Hy4Heat
demonstrating hydrogen for heat

Department for Business, Energy & Industrial Strategy

WORK PACKAGE 7

Safety Assessment:

Gas Dispersion 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 Dispersion Data Analysis report

1.0 | 1 May 2021

Department for Business, Energy & Industrial Strategy

Hy4Heat

Gas Dispersion Data Analysis report

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Contents

1. Executive summary

This gas dispersion report is part of the Hy4Heat Safety Assessment suite of reports. It assesses and compares the dispersion of hydrogen and natural gas in a domestic property, in the event of a leak, from the experimental data and testing results undertaken primarily by Hy4Heat. Understanding how the gases disperse in a property is critical in informing the overall safety assessment and Hy4Heat QRA. The analysis in this report is used to validate the gas dispersion modelling report, describes how the gases disperse, stratify and identifies the role ventilation plays in gases in a property.

Over 300 experiments have been carried out under a number of different projects to assess the dispersion of hydrogen and methane gas in a domestic environment. This has included test work in an old cottage (HyHouse [1]), a new build house (Hy4Heat [2, 3]) and simulated domestic kitchen environments (H100 [4, 5]). Gas injection rates between 0.4 and 264 kW have been trialled to simulate typical leak scenarios from a weeping joint up to a fractured gas main.

Gas concentrations at a range of heights throughout all rooms within the properties were measured to allow assessment of the gas in air concentrations (% GIA) reached and the resulting gas inventories (kWh) within the properties.

Gas injections into rooms, cupboards and basement environments were compared. For a given size of hole in a pipe, hydrogen leaks at 1.2 to 2.8 times the rate of methane on a volumetric basis. However, overall, the maximum concentrations measured for hydrogen and methane were comparable in all scenarios, meaning active gas dispersion within the space was apparent.

In all tests and as expected, the highest GIA concentrations were measured closest to the point of gas injection. Comparable maximum concentrations were observed in the room releases carried out at HyHouse and basement releases under the Hy4Heat programme at injection rates below 50 kW, suggesting dispersion patterns are consistent for both hydrogen and methane. Gas injection into kitchen cupboards resulted in very high concentrations of both hydrogen and methane within the cupboard space and the highest concentrations at the top of the kitchen.

Gas stratification in the room of release was evident in nearly all tests, where higher GIA concentrations were observed at the top of the room compared to the rest of the space. The effect was strongest in tests where the gas injection took place at height (for example in tall/high cupboards) and is broadly in accord with existing dispersion models, although this can be disturbed on windy days. Complex dispersion patterns were observed in the basement with direction of gas release affecting the level of gas stratification.

Ventilation in the property, particularly in the room of release, had a marked effect on the resulting GIA concentrations measured in the space when compared to tests in which no (or little) ventilation was present. This effect was seen when opening or closing doors, or when adding additional ventilation such as wall vents. The addition of wall vents ducted to outside was shown to reduce the maximum GIA concentration within the room of release and also lower the gas inventory within the whole house. Ventilation added to cupboards (when the gas injection took place in the cupboard) reduced the high cupboard concentrations; and when coupled with room ventilation reduced the maximum gas concentrations seen in the wider kitchen environment.

Gas injections into the basement resulted in the highest whole house inventories, likely in part due to the reduced ventilation factors active in a basement environment, but also likely due to the volume of house above the basement into which the gas could disperse. Basement injections were also the only tests where any notable concentration of gas (both hydrogen and methane) were measured in all void spaces of the house (e.g. cavity walls etc.) particularly at high injection rates (above 200 kW). It should be noted that high ceiling void (ground to first floor) concentrations were also observed during injections into kitchen cupboards at high injection rates, however this was greatly reduced when the ceiling vents were fitted. Opening the basement door noticeably reduced the maximum GIA measured within the basement.

Overall, the total gas inventory (expressed as kWh) in the property was lower for the hydrogen experiments than for the equivalent methane tests.

The experimental data analysed to date has suggested the following generalised conclusions for a typical domestic environment (excluding basements):

- Large escape rates (in excess of 100 kW or ~30 m^3/h) are required to generate high (20% or above) hydrogen GIA concentrations throughout the property. However, relatively small leaks into a confined space such as a cupboard can create localised areas of very high concentration.
- In certain circumstances, especially in the absence of Building Regulation Ventilation ADF, and if the doors of the room into which the gas release occurs are closed; gas escapes below 100 kW (~30 m^3/h) can result in high (20% or above) GIA concentrations in the room of release.
- Ventilation of a cupboard in which a gas appliance such as a boiler is located, has been shown to reduce the localised hydrogen concentration in the event of a leak, and is likely to reduce the risk of a sudden outflow of flammable gas in the event of a householder opening the cupboard door. Current building regulations (e.g. Approved Document J (England)) already require ventilation to be added to cupboards/ compartments containing combustion appliances, although many appliance manufacturers self-exempt. Such exemptions should be withdrawn.
- The pattern of gas accumulation and the maximum concentrations reached in the room of release is dependent on the height of gas release.
- Open and closed doors have a marked effect on the pattern of gas dispersion in a property. For hydrogen injection rates around 67 kW (~20 m^3/h) or below:
    - If the door of the room into which the gas was injected was open, concentrations throughout the house were higher than with the door closed, but generally below 13% GIA. The exception to this was the zone above the height of the door lintel within the room of release.
    - If the door of the room into which the gas was injected was closed, concentrations throughout the house (excluding room of release) were generally below 10% GIA. However, GIA concentrations in the room of release could reach approximately 30% (when no purpose designed ventilation present in the room).
- High level ventilation makes a marked difference to the maximum GIA concentrations seen at ceiling height in the room of injection. For hydrogen injection rates around 67 kW (20 m^3/h) kitchen concentrations almost halved when external ventilation (either a 100 or 200 cm^2 ceiling vent) was added.

Ventilation has been shown to be a key factor in pattern of dispersion as well as risk reduction measures. In context of the current natural gas environment; compliance with Building Regulations Approved Document F [6] effectively requires a home to have an average air change rate of about 0.4 to 0.45 air changes per hour (ACH). The latter would be equivalent to 90 m^3/h of air for a typical three-bedroom property of volume 200 m^3. This (at a conceptual level) explains why natural gas leaks generally need to be large to be highly destructive

Based upon the experimental data a simple two vent mathematical model has been developed to explore the sensitivity of hydrogen concentrations to vent areas. Consideration has also been given to the likely location of boilers and other appliances. Most boilers and gas cooking appliances (and associated pipework) are located in kitchens, bathrooms, utility room, or sanitary accommodation and (fortuitously) all these are required by ADF to have enhanced ventilation (typically and as minimum 1 to 1.5ACH).

Further work is recommended in this area.

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 Package 7 (WP7), specifically focusses on collating evidence to prove the safety case for hydrogen and develop a Quantitative Risk Assessment (QRA) for its use within the gas industry.

The primary risk from any flammable gas is ignition of a gas in air mixture which leads to deflagration and/or detonation. These events can result in structural damage to property and injury (or occasionally death) to persons involved. Both hydrogen and methane are flammable gases and therefore both present this risk. However, there are key parameters that determine the severity of a gas incident, including:

- Gas in air (GIA) concentration (%)
- Gas inventory (MJ or kWh)
- Available vent area
- Obstruction within the space of escape

WP7 has included the completion of several experimental studies supported with literature-based research to better understand the risk associated with hydrogen in comparison to methane. This document focuses on gas dispersion and GIA concentration in the event of an unexpected and uncontrolled gas escape within a domestic setting. A range of different leak scenarios and flow rates have been assessed for both hydrogen and methane in directly comparable situations. The work broadly aligns with Lots 2 and 3 as shown in Figure 1 and aims to address the following objectives:

- An understanding of gas dispersion patterns following a range of gas escapes within a domestic environment. Release rates were chosen to simulate likely gas escape scenarios, ranging from approximately 0.4 to 290 kW, indicative of a seeping joint and fractured main respectively.
- An understanding of any potential areas of gas accumulation or pockets within a property, which could give rise to high gas in air concentrations.
- An understanding of the impact that ventilation has on the resulting GIA concentrations in the room of escape and other areas in the house.
- An understanding of the impact of leak location (within a room or cupboard) and height in the accumulation of gas within the cupboard and surrounding environment.
- An understanding of the impact of additional ventilation in the cupboard shell, to the concentrations observed within the cupboard space and surrounding environment.
- The delivery of sufficient evidence to enable further analysis and modelling to take place to understand the consequences of ignition of the range of GIA concentrations observed in the reported experiments.

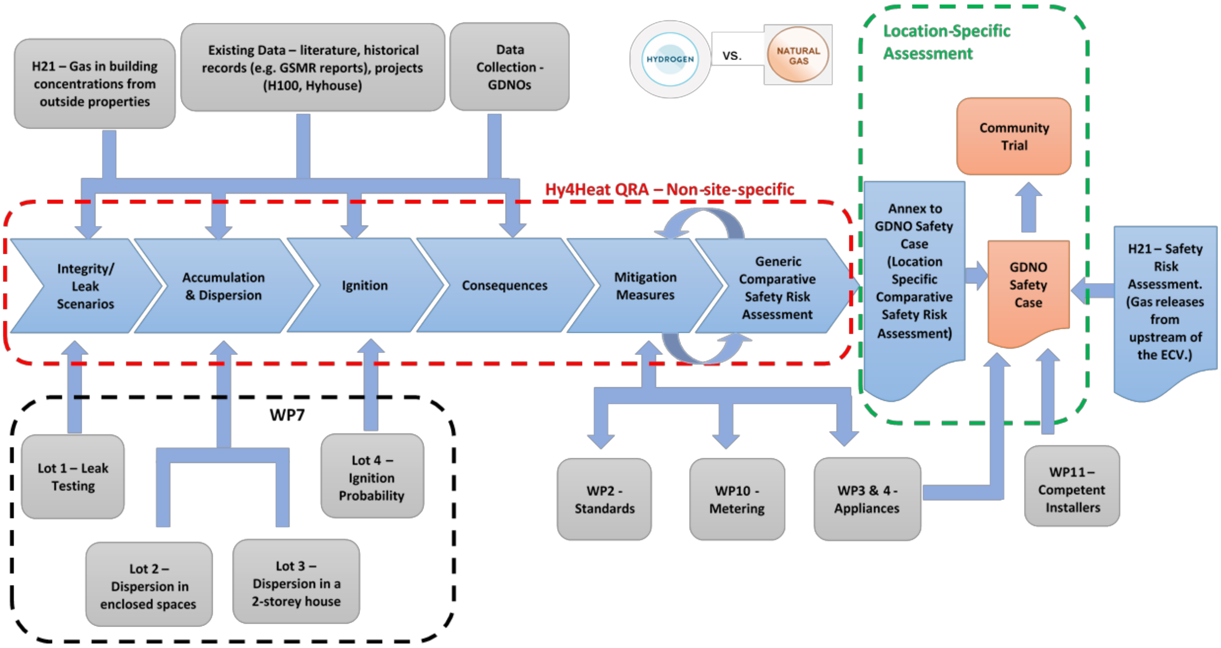


Figure 1: WP7 safety assessment – illustrative approach

3. Literature review

There are a considerable number of studies that have investigated the dynamics and characteristics of vented gas explosions involving hydrogen and these have been reported in a supporting WP7 document which looks at the consequences of flammable gas ignitions [7]. Key to understanding the impact of these events is an appreciation of the space in which the event occurs. Of particular importance is the maximum gas in air concentration, the level of obstruction, and available venting, e.g. presence of weaker structures such as doors and windows.

Hydrogen has a wide flammable range from 4-75% GIA and a low ignition energy of only 0.019 mJ [8] compared to natural gas at approximately 0.3 mJ. However, although the flammable range is wide for hydrogen, the resulting deflagration depends on the gas concentration present, with flame propagation only sustained in all directions at and above approximately 8.5% GIA concentration [9].

Daubech et al. [10] found that when igniting hydrogen in enclosed vessels, higher GIA concentrations led to the highest overpressure traces. This is supported by theory and many other experimental studies including those carried out by Gexcon [11] and Makarov et al [12]. Greatest risk from deflagration tends to correlate to stoichiometric GIA concentrations which are ~9% and ~29% for methane and hydrogen respectively [7]. However, limited data is available on ignitions of concentrations above stoichiometric levels and this could be a case for further work. Due to the strong influence of GIA concentrations on the severity of an ignition event, it is critical to understand the likely concentrations resulting from typical leak scenarios in a domestic property, when considering the safety case for hydrogen use within the gas network.

Hydrogen has a very low density of only 0.085 kg/m^3 (in comparison air density is ~1.225 kg/m^3). This means hydrogen released into a naturally ventilated space tends to disperse rapidly and exhibits strong stratification [1] [13] [14], whereby comparatively high concentrations are found at ceiling height with lower concentrations at floor level. Methane, with a density of 0.68 kg/m^3 also displays this behaviour to a lesser degree. The dispersion of hydrogen is driven largely by convective currents driven by its low density rather than molecular diffusion. Many of the studies that have investigated the severity of hydrogen ignitions have utilised a homogeneous gas mixture within the space of ignition, resulting in a limited understanding of the effect of stratification on the resulting overpressure of the ignition.

Swain and Swain [15] investigated the difference in leak rates of hydrogen and methane under laminar and turbulent flow conditions. They concluded that in a laminar regime (e.g. a weeping pipe fitting), hydrogen results in a volumetric flowrate 1.29 times higher than methane, increasing to 2.83 in a turbulent situation (e.g. a fractured gas main). This was consistent with work carried out by Steer Energy [16] under the Hy4Heat programme. It could therefore be expected that the resulting gas in air concentrations following a hydrogen leak would be proportionally higher than a comparable methane escape. In reality, this is not observed in the experiments as the low density and high buoyancy of hydrogen results in rapid gas dispersion in the event of an escape [1].

The key purpose of this paper is to understand the dispersion of methane and hydrogen gas around a typical domestic property to aid development of consequence models in a naturally ventilated and therefore stratified environment.

Additional modelling work to determine the GIA in the event of a gas escape has been completed by Hy4Heat based on the findings from the experimental studies reported in this document.

4. Research methodology

A series of experimental programmes have been carried out to understand the characteristics of gas leaks in a typical domestic environment. Full project details are reported separately (references included below).

In 2015 Kiwa completed HyHouse [1]; a government funded experimental programme which consisted of the controlled injection of methane, hydrogen and a simulated Town Gas into an aged farmhouse (Figure 2). 120 tests were completed to assess gas dispersion within the property resulting from a range of leak scenarios. Continuous sampling from multiple points throughout the house measured the gas in air concentrations reached in different rooms (and at different heights in the rooms) throughout the test work. The property was tested at three levels of air tightness to simulate varying ages of construction.

As part of the Hy4Heat programme and using a very similar method to that developed during HyHouse, DNV-GL completed over 170 tests [2] [3] to investigate the dispersion of gas within a new build domestic property (Figure 2). Here, gas was released into cupboards (to simulate an escape from a boiler, meter or faulty pipe/fitting) basement and living room. Numerous sampling points were installed around the property and the gas in air concentration measured throughout the injection period. This work included a large number of sample points including sampling in voids such as wall and floor voids. Like HyHouse, direct comparison is possible between hydrogen and methane in the same environment and from leaks of the same magnitude (on an energy basis). Two phases of test work were completed, the majority of analysis considers phase one. Phase 2 included 31 additional tests which considered the effect of increasing ventilation on GIA concentrations.

Also, as part of the Hy4Heat programme, Steer Energy completed a range of tests to understand gas leaks from common fittings, pipework and known gas escape scenarios, e.g. a nail through a pipe [16]. These tests were carried out using hydrogen and methane and a series of results including flow rate were obtained. Analysis of this work has been carried out separately [17], however the results have been used as a cross check in this work to ensure comparability between flow rates and thus escape (leak) scenarios used in each experimental programme.

Under SGN’s Hydrogen 100 (H100) programme [18], Kiwa also considered gas dispersion within a simulated kitchen environment [4] and a partitioned fire investigation box (FIB) [5]. This work has been included as a useful cross check to the data obtained from the property based experimental studies.

For ease of processing the data sets have been identified using the following formats:

Table 1: Test reference format
(the test number is represented by ‘xxx’)

Experimental programme	Test Reference Format
HyHouse	HyH-xxx
Hy4Heat Lot 2	DNVL2-xxx
Hy4Heat Lot 3	DNVL3-xxx
H100	H100-xxx
Hy4Heat Lot 1	Steer-xxx

<table>
<tr><th>Property image</th><th>Key characteristics</th></tr>
<tr><td>

<u>HyHouse</u>

</td><td>

- Built 1800’s
- Rendered solid stone
- 2 storey
- Single glazed
- 2 bed, 2 reception rooms, 1 kitchen, 1 bathroom
- Unfurnished with second fit
- Sample points:
  - High – 30cm from ceiling
  - Mid – middle of room
  - Low – 30cm from floor
- Air tightness at 50Pa:
  - Phase 1: 9.85 $m^3/h/m^2$
  - Phase 2: 6.64 $m^3/h/m^2$
  - Phase 3: 3.46 $m^3/h/m^2$

</td></tr>
<tr><td>

<u>Hy4Heat</u>

</td><td>

- Built 2019
- Unfilled cavity wall
- 2 storey with attic room
- Double glazed
- 1 bed (first floor was not partitioned), 1 reception room, 1 kitchen, 1 bathroom
- Unfurnished with second fit
- Sample points:
  - High– at ceiling
  - Mid – middle of room
  - Low – on floor
- Air tightness at 50Pa:
  - Without basement: 4.26 $m^3/h/m^2$
  - With basement: 5.58 $m^3/h/m^2$

</td></tr>
</table>

Figure 2: HyHouse and Hy4Heat property characteristics

The development of fuel gas accumulations in spaces is moderated by air leakage from the building. The current standard for air leakage in domestic buildings is defined in Building Regulations Approved Document F [6] (for England and Wales) and Building Standards 3.14 [19] (for Scotland). The lower the air leakage rate, the more rapidly gas accumulations will develop from a gas leak inside the space.

In England and Wales the minimum ventilation rate is 0.3 l/s per m^2 internal floor area equivalent to 0.45 air changes/hour for a typical two-storey property. In turn this is equivalent to a flow rate of 9 $m^3/h/m^2$ envelope area at 50 Pa for an 'in use' property, i.e. with ventilation left unsealed. The standards in Scotland are broadly similar, specifying trickle ventilation requirements for properties with infiltration rates of 5-10 $m^3/h/m^2$ at 50 Pa. This means the experimental work has been carried out in environments that represent a 'worst case' for gas accumulation.

These standards apply to the whole house and there will be wide variations in ventilation characteristics of individual rooms; which will be further influenced by internal doors being open or closed. Some degree of ventilation is likely always present due to gaps around internal doors; for example Approved Document F requires an undercut of 76cm^2 (10mm gap) below internal doors [6].

4.1. Data handling

Raw data from the experimental programmes listed above was collated into a combined data file using the key steps detailed in Figure 3. Data was processed and graphed using pipelines developed with Python 3.8 [20], NumPy 1.19 [21], SciPy 1.5 [22], Pandas 1.1 [23] and Matplotlib 3.3 [24].

A data quality review and cleaning process was carried out on the raw data files provided by DNV-GL under the Hy4Heat programme to identify and remove non-representative data points, including unrealistically low or high values (often seen in experimental data due to data collection and logging issues). Further details are provided in Section 4.3.

All data files were then assessed to ensure comparability; e.g. to ensure comparable flow rates and energy releases were used under each scenario across all the experiments. This process included comparison between the property-based experiments (HyH, DNVL2, DNVL3 and H100), and the results of laboratory testing carried out by Steer Energy.

Comparisons based on hole size were excluded from the analysis as some of the property-based test work used calculated hole sizes instead of measured holes. When calculating hole size the orifice plate equation was used (shown below). This includes a coefficient of discharge (C_d) which accounts for restrictions imposed to the flow due to the 'hole'. In most standard situations this factor is assumed to be between 0.6 and 0.75 [25]. However, in reality, there is a complex relationship between the C_d and the Reynolds number of the flow, therefore discrepancies will be apparent when comparing calculated hole sizes (and flow rates) between the different experiments even at the same specified flow rate, due to the experimental set-up. Instead, actual flow rates and resulting energy rates (kW) are used as the basis for comparison as these are based on measured data.

$$A = \frac{q_v}{C_d}\sqrt{\frac{\rho}{2\Delta p}}$$

Where:
A = *area*
q_v = *volumetric flow rate*
C_d = *coefficient of discharge*
ρ = *density*
Δp = *pressure difference*

A table showing indicative hole sizes and associated flow rates as used by Hy4Heat for dispersion modelling [26] has been included in Appendix 1 for ease of comparison.

