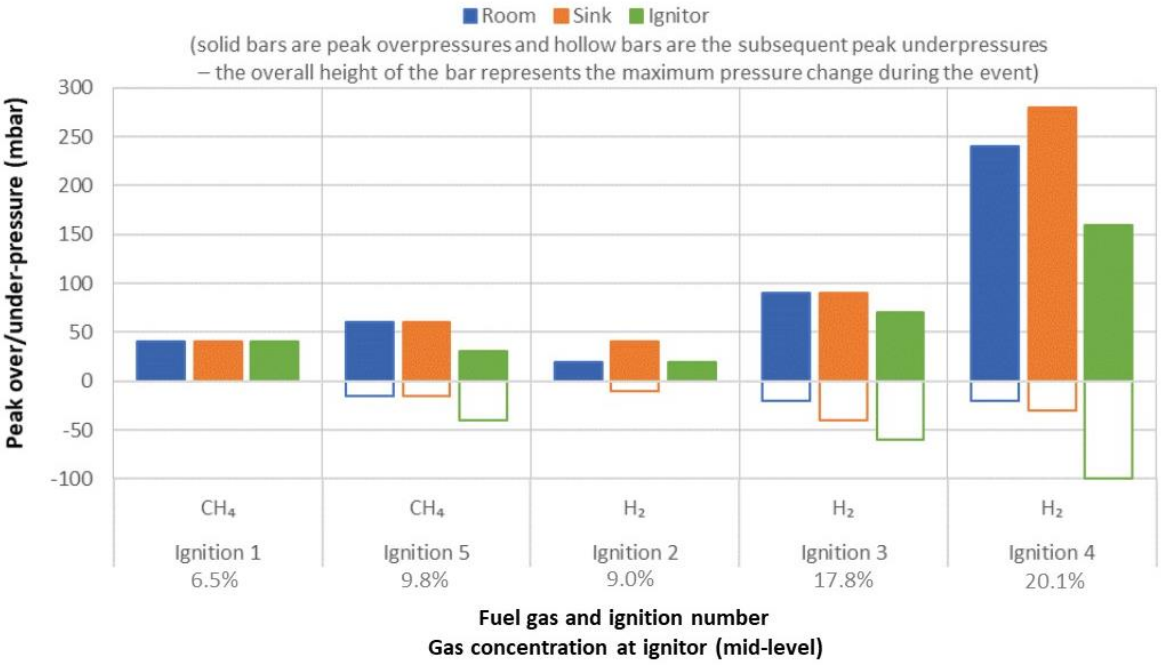


Figure 4: Peak over/under pressures measured during FIB ignitions [12]

## Key findings:

- Damage to the FIB from a concentration of methane of 6.5% and hydrogen of 9.0% were broadly similar. In these cases, combustion gasses were able to vent through the windows and doors
- For higher concentrations (9.8% methane and 17.8% hydrogen), windows and doors were blown out and there was damage to plasterboard, with both methane and hydrogen.
- There was some evidence of a localised deflagration to detonation transition during ignition 4. Although the concentration near the ignitor was around 20%, the concentration in the cupboard was thought to be much higher ~90%.
- Where very large volumes of hydrogen (100kW) were injected, and with hydrogen concentrations near the ignitor around 30%, there was severe damage to the enclosure. The glass throw graph (discussed below) would indicate an overpressure of about 360mbar. This overpressure is likely to be a

function of the failure point of the FIB, which was an old unit weakened by corrosion and holes cut for the windows and door.

- Pig carcasses placed in the room during ignition 4 and 5 were not moved from their original location during the ignition. There was some scorching to the skin of the carcass (more in the case of the methane ignition), but this was difficult to distinguish from intentional scorching carried out post-slaughtering to remove hair.
- An extension to the project (carried out during Phase 3 [13]) compared the data on glass throw obtained from the FIB experiments with data obtained by Harris et al. [11] (Figure 5). This followed a trajectory that might be expected for modestly sized panes of domestic glass.

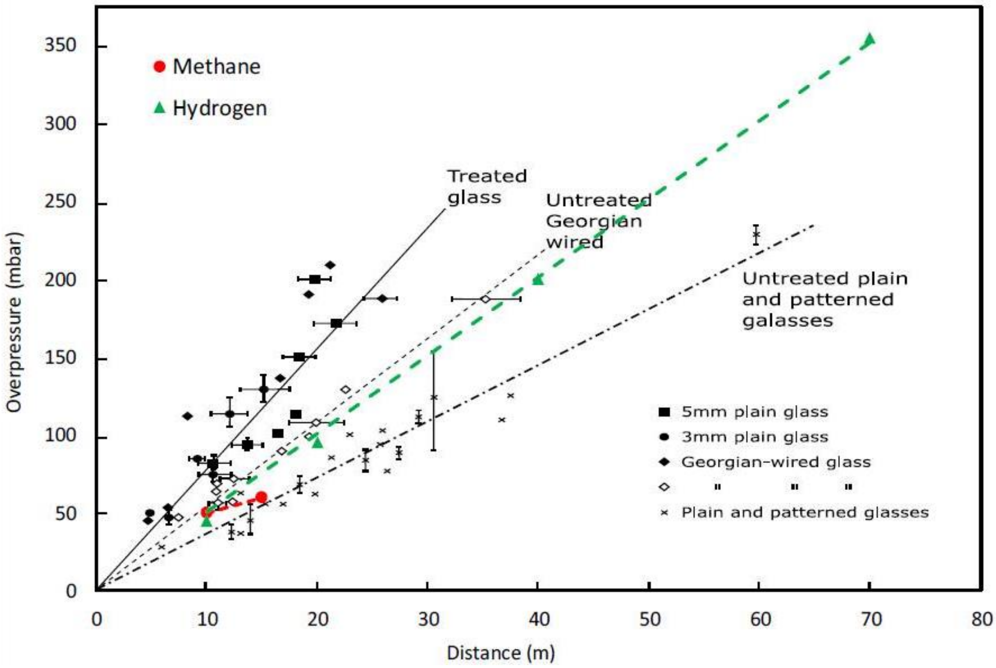


Figure 5: Glass throw vs. overpressure [11, 13]

## 4.6 Ignitions within a shock tube

Under Phase 3 of the SGN H100 programme, Kiwa performed a series of experiments to investigate the effect of explosions of methane and hydrogen gases within a purpose-built shock tube [13]. The tests investigated the effect of venting and obstruction within the tube.

A 2ft diameter, 1.8m long steel tube was fabricated, open at one end and capped at the other in which the ignitor was located. A pendulum formed of 2mm thick steel discs attached to an arm hanging from a bearing was hung in front of the open end. The pendulum was free to swing, and the angle of swing was measured. This allowed the energy transferred to the pendulum to be calculated. Discs of two different diameters could be fitted to the end of the pendulum. The larger disc completely covered the open end of the shock tube (full-bore pendulum) and was designed to represent a minimally vented situation. The smaller disc only partially covered the open end of the tube and represented a vented situation such as a room with a window or door.

Weights were added to the pendulum either side of the discs. Different weights were used for the large and small disc so that the mass of the pendulum per unit area of disc was similar to that of a single skin brick wall found in a property, For some tests a specially made insert was placed within the tube. This was geometrically designed to cause maximum acceleration of flame front and promote the most violent deflagration. This type of configuration could be thought of as representative of an enclosure filled with highly regulated fixed objects or split into compartments separated by partitions or baffles.

Three high speed pressure sensors were mounted inline inside the tube and gas was sampled and analysed from a further three points in the tube. Tests were carried out with hydrogen concentrations ranging from 5 – 45% and methane from 5 – 15%. Premixed flammable gas and air mixtures were injected at one end of the tube and vented at the other until the desired homogeneous concentration within the tube was achieved. The flammable gas within the tube was then ignited and the resulting overpressure measured and impulse calculated.

Tests were also carried out with varying quantities of high explosive to determine the TNT equivalence of the gas explosions.

**Key findings:**

- For concentrations of 5 – 10% the ignition of both gases resulted in similar overpressures.
- There appeared to be an inflection point around a concentration of 14 - 19% where hydrogen ignitions became increasingly more severe than the most severe methane ignition
- The shock tube with reduced bore pendulum resulted in lower overpressures than the shock tube with full bore pendulum.
- Adding the insert to the shock tube increased the over pressure by between 2 - 4 times for methane and 3 times for hydrogen.
- Whist the addition of the insert resulted in a significant increase in overpressures, there was limited evidence of a transition to detonation
- Tests on the reduced bore pendulum showed that peak overpressures were a maximum at around stoichiometric concentration for methane, and around 40 - 45% for hydrogen, or 10 - 15 percentage points above stoichiometric (Figure 6).

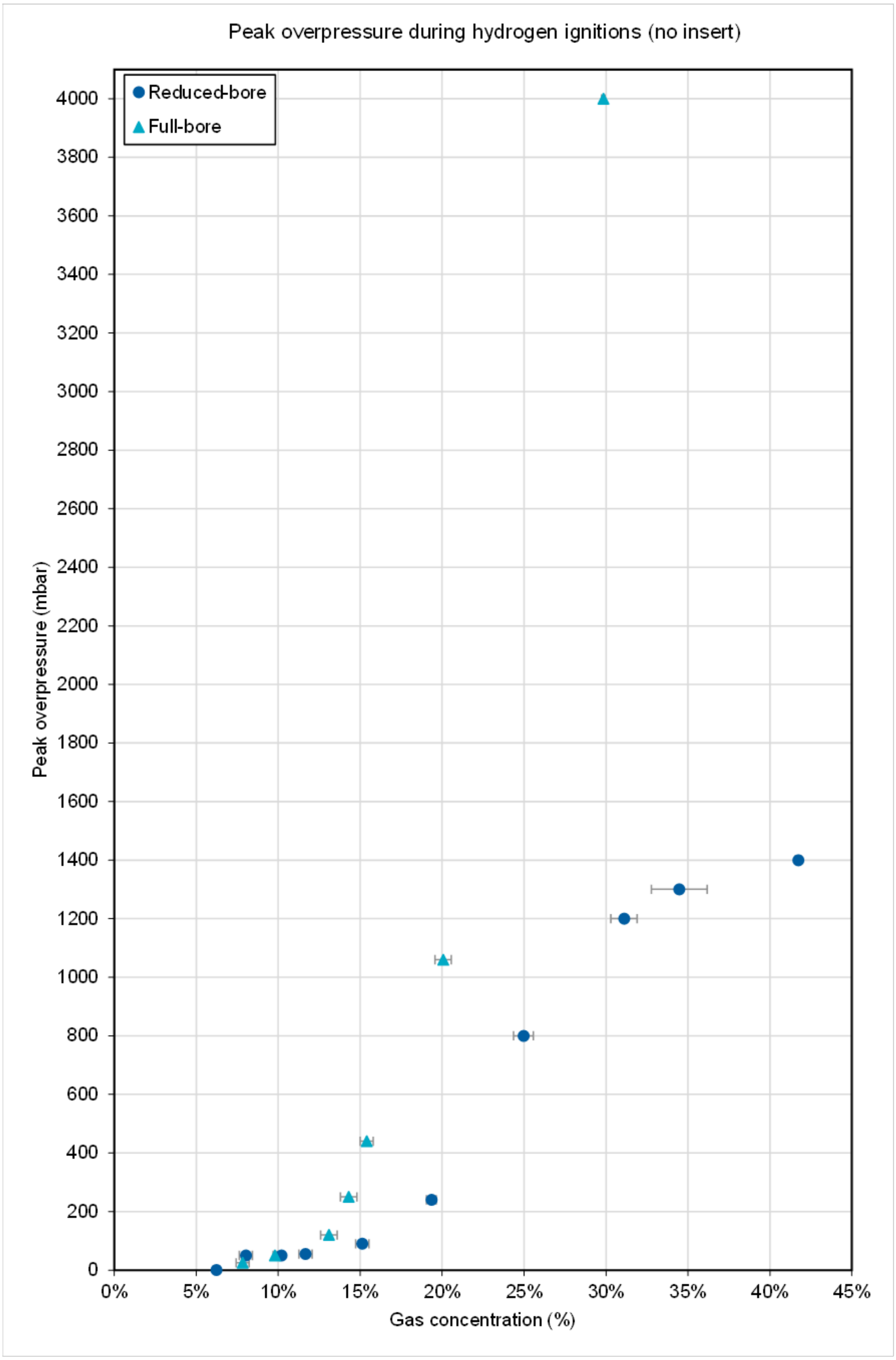


**Figure 6: Peak overpressure vs hydrogen concentration**

*Note: this figure includes results for the shock tube with full bore pendulum (light blue triangles). Whilst the overpressures from these ignitions are very significant, they represent a minimally vented case, and therefore should only be considered partially representative of a domestic situation.*

## 4.7 Ignitions of hydrogen within a simulated garage building

Blais and Joyce [14] investigated the impact of ignitions of different concentrations of hydrogen within a specially constructed “garage”, designed to simulate a leak of hydrogen from a fuel cell vehicle within a garage space.

Most of the garage was built using breeze block, and the front wall and ceiling were made from timber to enable blast venting.

Pressure was measured via two high speed pressure transducers, 0.3m in front of the door at a height of 2.59m and one on the centre of the right-hand wall.

Gas was injected at the centre of the enclosure at floor level and concentration was measured using thermal conductivity. The ignition point was located at the rear of the garage at a height of 2.59m above the floor. Tests were carried out with the garage either empty or containing a vehicle. Different sized vehicles were used.

A total of 25 tests were carried out with the following concentrations: 4-8%, 8%, 12%, 16%, 28.8%. The 8, 12 and 16% tests were repeated with a vehicle in the garage as was the 28.8% test which prematurely ignited at 17.7%.

The front wall, roof and main body of the garage all failed at different stages depending on the severity of the explosion. The destruction of the front wall was caused by a 12% ignition with vehicle, and the destruction of the front wall and roof was caused by a 16% ignition with vehicle. The main structure of the garage was badly damaged in the 28.8% test without vehicle and 17.7% test with vehicle (as shown in Figure 7).

**Key findings:**

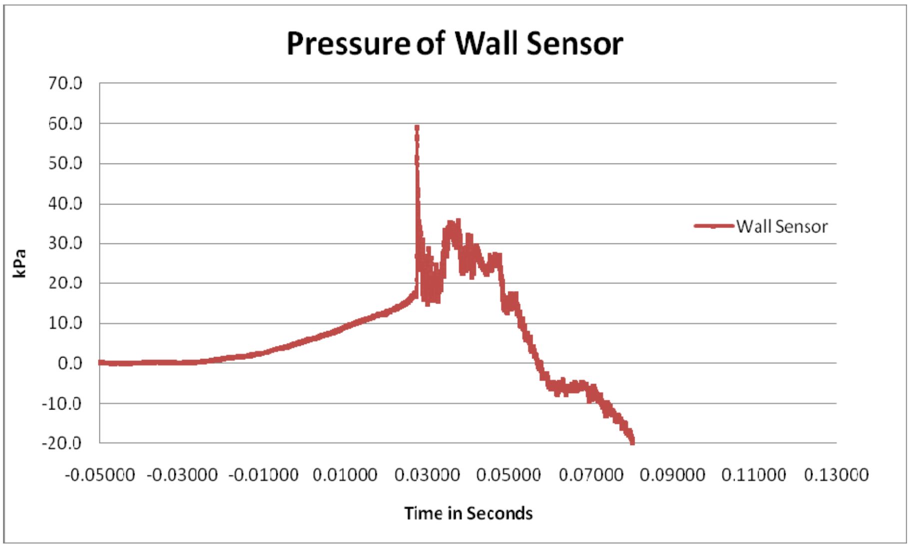
The presence of a vehicle in the structure had the following observed effects:

- it disrupted the natural stratification of the hydrogen and led to a more mixed concentration within the garage
- considerably higher concentrations of gas were found within the engine compartment of the vehicle than in the surrounding garage
- all tests carried out at 8% hydrogen did not damage the garage building
- all tests with a vehicle present led to more severe damage than without a vehicle. One test with a vehicle produced localised deflagration to detonation transition
- larger vehicles led to greater increases in damage, due to their larger engine sizes and other compartments in which higher localised high concentrations could accumulate

Figure 7: Blast damage from the 17.7% test with vehicle [14]

## Deflagration to detonation transition (DDT)

One test at 28.8 % hydrogen recorded evidence of a possible deflagration to detonation transition (Figure 8).



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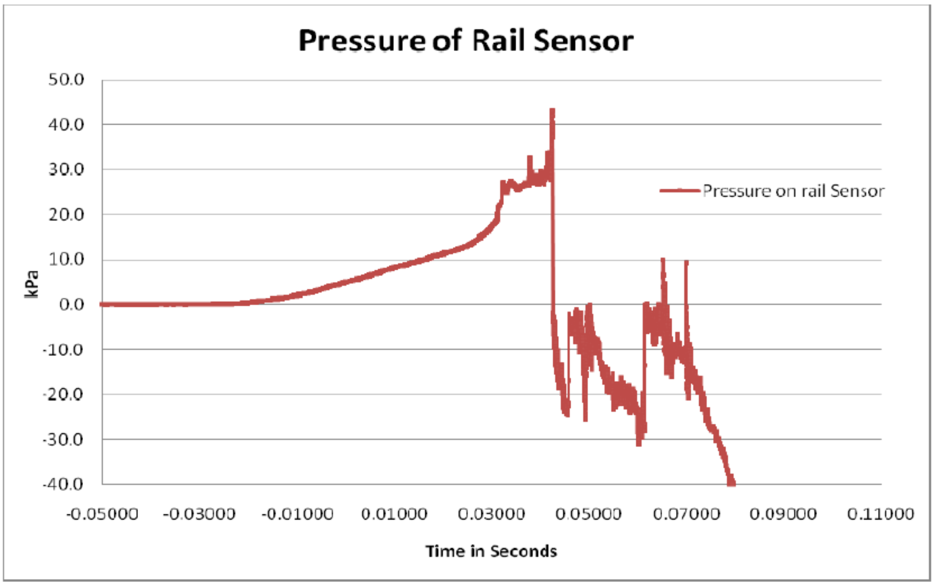


Figure 8: Localised detonation wall and rail pressure sensors [14]

It is suggested that the sharp vertical spikes are small-scale detonations, perhaps associated with restricted gas pockets within the vehicle; such as the boot or under the bonnet. Therefore, these results show an example of mixed deflagration, with some localised detonation.

Due to the relatively small volume of the enclosed and obstructed zones (especially around the engine) the impulse (the area under the pressure/time curve) from these detonations is small, less than a few percent of the total value.

## 4.8 Ignitions of hydrogen within an ISO shipping container

Skjold et al. [15] investigated the impact of ignitions of hydrogen within ISO containers of approximately 33m$^3$ volume. The study focused on the effect of congestion and venting of the container on the severity of the explosion.

A recirculation system was used to ensure homogenous gas air mixtures were present in the container prior to ignition.

Ignition was either at floor level in the centre of the container (for roof vented explosions) or at the middle of the back wall (for door vented explosions).

Eight pressure sensors were positioned around the inside of the container, 85mm from the wall and 200mm above the floor.

Three pressure sensors were located outside the container, in line with its centre.

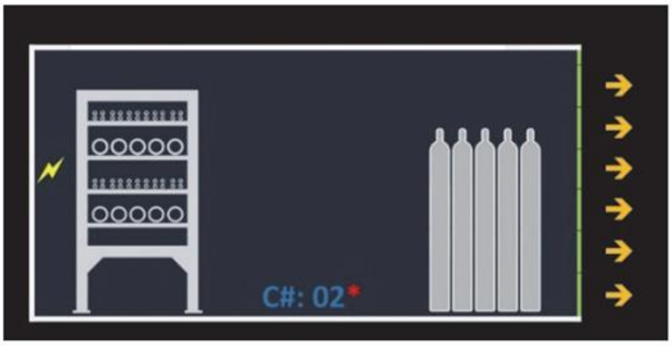


Figure 9: ISO Container with bottle basket and pipe rack obstructions [15]

Hydrogen concentrations of between 15 and 24% were studied with one roof-vented explosion with a concentration of 42%.

The inside of the container was configured in 3 different ways:

- with a metal basket holding 20 gas cylinders
- a rack holding sections of pipe
- both types of obstruction present

Explosions were either unvented (closed container) or vented through the door or roof. Venting through the roof was either via sections of perforated plastic film or commercial vent panels.