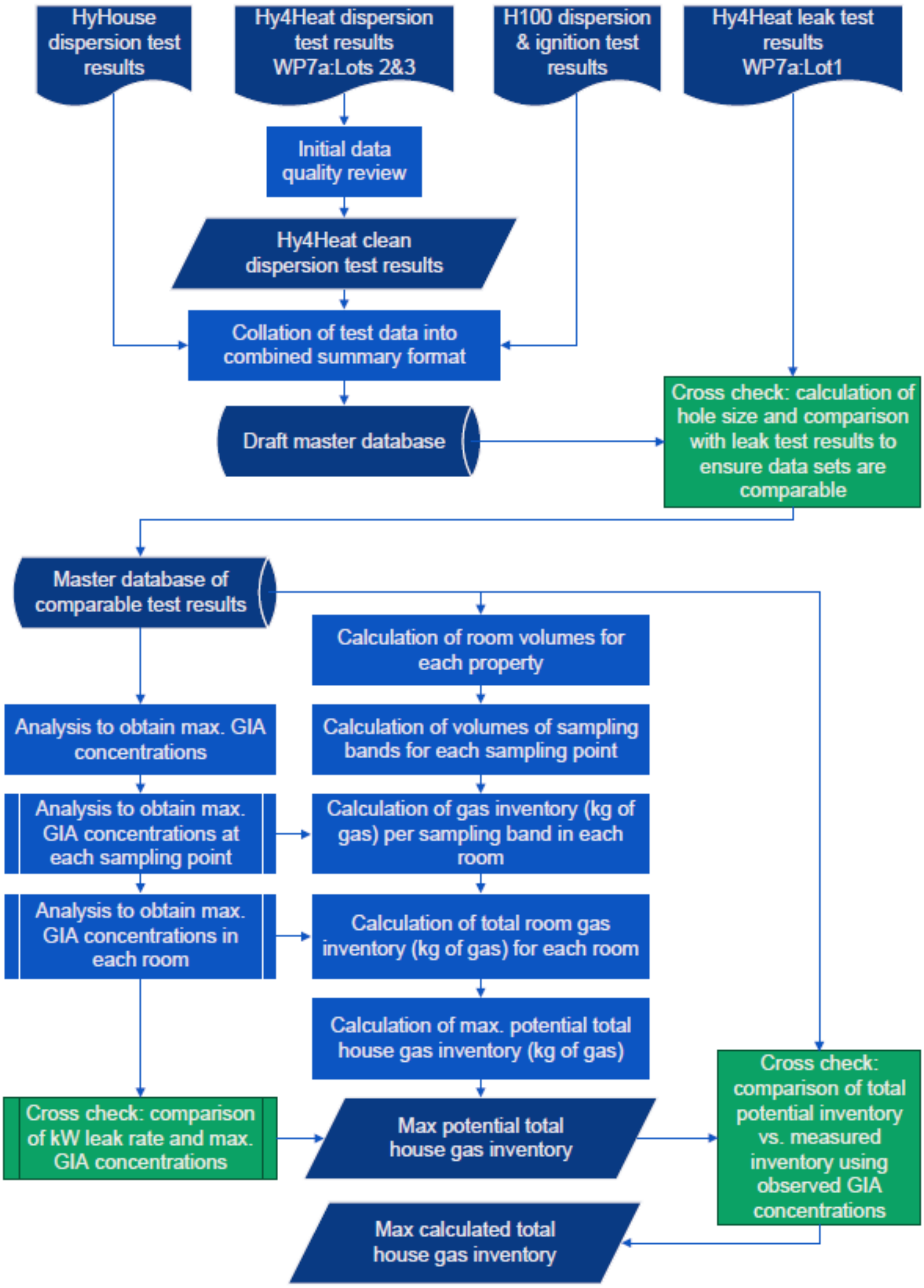


Figure 3: Dispersion data processing flow chart

4.2. Data processing

Each of the cleaned data files was processed to obtain key parameters from the raw data. A combined data file was compiled containing the results from every experiment. The following parameters were collated from each test:

- Test Reference
- Gas under test
- Release point
- Duration of gas injection
- Flow rate
    - Volumetric
    - Energy (kW)
- Hole Size
    - Calculated
    - Actual
- Total gas injected
    - Volumetrically
    - Mass basis
    - Energy (kWh)
- Maximum GIA concentration at each available sample point (note; not all experiments had all sample points):
    - Kitchen High, Mid and Low
    - Living High, Mid and Low
    - Upstairs High, Mid and Low
    - Loft Space High, Mid
    - Cupboard High, Mid and Low
    - Under Cupboard (limited tests)
    - Basement High, Mid and Low
    - Hallway High and Mid
    - Wall cavity
    - Stud wall cavity
    - Floor void (ground to first)
    - Floor void (first to loft)
    - Roof void
- Maximum GIA concentration in each room
- Gas Inventory (kg)
    - For each concentration 'band' within the room (as listed above)
    - For each room

The 'cupboard' sample points in the Hy4Heat experiments included a variety of cupboard types including:

- Wall cupboard (W 800 x D 385 x H 800)
- Base cupboard (W 800 x D 600 x H 800)
- Undersink cupboard (W 800 x D 600 x H 600)
- Boiler cupboard (W 800 x D 600 x H 2090)

The flow rates used for the cupboard (excluding the boiler cupboard) and room injections were chosen to be comparative to low pressure ~20 mbar, less than 70 kW (hydrogen) gas escape scenarios such as a cracked pipe, loose fitting or small hole.

The basement and boiler cupboard injections included higher flow rates to simulate gas tracking from an escape in an external pipe (such as a full-bore pipe failure) before the emergency control valve (ECV) at the meter. The maximum flow rate was approximately 265 kW (hydrogen).

4.2.1. GIA Concentrations

Using the combined data file, analysis was made of maximum GIA concentrations reached within each room and at all sampled heights within that space. Graphs were plotted for a range of scenarios:

- Gas release into a room – HyHouse and Hy4Heat
- Gas release into a range of cupboards – HyHouse and Hy4Heat
- Gas release into a basement – Hy4Heat only

Each scenario was tested at a range of gas escape rates.

4.2.2. Gas Inventory

Once the maximum GIA concentration was established it was possible to calculate the gas inventory of the space using the following equation:

$$\text{Gas inventory } (kg) = \sum_{\substack{\text{all} \\ \text{spaces}}} \left[\begin{matrix}\text{Gas concentration} \\ \text{in space}\end{matrix} \left(\frac{m^3}{m^3}\right) \times \text{Volume of space } (m^3) \right] \times \text{Gas density} \left(\frac{kg}{m^3}\right)$$

In rooms where multiple sampling points were present, the room was split into 'bands' depending on the sampling points present. For example, if there were high and mid sampling points the room was split into two bands assuming the maximum GIA concentration recorded at the mid-point represented the bottom half of the space and the high point represented the top half of the space. Likewise, if the room had three sampling points, the volume was split into three and the concentration within those three bands was assumed to be equal to the corresponding sampling point.

This method does not account for the changes in concentration across the bands and therefore may slightly over or underestimate the amount of gas present within each band. However, it provides a good approximation within the limits of the available data.

Using the gas inventory in each sample band, the total room inventory could be calculated by adding the various bands within the space.

4.3. Data quality

The dispersion data collected under the Hy4Heat programme by DNV-GL was not part of a previously published study, and so was subject to additional data quality checks before being included in the analysis. These checks were based on a three-way comparison of separate processing of the raw data files provided by DNV-GL.

The sources of data used in the quality checks were:

1. Maximum concentrations in each test as declared by DNV-GL, based on a manually selected 'averaging window' of typically 10 minutes towards the end of the test.
2. Extracted maximum concentrations based on a manual examination of the raw data by Kiwa (after adjustments for analyser calibration and offsets).
3. Extracted maximum concentrations based on automated processing of the raw data by Kiwa, informed by learnings from the manual processing.

The maximum concentrations in each test obtained by each of these three methods were compared. Where discrepancies where found, they were manually checked and cross-referenced with the concentration graphs and test comments. Specifically, discrepancies were flagged as values that differed by more than 1 percentage point of the reported % GIA, or by more than 10% (relative) of the % GIA value (whichever was greater).

The basis of the data included in the further analysis was the results declared by DNV-GL (“1”), unless after the review of a discrepancy it was determined that the reported value was not representative of the ‘true’ measured maximum concentration. In such cases, the maximum concentration determined by Kiwa’s automated processing (“3”) was used instead.

The primary reasons for discrepancies were:

- **The averaging window initially selected was too early** to capture the maximum gas concentrations in areas away from the room with the injection (for example upstairs, or in voids and cavities). In these cases, this value was effectively replaced by larger one from a later and more representative window.
- **The rest of house was not at steady state** even after several hours of gas injection and after reaching steady state in room with the injection. This is likely to be more significant for tests involving high release rate escapes (partly because it is difficult to sustain the high release rates required by the test). If the rest of house was further from steady state, then it could be that there were spaces (particularly upstairs and in voids and cavities) where the concentration was still increasing at the end of the test. Combined with an early averaging window, this meant the concentrations initially reported are lower than the maximum concentrations that would be observed. In these cases, this was partially remedied by using a later and more representative window, however it should be noted that this does not change the fact the rest of house was not at steady state and after continued injection some values would be expected to be higher. This will primarily affect the whole house gas inventories (see Sections 5.4 and Appendix 2).
- **The gas analysers were over-range** and reported a single unchanging value. The majority of these had been identified by DNV-GL but still required manual removal from the raw data provided. This primarily occurred in cupboards when the concentration was >70 % (sometimes also >30 % depending on range of the analyser in use), but also in some void and cavity measurements when the concentration was >~2 % (on a low-range analyser). In these cases, the values were reported as unavailable and not included in further analysis.

The review of the data resulted in the adjustment or removal of approximately 7% of the total number of data points, affecting approximately 25% of the total number of tests.

The data quality checks checked for and addressed issues that were more than ±1 percentage point or ±10 % (relative) of the ‘true’ measured value, with the remaining caveat for the non-steady state measurements in the rest of the house. Although this does not account for other sources of measurement uncertainty, if this ±10 % is treated as a form of uncertainty then it is broadly in line with scale of uncertainty observed in the other reported data sets.

5. Results and discussion

In all test work, the area of highest gas concentration was the space into which the injection took place.

Much of the analysis included below was carried out using data collected from the kitchen as all the cupboards under test were located within the kitchen space. The kitchen area is also often considered high risk due to likelihood of gas appliances being located there, e.g. gas hobs/ovens and boilers. Comparison was then made to the rest of the property in terms of adjoining rooms, voids and higher floors.

Figures 4 and 5 show the maximum gas concentration within the room where the injection was located, for all tests, split to show hydrogen and methane. These are shown on both an energy and a volume basis.

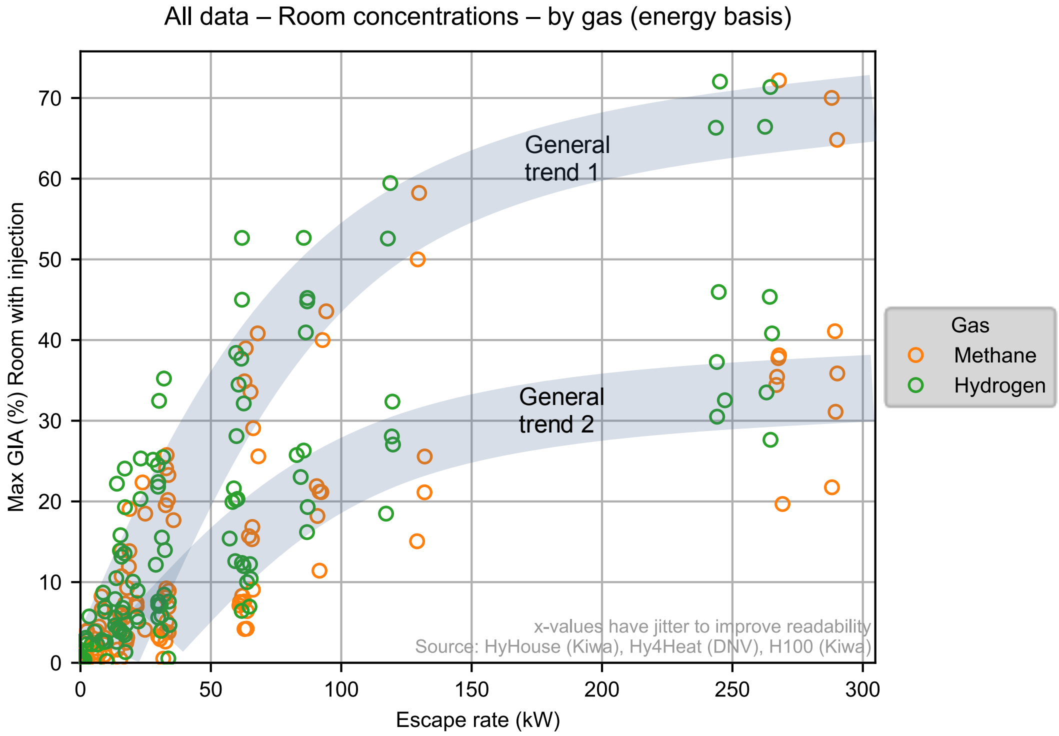


Figure 4: Maximum GIA concentration (%) found within room of injection during all experiments (escape rate on an energy basis)

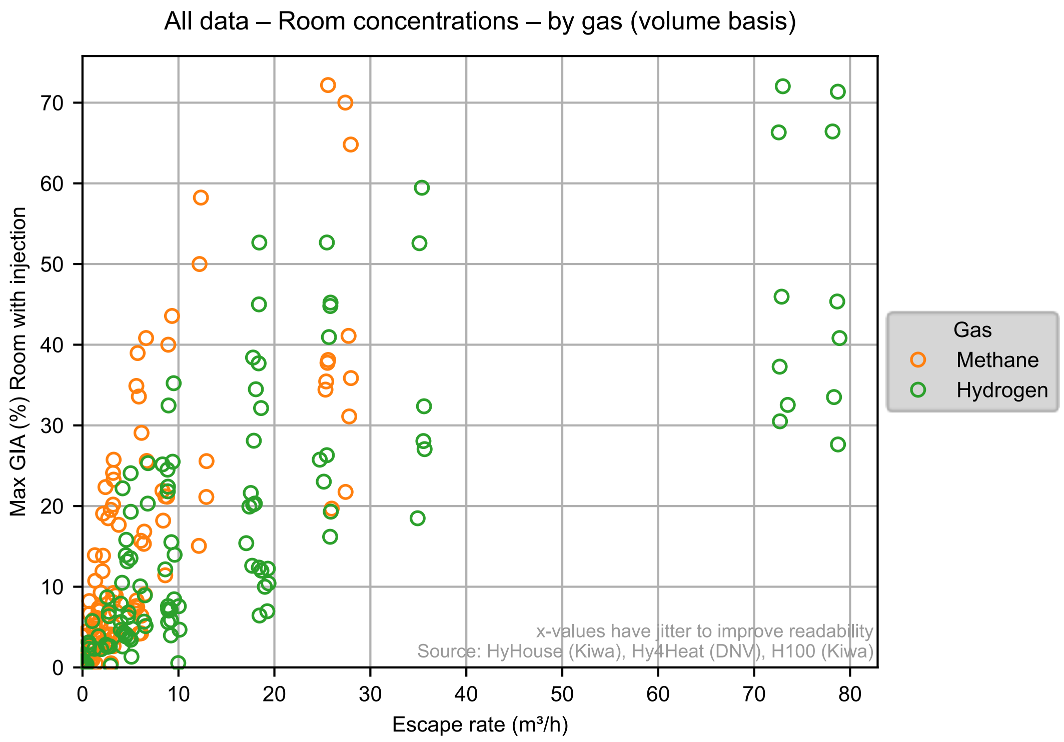
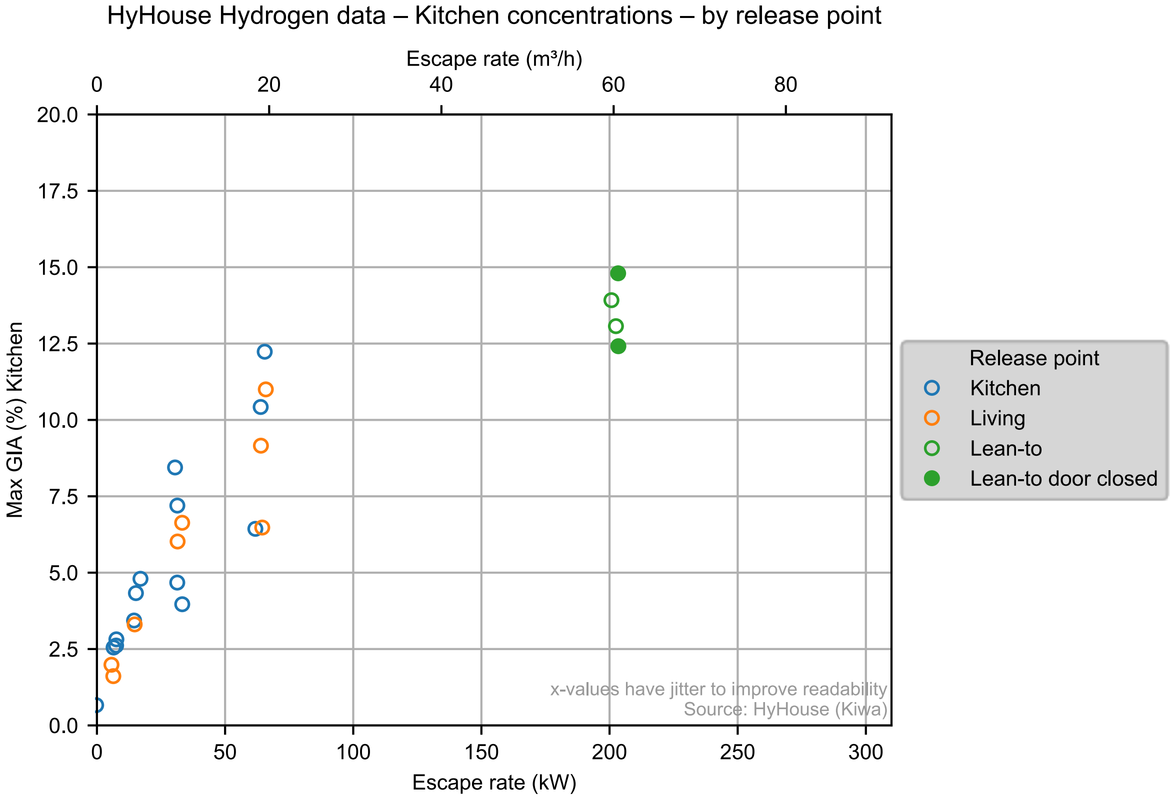


Figure 5: Maximum GIA concentration (%) found within room of injection during all experiments (escape rate on a volume basis)

When escape rate is expressed on an energy basis, hydrogen and methane show broadly similar maximum GIA concentrations for the same escape rate, with a tendency for hydrogen to result in slightly higher concentrations than methane. Conversely, when the escape rate is expressed on a volumetric basis, methane results in higher GIA concentrations than hydrogen. It is important to note that on a volumetric basis the flow of hydrogen through an equivalent hole size is approximately 1.2 to 2.8 times higher than methane depending on whether the leak exhibits laminar or turbulent flow characteristics [16]. The following figures show both relative energy and volumetric flows.

Two distinct trends are evident in the data (highlighted in Figure 4) where the same release rate resulted in significantly different maximum GIA concentrations; and this is apparent for both methane and hydrogen. This was further investigated by splitting the data by release point and is shown most clearly when also split by project (Figures 6 and 7). Further analysis of this is detailed in the following sections.