**Key findings:**

- For door vented explosions the highest peak overpressures were measured by the sensors closest to the back wall.
- Increasing the level of obstruction from just a pipe rack or bottle basket to both items increased the overpressure for all pressure measurement locations.
- The ignitions with the unvented container recorded the highest over pressures.
- There was no evidence of a DDT, even in the case of the container filled with pipe rack and bottle basket obstructions (Figure 10 and Figure 11)

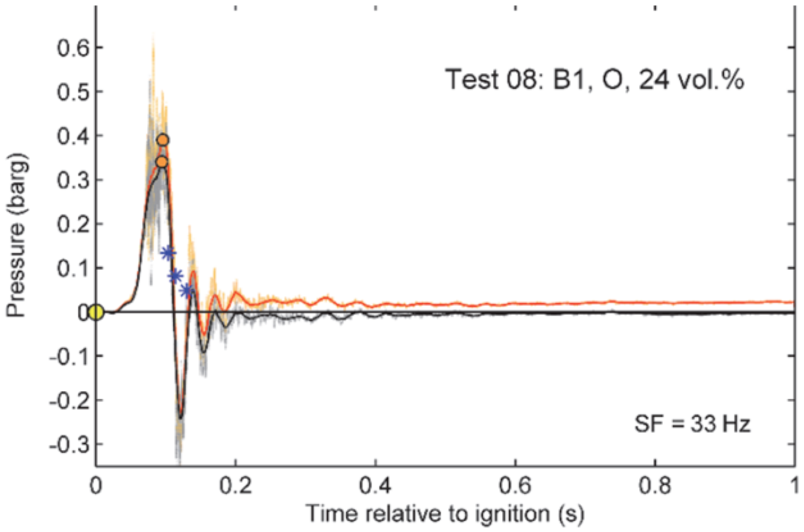


Figure 10: Typical pressure trace 24% hydrogen with bottle basket configuration [15]

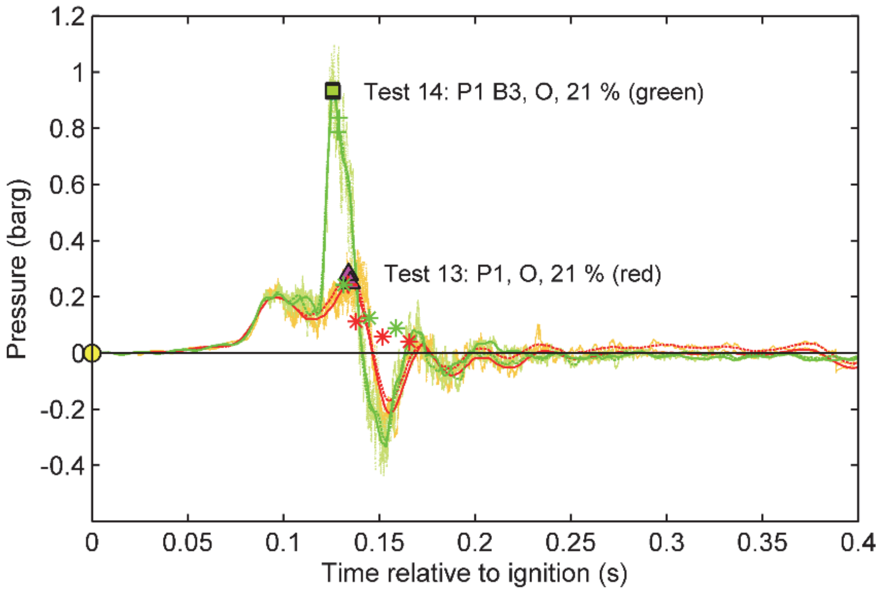
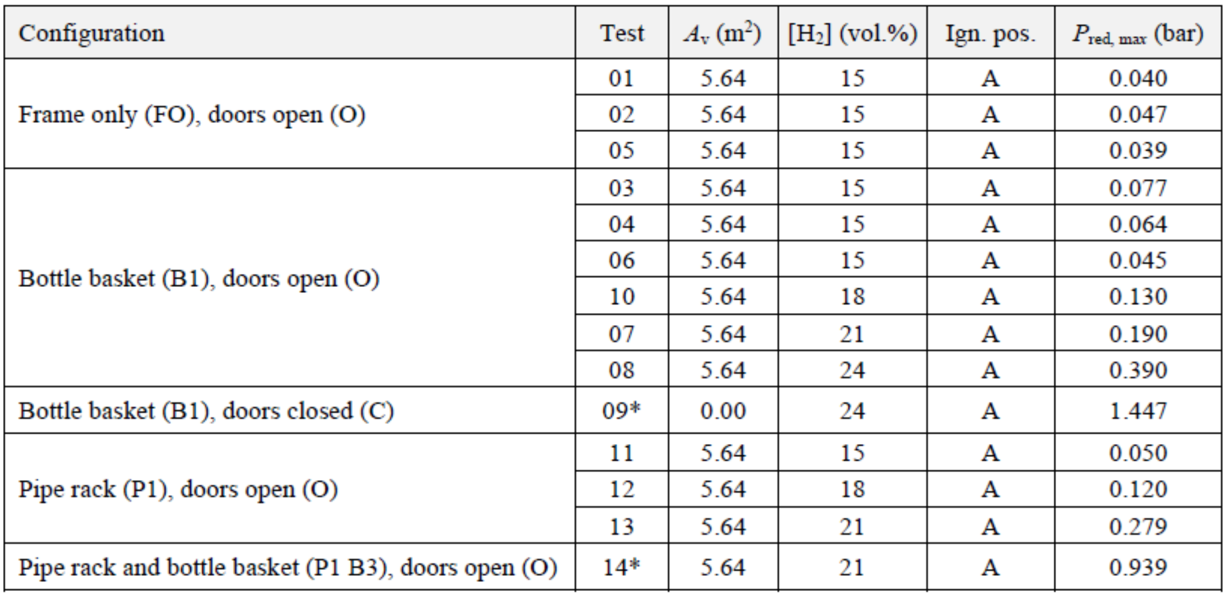


**Figure 11: 21% hydrogen ignition, pipe rack and bottle basket configuration (green line) [15]**

Despite the very quick pressure rise shown in Figure 11, the rate of increase is not steep enough to indicate a general transition to detonation (where pressure rise happens almost instantaneously).

The ISO containers generally showed damage (most serious in the test with the doors shut) but not of the type that would be associated with a substantial detonation. The products of combustion generally successfully vented through the right-hand end of the container.



| Configuration | Test | $A_v$ (m$^2$) | [$H_2$] (vol.%) | Ign. pos. | $P_{red,\,max}$ (bar) |
|---|---|---|---|---|---|
| Frame only (FO), doors open (O) | 01 | 5.64 | 15 | A | 0.040 |
| | 02 | 5.64 | 15 | A | 0.047 |
| | 05 | 5.64 | 15 | A | 0.039 |
| Bottle basket (B1), doors open (O) | 03 | 5.64 | 15 | A | 0.077 |
| | 04 | 5.64 | 15 | A | 0.064 |
| | 06 | 5.64 | 15 | A | 0.045 |
| | 10 | 5.64 | 18 | A | 0.130 |
| | 07 | 5.64 | 21 | A | 0.190 |
| | 08 | 5.64 | 24 | A | 0.390 |
| Bottle basket (B1), doors closed (C) | 09* | 0.00 | 24 | A | 1.447 |
| Pipe rack (P1), doors open (O) | 11 | 5.64 | 15 | A | 0.050 |
| | 12 | 5.64 | 18 | A | 0.120 |
| | 13 | 5.64 | 21 | A | 0.279 |
| Pipe rack and bottle basket (P1 B3), doors open (O) | 14* | 5.64 | 21 | A | 0.939 |

**Figure 12: Result summary for door vented ignitions [15]. (*) indicates last time a container was used**

## 4.9 Ignition of hydrogen, propane and natural gas within a 64m$^3$ room

Bauwens et al. [16] investigated the effect of vent size on the severity of ignitions of hydrogen, natural gas and propane within a 64m$^3$ room with two different vent sizes; a large (5.4m$^2$) or small (2.7m$^2$) square opening.

Ignition was from one of three locations, at the wall opposite the vent, at the centre of the enclosure and or the centre of the wall containing the vent.

Pressure transducers were located at the centre of the wall opposite the vent, one on the wall containing the vent, and two on a wall perpendicular to the vent (one on-axis with the centre of the chamber, one off-axis).

Flame speed was also measured using 20 thermocouples located inside and outside the chamber.

Tests were carried out using approximately 18% hydrogen and stoichiometric mixtures of methane (9.5%) and propane (4.0%), igniting the flammable gas mixture at the front, middle and rear of the enclosure.

**Key Findings:**

- The primary findings of this report related to the ability of CFD modelling to predict pressure against time. The model used gave a good prediction of initial pressure build-up for all ignition locations and vent sizes; and predicted maximum overpressures well for back and centre ignition tests. The model did not perform as well for front ignitions
- Transducers at different locations in the room measured broadly the same overpressures
- Combustion time decreased substantially as hydrogen concentration increased, ranging from approaching 1000ms (at 12%v/v) down to 80ms (at 19%v/v), with some laminar flame speeds at 19%v/v as low as 0.64m/s.
- There was no sign of detonation. This is consistent as concentration of 18% is generally taken as the lowest concentration for transition to detonation for a confined ignition of hydrogen [17]

## 4.10 Non-monotonic overpressure vs. hydrogen concentration behaviour during vented deflagration.

Sciavetti and Carcassi carried out work at the University of Pisa [18] involving ignitions of hydrogen within a 25m$^3$ purpose built cubic enclosure. The roof and one side were covered with glass panels and all other sides with steel panels (Figure 13).

Figure 13: Photo of the Chamber View Explosion (CVE) test facility [18]

The test programme was designed to investigate the phenomenon of non-monotonic behaviour of maximum overpressure in vented ignitions of hydrogen below stoichiometric concentration.

The CVE facility was fitted with an approximately 1.1m$^2$ vent that was designed to open at 2.4kPa and a safety vent which would open at 30kPa, thereby limiting any maximum overpressure within the facility.

The CVE facility could be configured in 8 different ways, to investigate the effect on an explosion of different levels of obstruction.

Hydrogen concentrations in the testing ranged from 7% to 13% and ignition was from in the middle of the wall opposite the vent at a height of 1m.

Pressure was measured at two locations, one in the centre of a steel side and one in the centre of the wall opposite the vent.

This paper provided pressure and impulse data for a range of concentrations between 9.6% and 12.3% hydrogen, for a range of different configurations of obstruction within the enclosure.

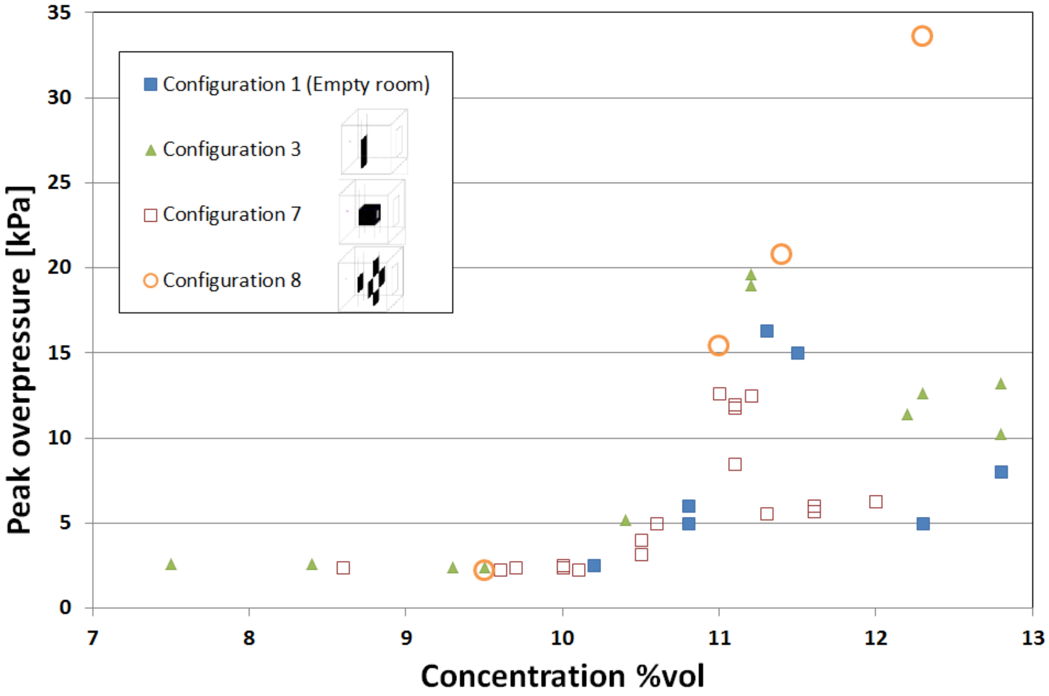


Figure 14: Effect of internal obstruction on peak overpressure [18]

**Key findings:**

- Figure 14 shows the peak over pressures measured in the enclosure for 4 different configurations. In most cases, the effect of adding obstruction to the test facility was to increase the overpressure (the more complex the obstruction the greater the effect) apart from at around the 11-11.5% concentration, where the overpressure of the empty room was higher or comparable to the room with obstruction. It was suggested that the non-monatomic behaviour was related to the geometry of the enclosure and the flame speed of the ignition.

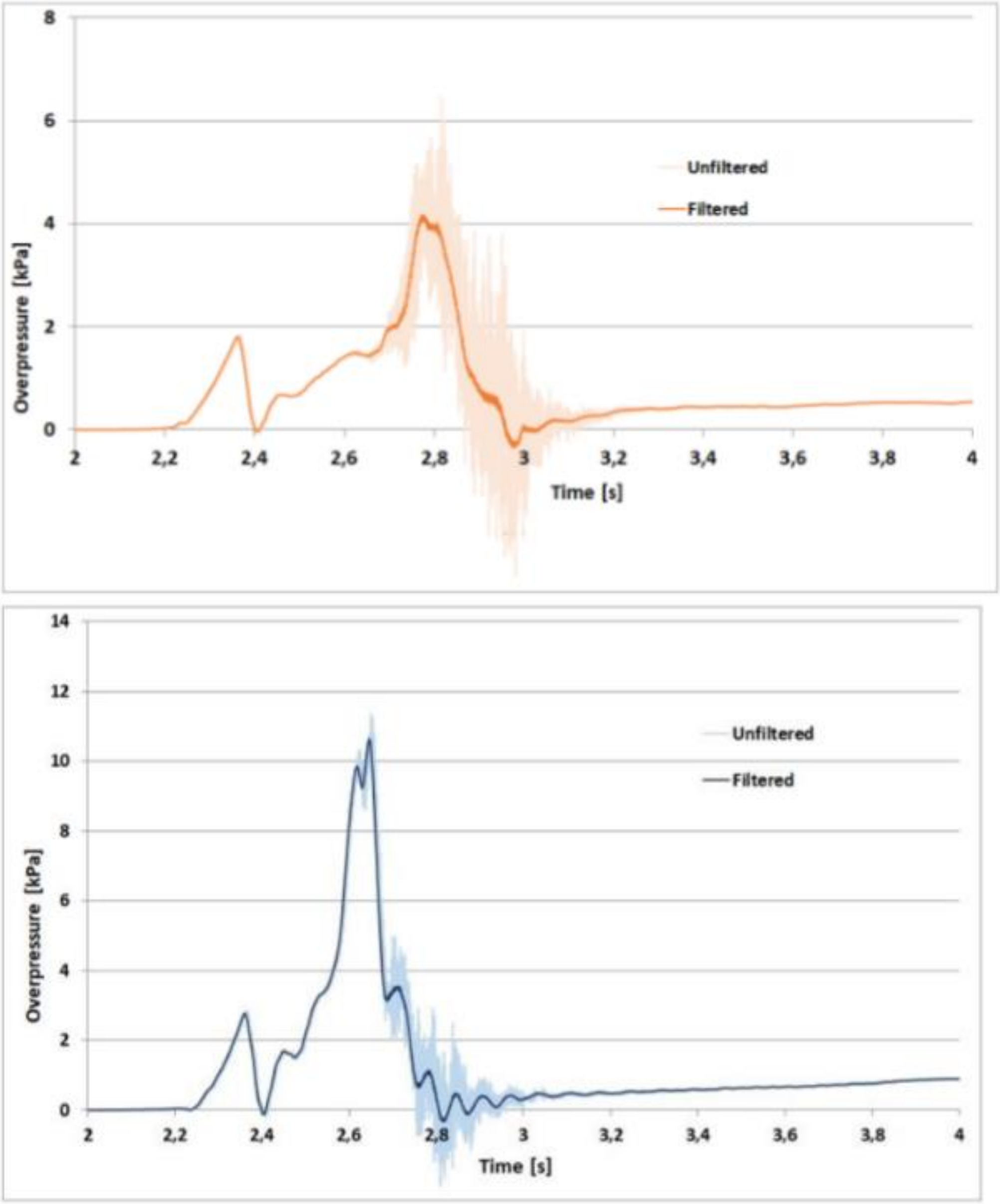


Figure 15: Examples of pressure histories for obstructed and unobstructed spaces [19]

- These graphs (Figure 15) from a presentation by the author of this study, Schiavetti and Carcassi show the pressure history for an ignition of hydrogen in an empty room and a room with obstruction. The effect of obstruction can be seen to produce an approximately 250% increase in peak pressure, but this was still below 120mbarg.
- No evidence of detonation was shown in any of the tests.

## 4.11 Laboratory testing of ignitions of flammable gases within a vessel

Marshall and Cubbage [20] investigated the relationship between pressure rise from ignitions of different quantities of stoichiometric mixtures of methane and the energy available in the mixture. The tests were designed to represent an explosion within a gas burning appliance.

Ignitions were carried out in a ~0.136m$^3$ bell-shaped vessel oriented horizontally with a tube protruding into the vessel from the narrow end. On the end of the tube, flammable gas mixtures were contained in a polythene bag which were ignited via an ignitor at the end of the tube. Pressure was measured next to the ignitor.

The effect on the overpressure of providing a vent to the chamber either directly, or through the inclusion of a flue, of short, medium and long length was explored.

Tests were carried out with different volumes of premixed stoichiometric methane air mixtures with volumetric energy content ranging from 0.29 to 5.9Wh/ft$^3$.

The flammable gas mixture in this study did not fill the entire container, rather the flammable gas was contained inside a polythene bag in the chamber.

An extension to the test looked at filling the remainder of the chamber with a sub-flammable gas in air concentration and looking at the effect on pressure rise.

Some additional tests involving towns gas and propane were carried out to examine the effect of burning velocities on pressure rise.

Key findings:

- The highest over pressure was recorded in the unvented chamber where the pressure trace reached a peak and decayed gradually as the temperature of the combustion gases cooled.
- A vent in the chamber reduced the over pressured recorded, however increasing the distance between the vent orifice and the chamber (via the flue) resulted in increasing over pressures until the maximum overpressure was comparable to the closed chamber.
- The addition of a flue created oscillations between positive and negative overpressures.
- The study found that there was an approximately linear relationship between pressure rise and energy contained in the gas mix (for small energy releases) up to about 1.5Wh/ft$^3$. Thereafter, the relationship became non-linear, with the pressure rise tending to increase more quickly.
- The study also found that the presence of a natural gas/air mixture below the LEL (<3.5%) surrounding the flammable mixture in the chamber, increased the overpressure recorded significantly, when the flammable mixture was ignited.

## 4.12 Investigation of large-scale deflagrations of flammable gases

Grothe et al. [21] conducted a series of experiments to assess the consequences of an accidental leak and ignition of hydrogen. The data collected was used in the evaluation of numerical models.

Ignitions were carried out in a 300m$^3$ dome, a tunnel, between two aluminium plates, in front of a blast wall and as an open release.

### 4.12.1 Dome

Homogenous concentrations of hydrogen (ranging from 15-30%) were contained within the dome by means of a thin polyethylene sheet, which was cut prior to ignition.

Ignition was from the bottom centre of the dome and the resulting overpressure was measured by sensors placed along the ground surface. In one experiment a high explosive charge was used to trigger a detonation.

The effect of obstruction was investigated by placing 18 cylinders of 0.46m diameter and 3m tall in two rings around the ignition point (this represented a volume blockage ratio of about 11%).

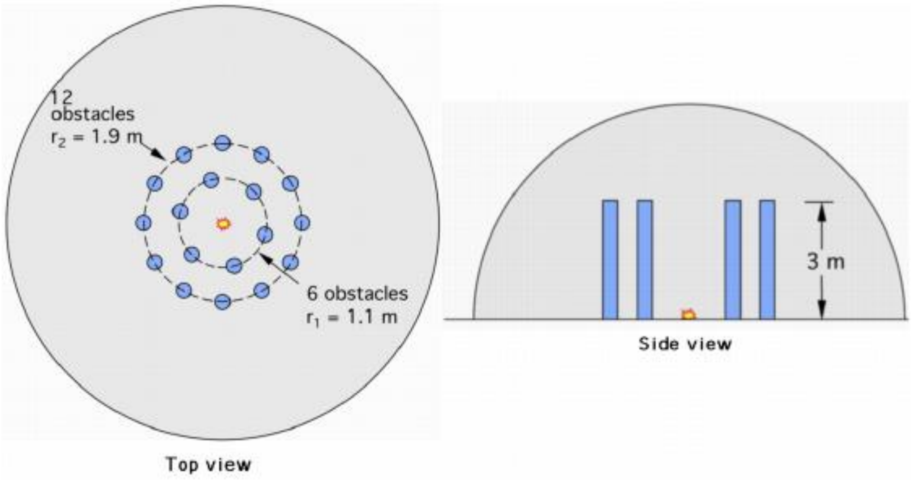


Figure 16: 300m$^3$ dome containing obstacles [21]

### 4.12.2 Tunnel

A 1/5 scale tunnel was constructed to investigate the result of an ignition of a leak in a road tunnel.

Homogenous mixtures ranging from 9.5% to 30% hydrogen were contained within a 37m$^3$ volume at the centre of the tunnel by HDPE film (cut prior to ignition).

Ignition happened at the bottom centre of the mixture and the resulting pressure was measured by sensors located down the length of the tunnel.

Additional tests explored the release of 0.1kg and 2.2kg of hydrogen into the tunnel both with and without forced ventilation.

Some tests involved model cars being placed within the tunnel, separated from each other by one vehicle length representing an aerial blockage of about 0.03.

The geometry of the tunnel is very different from a domestic situation and as such the results of these ignitions have been included for completeness only and has not been included in the consideration of the consequence of a hydrogen ignition in a domestic situation.

### 4.12.3 Partial confinement

The aluminium plate experiment was designed to investigate the effect of partial confinement on the flame speed and whether this might promote transition from deflagration to detonation.

Two 1m high 2m wide, aluminium plates of 6.4mm thickness were placed next to each other in parallel separated by 10mm.

A stoichiometric mixture of hydrogen was ignited by an ignitor in the gap at the bottom of the plates.

Pressure sensors measured the resulting blast.

### 4.12.4 Blast wall experiment

This experiment was designed to investigate the protection from a blast that might be offered by a wall.

A 4m by 10m wall was constructed and a 5.26m3 volume of stoichiometric hydrogen was paced 4m from the front surface of the wall and ignited. Pressure sensors on the ground, on the front of the wall and at two elevations (4m and 4m) behind the wall measured the overpressures from the blast.

### 4.12.5 Large scale release

This test was deigned to simulate what might happen from a large uncontrolled release of hydrogen from a storage container. Two vessels of volume 16.2m$^3$ were pressurised with hydrogen to 2.4MPa. It was then released vertically.

18m towers surrounded the release point, gas sampling points were fitted to the towers as were pressure and heat flux sensors. Ignitors were placed axially around the plume 5m above the release point.

The plume ignited spontaneously and prematurely, and the concentration could not be measured.

The overpressure and vertical flame speed were measured.

**Key findings:**

**Dome**

- The addition of obstacles in the dome did not increase the measured overpressures. It was suspected that the obstacles were too large to cause acceleration of flame speed.
- No evidence of DDT was seen during the ignition of 30% hydrogen (Figure 17)
- When the same concentration of hydrogen was ignited using high explosive a clear DDT event occurred (Figure 18). Note the near instantaneous pressure rise. High speed video and ionisation probe data was used to determine a detonation velocity of 1980m/s, which is in good agreement with the Chapman-Jouguet detonation velocity for a stoichiometric mixture of hydrogen and air [22].
- Despite the evidence of detonation, the free air overpressure was only about 800mbarg, which is lower than some ignitions where a DDT did not take place (e.g. the test in the closed ISO container [15]), this indicates that some confinement is necessary to generate very high overpressures.

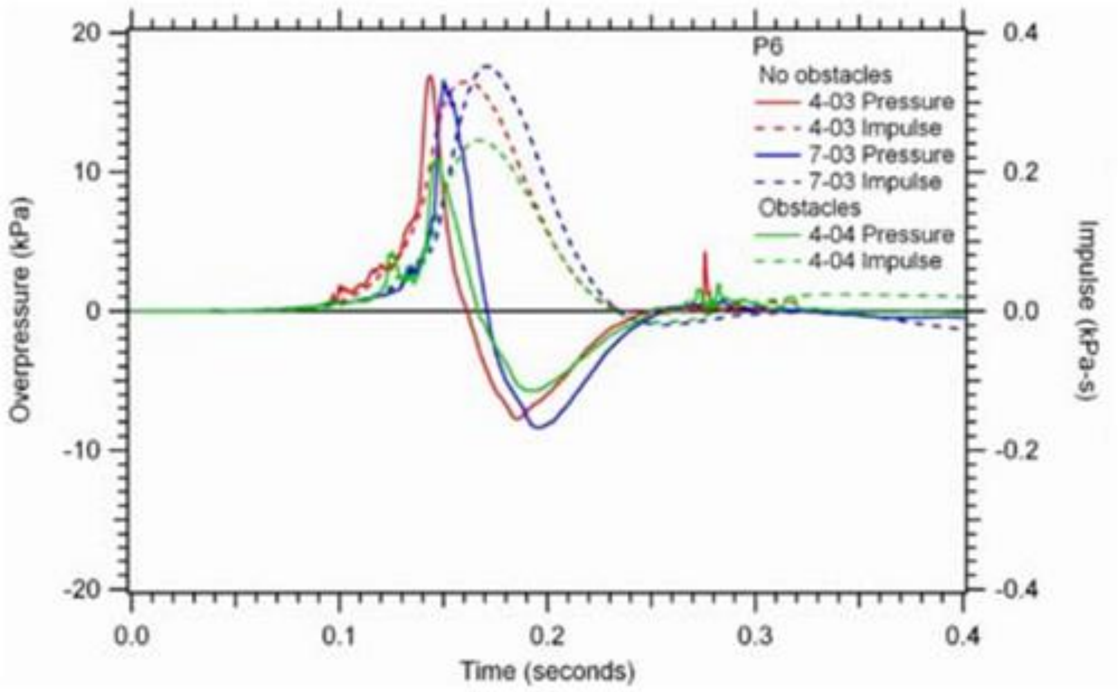


Figure 17: Overpressure/impulse for ignition of 30% hydrogen in a dome [21] at 15.61m from the centre

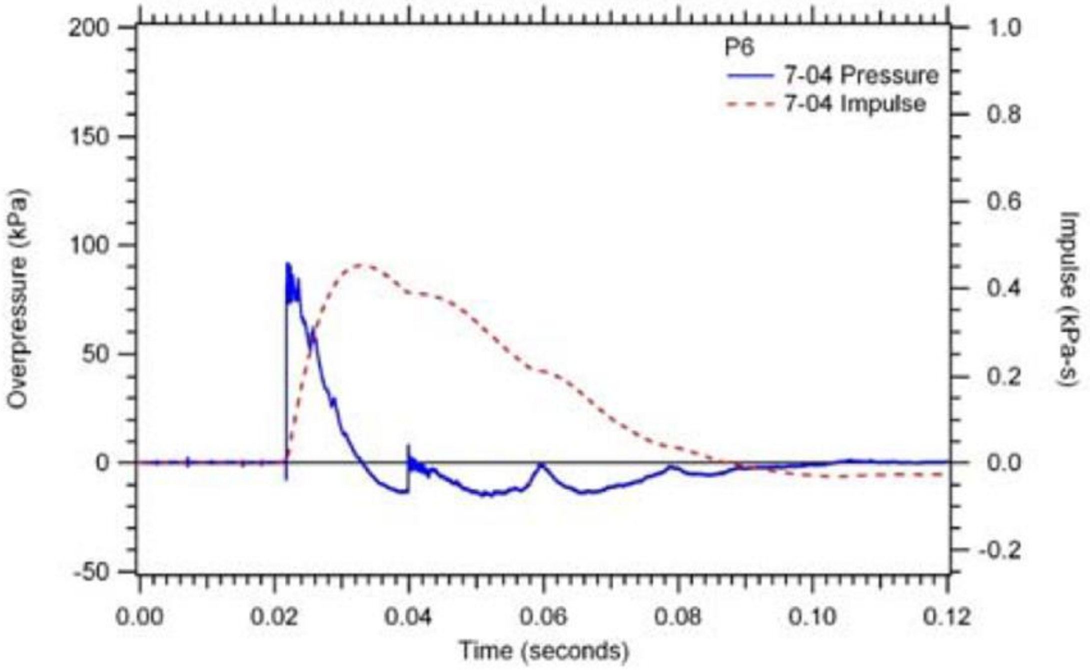


Figure 18: Evidence of DDT in the dome ignition using high explosive [21]

The shape of the pressure trace in Figure 18 (note the difference in scale to Figure 17) indicates an instantaneous transition of the whole combustion process from deflagration to detonation.

The pressure rise is an order of magnitude higher than in Figure 17 and the whole process is complete in around 10ms. Other experiments where DDT is observed indicate far more nuanced behaviour.

**Tunnel**

- For the homogenous gas mixture contained in the centre of the tunnel, the measured overpressure and impulse were fairly constant along the length of tunnel.
- The 30% tests resulted in very high over pressure and impulse compared to the equivalent test in the dome
- Release of small quantities of hydrogen in the presence of ventilation led to low concentrations along the tunnel which could not be ignited.

These results have been included for completeness only and should not be used in the discussion of a likely consequence of a hydrogen ignition within a domestic scenario.

**Partial confinement**

- Partial confinement did not lead to any enhancement of deflagration

**Blast wall**

- The blast wall showed a reduction in peak overpressure and impulse at close range behind the wall.

**Large scale release**

- Despite precautions being taken the experiment ignited prematurely.

## 4.13 Large scale hydrogen explosions and detonation

Rao et al. [23] conducted numerical modelling based on actual explosions in a simulated hydrogen refilling station and aimed to investigate how explosion overpressure decreased with distance from the enclosure.

An 8.25m by 3m by 2.7m test chamber was constructed that was open only on the front. All the other sides were closed. The chamber was partitioned along its length into three sections each with a volume of $22m^3$, giving a room volume to vent area ratio of $2.71m^3/ m^2$.

In each test, only one of the sections was filled with a hydrogen-air mixture.

Ignition was from a point at the centre of each filled section.

Pressure measurements were made at 5, 10, 15 and 320m from the open end of the chamber and no record was made of pressure within the enclosure.

**Key findings:**

- Figure 20 shows the pressure wave propagation for 30% hydrogen concentration at 5, 10, 15 and 20m from the enclosure exit.
- The further the distance from the enclosure the lower the overpressure
- There are multiple peaks for both overpressure and under-pressure at every distance which may be the result of blast wave interference and reflection from the structure
- The pressure traces measured outside the chamber did not show any evidence of detonation.

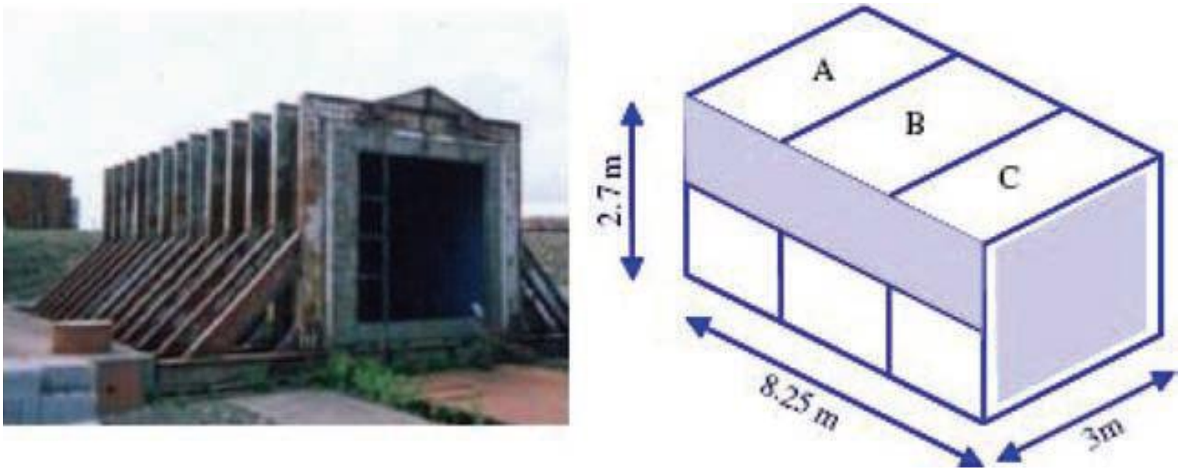


Figure 19: Simulated hydrogen refilling station (Reproduced from Tanaka et al. 2007 [24])

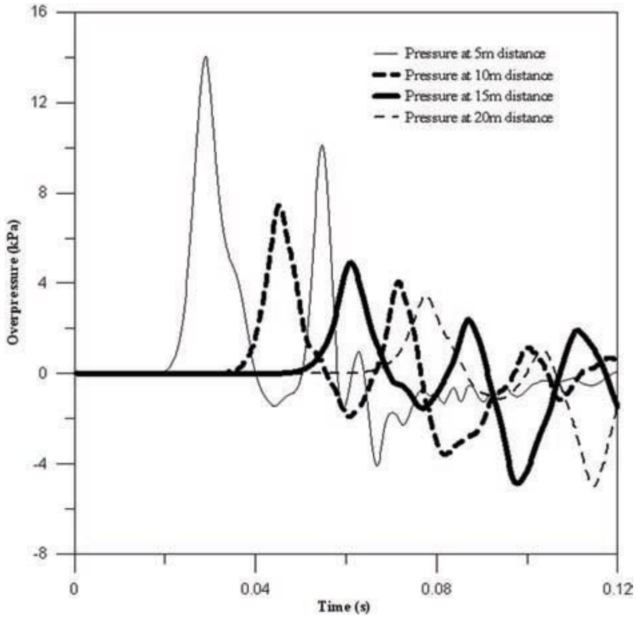


Figure 20: Overpressure curves at different monitoring points 30% hydrogen [24])

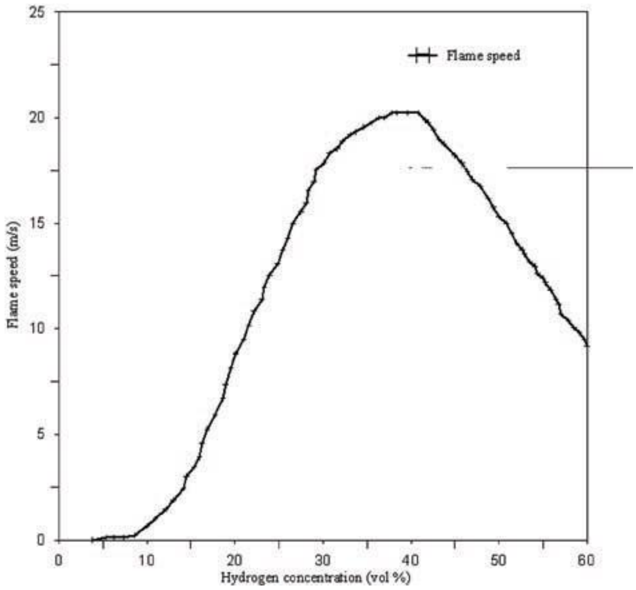


Figure 21: Flame speed vs. hydrogen concentration [24]

## 4.14 Vented Gas Explosions – PhD study

This PhD [10] investigated the design of venting that was required to be effective in mitigating the consequence of an ignition of flammable gas for industrial plant.

The study included a critical review of current US and European gas venting design standards and assessed their suitability against a programme of experimental work.

A series of experiments were carried out in 2 different cylindrical volumes, 0.2 and 0.0065m$^3$ with different levels of venting and different ignition locations. To safely vent combustion gasses, the test vessel was contained within a larger “dump vessel”.

Methane, propane and hydrogen and ethane were studied, and near stoichiometric concentrations were used.

**Key findings:**

- Evidence of partial detonation was observed for a stoichiometric mixture of hydrogen in the 0.0065 m$^3$ vessel. This was only seen for the hydrogen /air mixture,

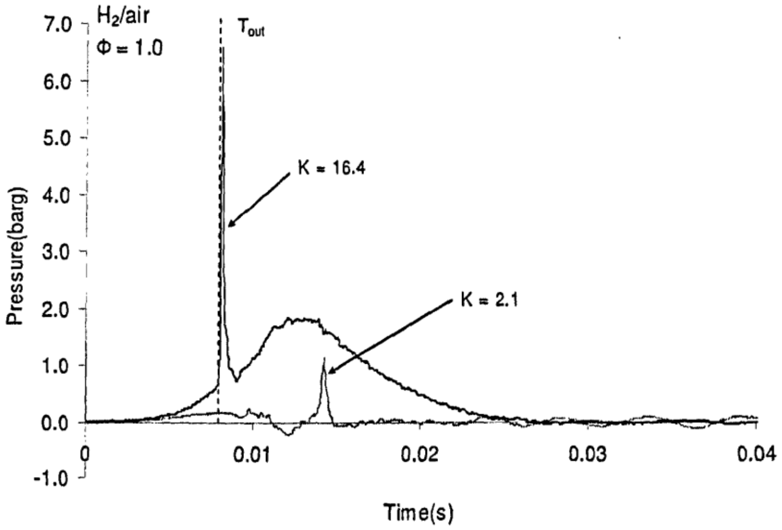


Figure 22: Detonation spike over deflagration - 29% hydrogen [10]

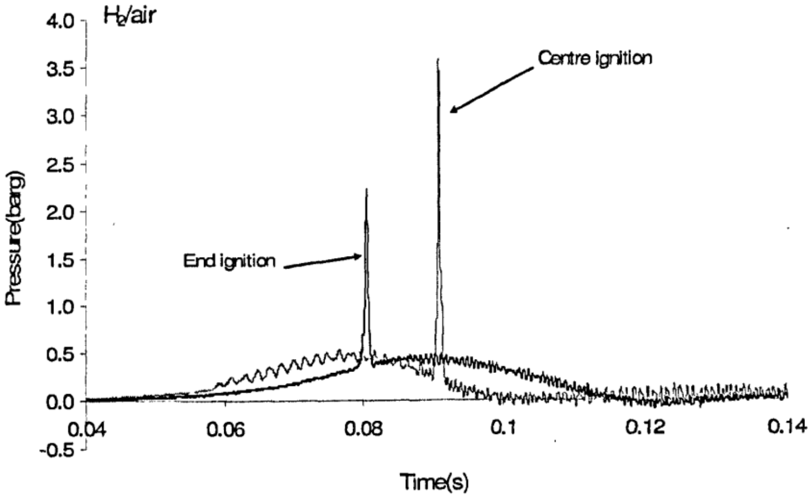


Figure 23: Detonation spike over deflagration - 16% hydrogen [16]

The sharp detonations are visible in Figure 22 and Figure 23 overlaying a general deflagration. The detonation spike in the 16% is unusual as this concentration is less than the usually accepted lower limit for detonation of 18% [17].

Kasmani believed that the spikes occur towards the end of the combustion process and postulated that it was caused by the combustion of unburnt pockets of hydrogen/air mixture around the vent connection. The vent diameter is much smaller than the vessel. It is not so much the precise shape of these detonations which is of interest but that they occur as adjuncts to general deflagration. The impulse within the detonation (areas under the curve) appears only a fraction of total impulse.

## 4.15 Resistance of brick buildings to gas explosions

Astdury et al. conducted a programme of experiments in response to the recommendation made by a tribunal following the Ronan Point disaster [25]. The Ronan Point disaster involved an explosion of towns gas within a tower block which caused the collapse of one corner of the building and the death of 4 people and injury to 17[1].

Tests were carried out in a structure built to simulate the top three stories of a tower block as well as within some neighbouring concrete granite hoppers. The test programme was designed to investigate the effectiveness of venting through windows and cladding and the resistance of brick walls (4½ and 9inch brick and 11inch cavity) to blast overpressure and resistance to collapse. The experiments also investigated how explosions cascaded from one room to another gas filed room within the tower building.