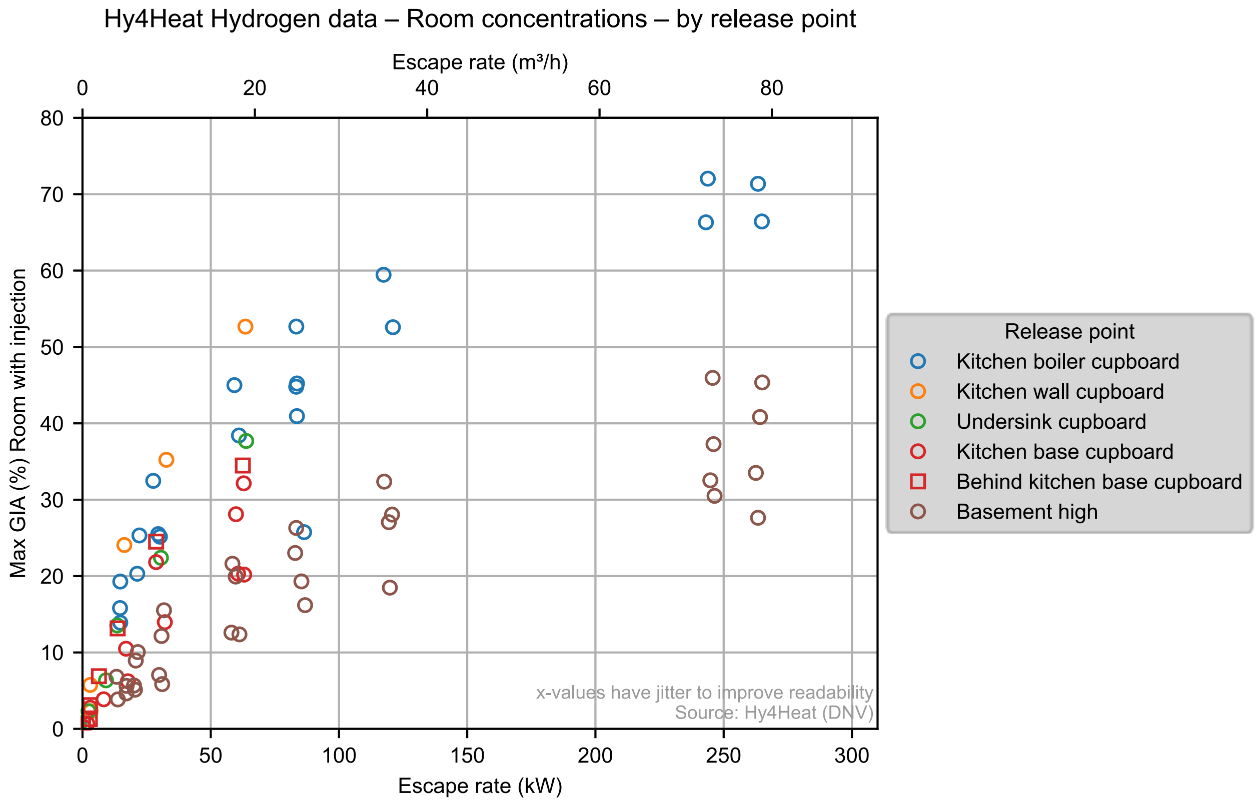
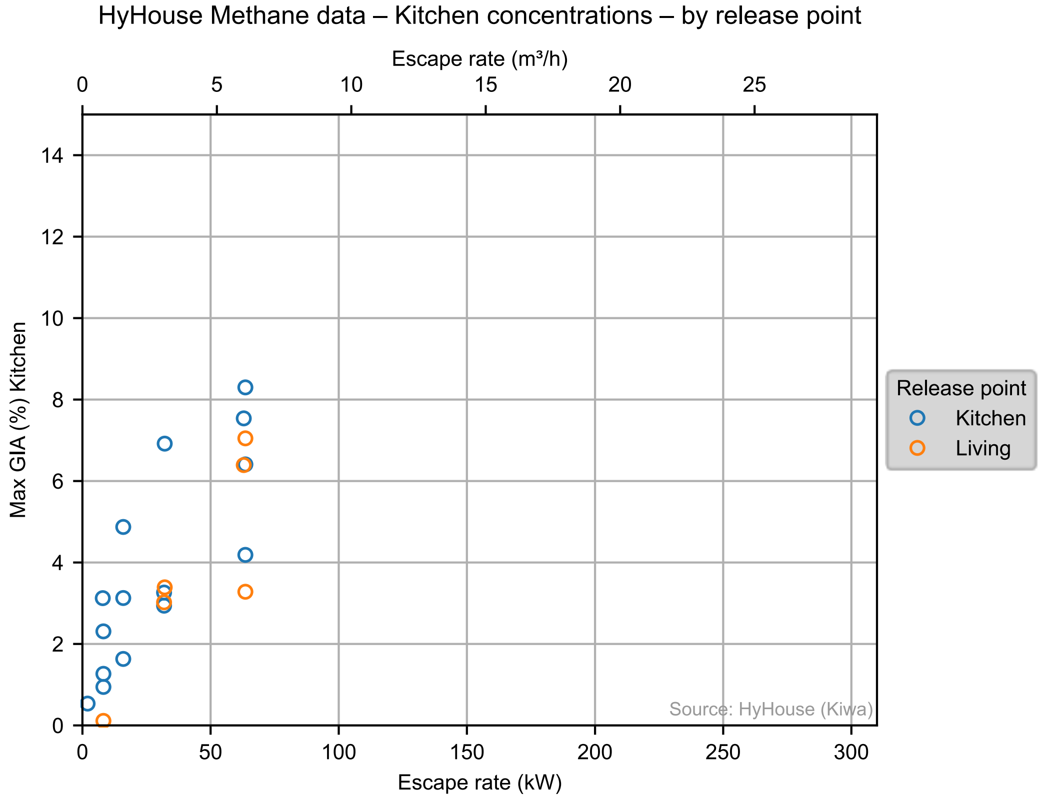


Figure 6: Hydrogen maximum GIA concentration (%) split by release point and shown for HyHouse (top) and Hy4Heat (bottom) projects



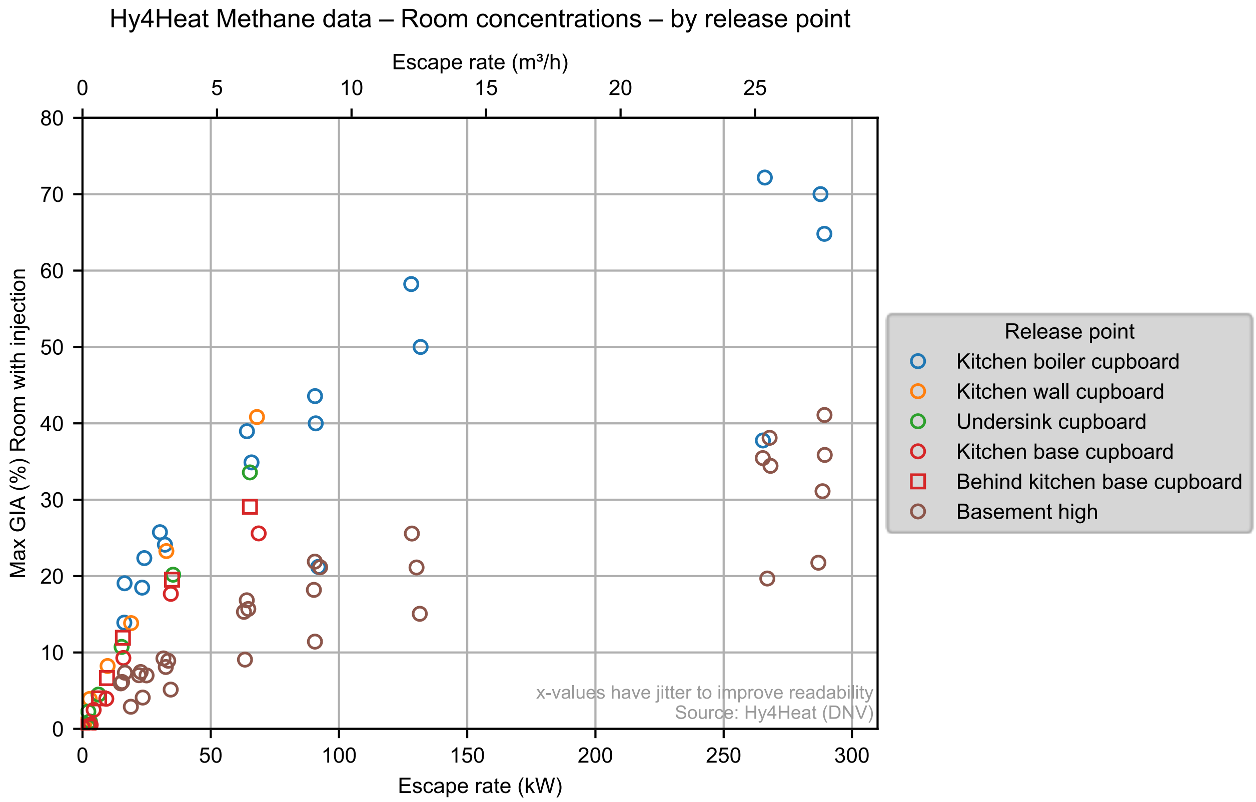


Figure 7: Methane maximum GIA concentration (%) split by release point and shown for HyHouse (top) and Hy4Heat (bottom) projects

5.1. GIA Concentration (%) – Releases from unenclosed pipes

A considerable difference in maximum GIA concentration was measured when an unrestricted gas release occurred into a room, compared with that observed when a release occurred within a closed cupboard and subsequently escaped from the cupboard into the room.

This section considers data collected when gas was released into a room (e.g. an unenclosed pipe). It includes data collected from HyHouse where releases were carried out into the kitchen and living room, and data from Hy4Heat where releases were carried out in the basement.

Figures 8 and 9 demonstrate the maximum GIA concentration observed in the room of release at different gas injection rates for hydrogen and methane. At low release rates (below 50 kW), akin to likely leak scenarios within a domestic setting, comparable maximum gas concentrations were observed in the basement tests as were seen during the HyHouse experiments, suggesting that even though the ventilation characteristics of these spaces are different, at low release rates, both hydrogen and methane disperse in a relatively consistent manner when released into a large space.

Overall, maximum hydrogen GIA concentrations resulting from small gas escapes into a room were relatively low, with flow rates of over 15 kW (4.5 m^3/h) required before a flammable atmosphere was measured. When internal doors were open, flow rates of approximately 60 kW (18 m^3/h) only resulted in maximum hydrogen concentrations of ~12% in the room of release (in the basement and at HyHouse at the greatest level of air tightness). Closing the basement door increased the maximum hydrogen concentration measured at lower release rates and this is discussed in detail in Sections 5.2.2 and 5.3.

Comparative concentrations were observed for methane and again the effect of closing the basement door on maximum concentrations was clear. However, the consequences of ignition of methane concentrations of this magnitude compared to hydrogen are likely to be different. Detailed discussion of the consequences of ignition of varying GIA concentrations for hydrogen and methane are included in a supporting WP7 document [7].

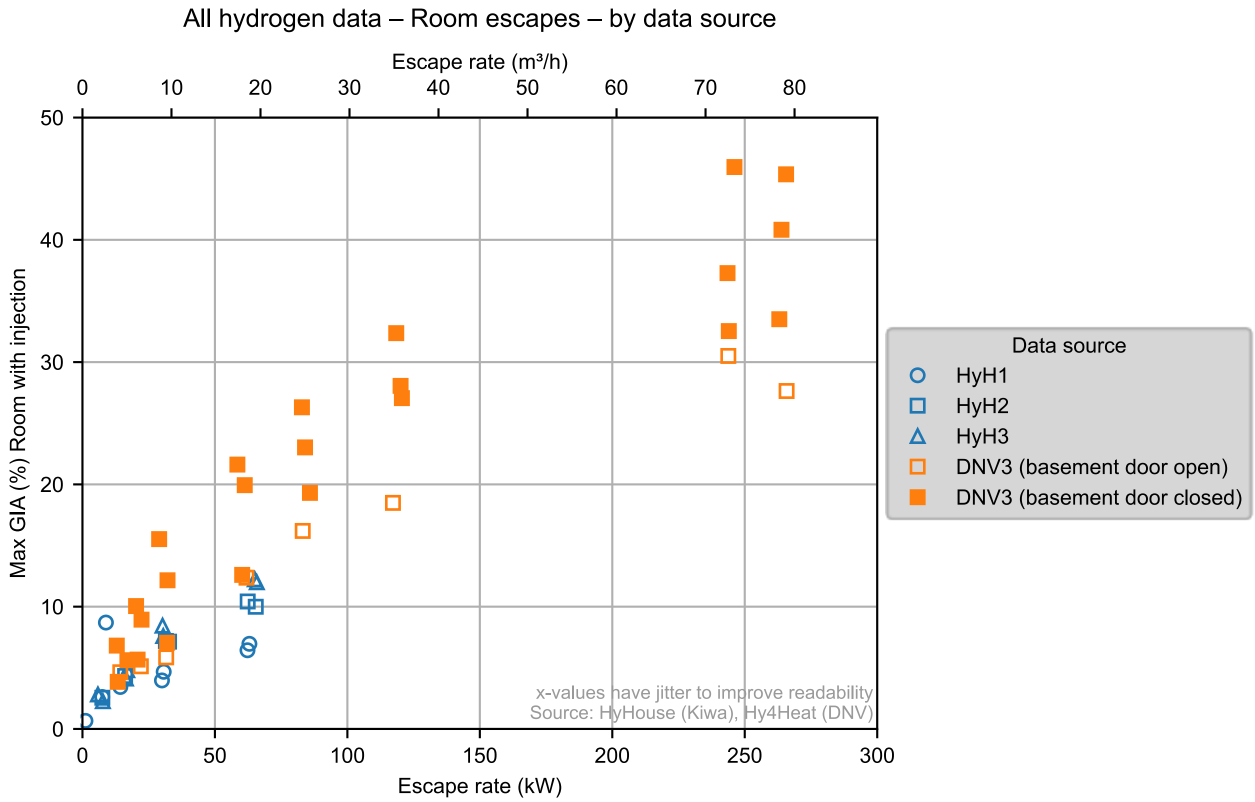


Figure 8: Maximum hydrogen concentrations for all tests for gas releases into a room

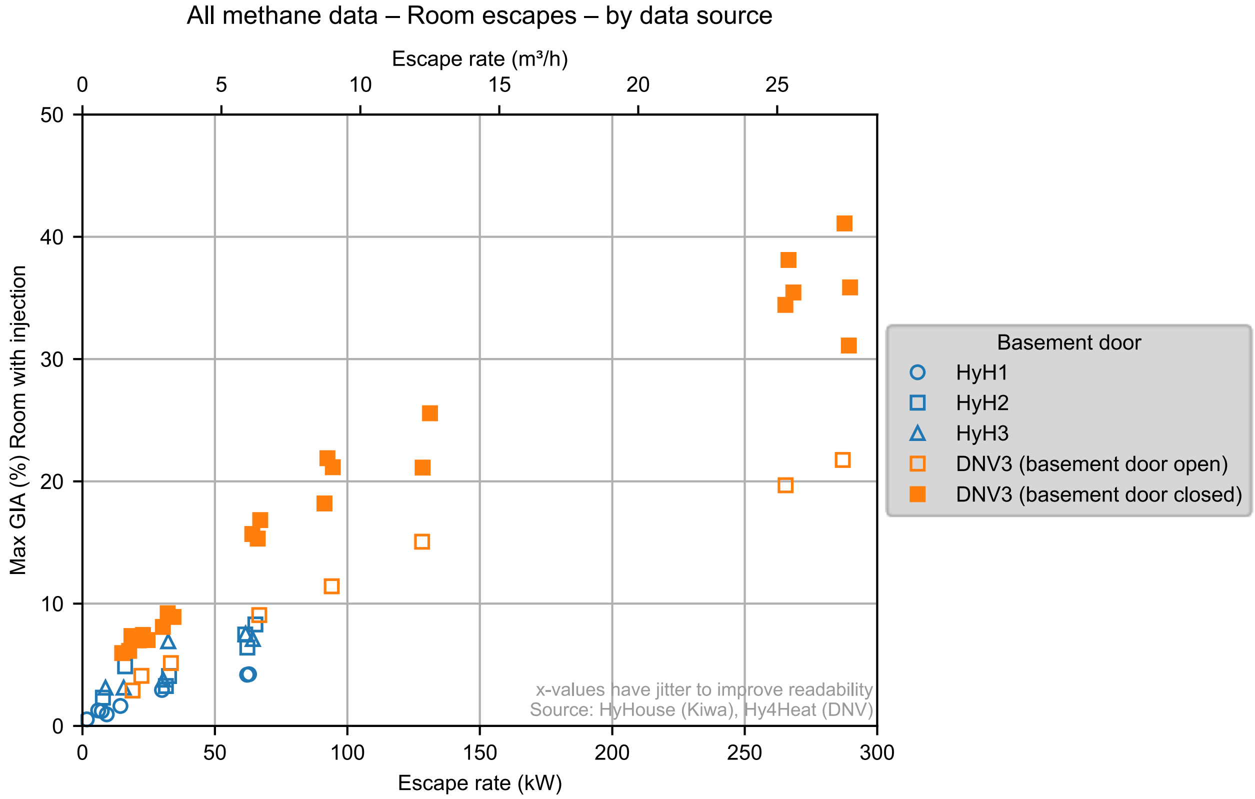
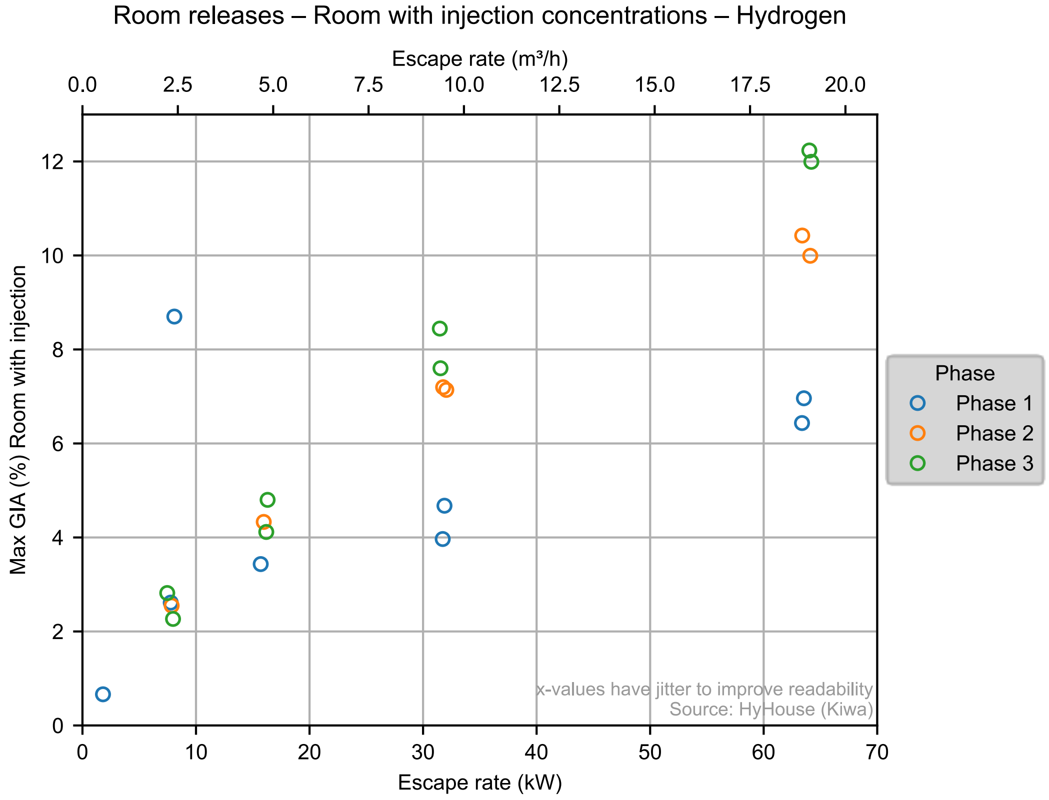


Figure 9: Maximum methane concentrations for all tests for gas releases into a room

Data from HyHouse has also been split to show how the maximum GIA concentration changed for the same gas release rate when the property was at different levels of air tightness (Figure 10). As air tightness increased, i.e. ventilation within the property reduced, the maximum gas concentration within the room of release increased. In fact the maximum gas concentration observed at HyHouse doubled when the air tightness of the property increased from the as built value of 9.85 $m^3/h/m^2$ (phase 1) to the phase 3 air permeability value of 3.46 $m^3/h/m^2$ (tightly sealed).

Ventilation characteristics of a basement are more complicated and basement concentrations are discussed in detail in Section 5.3, however their inclusion in this section helps to demonstrate that when gas is released into a room at low flow rates, the resulting maximum gas in air concentrations are lower than may be expected when comparing to the volume of gas injected.



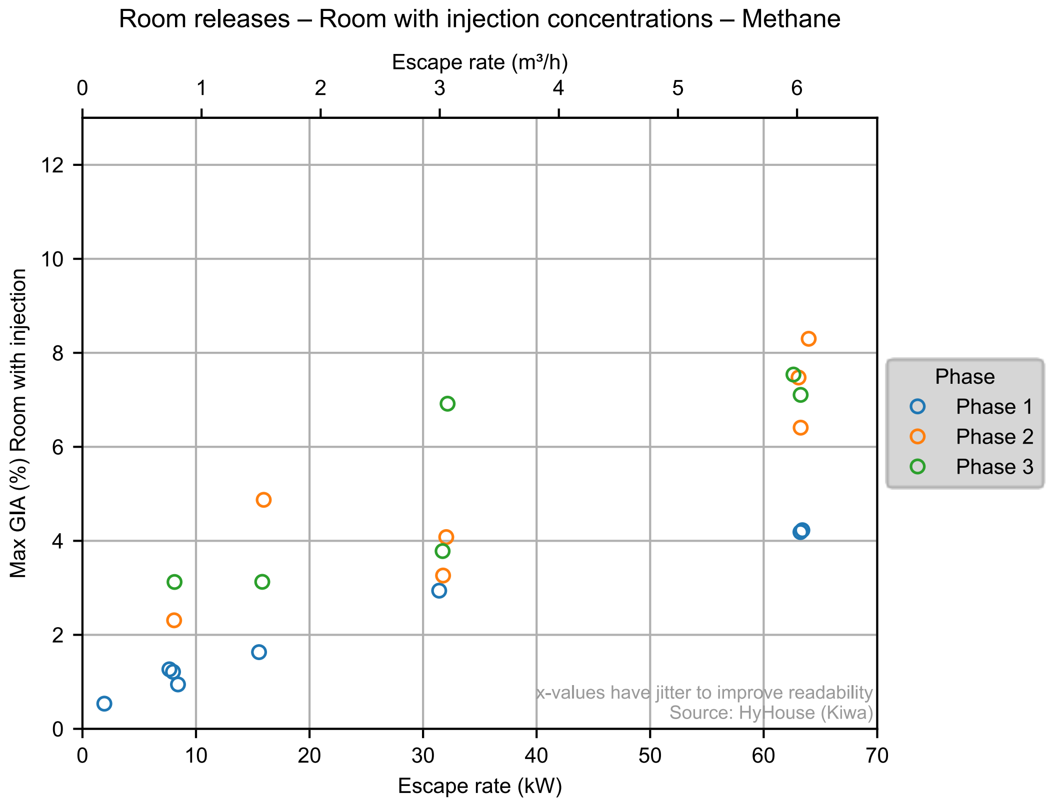


Figure 10: Maximum GIA concentration % during gas releases into a room for hydrogen (top) and methane (bottom)

5.1.1. Stratification

It is known that buoyant gases such as hydrogen or methane stratify when released into a naturally ventilated space [27, 28]. In low pressure systems such as those trialled in this work, dispersion is driven by a combination of momentum of the gas and buoyancy forces generated by the relative difference between the gas density and ambient air [29].