The overpressures required to damage a 4½inch, a 9inch brick wall and a 11inch cavity wall were studied.

Balloons filled with stoichiometric concentrations and stratified mixture of natural and towns gas were used.

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[1] https://en.wikipedia.org/wiki/Ronan_Point

**Key findings:**

- The effectiveness of venting was established and the pressures at which this occurred measured.
- Windows typically failed at 21mbar to 48mbar and chipboard cladding at about 70mbar.
- The pressure necessary to damage a load-bearing wall depended upon the restraint provided by the superimposed load and the ability to arch horizontality against vertical restraint.
- The 4½inch single leaf wall restrained on either side by the bunker walls, withstood pressures of 220mbar and failed at a peak pressure of 350mbar
- 9inch brickwork, fully restrained by the bunker walls withstood 210mbar without any damage at all and at 1050mbar suffered some cracking and bowing.

## 4.16 The relief of Gas and Vapour Explosions in Domestic Situations

This Fire Research Station note (FRN0759 [26] with correction/update in FRN 0847 [27]) was released to provide further information following the Ronan Point disaster. This note examined a similar flat to the one at Ronan Point and based on an estimation of the explosion relief potential of the flat and general principals of explosion relief developed in the note, estimated the maximum over pressure that could be realised from an explosion initiated at different locations in the flat.

The paper established which sections of each room could be expected to act as explosion relief (venting) and their approximate failure pressure, based on their construction, estimated weight and method of fixings.

A formula was proposed for the maximum overpressure that could be reached based on the failure pressure of the vent and the venting ratio (defined as the smallest cross-sectional area of the compartment/total area of the explosion relief).

Specially the note examined how to reduce the pressure experienced by external load bearing walls resulting from ignition of flammable gases and under what scenarios more than one load bearing wall may fail.

**Key findings:**

- Overpressure in unvented situations can reach up to 7bar, as expected for an adiabatic deflagration [26]
- Gas explosions take place more slowly (over several 100ms) than TNT explosions(<3ms). This usually gives burnt and unburned gases time to vent through an opening an external wall, reducing the pressure from the maximum. This is termed the maximum vented pressure
- In a domestic building there are several (potentially successive) sources of pressure relief e.g. Windows, doors, ceilings and lightweight doors. These mean small gas leaks resulting in small local deflagrations cause proportionally local damage e.g. just damage to one window or a window plus a door.
- Domestic buildings are a series of interconnected rooms rather than one space and the behaviour of explosion will depend on when different parts of the structure provide relief through failure
- Different maximum overpressures were predicted from explosions initiating in different rooms

- If external components to the building do not fail first, an explosion in one room may vent through an internal room into an adjacent room (e.g. through internal wall)
- Movement of gases through internal doors can create turbulence. Ignition of turbulent gases can create higher overpressures than non-turbulent gas
- A room should have means of explosion relief that happens before turbulent gas is ignited in an adjacent room

## 4.17 Report of the Inquiry into serious gas explosions

This report of the Inquiry into serious gas explosions was published in 1977 by King et al [28]. The Inquiry was ordered by the government of the day in response to a perceived increase in the number of gas explosions that were occurring as a result of conversion of the UK from town gas to natural gas. This conversion took place over the period 1968 to 1977 andis understood to have required the conversion of over 40m appliances in 13 m homes.

The report was over 100 pages long and had a major influence on gas safety. It reviewed in great detail the effect of the transition on all aspects of the gas network from low pressure distribution to the conversion of gas burning appliances.

The report is particularly interesting as it discusses the relative theoretical and observed overpressures generated by natural gas and town gas and compares these with actual overpressures and injury rates.

### 4.17.1 Theoretical difference in overpressures between gases

Figure 24 (taken from Appendix F of the report) is a graph of predicted overpressures for town gas and natural gas in a 28 m$^3$ room with a window of 2.7 m$^2$ and with a breaking pressure of 24 mbarg.

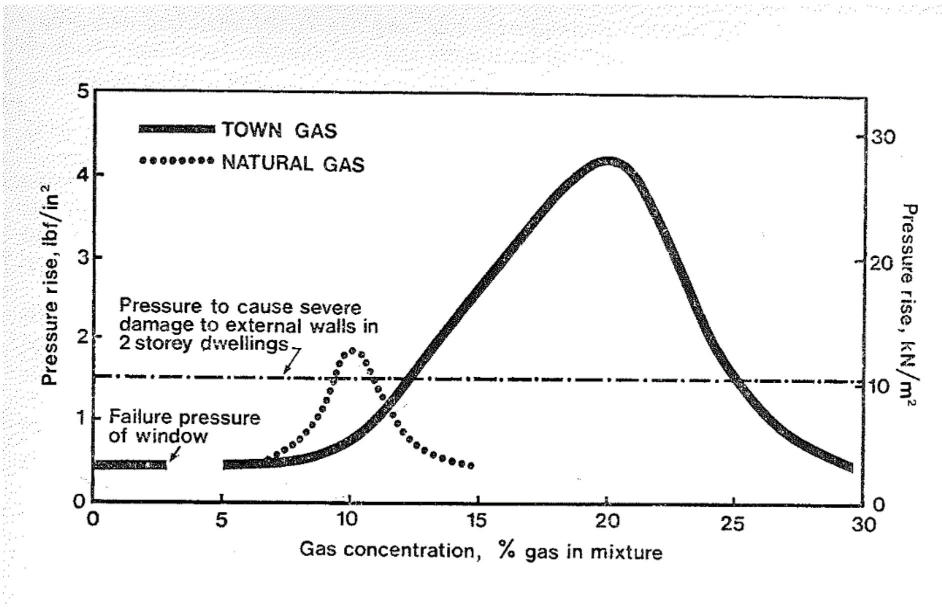

Figure 24: Town gas vs natural gas, calculated overpressure vs. gas concentration [28]

It shows that the expected overpressure from town gas is about 3 times that of natural gas. The report however also states that estimates of overpressures from observed damage from real incidents indicated that overpressures caused by ignitions of towns gas were on average only 20% higher than natural gas (13 kN/m$^2$ vs. 11k N/m$^2$). The reasons behind this apparent dichotomy (ie a theoretical threefold difference in overpressure and yet an observed difference of 20%) is explored further in section 6.7.

### 4.17.2 Fatality rate over the conversion period

Appendix E of the report presents statistics on gas explosions. Table 3 shows the number of fatalities caused by explosions over the year 1972/3 to 1976/7, during the conversion period. The net change over the period was equal to an increase of 1 fatality.

**Table 3: Fatality rate during period 1972/3 to 1976/7**

| Year | 1972/3 | 1973/4 | 1974/5 | 1975/6 | 1976/7 |
|---|---|---|---|---|---|
| **Fatalities** | 8 | 11 | 17 | 11 | 9 |
| **% Town Gas** | 45 | 33 | 22 | 11 | 1 |
| **% Nat Gas** | 55 | 67 | 78 | 89 | 99 |

Earlier data from Fire Research Notes 0826(1969) also observed little change in gas incidents or fatalities from the transition from town gas to natural gas per connected property per year.

**Table 4: Comparison of historic towns gas and natural gas incidents with recent natural gas incidents**

| 1969 | Consumers | Fires | Per million/y | Injuries | Per million/y |
|---|---|---|---|---|---|
| **Total** | 13,000,000 | | | | |
| **Town gas** | 11,700,000 | 138 | 11.8 | 53 | 4.5 |
| **Natural gas** | 1,300,000 | 18 | 13.8 | 7 | 5.4 |
| **2012-17** | | | | | |
| **Total** | 23,000,000 | | | | |
| **Natural gas** | 23,000,000 | 52 | 2.3 | 21 | 0.91 |

In addition to the theoretical difference in overpressures following ignition, predicted in the report, there are several technical reasons presented why the accident rate of natural gas and town gas might be expected to be different,

One such reason is the higher distribution pressure of natural gas than town gas (25-35 mbar for Natural Gas vs. 15-20mbar for town gas [28]) which might have resulted in more incidents from natural gas.

This apparent difference between theoretical overpressures and resultant damage is explored further in section 6.7.

### 4.17.3 Relevance to the relative consequence of an ignition of hydrogen

The purpose of making these comparisons between theoretical and actual overpressures and looking at real fatality data is to demonstrate that if town gas and natural gas were fundamentally different in terms of risk, a significant discontinuity would have been expected between the rates of incident involving each gas (tables 3 and 4).

The comparison of town gas (which is approximately 50% v/v hydrogen[2]) to natural gas, whilst not the same as comparing hydrogen to methane can provide some useful insight into the relative consequence of ignition of both gases.  This is explored further in section 6.7

**Key findings:**

- Despite a perceived increase in incidents over the town gas to natural gas conversion of the UK, there was no real increase in the incident rate of fires or fatalities over the conversion period
- The highest overpressure caused by an ignition of town gas (at around stoichiometric concentration) was theoretically modelled to be 3 times higher than an ignition of methane also at around stoichiometric concentration.
- From observation of actual incidents overpressures from town gas incidents were estimated to be only 20% higher than natural gas
- The explanation for the discrepancy was that stepwise failure of the windows, doors, ceilings and eventually the surrounding walls would limit the development of the highest overpressures. Many of these components begin to fail in the range 100-200mbarg.

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[2] https://en.wikipedia.org/wiki/Coal_gas

# 5 Summary of key findings from literature review

From examination of the evidence reviewed, it was found that:

1. Generally, the higher the concentration of flammable gases present, the more severe the consequence
2. There is evidence that the interaction between room shape and size and vent location can cause higher than expected overpressures from ignitions of very specific concentrations of hydrogen
3. The location of the point of ignition will affect the consequence of the ignition. The further the ignition point from the vent the higher the overpressure
4. The severity of a methane explosion was seen to peak at around stoichiometric concentration. The severity of a hydrogen ignition tended towards a maximum at around 10-15 percentage points above stoichiometric (40-45% hydrogen concentration)
5. The inclusion of obstruction, particularly highly ordered and repeated obstruction is likely to make the consequence of an ignition more severe
6. The presence of an area through which an ignition can be vented will lower the overpressure measured within an enclosure. The larger the vent area the lower the overpressure
7. General transition to detonation is very difficult to achieve, a general detonation involving most, or all the available flammable gas was only achieved by igniting the gas/air mixture with chemical explosives
8. Localised detonation was suspected in some cases. These cases involved enclosures within rooms where localised pockets of gas at a much higher concentration than the surroundings were able to accumulate or irregular shaped vessels where flow of unburned gas was able to accumulate. An example may be a cupboard space; when an escape occurs within a cupboard.
9. The behaviour of a deflagration in a domestic property (which is comprised of more than 1 adjacent room) depends on the location of the ignition, the layout of the property and the type of venting that is present in each room.
10. The King report (1977) indicated the much higher theoretical overpressures that can occur with Town Gas rather than natural gas, but that the observed pressures were only seen to increase by 20%. This is because of the stagewise failure of the weakest components of a property eg windows and then doors.
11. The ‘fire and explosion’ and death rates arising from Town Gas and Natural gas were very similar.

## 5.1 Exploration of experimental data

Pressure and impulse data extracted from the literature was plotted on iso-damage curves, in figures 25 to 29.

For ease of visualisation the data was split into gas in air concentration bands of 0-10%, 10-15%, 15-20% and 20-25% and 25%+. At:

0-10% hydrogen may be less severe than methane

10-15% there may be comparative damage between hydrogen and methane

15-20% hydrogen may be more severe than methane

20-25% hydrogen is likely to be far more severe than methane

25% + hydrogen is likely to be far more severe than methane

The Structural damage limits were derived by by W.E Baker et al [3] based on observed damage to buildings damaged by bombs during the second world war. The damage lines shown on the figures below correspond to:

- Lower – Threshold for minor structural damage; wrenched joints and partitions,
- Mid – Threshold for major structural damage; some load bearing members fall,
- Higher – Threshold for partial demolition; 50% to 75% of walls destroyed or unsafe.

The window damage limits (derived from experimental data, by Kummer [4]) correspond to:

- 5% window breakage (green),
- 50% window breakage (blue),
- 95% window breakage (red)

### 5.1.1 Comparison to modelled iso-damage curves

The iso-damage curves shown in figures 25 to 29 were derived from qualitative observations of damage to buildings during the second world war, including severity and type of damage, bomb crater size and location. Care should be taken when making comparisons to damage lines derived from theoretical modelling, however a comparison can be useful to provide context to the modelled lines.

Modelling work by Arup+ [29] (from first principles) generated iso-damage lines for two type of blast pulse (shock- and isosceles-triangle fronted).

Figure 68 in the Arup+ report [29] shows these modelled damage lines overlayed with the three experimentally derived lines by Baker et al [3] representing the thresholds for minor structural damage, for major structural damage and for partial demolition, respectively.

The modelled curves trend well with the experimentally derived line representing the threshold for major structural damage, in the impulsive region of the iso-damage curves (the vertical asymptotes to the left side of Figure 68).

Towards the horizontal asymptote of the graph, the modelled lines lie between the threshold for minor and major damage. This implies that the model may predict wall collapse more readily than suggested by the experimental data and thus the results of the modelling of deflagration consequence err on the side of caution.

### 5.1.2 Comparison of data from different experiments

Care must be taken when comparing pressure and impulse data obtained from experiments involving deflagrations in enclosures of different geometries. One traditional (although still potentially useful) concept is the “vent ratio” which can be expressed in different ways, for example as the ratio of the volume of the enclosure to the area of vent ($m^3/m^2$) or as the ratio of the cross sectional area of the enclosure to the vent area ($m^2/m^2$). The vent ratio, where relevant (expressed as volume of enclosure to surface area of vent) for each of the experimental configurations from which data has been extracted is presented in Table 9.

### 5.1.3 Consideration of relevant test data

The data presented in this section was obtained from experiments involving ignitions of flammable gas mixtures in different types of enclosure, constructed from different materials, with different levels of venting and with differing levels of obstruction.

None of the experimental configurations will perfectly represent a domestic property, but some tests were conducted in the enclosure configured in such a way that it is completely different to a realistic domestic situation. These test configurations must be identified as unrepresentative and data from these tests must not be used to inform the discussion surrounding consequences of ignition to a domestic property. As said above, the important difference between domestic property and single vent test boxes is ability of a domestic room to vent in a progressive fashion and thus not force (by way of example) the flame front to move only from the point of location to the window. If the overpressure in the room rises sufficiently to open a 2nd window or a door or some other weak spot in the fabric the bulk gas movement solely to the 1st window will be reduced, and is likely not continue to increase on its previous exponential trajectory. The property will not collapse until the rising pressure causes a structural member to fail. This might not occur until 150 mbarg or more. It is worth noting that as these deflagrations are slow (relative to sonic speeds) and the pressure on all of walls of room undergoing such a fire (and thus rising rapidly) will remain approximately equal.

Some experimental set-ups, although quite different to a typical domestic property might still be able to inform the discussion and these tests has been labelled as partially representative.

Deflagrations in domestic property will always have some means of relief via venting., for this reason the test carried out by Skjold et al. [15] in the ISO container with door closed has been considered unrepresentative. The ISO container tests were predominantly designed to investigate the consequence of a deflagration at industrial plant and the type of obstruction used was typical of the type that might be found at such sites.  The test involving the bottle basket and pipe rack obstruction has been identified as not representative as it is unlikely that such a large volume of a domestic property would be taken up by highly ordered repetitive obstruction. The data involving pipe rack and bottle basket obstruction has been identified as partially representative

The shocktube insert used in the tests by Kiwa was geometrically designed to cause maximum enhancement of the deflagration and it is highly unlikely that such purpose built obstruction would be found in a domestic property, thus the shocktube with insert configuration has likewise been considered unrepresentative.

The shocktube with full bore pendulum configuration was designed to represent a minimally vented enclosure and has been considered as partially representative.

The test in the tunnel has been considered unrepresentative due to the specific geometry of a tunnel and the dome test.

More discussion on the applicability of data to the domestic situation is given in section 6.

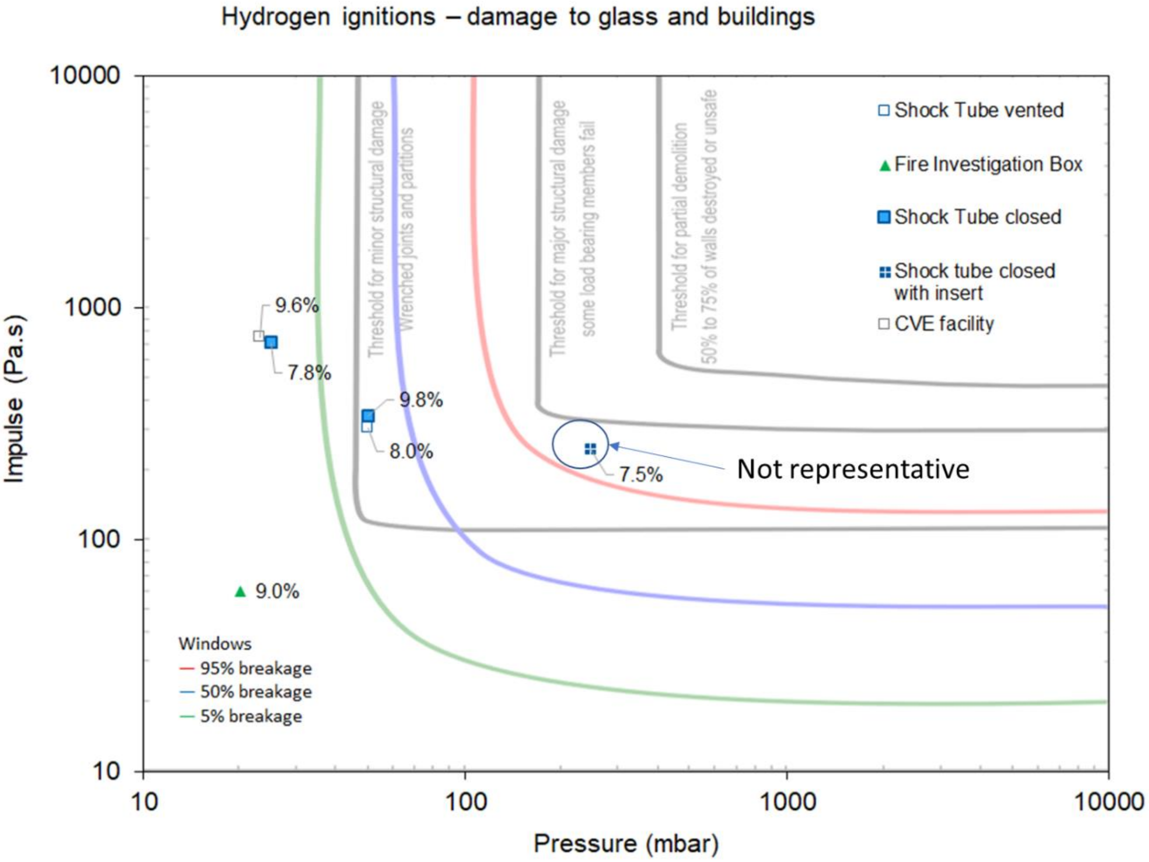
Data from all tests (including those identified as not-representative) has been included on the graphs in sections 5.1.4 to 5.1.8.  Whilst not directly relevant to the discussion surrounding consequences of ignition to a domestic situation, this data can provide insight into factors that generally affect the consequence of a flammable gas ignition

Table 5 summarises the experimental conditions and a brief explanation of their significance to the discussion around ignition consequence in a domestic situation.

Table 5: Selection of relevant data points

| Experiment | Configuration | Category | Rationale |
|---|---|---|---|
| Shock tube [13] | Reduced bore pendulum | Representative | Vented ignitions |
| FIB [12] | All | Representative | Vented ignitions in simulated kitchen |
| 64m$^3$ room [16] | All | Representative | Vented ignitions in purpose-built room |
| Garage tests [14] | All | Representative | Vented ignitions in purpose-built garage |
| CVE test facility [19] | All | Representative | Vented ignitions in purpose-built room with obstruction |
| ISO container [15] | Pipe rack obstruction | Indicative / partially representative | Vented ignition with regular obstruction |
| ISO container [15] | Bottle basket obstruction | Indicative / partially representative | Vented ignition with regular obstruction |
| Large scale deflagrations [21] | Dome | Indicative / partially representative | This was an ignition within an unenclosed space |
| Shock tube [13] | Full bore pendulum | Indicative/ partially representative | Minimally vented ignitions |
| ISO container | Doors closed | Not representative | Unvented ignition |
| ISO container | Pipe rack and bottle basked obstruction | Not representative | Vented ignition with regular obstruction unlikely to be found in domestic situation |
| Large scale deflagrations [21] | Tunnel | Not representative | Unusual geometry unlike domestic situation |
| Shock tube [13] | Full and reduced bore. with insert | Not representative | Specific obstruction unlikely to be found in domestic situation |

### 5.1.4 Damage graphs 0-10%



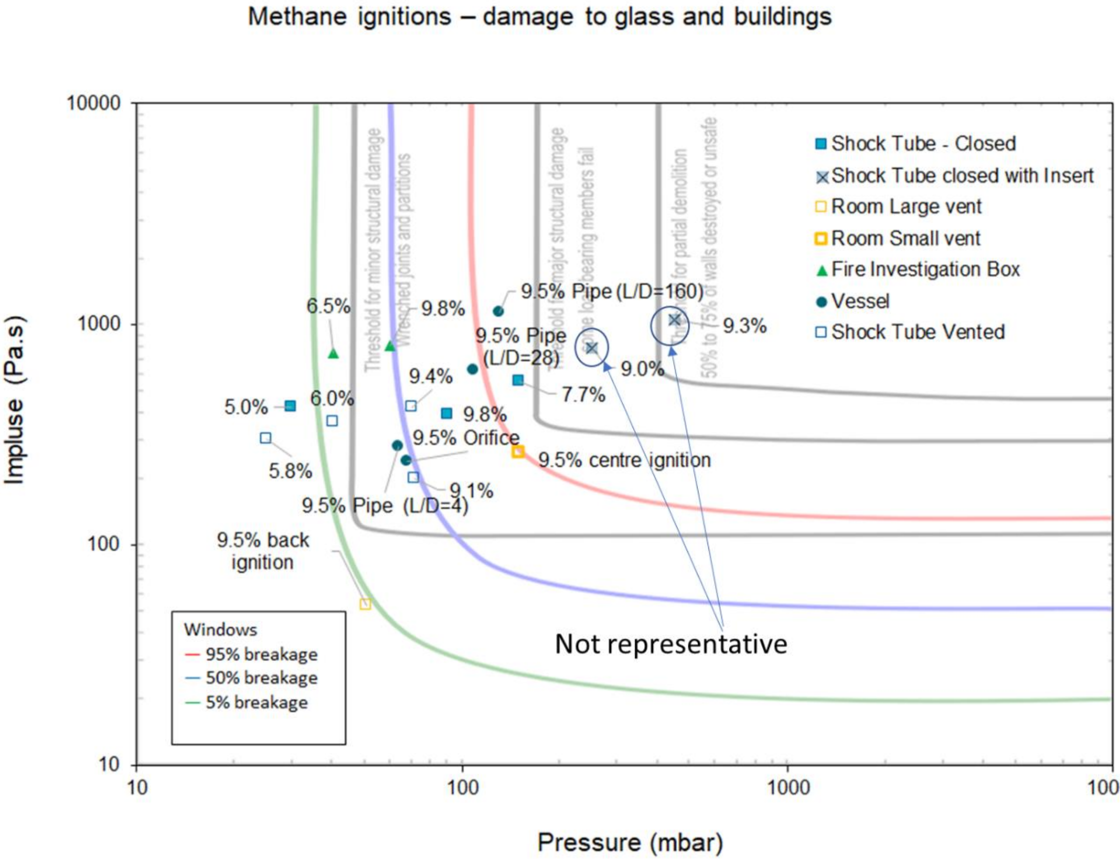


Figure 25 iso-damage graph 0-10% hydrogen and methane

The effect of venting can also be shown by comparing the results of the open and closed shock tube and room with small vent and large vent. The effect of venting is to reduce the overpressure. When the results of the closed shock tube with insert are removed as unrepresentative (see section 5.1.3) the remaining results demonstrate the consequence of a sub 10% (but above LEL) ignition of hydrogen. Such an ignition could result in some minor structural damage with between 5-50% glass breakage at the higher end and no damage at the lower.

The pressure/impulse points for a sub-10% methane ignition are generally towards the higher damage area of the graph although all points are below the threshold for major structural damage. The effect of vent size on the impact of an ignition can be seen from the room with different vent sizes. The lower the vent area, the higher the consequence of ignition.

The effect of the geometry for the vented vessel can be seen; the consequence becomes more severe as the vent location is moved further from the chamber (represented by the increasing ratio of tube length to vent diameter).

The results for the room with large vent, the FIB and the vessel vented through the orifice can be used to predict the consequence of an ignition of sub 10% methane. Such an ignition is likely to be similar for sub 10% Hydrogen with minor structural damage and over 5% of glass breakage.

It is appreciated that this data is very restricted in terms of the insight it offers of the impact of chamber volume, shape and vent area vs overpressure. This explains why (for example) the H100 FIB (with three windows and door) showed little damage with methane below 10% when it is known that methane can demolish whole properties. Essentially the structures (i.e. the FIB) within which the deflagrations were carried out were strong enough to resist damage given the relatively large area of the vents, windows or doors and the strength of its construction vs. a house (the FIB is a corrugated steel ISO container vs. a kitchen, which would normally be expected to have a timber/concrete floor, brick walls and a timber/concrete ceiling).

### 5.1.5 Damage Graphs 10-15%

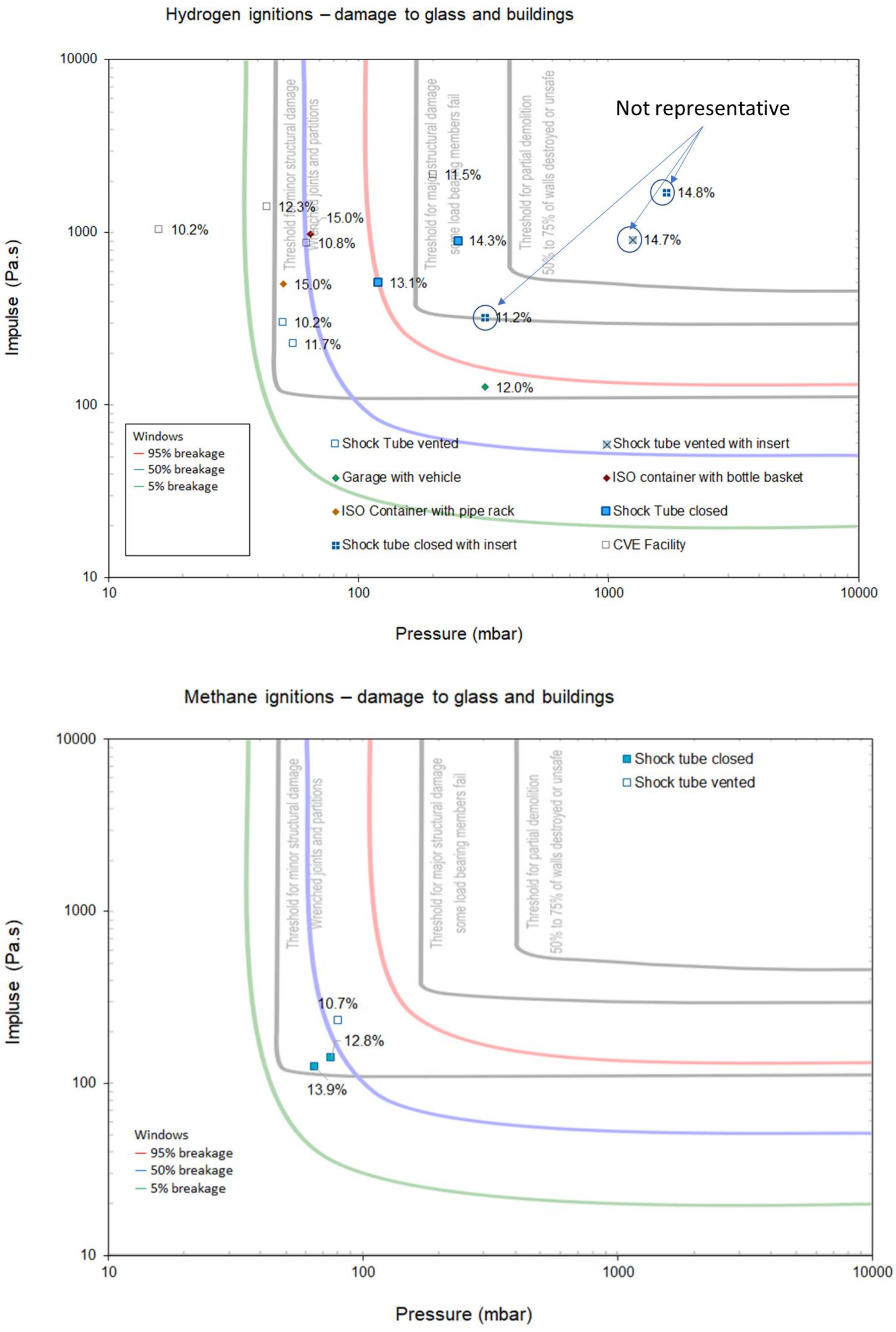


**Figure: 26 a and b 10-15% ignitions**

The results of the shock tube with specially designed insert (open and closed) lie towards top right of the graph representing significant damage but un unrepresentative of a domestic situation (see section 5.1.3). . Once these are removed the results of the CVE Facility, ISO container (with bottle basked and pipe rack), vented shock tube and garage with vehicle, can be used to give an indication of the consequence of an ignition of 10-15% hydrogen.

The consequence of such an ignition could range from no structural damage at the lower end of the concentration range with major structural damage with over 95% glass breakage at the higher end.

The only available comparative data for a sub-15% ignition of methane is for the closed shock-tube; however, the consequences are less severe, with the damage caused being structural and perhaps 50% glass breakage. This is even in the case of a closed shock tube, representing a room with little venting.

Again, the iso-damage lines appear to underestimate the damage from methane (real destruction can be much worse), and it may be possible that the same would apply to the hydrogen results. However, the purpose of the charts is to enable a comparison between the gases to be made within the same band of concentrations.

### 5.1.6 Damage Graphs 15-20%

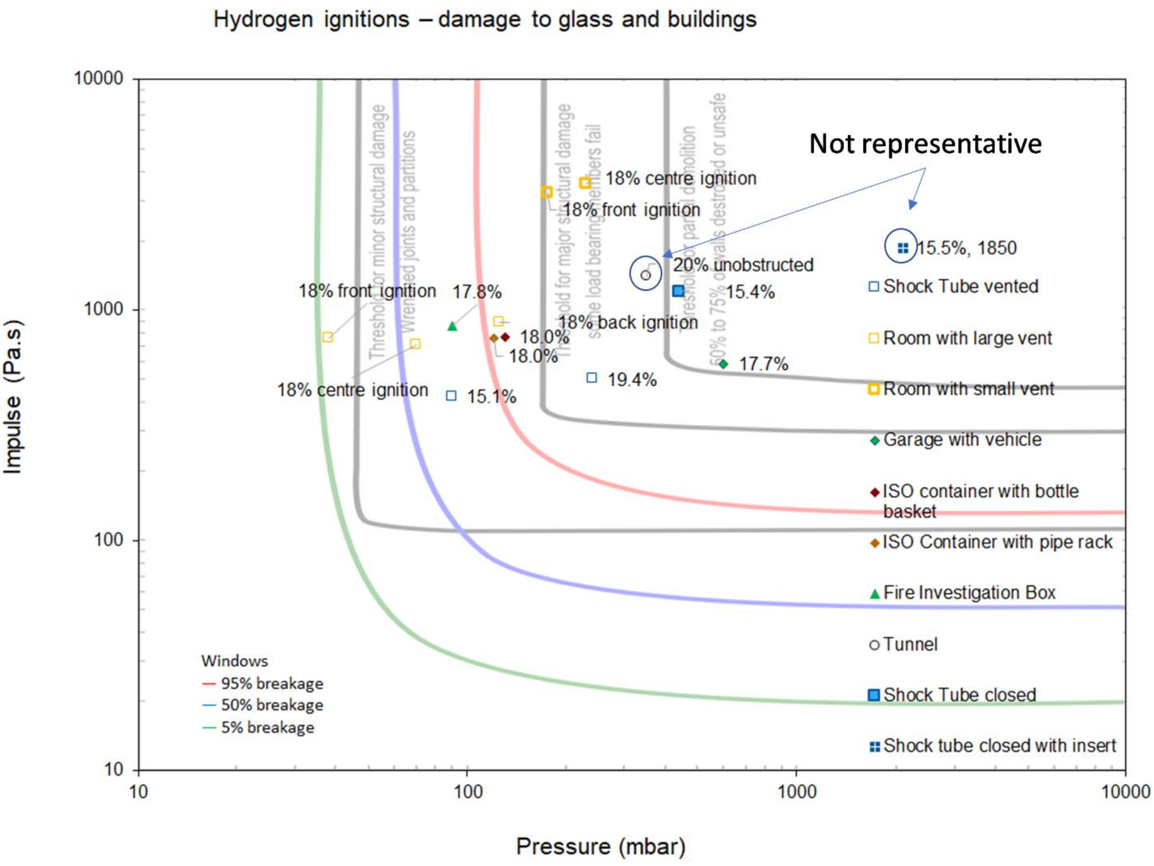


Figure 27: 15-20% ignitions

The effect of ignition location can be seen from the results of the room with large vent. The further the ignition location from the vent location, the large the peak overpressure for a similar impulse.

The results of the tunnel are not applicable to the domestic situation given the very different geometry of the structure. The closed shock tube with insert lies to the very top right of the graph representing significant damage but also should not be considered in the case of domestic situation (see section 5.1.3).

The results for the open shock tube, ISO container with 2 levels of obstruction and room with large and small vents can be used to determine the effect of an ignition of 15-20% hydrogen.

The consequence of such an ignition could range from no structural damage (with some window breakage) for an ignition in a room with large venting and ignition point close to the vent to minor structural damage to load bearing components and over 95% window breakage.

The closed shock tube results, although only partially representative of a domestic situation (see section 6) indicate that partial demolition is possible in the case of a minimally vented enclosure.

An ignition of such a concentration in a garage containing a vehicle is likely to produce a more severe consequence with 50-75% destruction of the garage.

There is no experimental data with which to compare a methane ignition of similar concentration.

### 5.1.7 Damage Graphs 20-25%

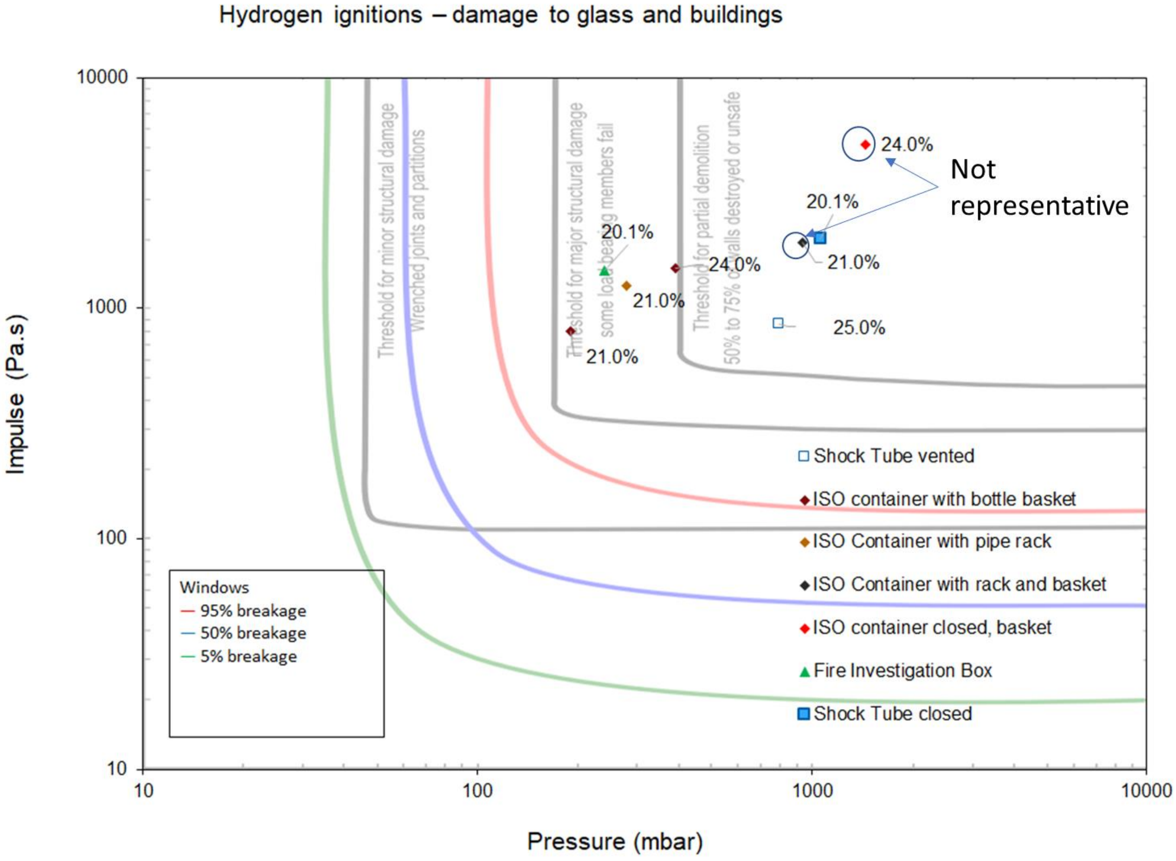


Figure 28: 20-25% ignitions

The effect of obstruction on consequence can be seen for the ISO container tests with 3 different levels of obstruction. An ignition of 21% hydrogen has a more severe consequence for the container containing both pipe rack and bottle basket, however this type of highly regulated and repetitive obstruction is unlikely to be found in domestic situation.

The result with the most severe consequence was the result of the closed ISO container. This is also not considered to be representative of a domestic situation as a domestic situation will usually feature some method of venting.

After removal of the most severe results, the data suggests an ignition of 20-25% hydrogen could lead to major structural damage with load bearing components failing at the lower concentration end, up to 50-75% demolition at the upper end.

There were no methane ignitions of similar concentrations with which to make a comparison.

### 5.1.8 Damage Graphs 25%+

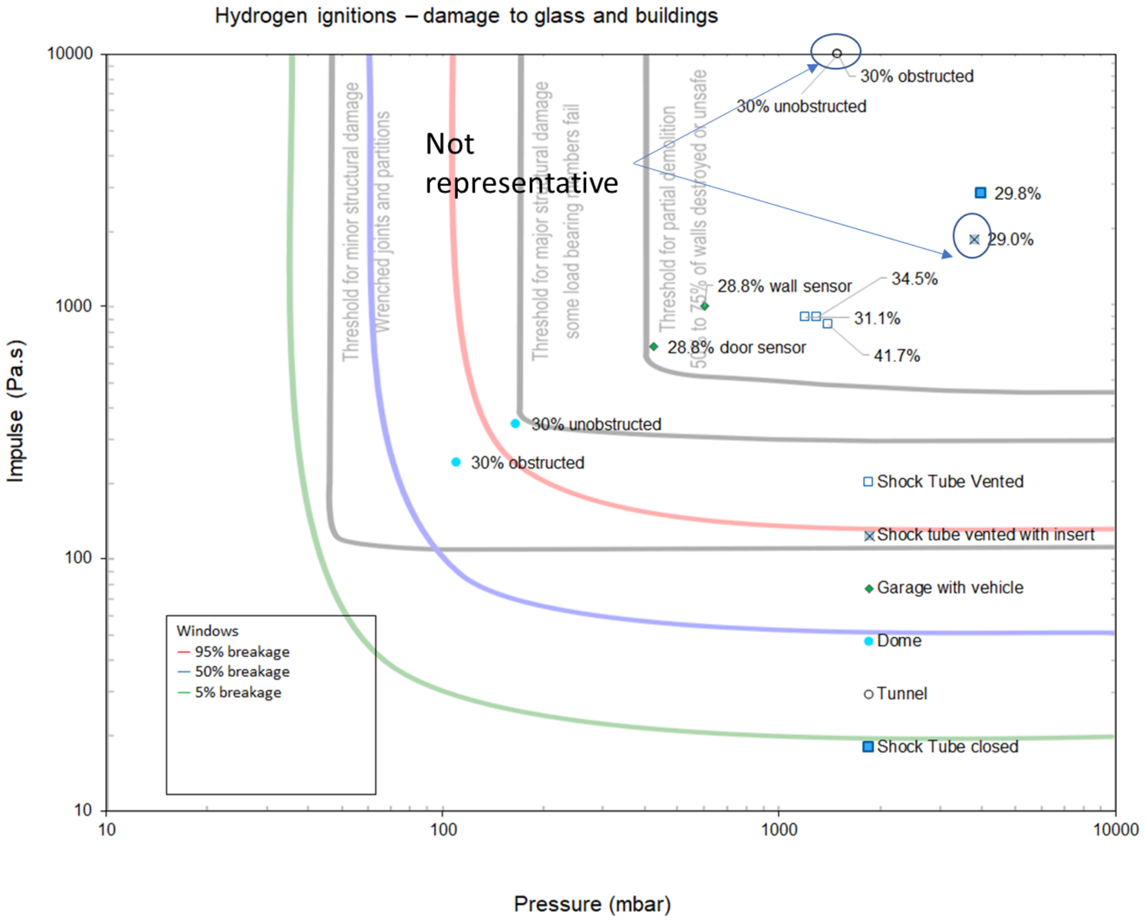


Figure 29: 25%+ Ignitions

The effect of an ignition of 30% hydrogen in an unenclosed space can be seen from the ignition in the dome. An unenclosed ignition is likely to result in lower over pressures than would be realised in a domestic situation. Although this situation could represent an enclosure with extremely high vent area for example a glass conservatory.