As the gas disperses away from the escape point, air is entrained into the gas stream, decreasing the gas jet concentration and resulting in a gas / air mixture which leads to the observed GIA concentration. The mechanism of air entrainment and dispersion is highly complex, depending on the escape exit conditions, gas pressure, flow rate, and environment into which the escape occurs; and as such detailed modelling of this nature is not included in this document.

As the buoyant gas rises away from the point of release, it is constrained by the environment into which it escapes. For a domestic setting such as those trialled in this work, this means the gas hits the ceiling of the room and accumulates; resulting in a layer of high GIA concentration at the top of the room and far lower concentrations in the rest of the space.

Data collected from all the experiments demonstrates clear stratification within the property. Figure 11 shows an example of this for both hydrogen and methane during the HyHouse study, when escapes took place in the kitchen. The data shows the same release rate carried out in phase 2 and 3 of the HyHouse test work, therefore also demonstrating the general trend of increasing GIA concentrations observed as the air tightness of the property increased.

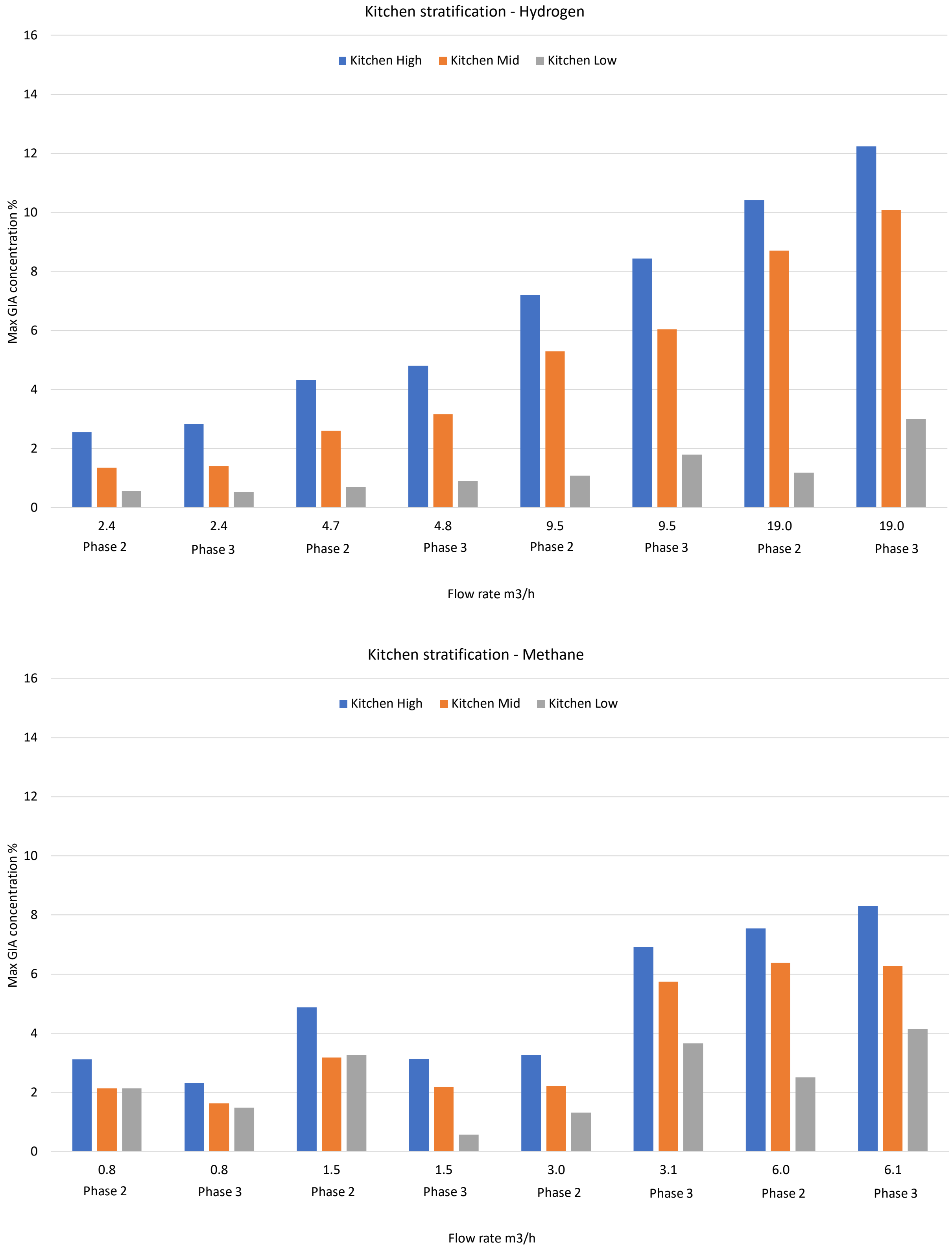


Figure 11: Stratification of gas within the kitchen for hydrogen (top) and methane (bottom)

5.1.2. Rest of house GIA concentrations

During the HyHouse test work, the maximum concentration seen elsewhere in the property, e.g. in upstairs rooms, when a release took place in a downstairs room (e.g. kitchen or living room) was comparable to the maximum concentration observed in the room of release (Figure 12). This is likely in part due to the doors throughout the house being open and allowing easy dispersion.

This was not observed to such an extent, during the Hy4Heat test work, where lower concentrations were observed in upstairs rooms compared to the room into which the injection took place. This was heavily influenced by doors being open or closed (as detailed in Section 5.2).

As discussed in Section 4.3, in almost all the Hy4Heat test work, the concentration in rooms in the rest of the house did not reach steady state; meaning the gas concentration was still increasing in most parts of the house (apart from the room in which the injection took place). In contrast, most of the HyHouse tests continued until all rooms had begun to reach steady state. Although this does not affect the results of the investigations as reported, it is worth noting that if the gas were to continue leaking beyond the time allotted to tests during the Hy4Heat test work, it is likely that higher gas concentrations would be observed in the rest of the property.

It is important to note that in all test work, the upstairs rooms did not exhibit the same stratification as was observed downstairs. Each of the upstairs rooms displayed a far more homogeneous mix, therefore the maximum GIA concentration observed was apparent throughout the entire space.

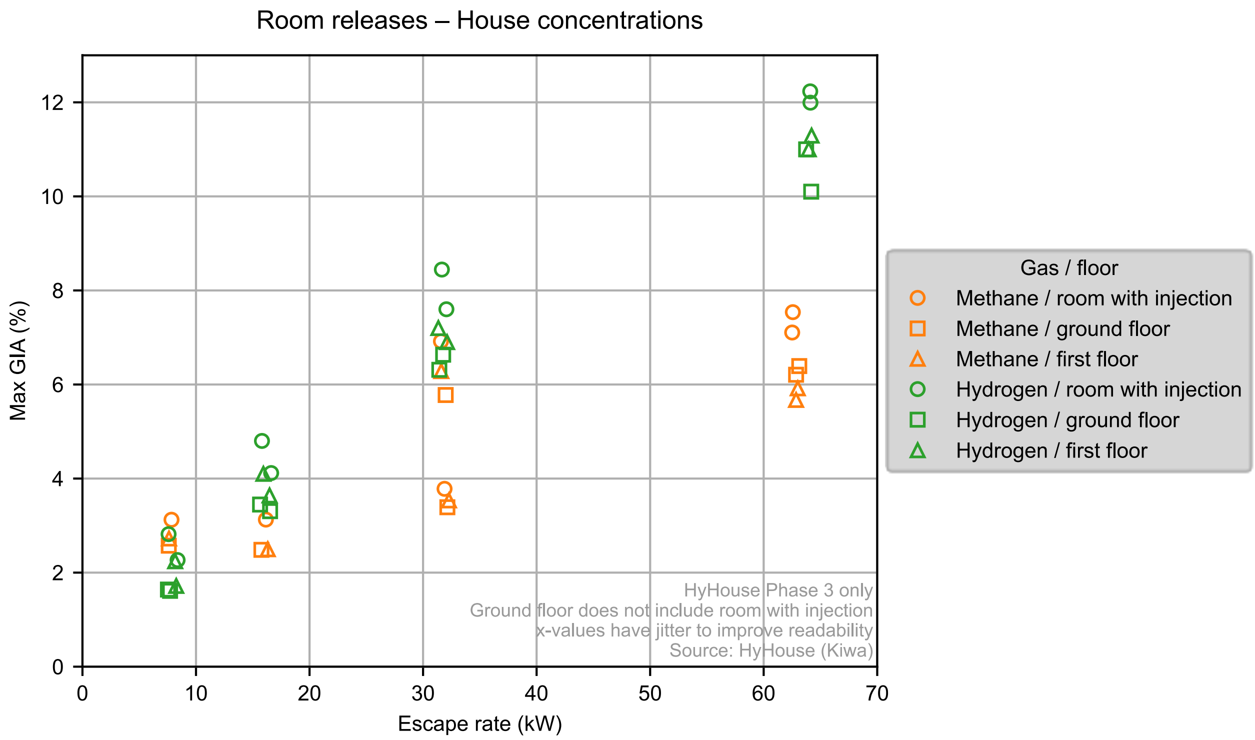


Figure 12: GIA concentration in the rest of the property during a release into a downstairs room for hydrogen and methane

5.2. GIA Concentrations (%) – Release into Cupboards

A large proportion (57%) of the tests completed under the Hy4Heat programme were gas releases into a kitchen cupboard (as detailed in Section 4.2). The resulting maximum cupboard concentrations are shown in Figure 13, for hydrogen and methane respectively.

These releases equate to escape rates of between approximately 0.4 and 290 kW. It is clear even very small gas escapes result in high cupboard GIA concentrations for both hydrogen and methane.

Unlike the gas concentrations measured in the rooms, the GIA concentration within the cupboard did not exhibit strong stratification. Highest concentrations were recorded at the sensor closest to the point of injection, and in some cases, this was the lowest sensor in the cupboard; below the bottom shelf. It is likely that the presence of shelves results in accumulation of gas as it escapes, however the overall effect on the concentration in the cupboard was minimal and a fairly uniform concentration was observed throughout the cupboard space.

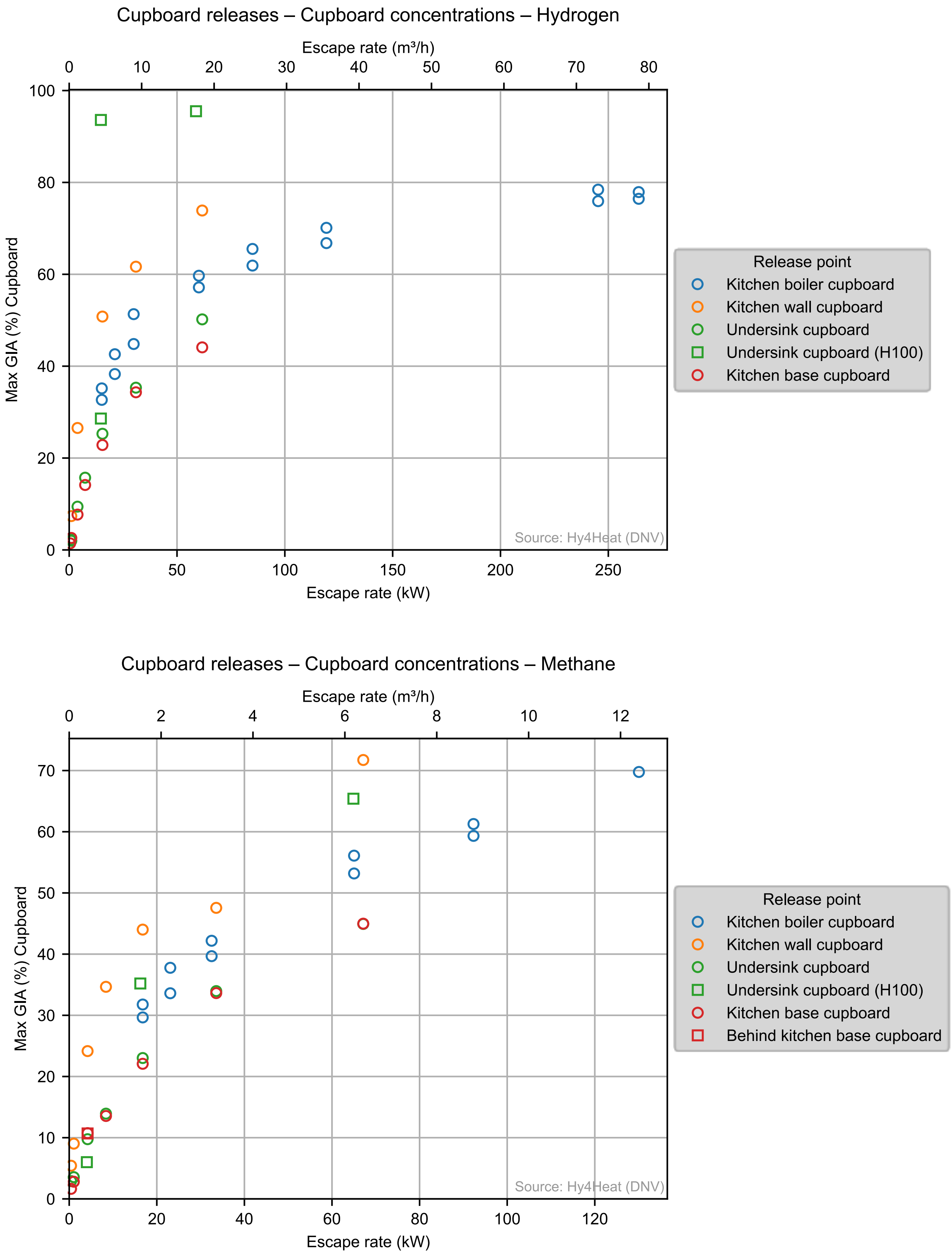


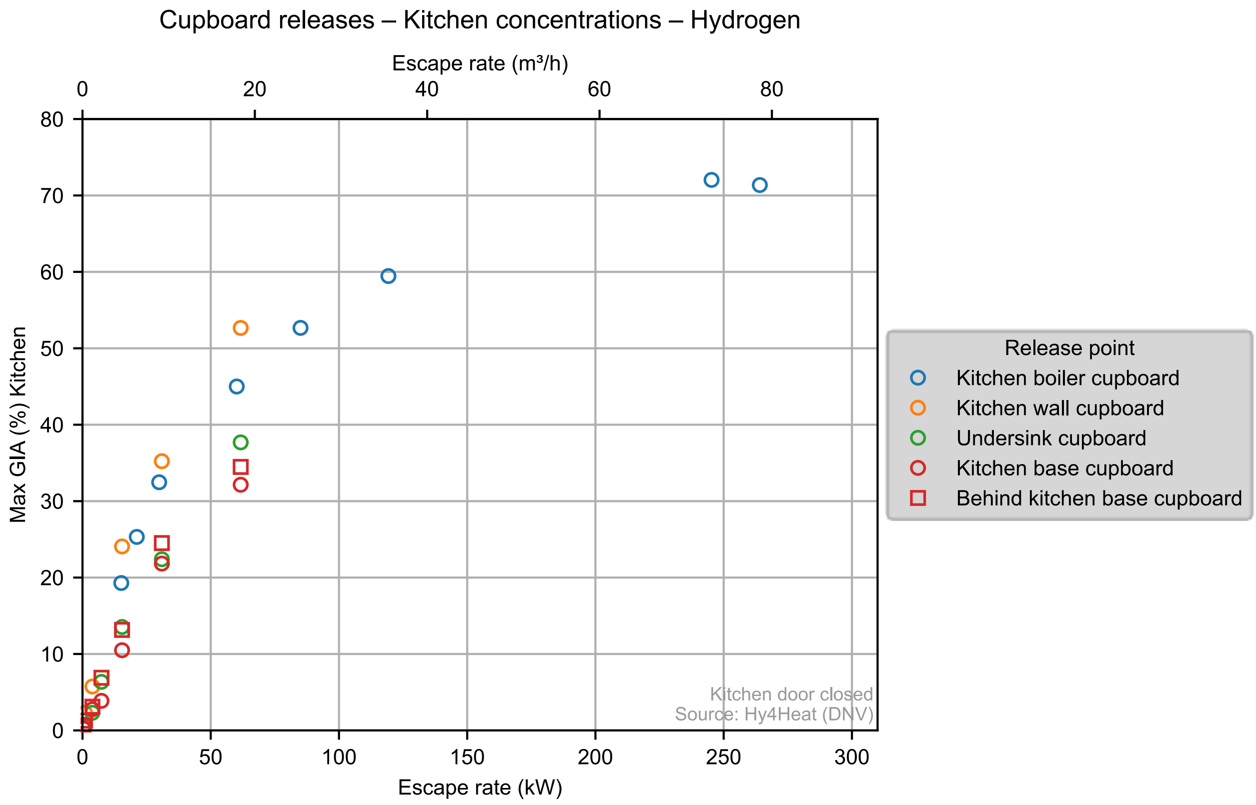
Figure 13: Maximum cupboard GIA concentration (%) split by cupboard type for hydrogen (top) and methane (bottom)

5.2.1. Kitchen GIA concentrations

The resulting maximum GIA concentrations in the kitchen from a release in a cupboard are shown below. These tests were carried out with the kitchen door closed; the effect of open and closed doors is discussed in Section 5.2.2. Comparable results were seen for hydrogen and methane (Figure 14).

Although the maximum GIA concentrations measured in the kitchen were lower than those observed in the cupboard space; concentrations which could lead to damaging deflagrations were recorded, even at low flow rates for both hydrogen and methane.

Higher maximum GIA concentrations were observed in the kitchen when the release was into the wall or boiler cupboard, compared to the lower undersink or base cupboards (both the wall and boiler cupboard had an ‘opening’ at high level, e.g. the top of the cupboard was close to the ceiling). Gas stratification within the kitchen space was also exacerbated when the gas release was in a cupboard with a high opening (Figure 15); this was most evident for boiler and wall cupboard releases with hydrogen and boiler cupboard releases with methane.



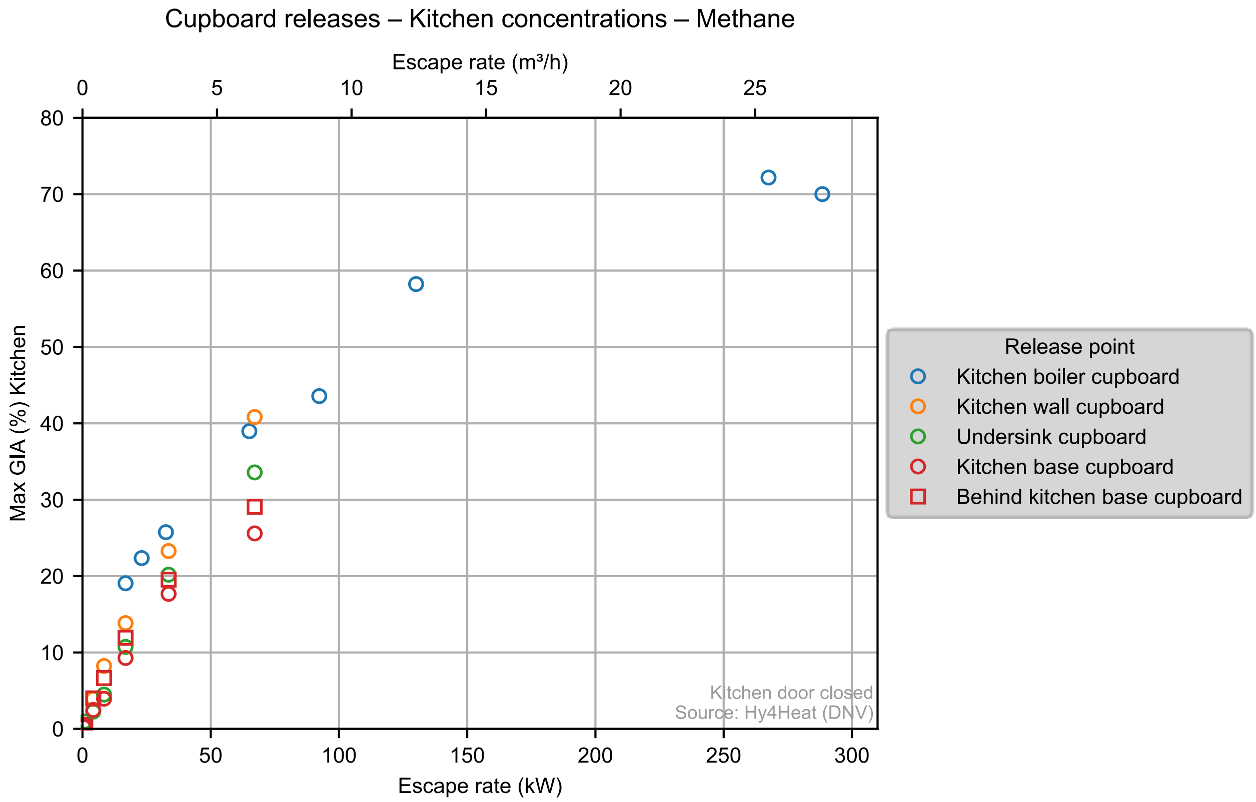
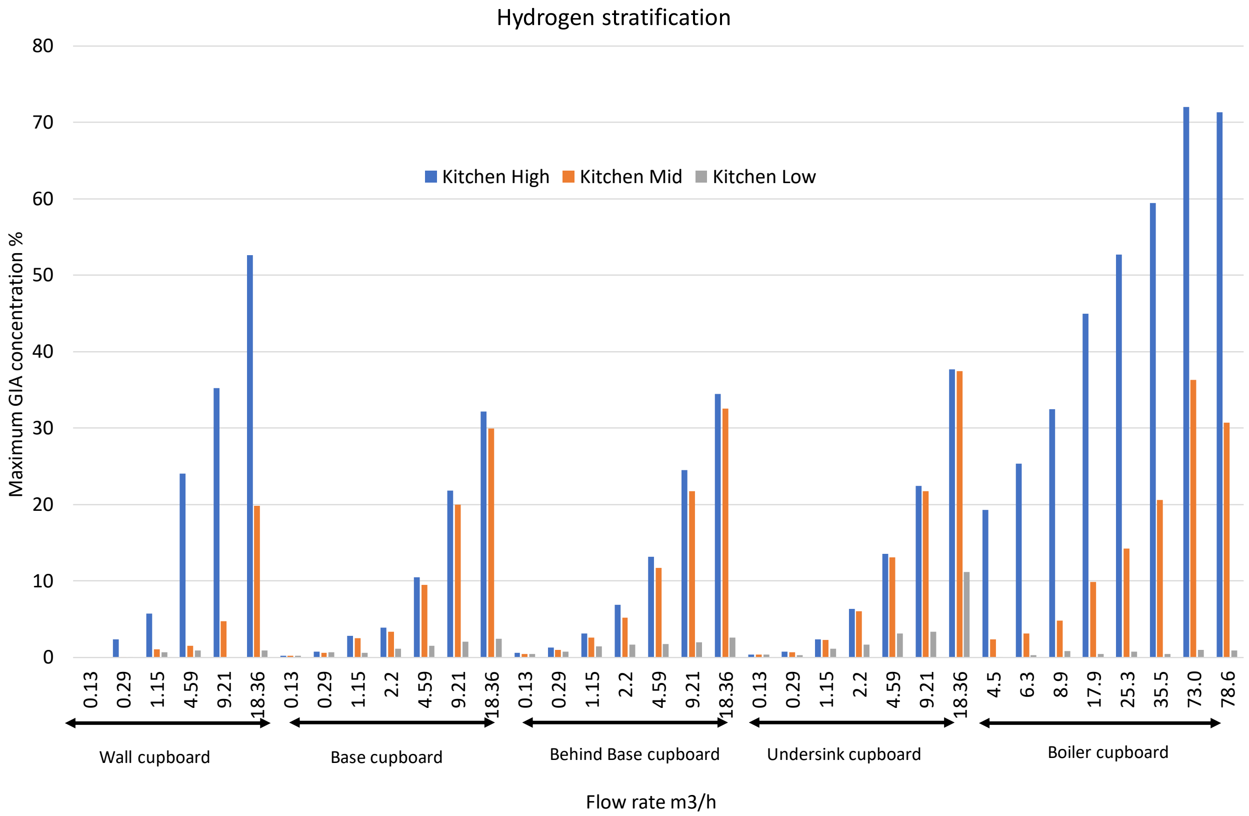


Figure 14: Maximum kitchen GIA concentration (%) split by cupboard type for hydrogen (top) and methane (bottom)



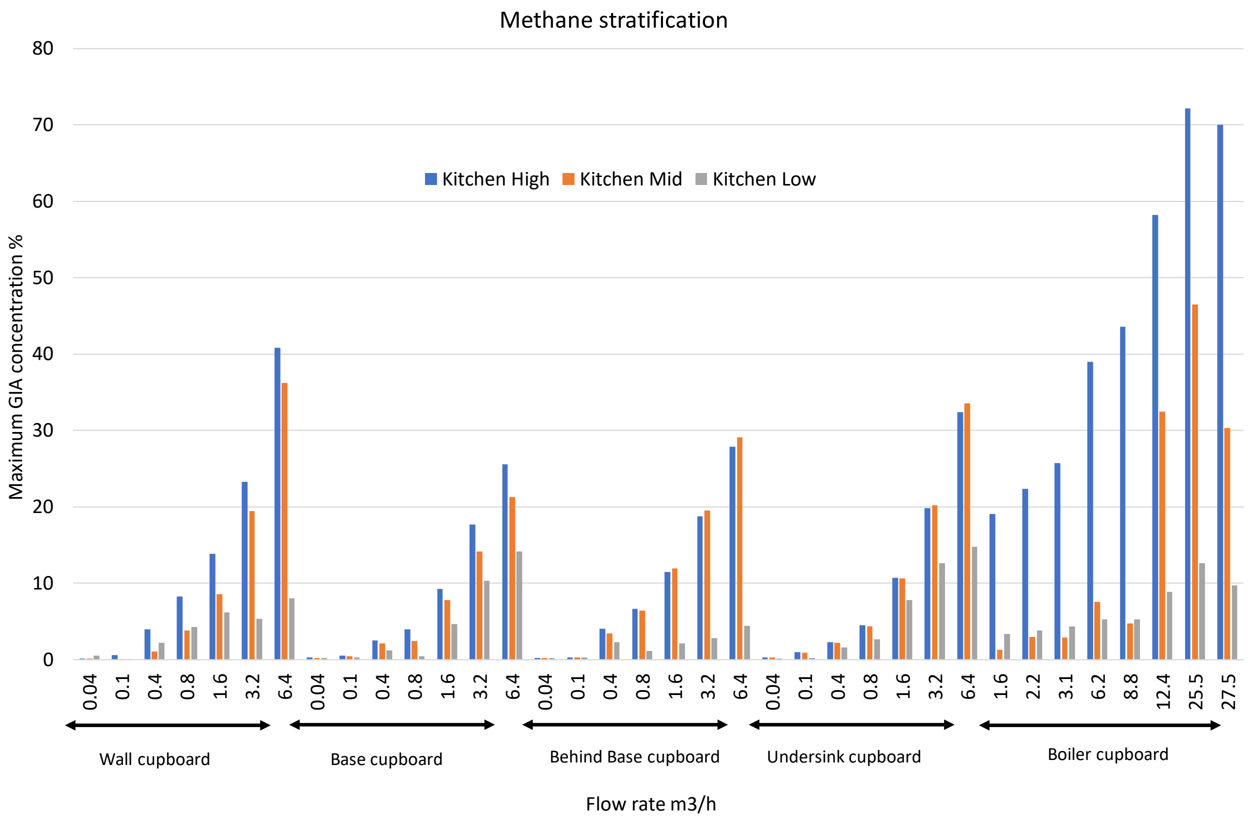


Figure 15: Gas stratification within the kitchen during cupboard injections for hydrogen (top) and methane (bottom)

As the cupboard fills up, gas is released through the gap between the cupboard shell and door. It appears that the method of gas release from a cupboard located near the ceiling (e.g. wall or boiler cupboard) results in a layer of high GIA concentration across the ceiling with lower concentrations within the rest of the space, as shown in Figure 16.

As described in section 5.1.1 above, when methane or hydrogen escapes from a pipe the gas jet entrains the surrounding air (or air/gas mixture). The lower density gas plume (compared to the surrounding room) rises, driven by local convective density forces, and disperses into the top of the space at a relatively dilute concentration (compared to the escaping gas).

As the gas escape continues, a zone of gas/air mixture forms across the ceiling. As the escaping gas plume enters this zone, the buoyancy driven convective forces reduce as the density of the zone becomes akin to that of the escaping gas plume. The gas/air mixture becomes effectively trapped near the ceiling and a layer of fairly uniformly mixed gas and air then accumulates in a downward direction from the ceiling. This applies to both hydrogen and methane.

However, if the release point occurs at height as it did in the wall and boiler cupboard experiments; a situation arises whereby the zone into which the gas disperses and mixes with air (thereby diluting the gas plume concentration) is volumetrically reduced compared to a gas escape at low level (e.g. a pipe near the ground). Although the initial stages of the gas escape are comparable, the zone into which the gas plume accumulates quickly increases in concentration. This results in a band of high GIA concentration at the top of the room and lower concentrations within the rest of the space (as shown in Figure 15 for the boiler and wall cupboards).

An added complication occurs if the gas escape in the cupboard is of sufficient quantity to limit the air ingress into the cupboard space (ie by pressurizing the cupboard), which reduces the dilution of the gas prior to its release into the room. This further increases the likely maximum GIA observed in the ceiling zone outside the cupboard space. High concentrations across the ceiling can in turn lead to high concentrations in 1st floor voids. Over time this zone of high concentration will extend downwards from the top of the room as more flammable gas is released.

Models by Molkov et al [30] and Linden [31] support this theory and have shown that the height of gas release has a direct impact in the resulting gas concentrations observed in space in which a gas escape occurs.

To reduce the risk associated with these scenarios, cupboard and room ventilation is suggested and the effect of these on GIA concentrations is discussed in section 5.2.2 below.

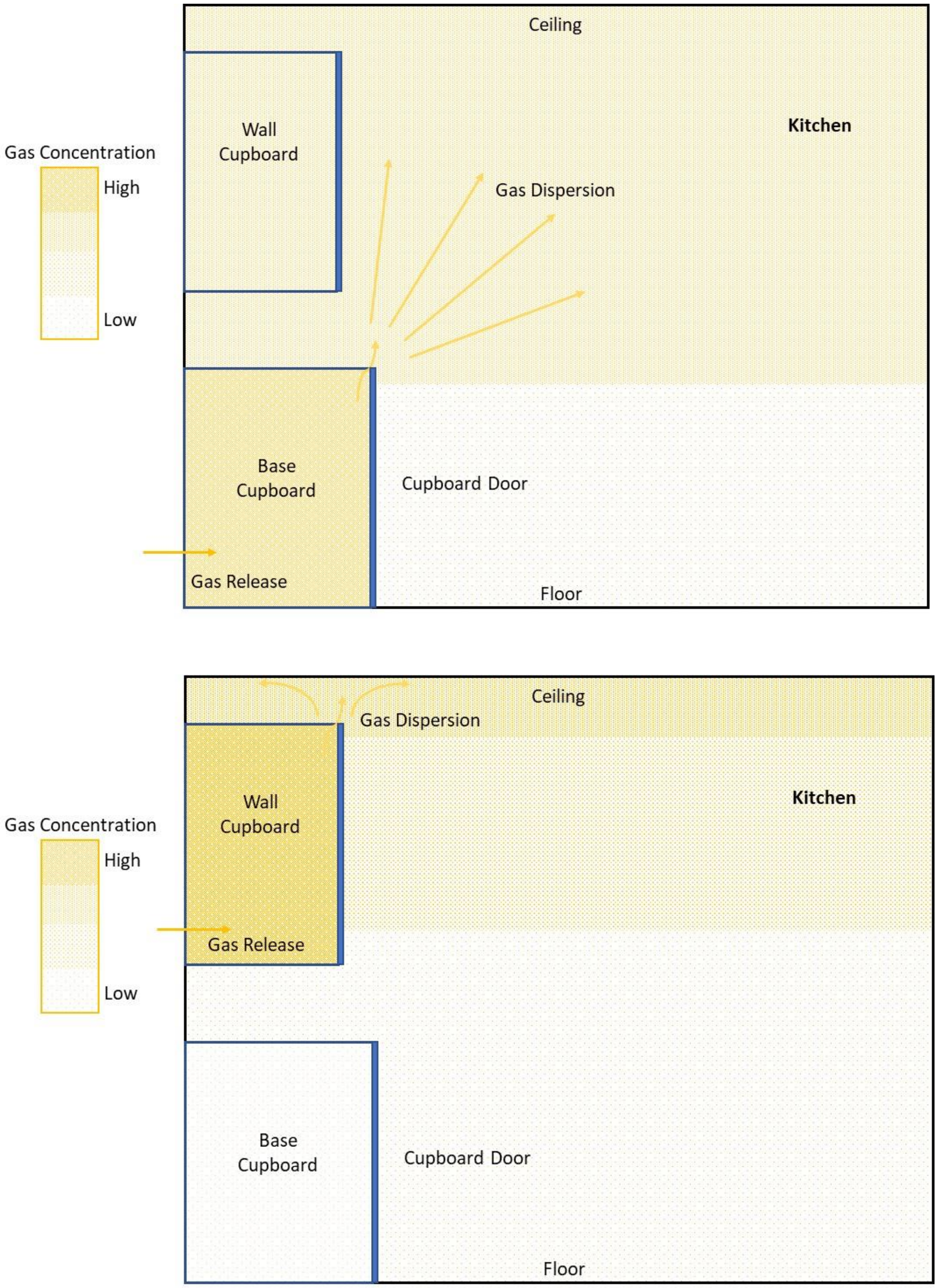


Figure 16: Diagram of gas escape mechanism when a release is within a base or wall cupboard (boundary levels are for illustrative purposes only)

5.2.2. Increasing ventilation

The HyHouse study demonstrated that changing ventilation in a space has an impact on the maximum GIA concentrations observed after an escape. This was further investigated under the Hy4Heat programme by repeating the boiler cupboard experiments (which resulted in the highest GIA concentrations within the kitchen), with the doors open as well as closed. The results of this for both hydrogen and methane for an injection in the boiler cupboard are shown in Figure 17 and suggest around a 5% change in maximum concentration measured in the kitchen space when the doors were open compared to closed.

The effect of opening the door has a much more dramatic effect on mid-point hydrogen concentrations (Figure 17) reducing maximum GIA concentrations to almost 0% for injections below 150 kW; and to less than 5% even at high release rates. The same effect is seen for methane, but to a lesser extent with resulting concentrations still at or just above the LFL for injections above 50 kW. The concentration recorded at the lowest sampling point remained unchanged at very low GIA levels when doors were open and closed.

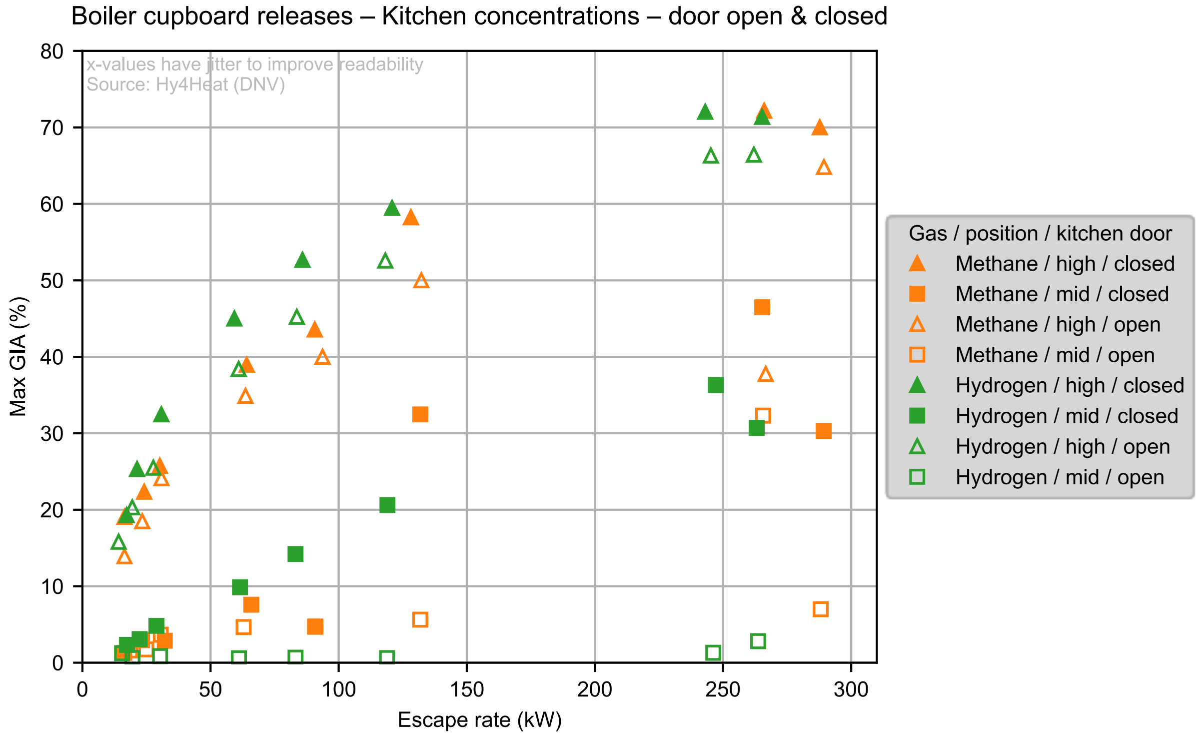


Figure 17: Maximum high and mid-level GIA concentration in the kitchen – kitchen door open and closed

Seeing the effect of an open door on maximum kitchen GIA concentrations, additional tests were completed with hydrogen in the boiler and base cupboards to consider the effect of adding a 100mm diameter wall vent above the kitchen door (between the kitchen and hallway) when the kitchen door was closed. Additional tests were also completed with 4 circular 100mm holes added to the side of the cupboard to act as a cupboard vent as described in Approved Document J (ADJ) [32].The following figures show the results of these tests. Adding ventilation to the kitchen in the form of an internal wall vent reduced the peak GIA concentration observed within the kitchen space (Figures 18 and 20). This was more effective than just adding cupboard ventilation which although this decreased the maximum GIA in the cupboard resulted in a higher average concentration in the kitchen (Figures 19 and 21). Adding both a cupboard and wall vent reduced maximum GIA concentrations seen in all measured spaces.

The total house gas inventory remained similar, with a variation of between 0.2 and 0.5 kg for base cupboard and boiler cupboard experiments respectively. Gas inventory is discussed in detail in Section 5.4.

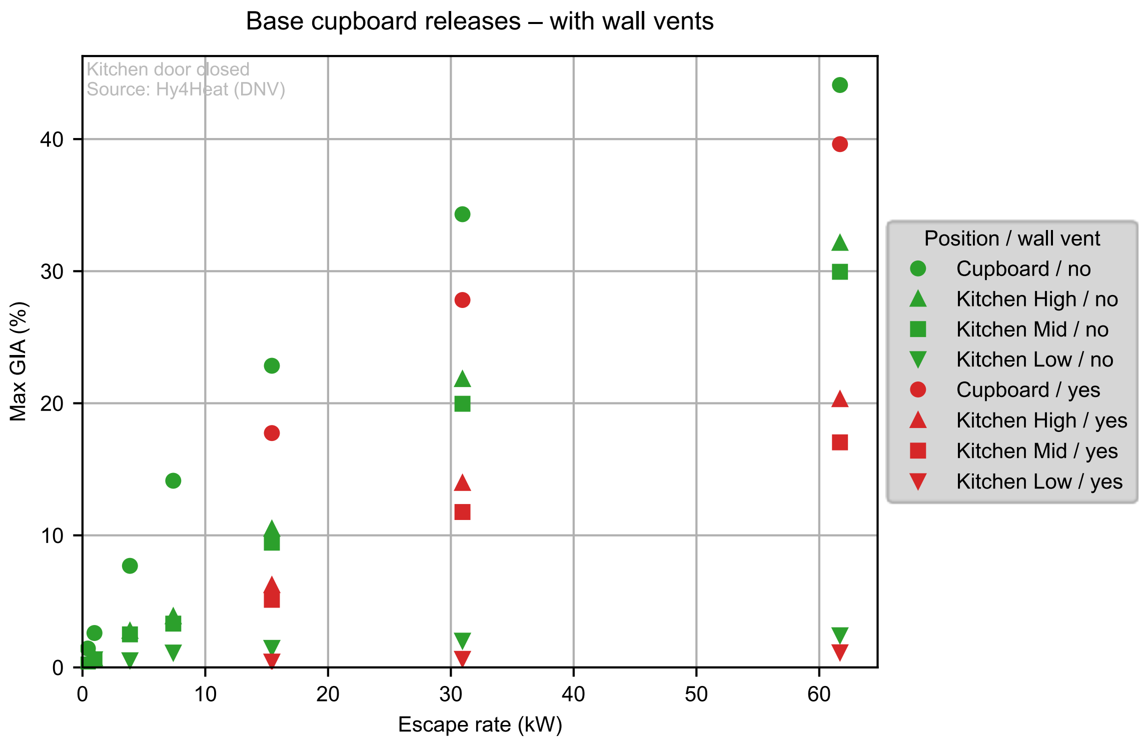


Figure 18: Maximum kitchen and base cupboard hydrogen GIA concentrations with and without a wall vent above the kitchen door

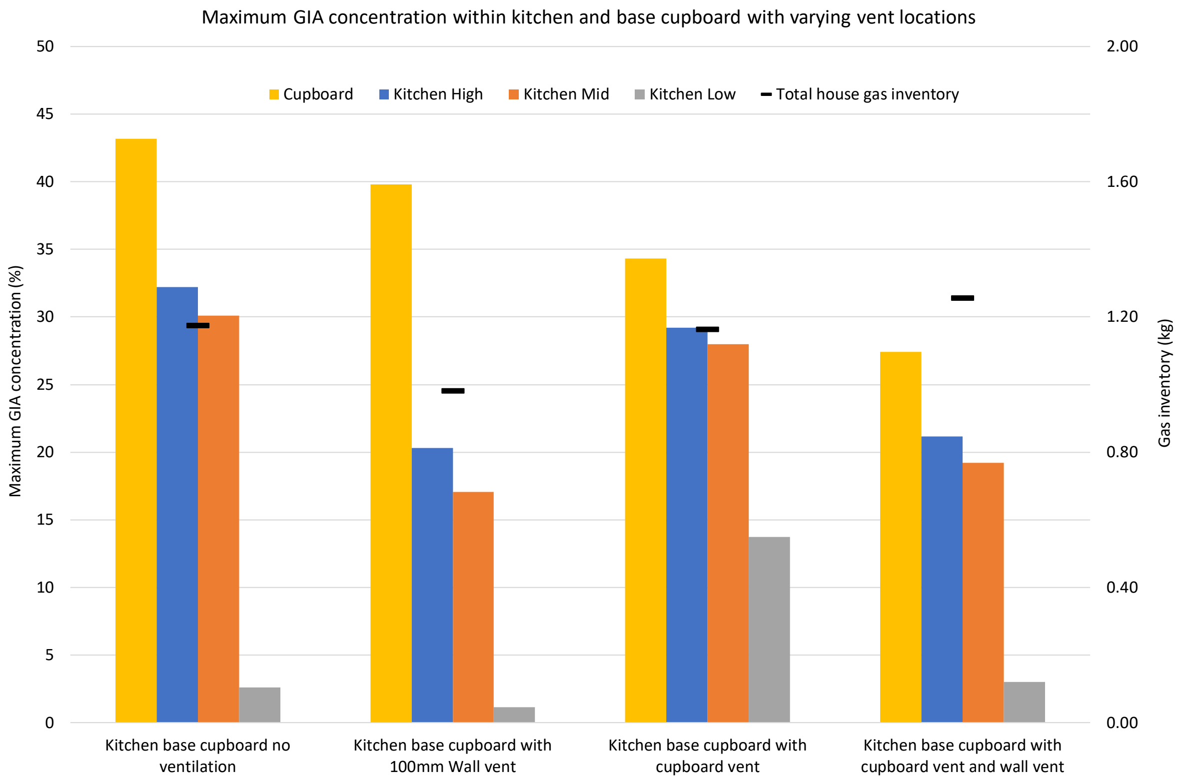


Figure 19: Maximum kitchen and base cupboard hydrogen GIA concentrations with varying vent locations, compared to total house gas inventory