The 30% ignitions in the tunnel has the most severe consequence. In this situation the addition of obstruction makes no difference to the result, and the authors of this study speculated that it was due to the model cars occupying too small a volume to disrupt the deflagration. The geometry of the tunnel is very different to, and cannot be considered representative of, a domestic situation.

The garage ignitions and shock tube results show that an ignition >25% of hydrogen could cause partial demolition of the enclosure, with the partially representative closed shock tube demonstrating that the consequence would be most severe in a minimally vented enclosure.

The open vented shock tube results show a reasonably similar consequence for concentrations of between 31% and 41% hydrogen again with partial demolition of the enclosure.

There are no >25% methane results with which to make comparisons.

# 6 Discussion of literature and applicability to domestic situation

Analysis of the literature suggests that the following factors have an impact on the consequence of igniting flammable gas/air mixtures.

## 6.1 Concentration of flammable gas

### 6.1.1 The general ignitability of hydrogen

Because of the relatively high concentration of hydrogen required for stoichiometric combustion in air (~30% compared to 9.5% for methane), the energy content (kJ/m$^3$) of the very lowest flammable limit of hydrogen combustion is low

In addition to the flammability ranges of gases obtained through experimentation by Coward and Jones (section 4.1), Molkov [8] summarised the flammability ranges of hydrogen in Table 1

Table 1 shows that a deflagration of hydrogen will not propagate in all directions for concentrations less than about 8.5%. This means that an ignition of a concentration lower than this may not burn in all directions and may not consume all the flammable gas present, leading to lower over pressures and impulses than if the deflagration was more general and consumed all the flammable gas. These are frequently referred to as flash fires. Experiments in the garage of 8% concentrations of hydrogen showed that flames did not have enough energy to be self- propagating and flames tended to self-extinguish [14].

The lower flammability limit of methane is around 5% and whilst a flame at this concentration will tend to propagate in all directions it will only remain self-sustaining close to the point of ignition [7]. Thus, the nature and consequence of a hydrogen ignition of less than 8.5% concentration will be different to a deflagration of around 5% methane.

An ignition of sub 8.5% hydrogen still has the potential to cause significant overpressures within a sealed chamber but in practice and in any domestic situation the overpressure will be reduced via venting through a door or a window (see section 6.2). In a domestic situation the primary risk at such a concentration is from flash fires and burns to occupants or ignition of other combustible material.

### 6.1.2 Concentrations above the upper flammable limits

In all experiments studied, the higher the concentration of gas, the higher the overpressure for the same test parameters, however most studies did not test concentrations of flammable gas that were much above stoichiometric. The data on consequences of ignitions much above stoichiometric conditions is limited.

## 6.2 Blast venting

The studies examined showed that an ignition within a vented enclosure will lead to much lower overpressures than a similar explosion within a completely enclosed structure. This is known as the reduced overpressure. In a typical domestic environment this is <200 mbar (0.2 bar) compared to an adiabatic pressure rise to 7 bar [26].

Experiments by Bauwens et al. [16] showed that increasing the vent area reduces the overpressure for both methane and hydrogen.

The unenclosed dome used in the tests carried out by Grothe et al [21] is an example of a completely vented space i.e. with no surrounding walls and the overpressure and impulse for this test was significantly lower than for other tests of similar concentration, for example the test carried out in the tunnel. When ignited conventionally this resulted in a maximum overpressure of only around 170 mbar.

The combustion chamber type tests by Marshall and Cubbage [20] showed that increasing the separation from the enclosure to the vent location (via a length of flue pipe) results in increased overpressure until it is, in effect, behaving like an unvented space.

In most domestic situations, windows and doors provide the means for an explosion of flammable gas to be vented.

## 6.3 Construction of enclosure

The material construction of the enclosure will impact the overpressures recorded. As demonstrated in the garage tests, the weaker sections of the garage (the timber door, then timber roof and then main block structure) each failed at progressively higher overpressures. These failures provide a means of venting the explosion.

Similarly, an explosion within a domestic space will be vented through the window, or door or other weaker parts of the building as the pressure builds and exceeds the failure pressure of the different components. Thus, for any experimental results to be relevant to a domestic situation they must be from explosions in vented enclosures, preferably made from similar materials to those found in buildings and not steel boxes.

## 6.4 Obstruction within the space

The studies involving obstruction were primarily intended to model industrial situations. They demonstrated that the effect of adding obstructions within an enclosed space will result in increased overpressures, particularly where this obstruction is ordered and repetitive (for example the pipe rack and bottle basket obstructions).

The effect on obstruction on overpressure was most pronounced in the case of the shock tube insert which had been geometrically designed to enhance the deflagration.

An exception was in the case of the dome and tunnel where the addition of obstruction did not cause an overpressure to increase, it was theorised that the obstructions were either too small or too large to cause significant enhancement of the deflagration.

This type of highly ordered, repetitive obstruction is unlikely to be present, and so can be considered not representative of, a domestic situation.

### 6.4.1 Enclosures within a space

Both the FIB [12] tests and the garage [14] tests showed that when there were other compartments or enclosures within a space, and the gas was leaked either directly into the enclosure or from below it in such a way that there was preferential flow into the enclosure, it was possible to get localised build ups of higher concentrations than the average concentration within the space.

These studies also showed that it is possible that the presence of local pockets of high concentration gas within a deflagration could promote a localised transition to detonation (see section 6.5).

Hy4Heat is considering the effect of adding additional ventilation to cupboards, although this primarily to reduce hydrogen concentration.

## 6.5 Deflagration to detonation transition (DDT)

The deflagration to detonation mechanism can be instantly initiated using explosive igniters (as seen in the Dome test in the study by Grothe et al. [21]. Alternatively, it can also occur from turbulent flame acceleration often associated with a phenomenon known as “Flame Wrinkling” where the surface area of the flame become expanded, increasing the reaction between burning and unburned gases.

Severe turbulence can be generated by:

- a flame front accelerating down a pipe
- a mechanical device like a fan
- a series of bluff bodies sufficient to raise average gas flow
- a small isolated zone which is heated and then ‘collapses’ after the combustion front passes by.

A hydrogen concentration of 18% is generally taken as the lowest concentration for transition to detonation [17] for a confined explosion.

The total transition of hydrogen explosions from deflagrations to detonations has been intensely studied and clearly can occur in a range of situations, but is unlikely:

- below 18% v/v
- and in a simple unobstructed box (as occurs for example near the ceiling of a domestic room e.g. a kitchen)

The existence of explosive charges is not considered reasonable in a domestic situation.

Even above 18%v/v where some detonation has been suspected e.g. by Kasmani [10], in garage study [14] and FIB experiments [12] it is often very localised, the bulk of the combustion taking several 10s to 100s of milliseconds. These are long time periods compared to the very short time frame associated with detonation (for example, in the dome ignition initiated with high explosives Figure 18).

In these cases where localised transition to detonation was shown, the detail of the experiments suggested that there might have been complex geometry within a hydrogen filled compartment that could offer significant obstruction, leading to one of the mechanisms by which severe turbulence is formed, leading to localised DDT. The general shape of the pressure time history in these experiments (i.e. sharp pressure spikes imposed on a general deflagration shape (figures Figure 8, Figure 23 and Figure 22)) suggest that the energy created from these local detonations is not large enough to back detonate the remaining gas, which in turn seems logical because as the bulk deflagration occurs, the general hydrogen level reduces. This is particularly the case where the localised detonation spike occurs towards the end of the general deflagration.

A similar situation may occur in a kitchen when an ignition of a flammable atmosphere of gas leads to a general deflagration, which in turn ignites a pocket of higher concentration gas within a suitably obstructed enclosure (such as an under stairs or under sink cupboard). In this situation some localised detonation within the cupboard may occur. The SGN H100 FIB tests simulated this with the hydrogen released into a cupboard under the kitchen sink. The results are described in the Annex; as the sink cupboard doors opened (as a result of ignition from outside of the cupboard) some step change in local combustion was observed but this had no detectable effect on the pressure traces.

Theoretically, if DDT did occur within the cupboard (from an internal ignition source) it could possibly provide enough energy to back detonate the remaining gas in the surrounding space leading to general DDT, further experimental work would be required to better understand this risk; however the likelihood of an ignition source and subsequent local DDT within such a cupboard (which must be both strongly built and obstructed) is considered low.

## 6.6 Properties with multiple rooms

The experimental data in this report has dealt mainly with vented deflagrations in a single room.

The behaviour of a deflagration in a real domestic situation with interconnected rooms is likely to be more complicated.

The fire research notes (FRN0759 and 0847) show that different components of the property fail at different pressures and relieve the blast at different stages of the deflagration. The maximum pressure that would occur is likely to be different depending on the room in which the deflagration was initiated.

How far the deflagration spreads throughout the property will depend on the strength of the walls, doors and windows in the room of ignition as well as between adjacent rooms. The location of load bearing walls in the property is critical to understanding the consequence of an explosion

A related issue that is more concerned with dispersion, but that can affect the consequence of an ignition, is the build-up of high levels of flammable gases (particularly methane) in the room with a leak, which then starts to dissipate (through internal doors and windows) into adjacent rooms. If the deflagration is initiated in the room containing the leak the presence of the unburned gas around the room vents will act as a barrier to the escaping combustion gases and act to reduce the blast relief potential of the vent. This is well documented but is impossible to quantify, especially as in a real domestic property there are likely to be several vents. This mechanism is the origin of the clouds of flame seen outside rooms containing fuel rich explosions. It is one reason to at least consider total energy inventory (MJ) as an important reference point.

Current industry models work on the basis of predicting overpressures based on a deflagration in a single room venting through a single location to outside.

In practice it is known that if this single vent (e.g. a window) is of insufficient area, then the expanding gas will induce failure of another low strength panel e.g. a door, followed by a 3rd panel, or the ceiling. A property will only collapse when the failing panel is structural. It is therefore suggested that more work is required regarding the consequence of a deflagration in multiple room enclosures as well as developing the current models to work with multiple room scenarios containing a mixture of structural components. Such investigations will be very useful in assessing the risk from complex structures currently outside the scope of Hy4Heat, e.g. flat complexes.

## 6.7 The relationship between flame speed and overpressure.

FRN 0759 [30] and 0847 [26] indicate that peak overpressure in a vented room is a linear function of burning velocity and the ratio of the vent area to the cross section of the room. The equation is given for natural gas (methane) as:

$$P_m = 1.5\, P_V + 2.8\, K$$

Where:

$P_m$ = maximum pressure reached in the explosion (kN/m$^2$)

$P_V$ = the pressure at which the relief vent opens (kN/m$^2$)

and $K$ = the ratio of minimum cross-section of compartment to the area of the vent

FRN 0759 suggests values for the fundamental burning velocities of methane, town gas and hydrogen of 0.37, 1.2 and 3.4 m/s respectively.

The FRN papers explain that the 2.8 constant in the equation above, is a linear function of laminar burning velocity at stochiometric conditions but do not offer specific methods of modifying this equation to different flammable gas concentrations. It is however, possible to apply a factor based upon a general knowledge of deflagration.

Bauwens et al [16] stated that:

Observed flame speed = Laminar burning velocity X Expansion ratio

i.e. that flame speed relative to an external reference frame is a function of linear flame speed multiplied by the expansion ratio.

In simple terms - the **expansion ratio** is the ratio of the volume taken up by a quantity of gas after combustion to the same quantity prior to combustion.

This is given in the literature [16] and can (at constant pressure) be equilibrated to the increase in pressure that occurs during adiabatic combustion. It is fully appreciated that this is an assumption, but in accord with the simple nature of this 1960s model is regarded as acceptable.

This then leads to the following equation:

$$\mathrm{Pm} = 1.5Pv + \frac{2.8\ S_L.\ \sigma}{S_{L\ CH4\ ref}.\ \sigma_{CH4ref}}\ .K\ kN/m2$$

Where:

- $S_L$ is the laminar burning velocity of the flammable gas at the relevant concentration
- $\sigma$ is the expansion ratio of the flammable gas at the relevant concentration
- $S_{L\ CH4\ ref}$ is the stochiometric flame speed of methane
- $\sigma_{CH4ref}$ is the stochiometric expansion ratio of methane.
- K the ratio of minimum cross-section of compartment to the area of the vent
- Pm is the maximum pressure kN/m2
- Pv is the pressure at which the relief (window or door etc) opens.

There are a number of approaches of varying sophistication to calculate the expansion ratio for a particular GIA concentration. The following approach assumes that in sub-stochiometric mixture it is a linear function of the ratio of actual gas concentration to the stochiometric mixture of that gas. And within rich mixtures it remains at stochiometric expansion. This will tend to give high (cautious) pressures.

Thus, if a flammable gas mixture is half of the stochiometric concentration, there is only (approximately) half the chemical energy to raise the temperature of the products of combustion and the expansion ratio will be half that at stochiometric conditions ie for a concentration of hydrogen of 14.5%, the expansion ratio will be 14.5/29 (i.e 0.5) times the expansion ratio at stoichiometric concentration. For methane at a GIA concentration of 7% it is (7/9.8) =0.71 times the expansion ratio at stoichiometric concentration..

It is appreciated that this a simplified approach, but it is inappropriate to be overly complex in the context of what has to be straightforward model, and the same assumptions are applied to all three gases.

Using the proposed relationship for expansion ratio as a function of GIA concentration and using data on laminar burning velocities presented in a thesis by Hermann [31], flame speed versus GIA concentration has been plotted (Figure 30)

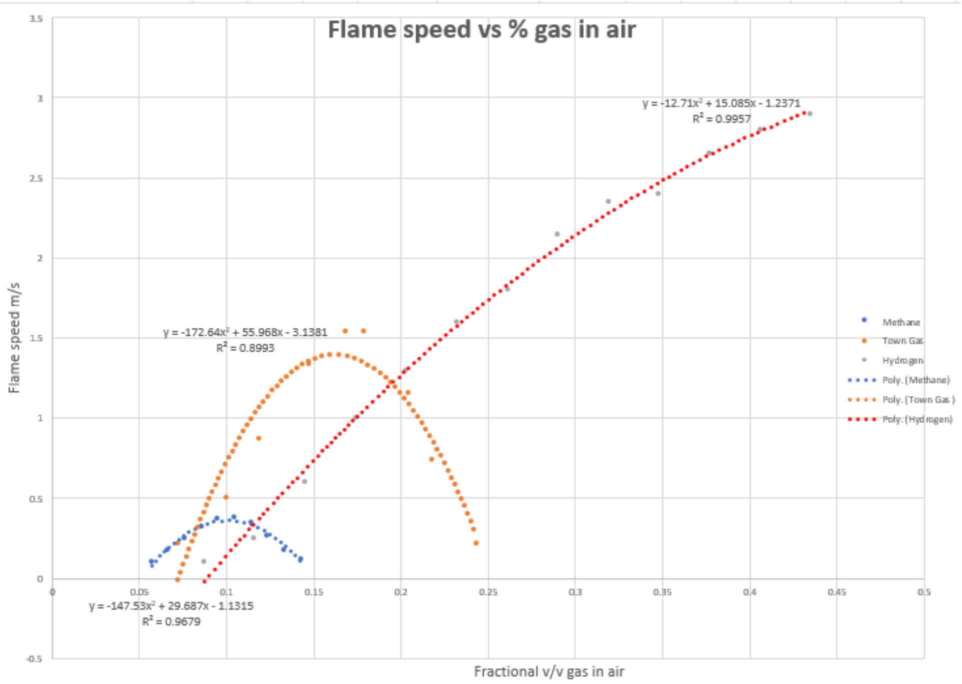


Figure 30: Flame speeds for natural gas, town gas and hydrogen as a function of GIA concentration

### 6.7.1 Modelling of overpressures from flame speed

Consider a room with the characteristics shown in Table 6. The value of K (cross sectional area/volume) is calculated as 1.87

Table 6: Modelled room characteristics

| Characteristics of room | Unit | Value |
|---|---|---|
| **Length** | m | 5.75 |
| **Height** | m | 2.3 |
| **Width** | m | 2.2 |
| **Floor area** | m2 | 12.65 |
| **Vol room** | m3 | 29.095 |
| **Minimum cross-sectional area of room** | m2 | 5.06 |
| **Area of window & door** | m2 | 2.7 |
| **K (Cross sectional area/volume)** | $m^{-1}$ | 1.87 |

The expansion ratio of the flammable gas at a certain GIA concentration is a linear function of the stoichiometric expansion ratio (for concentrations below stoichiometric).

Table 7: Expansion factors at stoichiometric concentrations

| Stoichiometric | % | Expansion factor at stoichiometric conditions |
|---|---|---|
| **Methane** | 9.8% | 7.8 |
| **Hydrogen** | 29% | 8.8 |
| **Town /Coal gas** | 18% | 8.3 |

The laminar burning velocity of methane at stoichiometric conditions is given as 0.36 m/s

The breaking pressure of the window (Pv) has been assumed to be 24 mbarg

Figure 31 shows graphically the result of modelling peak overpressures for ignitions of different GIA concentrations for natural gas, town gas and hydrogen. The modelled room characteristics shown in Table 6.

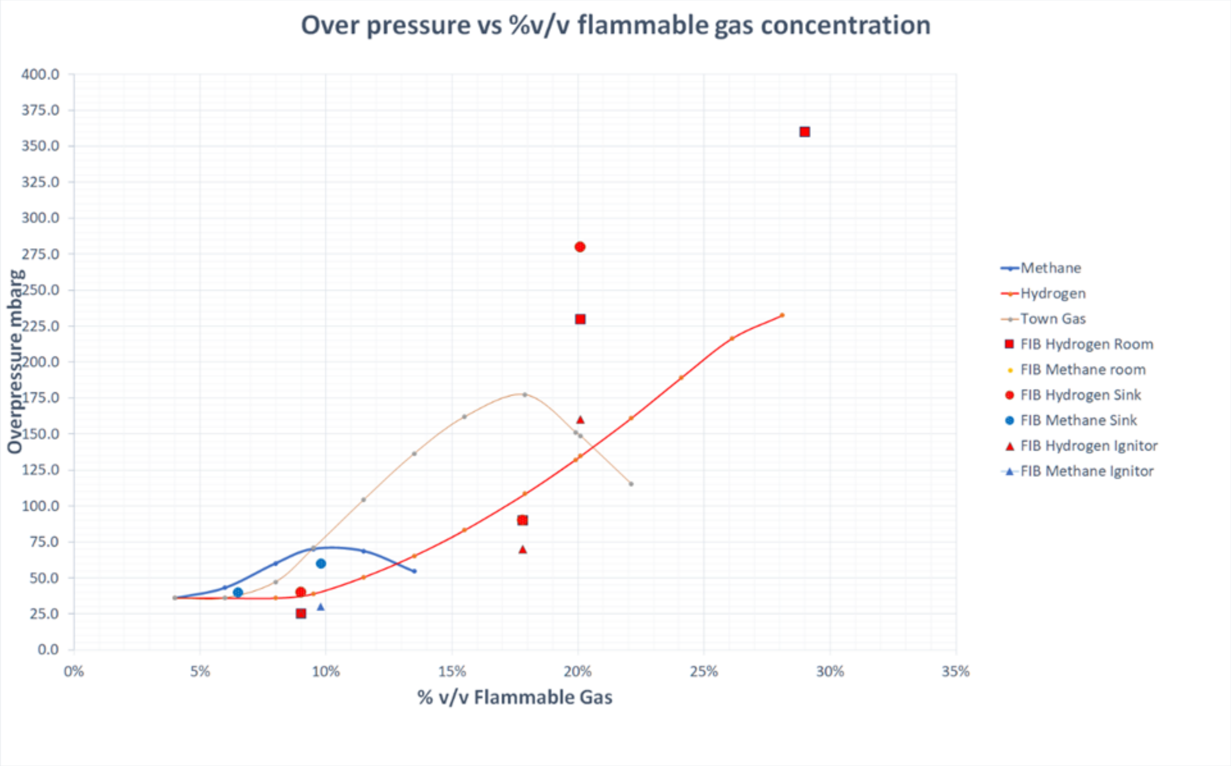


Figure 31: Modelled peak overpressure vs. GIA concentration

Figure 31 shows that overpressure for natural gas peaks at about 10%, town gas at 18% and hydrogen continues to increase up to its stochiometric concentration. It should be noted there is good qualitative similarity between both the shape and the absolute values of the overpressures between the King Report [28] and those calculated from FRN 0847. The vent area in both cases has been taken as 2.7m$^2$. Figure 1 King report [28] shows natural gas peaking at about 120mbarg (10%v/v) and Town Gas 280mbarg (20%v/v).