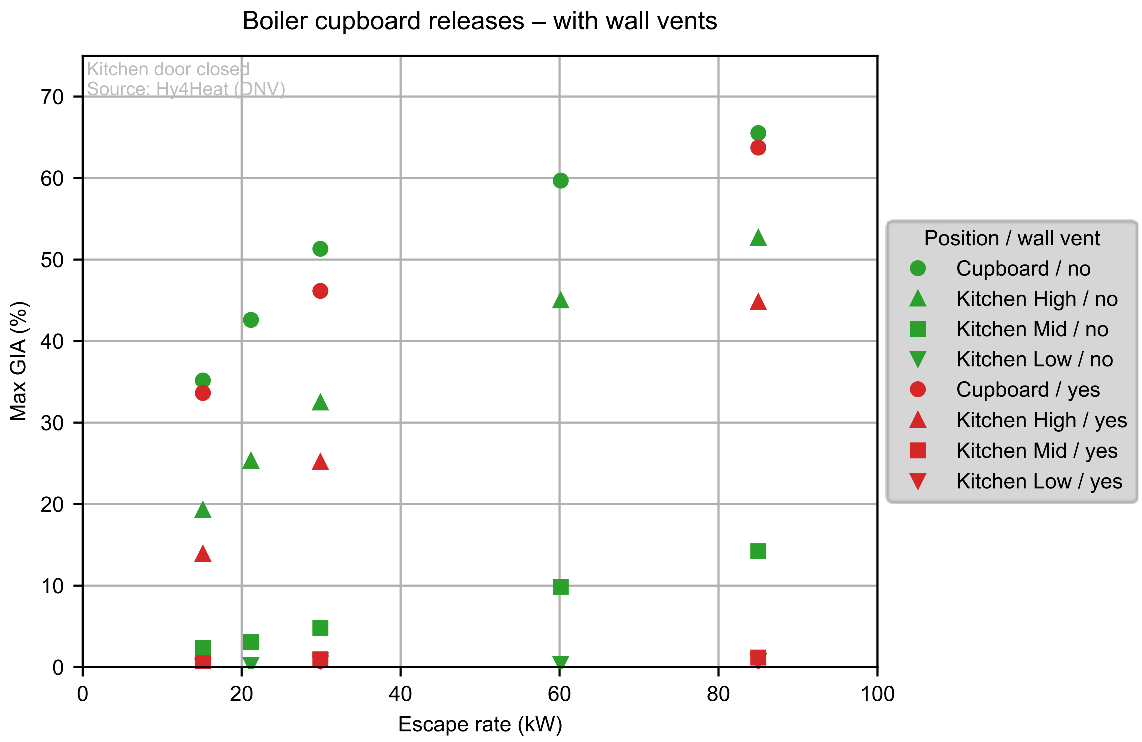


Figure 20: Maximum kitchen and boiler cupboard hydrogen GIA concentrations with and without a wall vent above the kitchen door

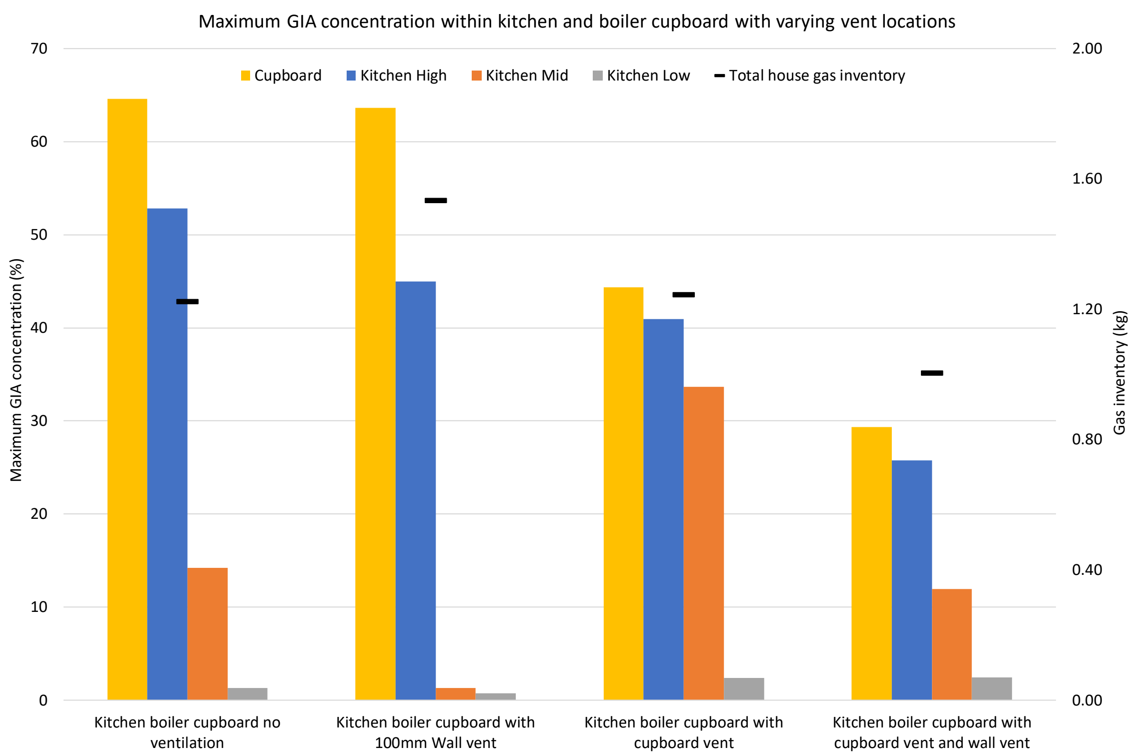
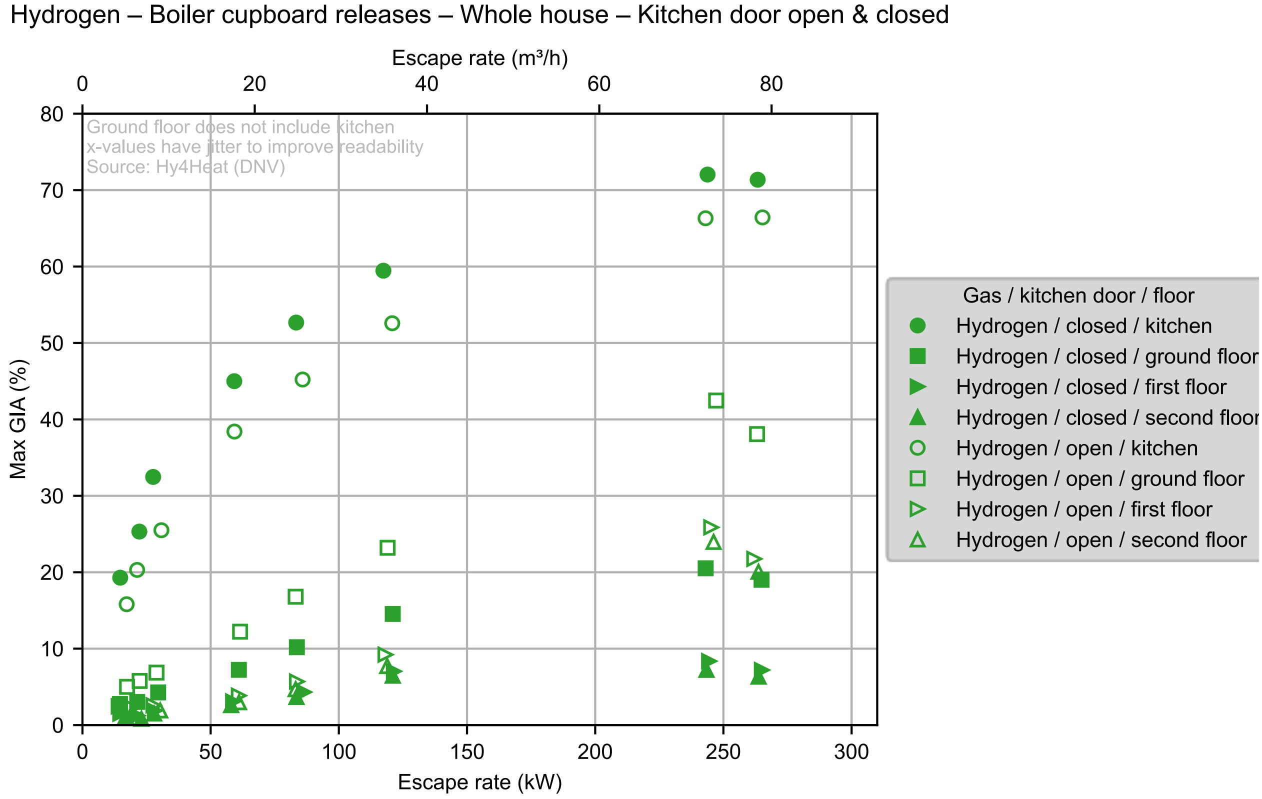


Figure 21: Maximum kitchen and boiler cupboard hydrogen GIA concentrations with varying vent locations, compared to total house gas inventory

5.2.3. Rest of house GIA concentrations

In all cupboard tests, the kitchen was the room with the highest GIA concentration. It is important, however, to also consider the risk associated with the rest of the property. GIA concentration for the rest of the house is shown below, split to demonstrate upstairs and downstairs rooms (Figure 22).



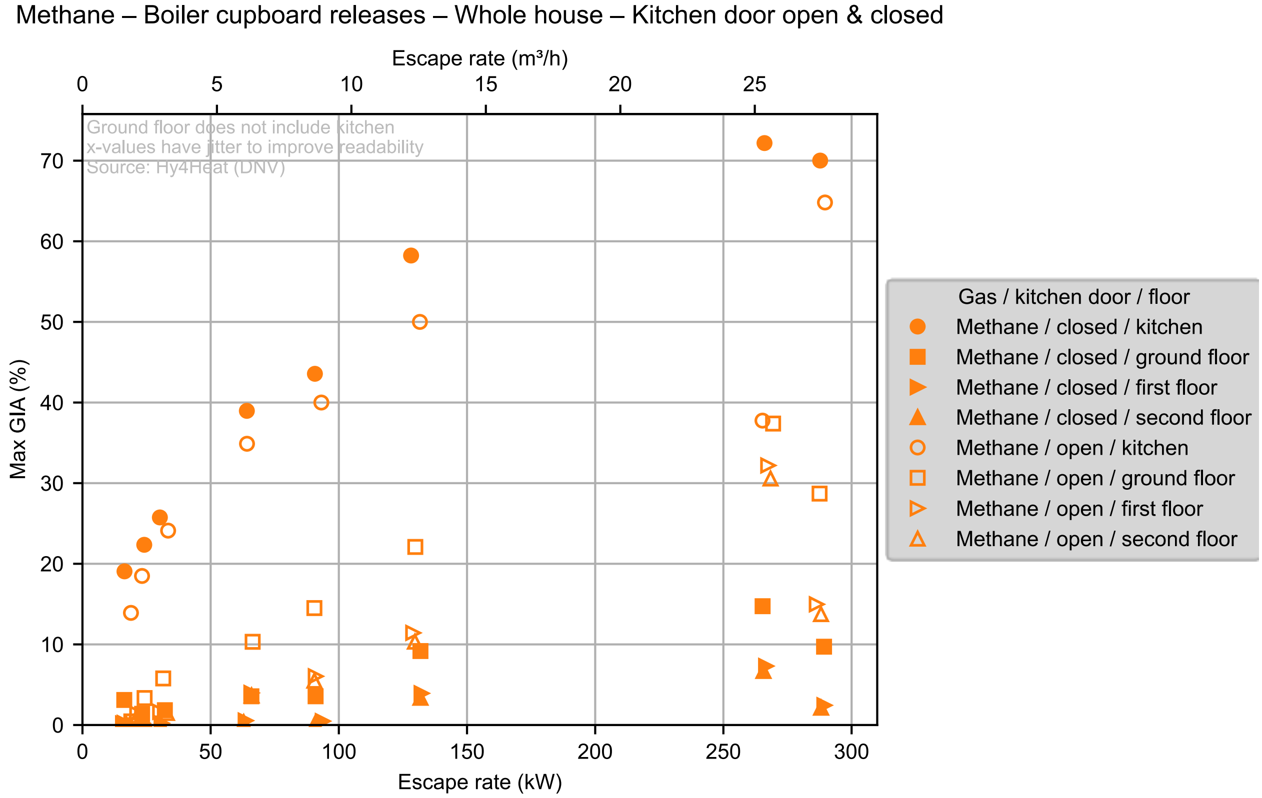


Figure 22: Rest of house maximum concentration for hydrogen (top) and methane (bottom)

As discussed above, when the kitchen doors were open, the maximum concentration within the kitchen space was reduced. However, the maximum concentration measured in the other downstairs rooms increases by a comparable amount. It should also be noted, that although the concentration increases within the downstairs rooms, it is only just above the LFL at escape rates most likely to occur within a domestic setting, e.g. below 50 kW.

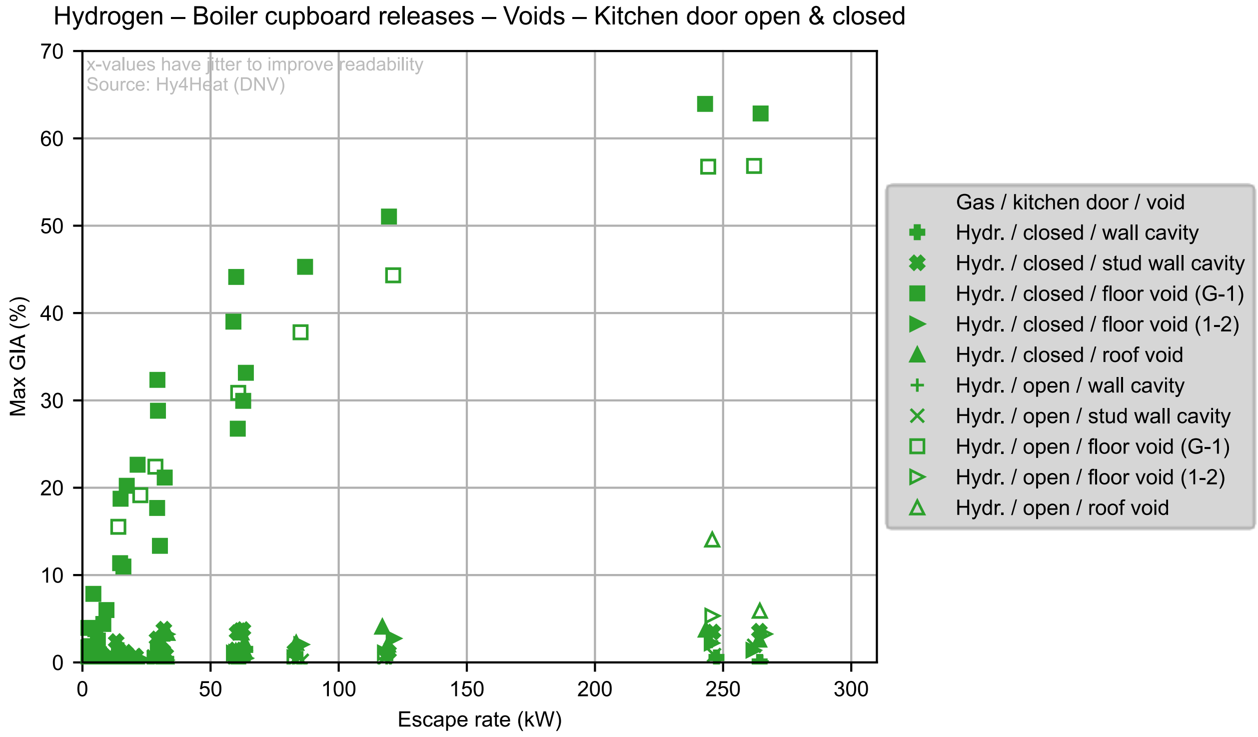
For hydrogen, maximum concentrations measured on the first and second floors showed little change whether the kitchen door was open or closed; except at high flow rates (above 200 kW). The same applied to methane at low flow rates, but a more marked change in maximum gas concentrations observed upstairs was seen for flow rates greater than 50 kW.

5.2.4. Void GIA concentrations

Void concentrations were only measured in a limited number of locations in the Hy4Heat experiments, but they provide useful information with regards to tracking of gas within floor and wall voids. Nearly all hydrogen cupboard releases resulted in flammable GIA concentrations within the kitchen ceiling void, but low gas concentrations in voids elsewhere. The exception to this was during the very high leak rate simulations when the kitchen door was open; here flammable GIA concentrations were also observed within the roof and first-to-second-floor ceiling voids (Figure 23, and 24 for close-up).

The gas distribution is slightly different when considering void concentrations observed during the methane experiments. Here, flammable GIA concentrations were observed in both the ground to first, and first to second floor voids, and the internal stud wall cavity at high release rates. This was further exacerbated when then kitchen door was opened.

It is important to note however, that the high flow rates included in this test work are in excess of the vast majority of gas escape scenarios experienced in a domestic setting.



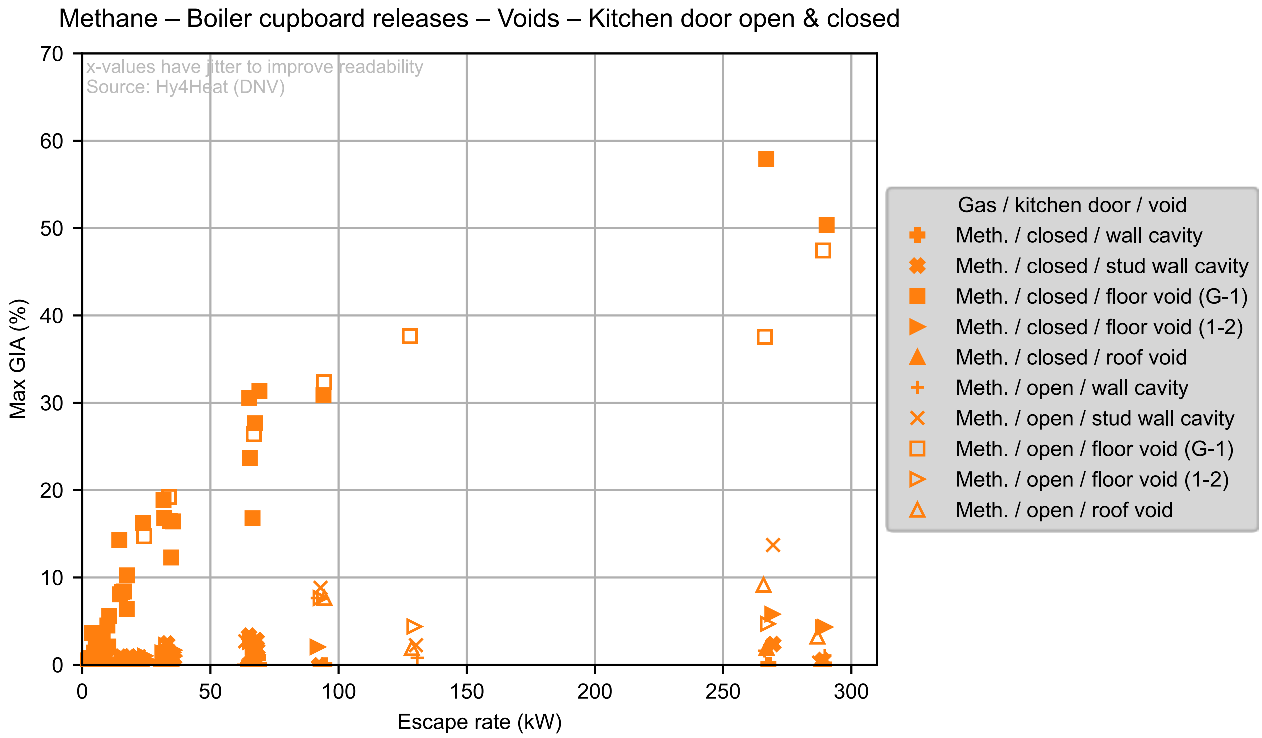
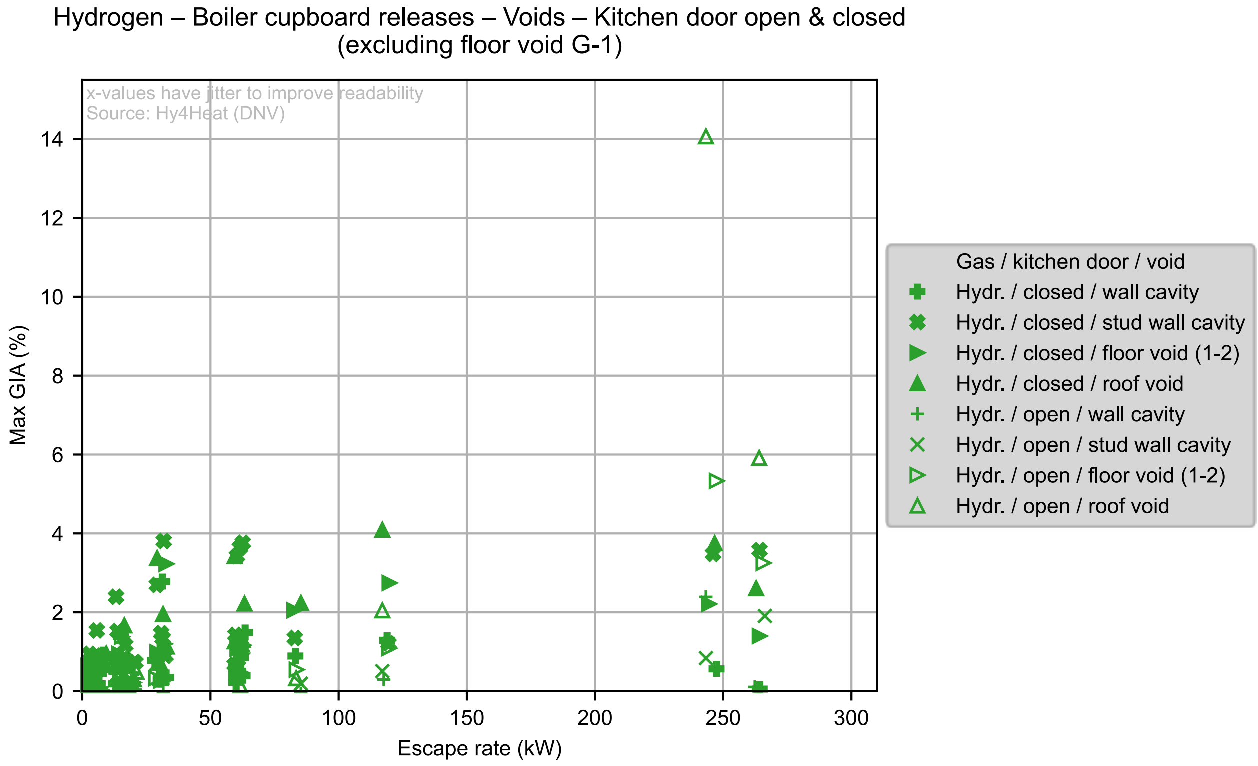


Figure 23: Void GIA concentrations for cupboard releases with hydrogen (top) and methane (bottom)



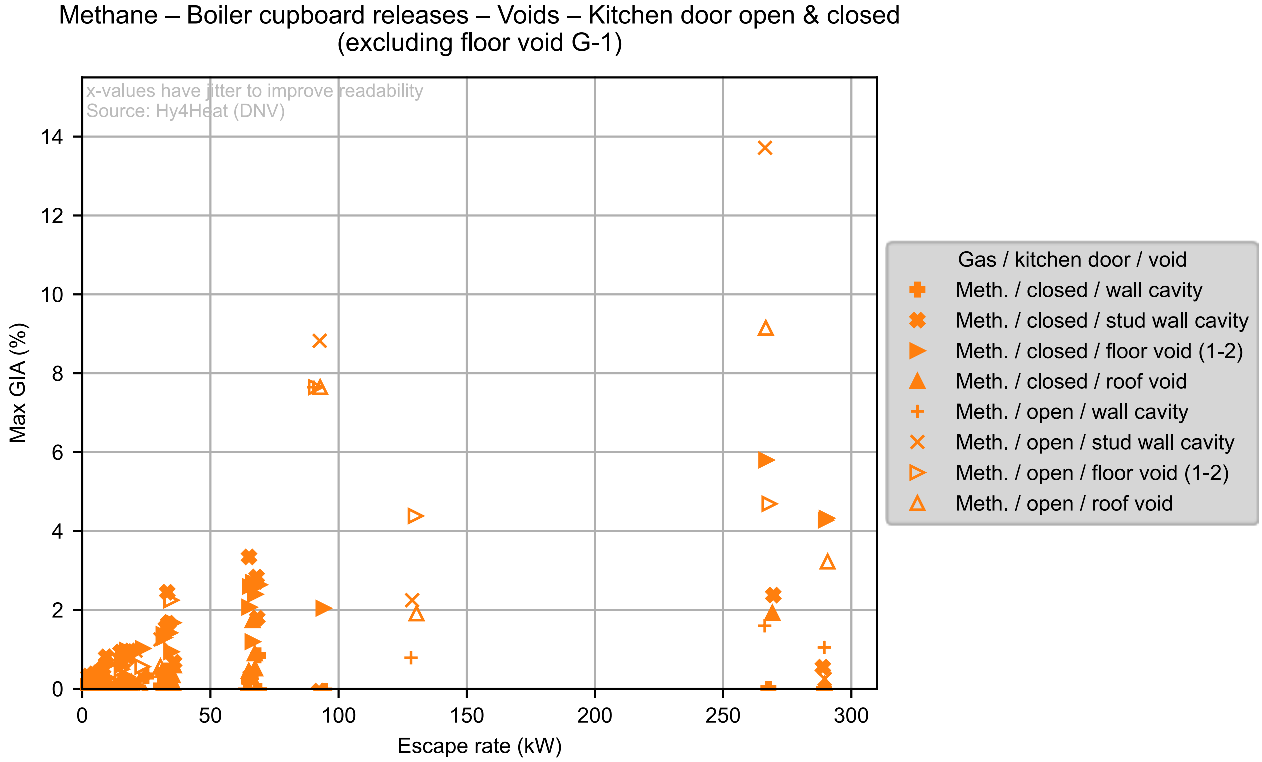


Figure 24: Void GIA concentrations for cupboard releases – close-up excluding void between kitchen and first floor

5.3. GIA Concentration (%) – Release into basement

A basement offers very different conditions to a conventional above-ground room within a property. The opportunity for air exchange through doors and windows is greatly reduced; and depending on the presence of a waterproofing system, other air ingress can be limited [33].

Releases into the basement were carried out at three directions:

- Upwards
- Downwards
- Horizontal

The direction of the injection had an inconsistent effect on the resulting maximum GIA concentrations (Figure 25). However, a significant difference was observed in gas stratification depending on direction of release (Figure 26). When released downwards at rates more than 50 kW, significantly reduced stratification was seen in the space with comparable mid and low-level concentrations, which were only ~10 percentage points lower than the maximum concentration observed at high level; and almost completely mixed at the largest release rate (~250 kW). A similar but less marked effect was seen for a horizontal release and the effect was more obvious for methane than hydrogen.

This means in some scenarios the basement space presents a relatively well mixed environment, which results in higher gas inventories than a stratified space (discussed more in section 5.4). This is likely a result of the reduced ventilation factors present in the basement and the fact that the release was carried out at height. Further work is required to understand this phenomenon fully.

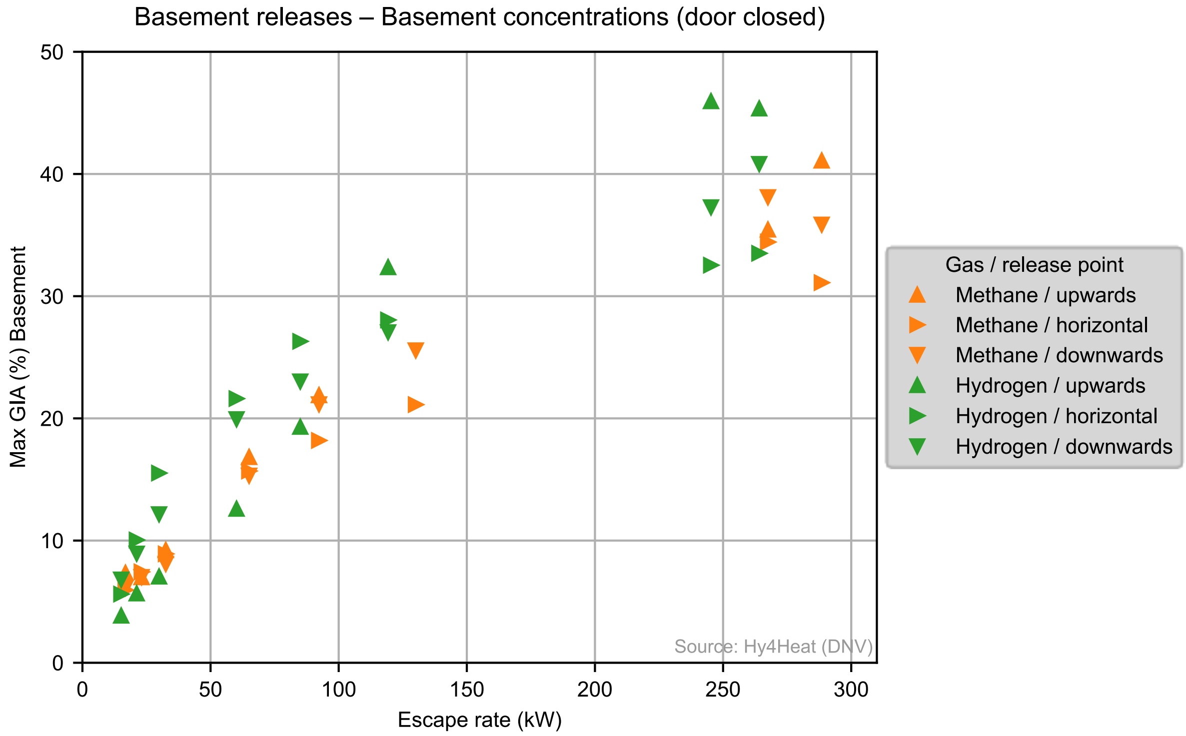


Figure 25: Maximum GIA concentrations measured for releases in different directions

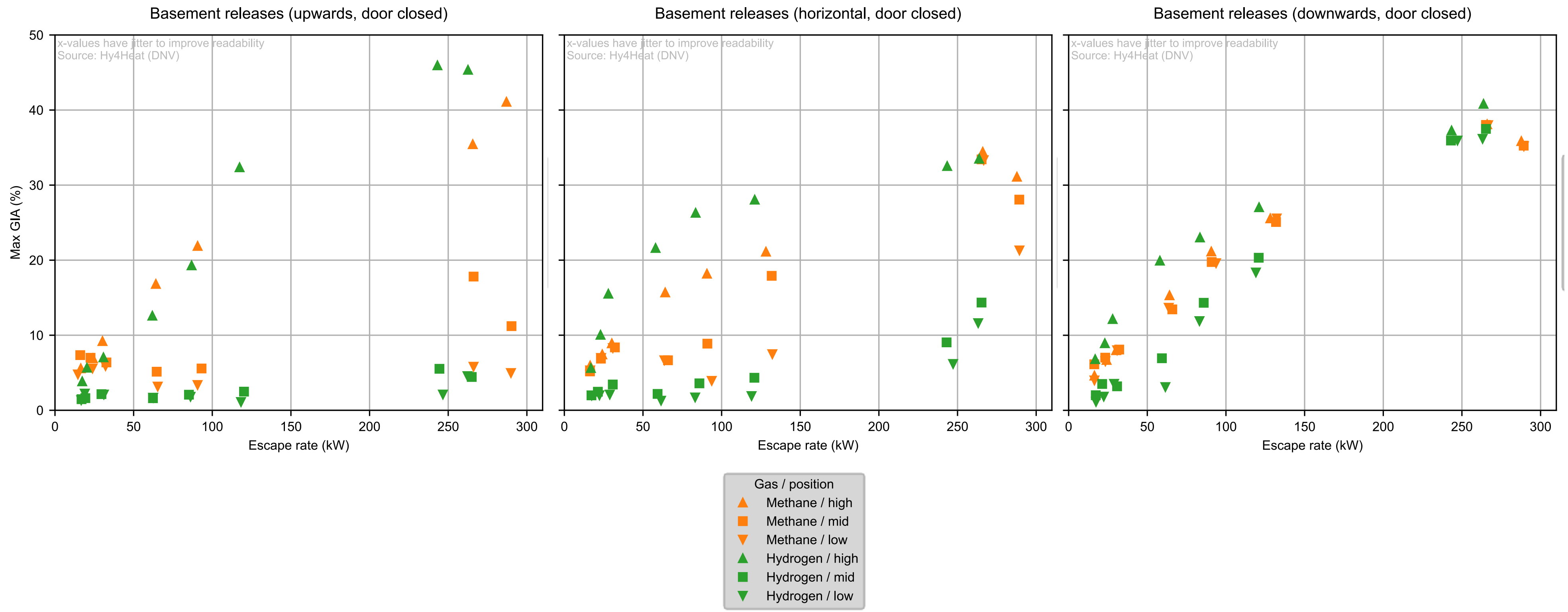


Figure 26: Maximum GIA concentrations at different sensor heights, measured for releases in different directions

The tests were also carried out with the basement door open and closed. As expected, this had a marked effect on the maximum GIA concentration recorded in the basement for both hydrogen and methane.

In the rest of the house, opening the door had a limited effect on the maximum concentrations measured when injecting hydrogen. However, a more marked effect was seen in the methane tests, where maximum concentrations observed in the house increased when the basement door was open, particularly for tests greater than 50 kW (Figures 27 and 28). Downward releases have been used for this and all other analysis using basement data as this represents the worst case.

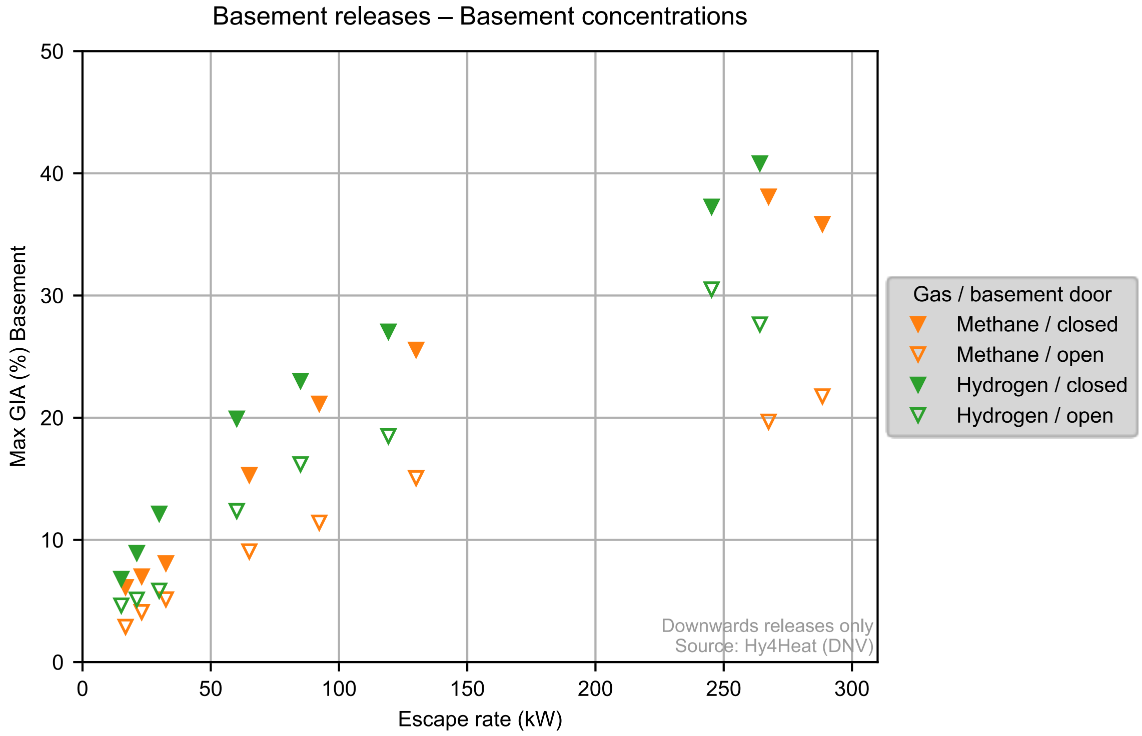


Figure 27: Maximum basement GIA concentrations with doors open and closed (downward releases only)

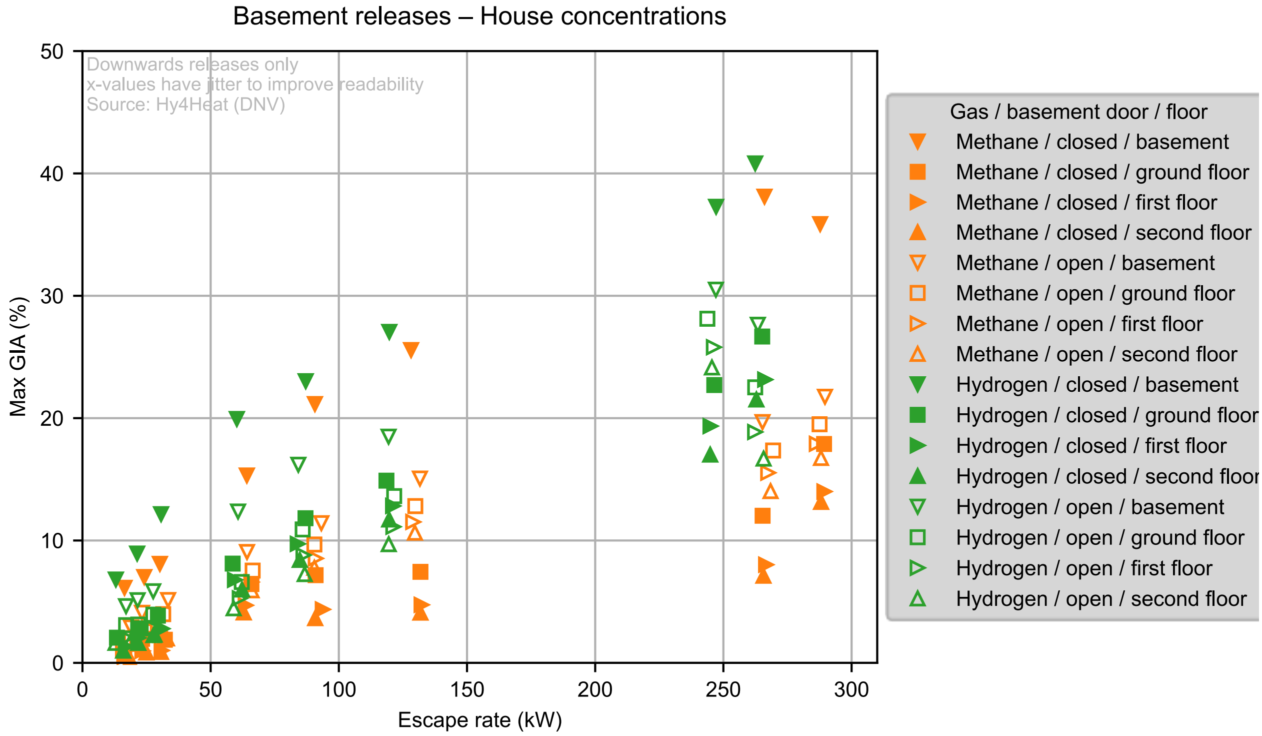


Figure 28: Maximum GIA concentrations in the rest of the property during basement releases (downward releases only)

5.3.1. Void GIA concentrations

Only large hydrogen escapes in the basement resulted in flammable GIA concentrations in voids in the rest of the house as shown in Figure 29. During the largest escapes, flammable GIA concentrations were observed in all measured voids and this was apparent for both hydrogen and methane. This was not observed in any of the other test work.