The reason for the quantitative discrepancy is unknown. It could be the King report assumes stronger windows or a different shaped room. For ease of understanding, the above graph also plots theoretical overpressures vs observed over pressures for 2.7m$^2$ of vents. Whilst probably reasonable from an explanatory perspective this assumption of a 2.7m$^2$ vent opening as single entity is also incorrect as the windows and doors opened stagewise, the following paragraph and table endeavours to use real vent areas from visual analysis of the videos taken during the deflagration (see Annex below)

A more detailed comparison has been made between the peak overpressures predicted by FRN 0847 and observed pressures in the FIB kitchen allowing for the area of windows and door that was actually opened by each deflagration. These are shown below

Table 8: Calculated vs. observed peak pressure - FIB ignitions

| Test no. | Gas | % Flamm gas | Area vent m2 | Calc peak mbarg | Obs peak mbarg |
|---|---|---|---|---|---|
| **Test 1** | CH4 | 6.50% | 1.5 | 66 | 40 |

| | | | | | |
|---|---|---|---|---|---|
| **Test 2** | H2 | 9% | 0.3 | 76 | 20-40 |
| **Test 3** | H2 | 17.90% | 4 | 109 | 65-90 |
| **Test 4** | H2 | 20% | 4 | 135 | 150-280 |
| **Test 5** | CH4 | 9.50% | 4 | 70 | 30-60 |
| **Test 6** | H2 | 29% | NA | NA | ~350 |

Due to the structural failure of the FIB at stochiometric hydrogen no calculation was possible. It suggested that agreement between the calculated and observed peaks is good, especially against the background of the acknowledged poor accuracy of many combustion models.

It is worth noting that  whilst the stochiometric (29%) hydrogen test did cause severe damage to the FIB one of the wooden chairs placed 5m from the FIB was only knocked over and not physically moved and a traffic cone at 10m was unaffected. Another wooden chair was moved about 5m. This observation is particularly useful in supporting the proposal that the overpressures generated by hydrogen deflagrations within detached property are not especially likely to create significant damage to a masonry structure next door.

The above graph is also considered particularly useful in considering the comparative damage likely to occur. It can be seen that peak town gas (at stochiometric concentration) offer similar explosive overpressures up to about 23% H2v/v.

Some Town Gas was of a higher hydrogen content (and hence greater % stochiometric mixture (~23%) and higher flame speed) is likely to reflect the behaviour of even higher concentrations of neat hydrogen.

As indicated in this report all observed hydrogen ignitions in a pseudo domestic situation are deflagrations, as are (and were) town gas and natural gas ignitions. The flame front moves relatively slowly compared to the speed of opening of any vent. It is thought important to stress this relativity, as it is this which explains why higher flame speeds do not correlate with a substantial increase in building damage or injury.

The timings of damage from the SGN H100FIB programme are detailed in Annex A. These essentially show that natural gas and hydrogen deflagrations are fundamentally similar. The higher flame speed of hydrogen results in faster pressure rise, but the whole deflagration of duration 100-300 ms is much slower than the failure time of a window or door which takes 30-50 ms. Higher concentrations result in shorter deflagrations but even with stochiometric (29%v/v) $H_2$ combustion extended to 100ms. The H100FIB tests released both methane and hydrogen via the cupboard under the sink. Ignition was from an ignitor located adjacent to a light switch at the door; none of the deflagrations showed unexpected over pressure characteristics because of this cupboard i.e. zone of high concentration.  The gas in the cupboard ignited, and a fire ball emerged.  This addresses the question whether such a physically modest volume, but of very high concentration, of hydrogen dramatically changes the nature of the combustion in a room. The evidence indicates it does not.

The stagewise opening of windows and the door confirms that a single vent explosion model is gross simplification of what is really occurring. Exactly the same sequence arises from a gas deflagration within any domestic room i.e. the window fails, the door fails, the ceiling fails etc. All of these occur within a relatively tight pressure band. Thus, in a property of conventional construction the room and/or building will fail consecutively until there is total release of the over pressure. The evidence from the King Report is this limited to about a 20% range. By way of example this could be 120mbarg to 144mbarg.

In practice the injury rates tend not to be affected by whether one, two or more windows or doors fail but by the degree of building failure.

## 6.8 Overall conclusions regarding effect of flame speed.

The above indicates how hydrogen up to concentrations of about 23% behave similarly to those exhibited by the town gas (for the composition chosen). The concept of an average pressure from a gas explosion has only limited validity as each explosion is different, but accepting this caveat, when moving from natural gas to hydrogen only a modest (probably somewhat greater than the 20% observed for Town Gas) increase in observed overpressures is expected.

Table 9: Summary of experimental setups from literature short list

| Test Condition | Gasses Tested | Volume of enclosure (m³) | H2 Conc. (%) | CH4 Conc. (%) | Type of venting | Vent ratio (m³/m²) | Construction | Obstruction |
|---|---|---|---|---|---|---|---|---|
| **Fire Investigation Box [12]** | $CH_4$, $H_2$ | 29.1 | 4.5 - 12.5 | 4 - 6 | Door and windows | 7.3 | Metal frame wooden doors and windows | Kitchen furniture |
| **Shock Tube [13]** | $CH_4$, $H_2$, explosives | 0.52 | 7.5 - 41.7 | 5 - 13.9 | Vented / Unvented | 3.0 (reduced bore)<br>N/A (full bore) | Metal | Empty/<br>Insert |
| **Garage Building [14]** | $H_2$ | 113.5 | 12 - 28.8 | N/A | Doors / roof | 1.5 – 3 | Block and timber | Empty/<br>With car |
| **ISO container [15]** | $H_2$ | 33.1 | 15 - 24 | N/A | Doors /roof / unvented | 5.9 (door vented) | Metal | Empty/<br>pipe rack/<br>bottle basket |
| **64m³ Room [16]** | $H_2$, $CH_4$, Propane | 64 | 18 | 9.5 | Large/small | 11.9 (large vent)<br>23.7 (small vent) | Unknown | Empty |
| **Vessel [20]** | $CH_4$ | 0.136 | N/A | 9.5 | Orifice / 2x pipe / unvented | Various | Glass | Empty |
| **Dome [21]** | $H_2$ | 300 | 30 | N/A | 1 | N/A | Aluminium frame | Empty /<br>Cylinders |
| **Tunnel [21]** | $H_2$ | 37 | 20<br>30 | N/A | 1 | 39.3 | Metal | Empty/<br>With “cars” |
| **CVE Facility [19]** | $H_2$ | 25 | 9.6-12.3% | N/A | 1.1 | 22.7 | Steel and glass | Various |

# 7 Conclusions

The aim of this study was to draw together the evidence that exists on the consequences of an ignition of hydrogen within an enclosure and use this to draw up a range of likely outcomes for ignitions of different concentrations of hydrogen within a domestic space. Where possible, a comparison with methane was to be made.

A literature review identified multiple studies from which results of experiments could be extracted. This data was extracted and the maximum overpressure (bar) and impulse (Pa.s) was calculated for each result and plotted on the same iso-damage curve, separated into five concentration bands.

The complete set of data included results from several experiments that were considered not representative of domestic situations. Including the representative results, it has been shown that:

- An ignition of below 10% v/v hydrogen could (at the higher end), result in some minor structural damage, whilst at the lower end lead to flash fires. An ignition of the same concentration of methane is likely to have worse consequences. Whether this causes major structural damage will depend upon the details of the incident and whether the area available for venting (e.g. the window or door) is sufficient to avoid failure of a structural wall
- The consequence of an ignition of between 10-15% hydrogen could range from minor structural damage at the lower end of the concentration range; to major structural damage with over 95% glass breakage at the higher end. The corresponding concentration of methane has less severe consequences, with the iso-damage charts indicating minor structural and perhaps 50% glass breakage. At the top end of this range, hydrogen may be worse in terms of direct structural consequences.
- The consequence of a 15-20% ignition of Hydrogen could range from no structural damage (with some window breakage) for an ignition in a room with a large vent area and ignition point close to the vent; to major structural damage to load bearing components and over 95% window breakage. An ignition of such a concentration in a minimally vented enclosure or in a garage containing a vehicle could produce a worse outcome with 50-75% destruction of the garage. There was no experimental data with which to compare a methane ignition of similar concentration. In real situations due to the stratification of the gas it is likely there will be a zone of flammable gas somewhere within the room [2]. Ignition of gas in this zone can force fuel rich concentrations of gas outside the room where it is diluted and becomes flammable. This can lead to a fireball outside the structure. Towards the 20% level an ignition of hydrogen would produce significantly higher overpressures, which are very likely to produce more local damage than stochiometric methane (for example more broken windows and structural cracks)
- An ignition of 20-25% hydrogen will lead to major structural damage with load bearing components failing at the lower concentration end, up to 50-75% demolition at the upper end. There were no methane ignitions of similar concentrations with which to make a comparison. As with the 15-20% range, a large fireball may be formed outside the enclosure. Damage from hydrogen will be severe, unless the inventory is small. This latter is important if the hydrogen leak rate into a building is limited through use of an excess flow valve.
- An ignition >25% of hydrogen will lead to demolition of the enclosure. It is, therefore, critical to design safety measures that minimise the likelihood of such concentrations occurring anywhere within the room.

# Annex A: Further analysis of H100 FIB Ignition videos

## 1 Introduction

Six flammable gas explosions (two with methane and four with hydrogen) were carried out in Fire Investigation Boxes (FIBs) over the period 16th to the 26th of January 2018. The work was carried out for SGN as part of the H100 programme and was reported under project number 30875 [32], which contains a full description of the work. This document provides more detailed semi-quantitative analysis of the precise nature of the resulting fires and the damage caused to the structures of the FIBs themselves,

The objectives of this work were to:

1. Identify the time from ignition that important events occurred in the deflagration (e.g. failure of window, door etc)
2. Compare the timings of these events with pressure traces recorded during the same deflagration event
3. Where possible, identify at what pressure structural components fail

The following document presents the results of this further analysis.

### 1.1 Methodology

Slow motion video of six flammable gas ignitions within the FIB were viewed in detail to establish the point in the deflagration where key events took place. The timing of key events was checked (where possible) using multiple cameras filming the same deflagration.

The approximate time at which key events happened during each deflagration was noted using the frame rate and frame counter on each camera.

Key events included:

1. Window starting to deform
2. Window and door opening
3. Glass breakage
4. Presence of fire within the FIB or outside
5. Structural failure of the FIB

Once the timing of key events had been established, they were compared with the pressure traces taken from the deflagration (not including the pressure at ignitor which was generally lower than at the other locations).

The process of identifying key events from video footage inevitably has a subjective element and thus carries a degree of uncertainty. The use of multiple cameras to observe key events provided a time interval over which the event occurred.

Reading the pressures from the pressure traces was also a subjective, manual exercise. All pressures are given as indicative only.

#### 1.1.1 Determining test start time

One challenge was how to determine the ignition time of the deflagration from the video footage. In most cases the first visible event on the footage was distortion of a windowpane, which was assumed to be caused by the pressure wave (caused by the ignition), reaching the window.

During ignition 3, one camera was used to film the deflagration from inside the FIB. Footage from this camera was used to estimate the time taken between ignition and the pressure wave reaching the camera (which was located next to the North facing window).

This time was used in the other tests, to infer the time of ignition based on observations of window distortion.

Based on examination of the internal footage, in tests where the first observed event was distortion of the windowpane, a time of between 50-70ms has been used to infer the time of ignition. This number will vary slightly with gas concentration and type.

### 1.1.2 Description of FIB

FIBs were constructed from modified standard shipping containers with steel sides and roof. The containers were modified to include openings for three windows (on the West, North and East side) and a door on the East side.

In the following sections the windows are referred to as W, N and E, depending on which compass direction they face.

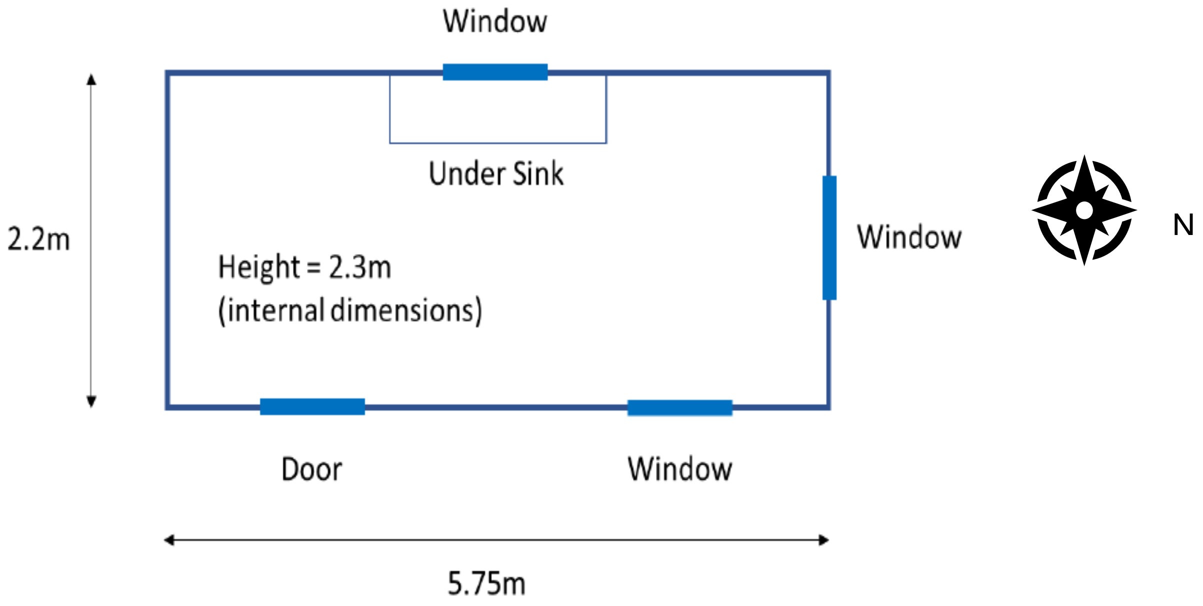


Figure 32: Dimensions of FIB [32] showing location and orientation of doors and windows

# 2 Findings

The following FIB tests were analysed, the results of which are presented below.

Table 10: Summary of tests analysed

| Ignition | Gas | Nominal Leak Rate (kW) | Concentration at ignitor (mid-level) (%) |
|---|---|---|---|
| **1** | Methane | 16 | 6.5 |
| **2** | Hydrogen | 16 | 9.0 |
| **3** | Hydrogen | 64 | 17.8 |
| **4 (repeat of 3)** | Hydrogen | 64 | 20.1 |
| **5** | Methane | 64 | 9.5 |
| **6** | Hydrogen | >100 | 30 |

In all tests, gas was injected into an under-sink cupboard within the FIB via 28mm copper pipe.

## 2.1 16 kW ignitions

### 2.1.1 Ignition 1 – Methane (16kW)

Gas concentration at ignitor (mid-level) 6.5%.

Table 11: -Methane 16 kW - Key Events

| Event | Approx. time (ms) | Approx. pressure (mbar) |
|---|---|---|
| **Ignition (inferred)** | 0 | <10 |
| **Window first deforms** | 50-70 | <10 |
| **Window (E) starts to open** | 565 | 30 |
| **Window (W) starts to open** | 575 | 30 |
| **Container at max expansion** | 580 | 30 |
| **First visible flame outside window** | 580 | 30 |
| **Window (E) fully open, hits container, glass breakage** | 705 | <10 |
| **Window (W) fully open, hits container, glass breakage** | 725 | <10 |
| **Window frame detaches from container** | 770-820 | <10 |

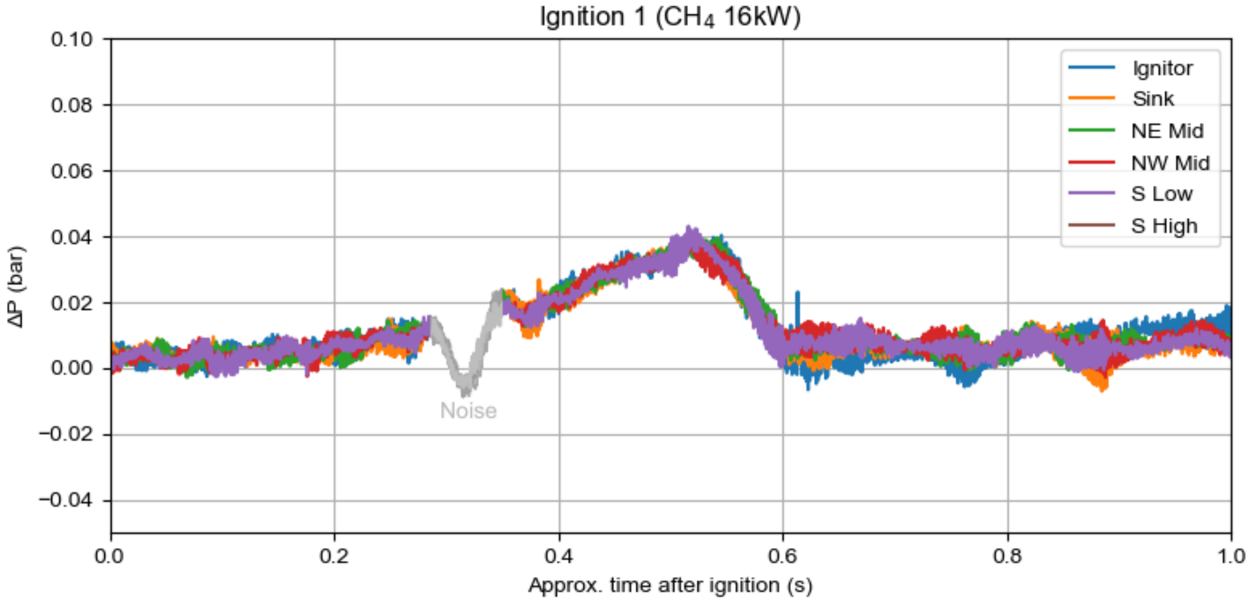


Figure 33: Methane pressure trace ignition 1 [32]

### General description and observations

After ignition, windows deformed, windows (E then W) opened in quick succession, glass only broke when windows fully open and hit side of container. Window frames then came away from container. Window frames/foam continued to burn until the end. Window (N) remained closed throughout as did the door.

The window appears to open near or just after the peak overpressure of the deflagration. The pressure was insufficient to break the glass.

## 2.2 Ignition 2 – Hydrogen (16kW)

Gas concentrations at ignitor (mid-level) 9.0%.

Some events occur at a time beyond the recorded pressure trace, so the pressure cannot be estimated.

Table 12: -Hydrogen 16 kW- Key Events

| Event | Approx. time (ms) | Approx. pressure (mbar) |
|---|---|---|
| **Ignition (inferred)** | 0 | <10mbarg |
| **Window first deforms** | 50-70 | <10mbarg |
| **Door opens (1)** | 1010 | <20mbarg |
| **Container at maximum expansion (1)** | 1090 | Unknown |
| **Fireball visible in container** | 2480 | Unknown |
| **Door opens (2)** | 2500 | Unknown |
| **Container at max expansion (2)** | 2515 | Unknown |
| **Glass breaks – Window (E)** | 2520 | Unknown |

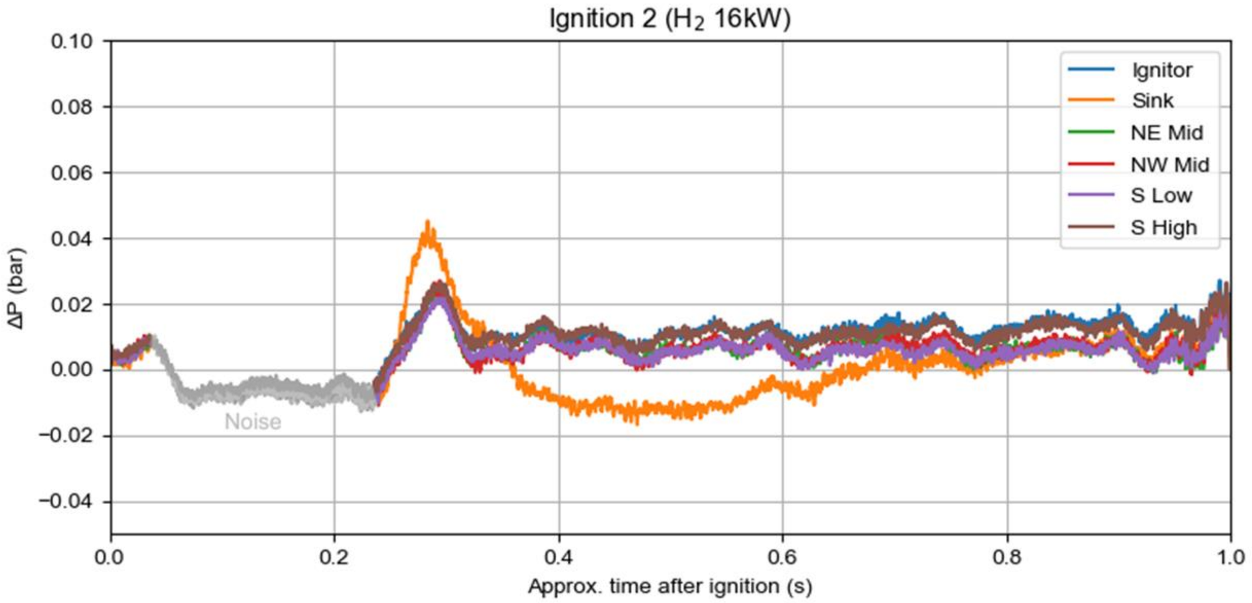


Figure 34: Hydrogen 16 kW pressure trace [32]

### General description and observations

This deflagration took place over a much longer period than ignition 1. There was an initial ignition and then some time before the door opened and then swung back to be partially open. All windows remained closed and there was no glass breakage during this initial event. The door opened very soon after the end of the recorded pressures trace, (Figure 34), after 1s, where the pressure appears to be rising again.

There was then a clear second event where a fireball was visible in the container at around 2500s after ignition which causes the door to open again. All windows remained closed and undamaged through the second event apart from window (E), which remained closed but the glass pane broke and then fell out. The secondary event that causes the door to open again and the glass to break, happens sometime after the end of the recorded pressure trace.

## 2.3 64kW ignitions

### 2.3.1 Ignition 3 – Hydrogen

Gas concentrations at ignitor 17.8%

**Table 13: Hydrogen 64 kW - Key Events**

| Event | Approx. Time (ms) | Approx. pressure (mbar) |
|---|---|---|
| **Ignition (inferred)** | 0 | <10 |
| **Window first deforms** | 50-70 | <10 |
| **Window (N and E) start to open** | 110 | <10 |
| **Window (W) starts to open** | 125 | <10 |
| **Frames and glass break, gas expelled from container** | 120-135 | <10 |
| **Door starts to open** | 120 | <10 |
| **Window frames detach from container** | 150-175 | 20 |
| **Visible flame outside container** | 150-175 | 20 |
| **Gas from under sink cupboard ignites** | 165 | 20 |
| **Container at max expansion** | 210 | 75 |
| **Noticeable increase in intensity** | 235 | 40 |
| **Door detaches from container** | 250 | 40 |

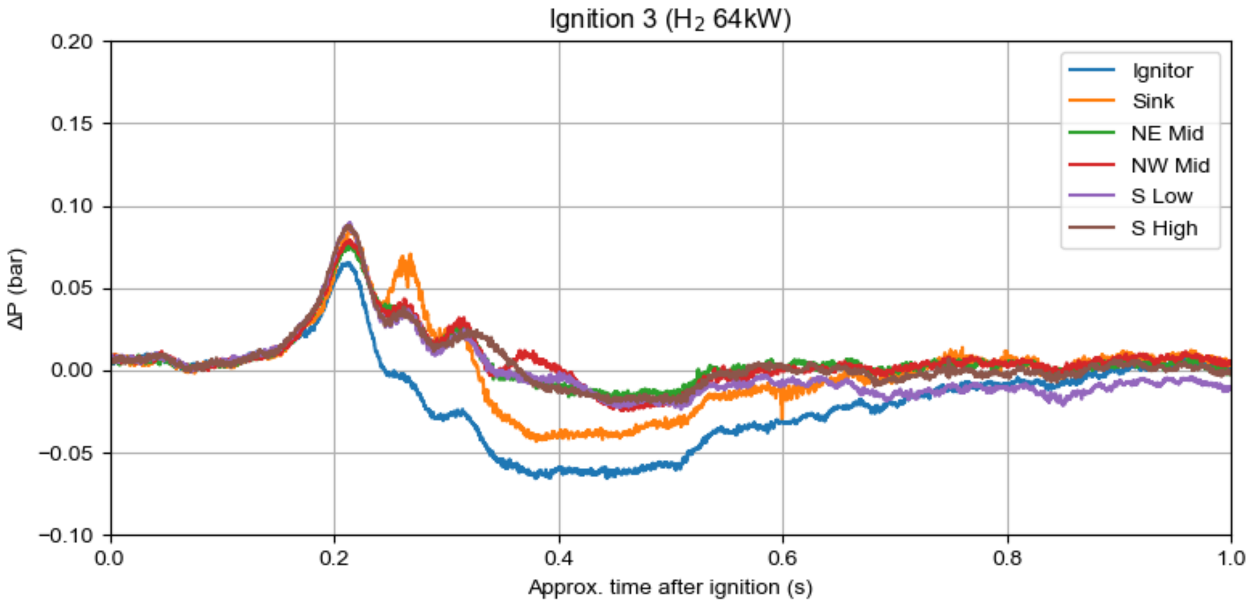


**Figure 35: Hydrogen 64 kW pressure trace [32]**

## General description and observations

The windowpane deformed followed by the door and all windows opening within approximately 15ms of each other. The glass broke and then the window frames detached from the container. Unburned or invisible burning gases were expelled from window and bottom of container, followed by jets of flame through window. Frame (and surrounding foam) started to burn and continued throughout. Door swung open and detached from container towards end of test.

The observed events correlated well with the recorded pressure trace (with the container maximum expansion occurring around the time of maximum overpressure).

Most events happened very early on in the deflagration with the door and windows opening and the glass breaking within 135ms of ignition.

Ignition of a gas pocket in the under-sink cupboard was clearly visible on the camera from inside the FIB (Figure 36). This happened at around 165ms from ignition.

At around 235ms from ignition the internal camera also showed a marked increase in deflagration intensity. This appeared to coincide with an increase in the pressure recorded at the under-sink location (Figure 35). This may be evidence of an ignition of a pocket of unburned gas or localised transition to detonation, although detonations are very fast (typically <5ms) and there is no evidence of such an event in the pressure trace (Figure 35).

Figure 36: Internal camera showing ignition of pocket of gas from under sink cupboard

### 2.3.2 Ignition 4: Hydrogen repeat

Gas concentrations at ignitor (mid-level), 20.1%

Table 14: Hydrogen 64 kW (repeat) - Key events

| Event | Approx. Time (ms) | Approx. pressure (mbar) |
|---|---|---|
| **Ignition (inferred)** | 0 | <10 |
| **Window first deforms** | 50-70 | <10 |
| **Window (N and E) start to open** | 60 | <10 |
| **Door opens** | 70 | <10 |
| **Window (W) starts to open** | 80 | <10 |
| **Glass breaks** | 60-90 | <10 |
| **Burning gases venting from windows** | 110 | 25 |
| **Burning gases venting from beneath container** | 120 | 40-50 |
| **Burning gases venting from side of container** | 150 | 120 |
| **Camera shakes** | 155 | 150 |
| **Container at max expansion** | 160-215 | 100-200 |

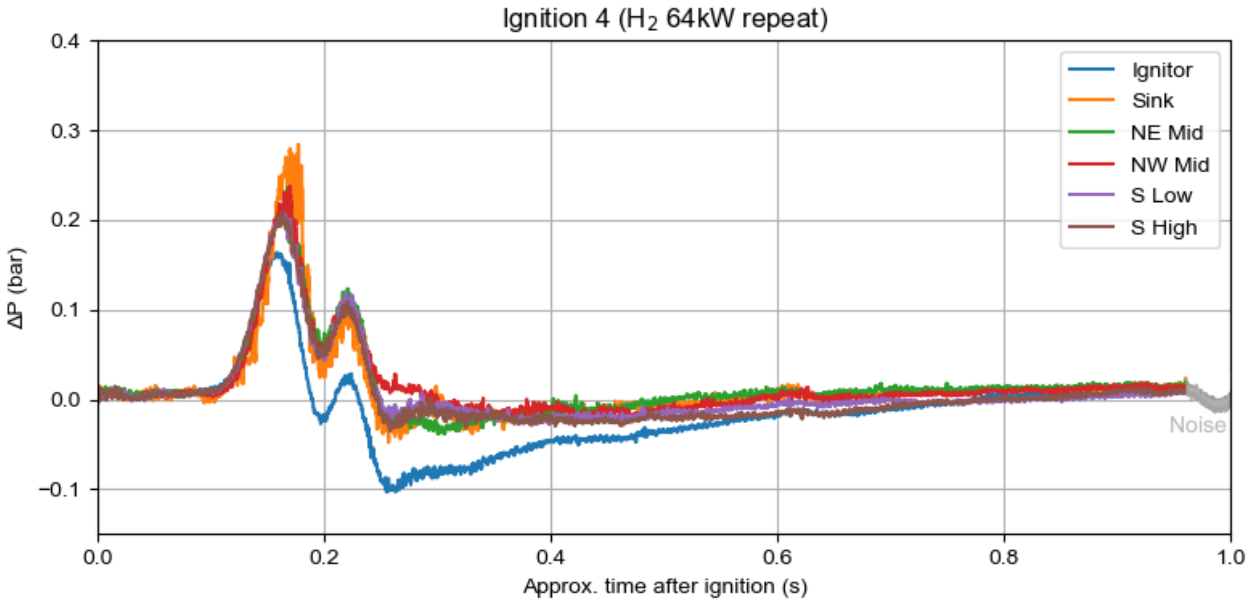


Figure 37: Hydrogen 64 kW (repeat) pressure trace [32]

### General description and observations

Glass deformed, followed by opening of windows (N and E) and then window (W) and the door. Door detached and glass broke. A fireball formed outside windows followed by burning gases venting from underneath and then from sides of container. Prolonged period of burning gas expulsion, and the door was projected from the container

This deflagration was considerably more violent that ignition 3 and correlated reasonably well with the pressure trace.

The higher recorded overpressure (in comparison to ignition 3) enabled estimation of the localised failure pressure of the bottom and sides of the container. These points failed at around 120 and 150ms after ignition and are estimated to fail at around 40-50 and 120 mbar respectively. Figures 38 to 40 show burning gases venting through first the windows, then the bottom of the container and then the sides.

There is an extremely brief event just after 150ms from the ignition where camera 1 (external to the FIB observing the west window), shakes. This could be evidence of a localised transition to detonation (e.g. very localised inside a pot or pan). However, a review of experimental literature where such events were reported [33] showed that evidence of transition to detonation was usually detectable in the pressure trace (ref US Garage 100m$^3$ experiments) and no such evidence was seen in the pressure trace for this ignition (Figure 37).

The pressure traces (Figure 37) shows an initial pressure peak followed by a decreased in pressure followed by a second pressure rise, similar to that in ignition 3. The difference here is that all pressure locations register the second peak.

Figure 38: Burning gases venting from windows (approx. time after ignition - 110 ms)

Figure 39: Burning gases venting from windows and underneath container (approx. time after ignition - 120 ms)

Figure 40: Burning gases venting though windows, bottom and sides of container (approx. time after ignition - 150 ms)

### 2.3.3 Ignition 5: Methane

Gas concentration at ignitor (mid-level), 9.5%

The first observable event for this ignition was believed to be the ignition, rather than deformation of the windowpane.

Table 15: Methane 64 kW Key events

| Event | Approx. Time (ms) | Approx. pressure (mbar) |
|---|---|---|
| **Ignition** | 0 | <10 |
| **Window bulges** | 70 | <10 |
| **Window starts to open (N and W)** | 350 | 55 |
| **Door starts to open** | Unknown | Unknown |
| **Glass breaks** | 375 | 50 |
| **Venting from beneath container gate** | 380 | 40 |
| **Container at max expansion** | 370-380 | 55 |
| **Fireball ignites outside window** | 420 | <10 |
| **Flames visible from beneath container** | 490 | <10 |
| **Approximate time of door opening** | 650 | <10 |

Note: The pressure at ignitor has not been considered in Table 15.

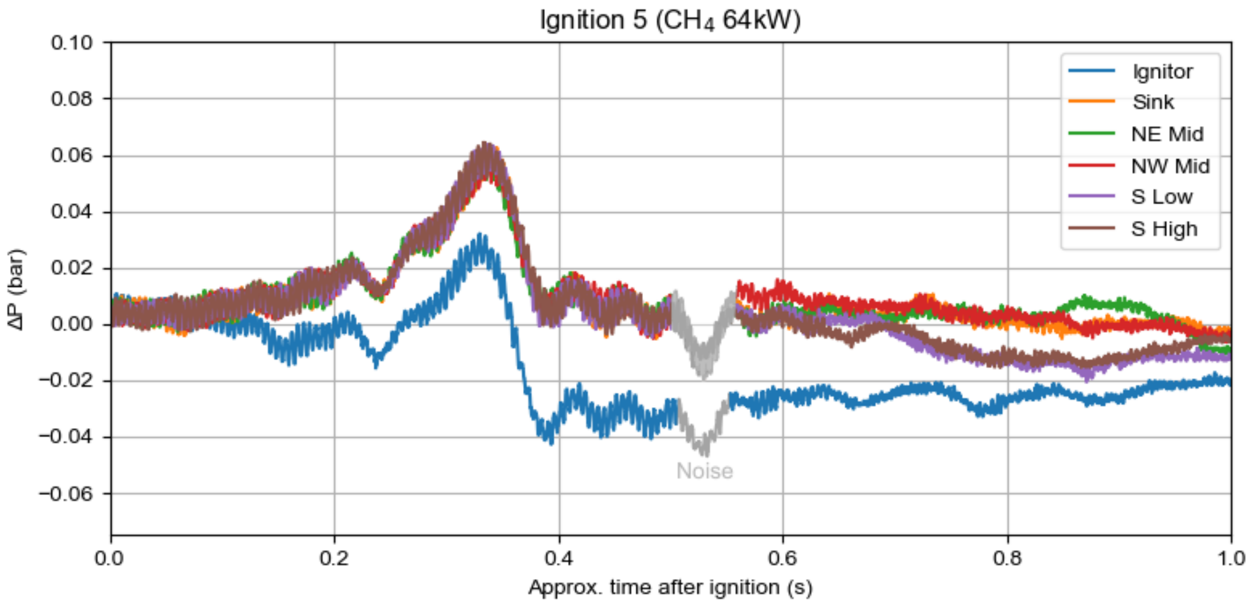


Figure 41: Methane CH4 64 kW pressure trace [32]

**General description and observations**

The ignition event was followed by deformation of window paned, followed by opening of windows (W and N visible) and breaking of glass. Gasses vented from beneath the container and the fireball was formed outside the windows, followed by visible flames from beneath container.

The opening of the door was directly visible but camera 1 showed it detaching from the container towards the end of the deflagration.

Window opening and glass breakage happened at the end of the peak over pressure of the deflagration with the opening of the door happening much later.

### 2.3.4 Ignition 6: Stoichiometric Hydrogen

Gas concentration at ignitor, ~30%

The first observable event for this ignition was believed to be the ignition itself, rather than deformation of the windowpane.

There was no pressure trace for this ignition due to the sensors being damaged in the blast.

Table 16: Ignition 6: H2 stoichiometric - key events

| Event | Approx. Time (ms) | Approx. pressure (mbar) |
|---|---|---|
| **Ignition** | 0 | Unknown |
| **Window deforms** | 30 | Unknown |
| **Window (all) starts to open/glass breakage** | 40 | Unknown |
| **Fireball outside window** | 50 | Unknown |
| **Sides and walls of container start to fail** | 60 | Unknown |
| **Venting from all side joints of container** | 70 | Unknown |
| **Sides of container completely detached** | 100 | Unknown |

#### General description and observations

This was the most violent of explosions and happened extremely quickly; the time from ignition to the container sides and walls becoming completely detached was less than about 100ms. Internal pressure at time of failure was estimated at over 350 mbar from correlation of glass throw vs distance [34].

It should be noted that even this stochiometric fire took 70-100ms. This is considerably longer than the <5ms that might be expected to arise from a detonation in a such a container.

Chairs were placed in front of the FIB on the North, East and West sides, at 5m distance and road cones placed at 10m on the same sides.

The chair on the North side was knocked over following the blast but not moved more than a of meter or so from its original position. The road cone on this side was not moved (Figure 42).

In contrast the chair on the west side was move all the way to the position of the cone and appeared to have flipped over. The cone on this side was also knocked over.

Following the deflagration, the damage to the sides (Eat and West) of the container appeared worse than to the end (N).

Figure 42 Location of chair and cone before and after Ignition 6

# 3 Discussions and conclusions

Apart from ignition 2 (16kW hydrogen) the hydrogen deflagrations were over more quickly than the methane tests, almost by a factor of 3, this seems reasonable given the much higher laminar flame speed of hydrogen [30].

For the hydrogen tests (with the exception of ignition 2) there was not a great difference in the time taken for windows on different sides of the container to open and for the glass to break. This showed that the pressure rise was reasonably consistent across the container. The door opened around the same time as the windows. These components failed very early in the hydrogen ignitions before the pressure really began to rise, at less than approximately 10mbar.

During ignition 1 (16kW methane) the window opened but did not break when the blast first reached it. The glass only broke after the window frame had fully opened and hit the side of the container.

Ignition 4 (64kW hydrogen repeat) was sufficiently violent to more clearly see that the components of the FIB failed at different times and pressures during the deflagration. It was possible to observe burning gasses venting freely from the separated joints between the wall and bottom of the contained and then the joints between the side walls themselves. This happened at approximately 40-50mbar for beneath the container and at approximately 120mbar for the sides.

During ignition 5 (64kW methane) the windows opened, glass broke and gases vented from beneath the container towards the time of the end of the peak overpressure recorded during the deflagration (between 350-380ms after ignition and at around pressure of 40-60 mbar). Although he exact time of door opening could not be observed, this appeared to open sometime after the windows

Pressure traces for Ignitions 3 and 4 showed an initial rise to peak overpressure, followed by a decrease, followed by a second rise.

A “double peak” pattern can sometimes indicate where a component has failed during increasing overpressure caused by a deflagration. In these cases, the failure of the component (e.g., a window) acts to temporarily relieve the pressure, which then continues to rise, leading to a double peak on the pressure trace. Double peaks are well reported in literature [35] for a range of hydrocarbons and result from the opening of a vent (in this instance a window or door) whilst the fire ball is still growing.

Video evidence suggests that this was not the cause for the double peak pattern seen in ignitions 3 and 4, where the structural components failed before the pressure began to rise quicky. The second pressure rise is most likely due to a delayed event following the initial ignition.

In summary the nature of the natural gas and hydrogen deflagrations were essentially similar but depending upon the concentration, the increased flame speed of the hydrogen caused greater overpressure and thus more damage. There was no evidence of detonation in the pressure traces, including where there was a possible zone of very high concentration within the FIB (i.e. under the sink cupboard)

For hydrogen ignitions where there was failure of doors and windows, this was quick relative to the duration of the fire. It is likely that this phenomenon would lead to stagewise pressure relief, but this level of detail is not visible in the pressure traces.

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