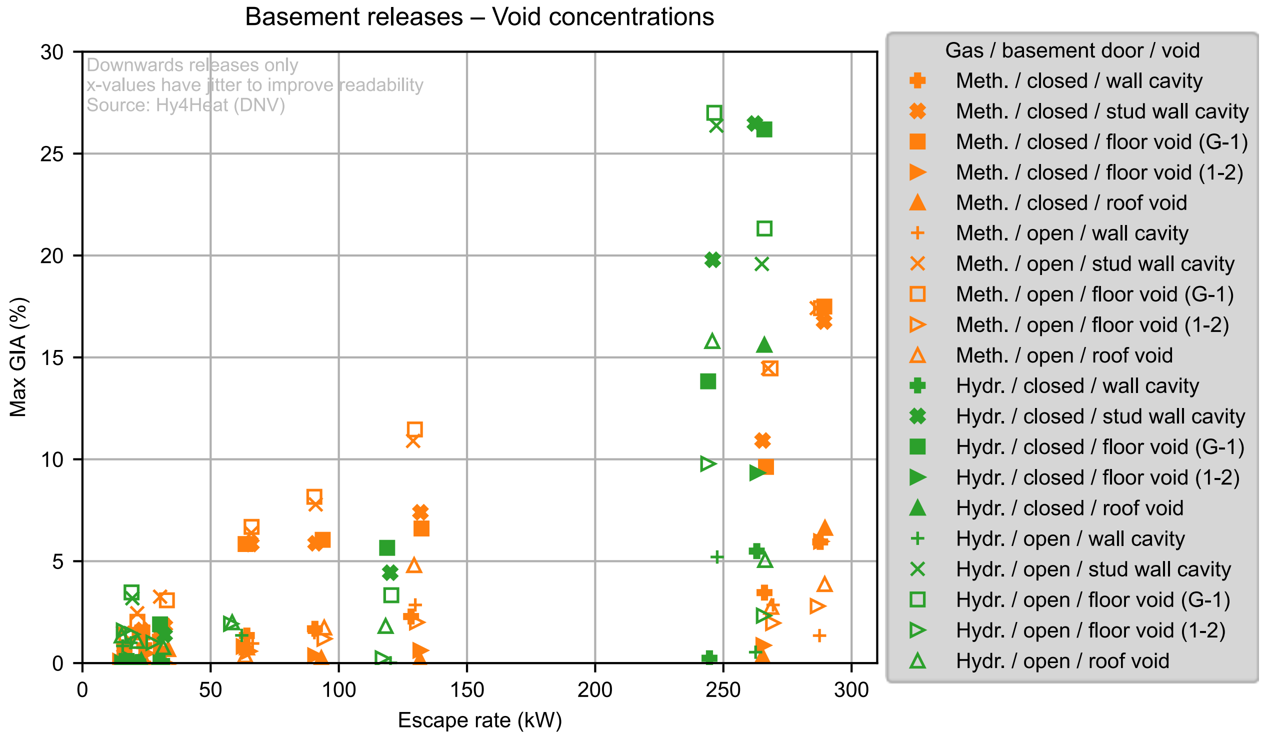


Figure 29: Void GIA concentrations during basement releases (downward releases only)

5.4. Gas inventory

An alternative standpoint is to consider the gas inventory of the property and therefore the available energy within the building at the maximum GIA concentrations. This has been calculated for hydrogen and methane for each of the test scenarios (Figure 30, and close-up in Figures 31 and 32). The highest inventory in the property is generally seen when the gas release took place in the basement. This may be due to the reduced ventilation forces active in a basement environment to disperse the gas out of the house and/or the increased volume of house available for the leaking gas to disperse into. Lowest total gas inventory was observed during releases into a room where there was no confinement of the escaping gas.

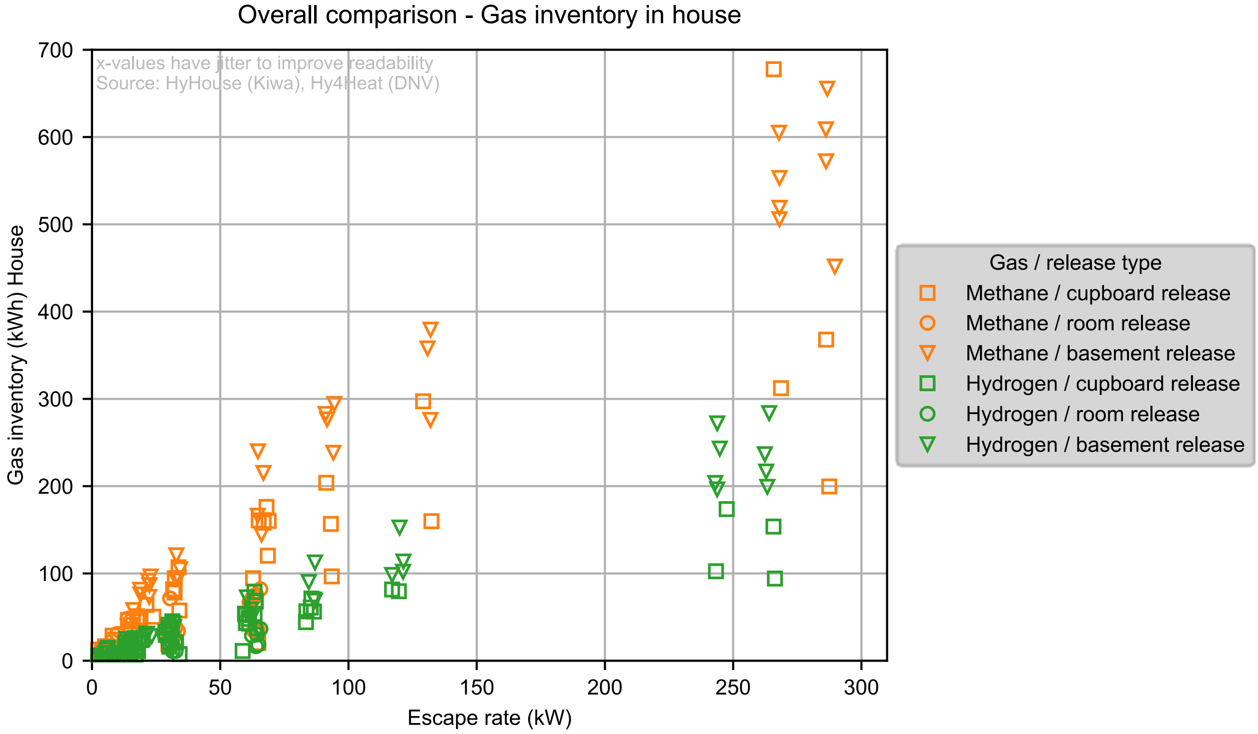


Figure 30: Total property gas inventory (energy basis) for each test scenario

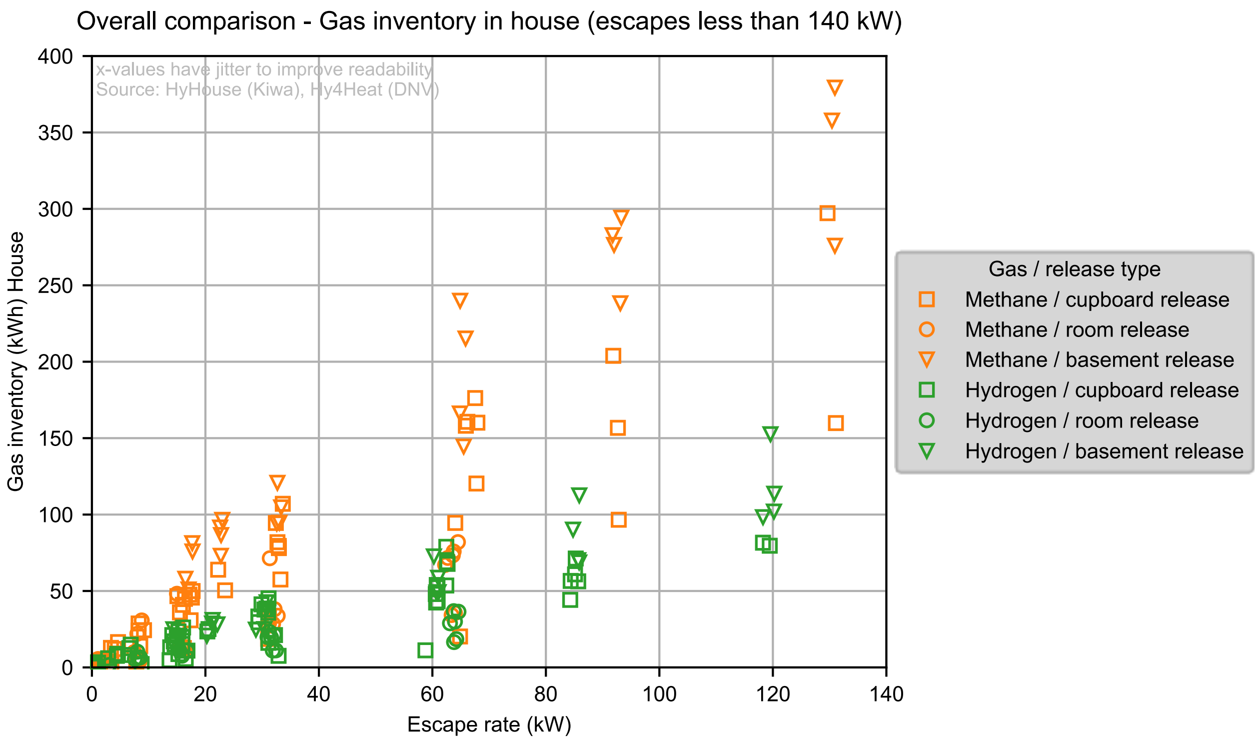


Figure 31: Total property gas inventory (energy basis) for escapes less than 140 kW

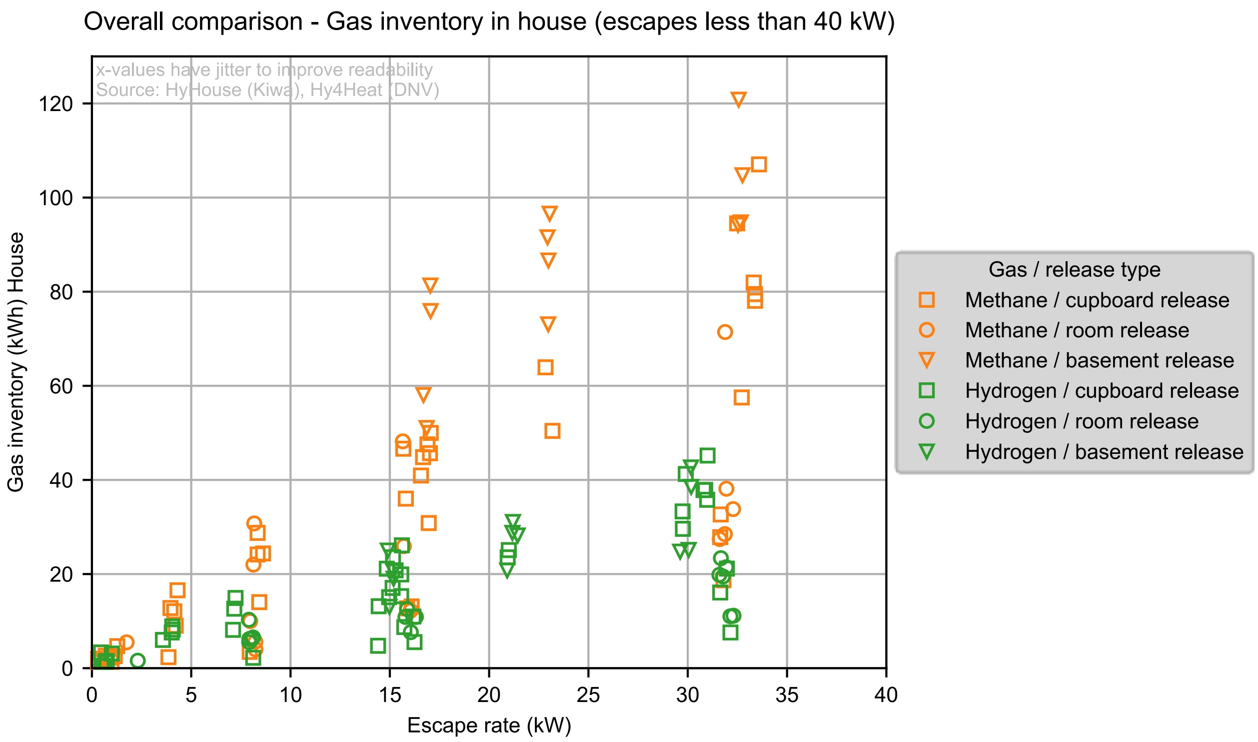


Figure 32: Total property gas inventory (energy basis) for escapes less than 40 kW

In all of the above scenarios, the total amount of flammable gas available within the house (on an energy basis) was considerably lower during the hydrogen experiments than the equivalent methane tests. However, it was thought useful to further understand the distribution of this, based on the dispersion of the gas around the property.

It is clear from the GIA dispersion graphs discussed above, that the majority of the escaped gas was located within the kitchen space; and that the kitchen doors being open or closed had a significant impact on the resulting gas concentration. Figure 33 shows the proportion of the total inventory in the kitchen when a gas release occurred within the boiler cupboard when the kitchen door was open or closed. A marginally higher gas inventory is evident in the kitchen with the doors closed.

For all but two tests, the total hydrogen gas inventory in the house was almost exactly the same when the kitchen doors were open or closed for the same gas release rate. However, at the highest release rate, there was a clear increase in the gas inventory in the total house when the kitchen door was open compared to when it was closed.

In contrast the methane tests all show a higher total house inventory when the kitchen door was open compared to the same test when the door was closed. At high release rates, the difference between the inventory with doors open and closed becomes even more marked.

The flow rates considered in this situation are considerable and would only likely be observed during a mains failure. However, it is suggested that if this is a real finding, a preventative measure to reduce this risk would be to locate all gas meters external to the property so that any unrestricted leak (e.g. prior to the gas meter regulator and emergency control valve) would not occur within the property boundary but in fresh open air.

It is also suggested that a form of flow restriction such as an excess flow valve is included in new hydrogen systems to reduce the risk of these high flow rate scenarios occurring.

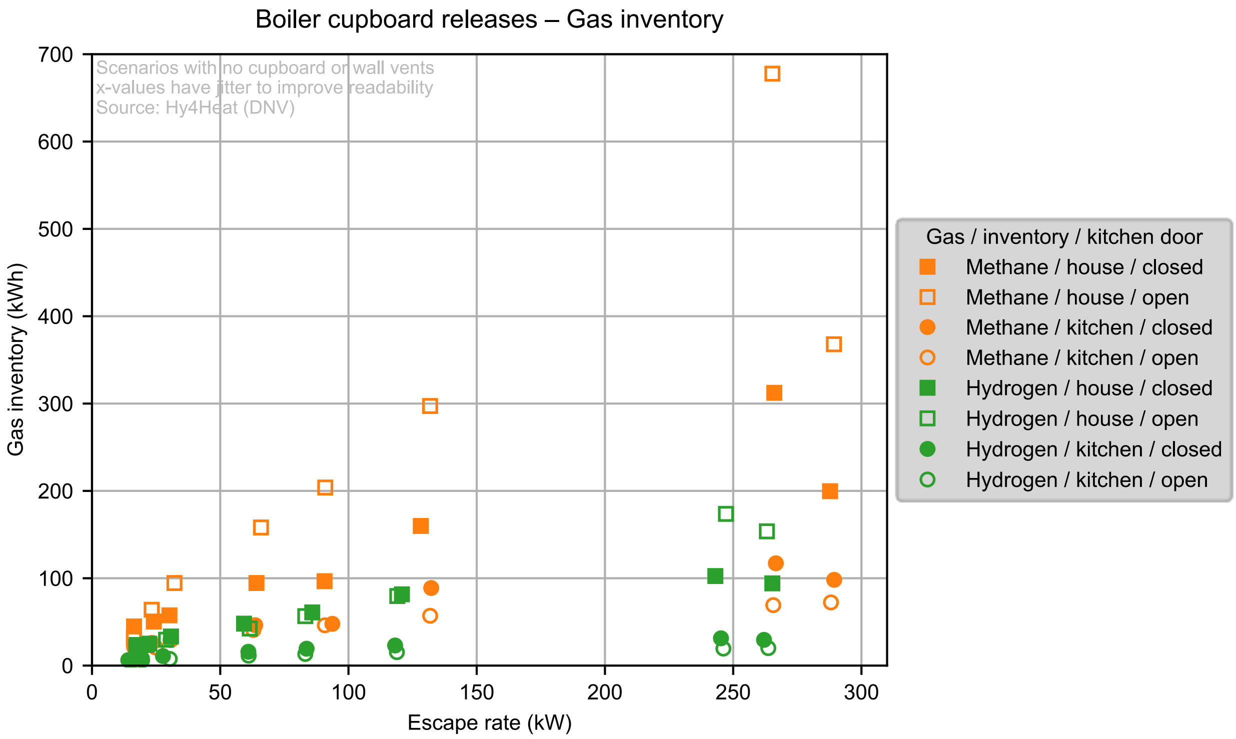


Figure 33: Gas inventory split to show kitchen and whole house with doors open and closed during a release into a cupboard

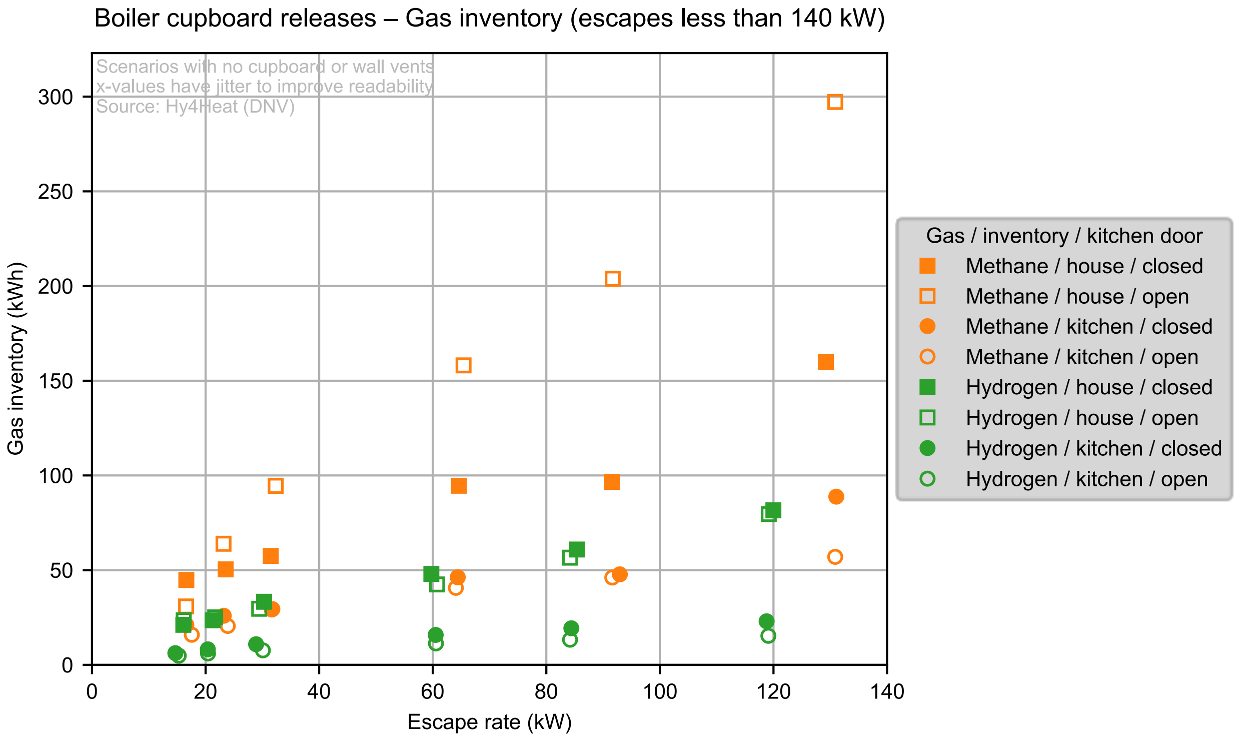


Figure 34: Gas inventory split to show kitchen and whole house with doors open and closed during a release into a cupboard (escapes less than 140 kW)

6. Effect of ventilation on GIA concentrations

The data considered above begins to demonstrate the effect of opening doors and including additional ventilation within high risk areas such as the boiler cupboard and kitchen. In light of these findings additional test work was commissioned by Hy4Heat to further investigate these scenarios. A further 31 tests were carried out as a phase two programme of works with additional ventilation [2] [3]. The test work consisted of:

- Injections into both the kitchen base cupboard and boiler cupboard, with 100 cm^2 and 200 cm^2 ceiling vents ducted through external wall, both with and without additional cupboard vents
- Basement injections with 200 cm^2 and 400 cm^2 external wall vents
- Living room injections with 100 cm^2 and 200 cm^2 vents above the living room door[1]

The results of these tests are discussed below.

6.1. Kitchen and cupboard ventilation

In phase 1 the kitchen base cupboard and boiler cupboard were tested with additional cupboard ventilation and an internal wall vent above the kitchen door. The resulting maximum hydrogen concentrations within the cupboard and kitchen were assessed (Section 5.2.2).

It was shown that including cupboard ventilation reduced the maximum concentration measured in the cupboard space but increased the maximum concentration in the kitchen. Including an internal wall vent reduced the maximum concentrations measured in the kitchen but did not affect the maximum cupboard concentrations. When both cupboard and wall vents were present, the maximum gas concentration in the cupboard and kitchen were reduced. However, the use of an internal wall vent resulted in the gas dispersing into the rest of the property.

To reduce the risk associated with this and with the aim to reduce the overall gas concentration and inventory in the house, ventilation ducted to outside through a ceiling vent was installed in the kitchen and was tested in phase 2 (using the same cupboards as in phase 1). Two vent sizes were assessed in separate tests and for a range of hydrogen flow rates from 30 to 264 kW (9–79 m^3/h). Cupboard ventilation was also included and the impact this had on kitchen and cupboard concentrations was assessed (Figures 35 and 36). Data from phase 1 where there were no room or cupboard vents has been included for comparison[2].

Adding a ceiling vent of either 100 or 200 cm^2 reduced the maximum concentration in the cupboard and dramatically reduced the maximum concentration in the kitchen compared to a non-vent scenario. The 200 cm^2 ceiling vent resulted in the lowest gas concentrations in all but one test, however the difference between the two vent sizes was much less than the effect of adding a vent to a non-vented environment.

---

[1] The living room injections sought to investigate the layering of gas as it dispersed and further investigate the effect of internal wall vents on GIA concentration. The collected data however was not comparable to the other tests and as such it has not been included in the subsequent analysis.

[2] Except the highest flow rate into the base cupboard which was not available in phase 1.

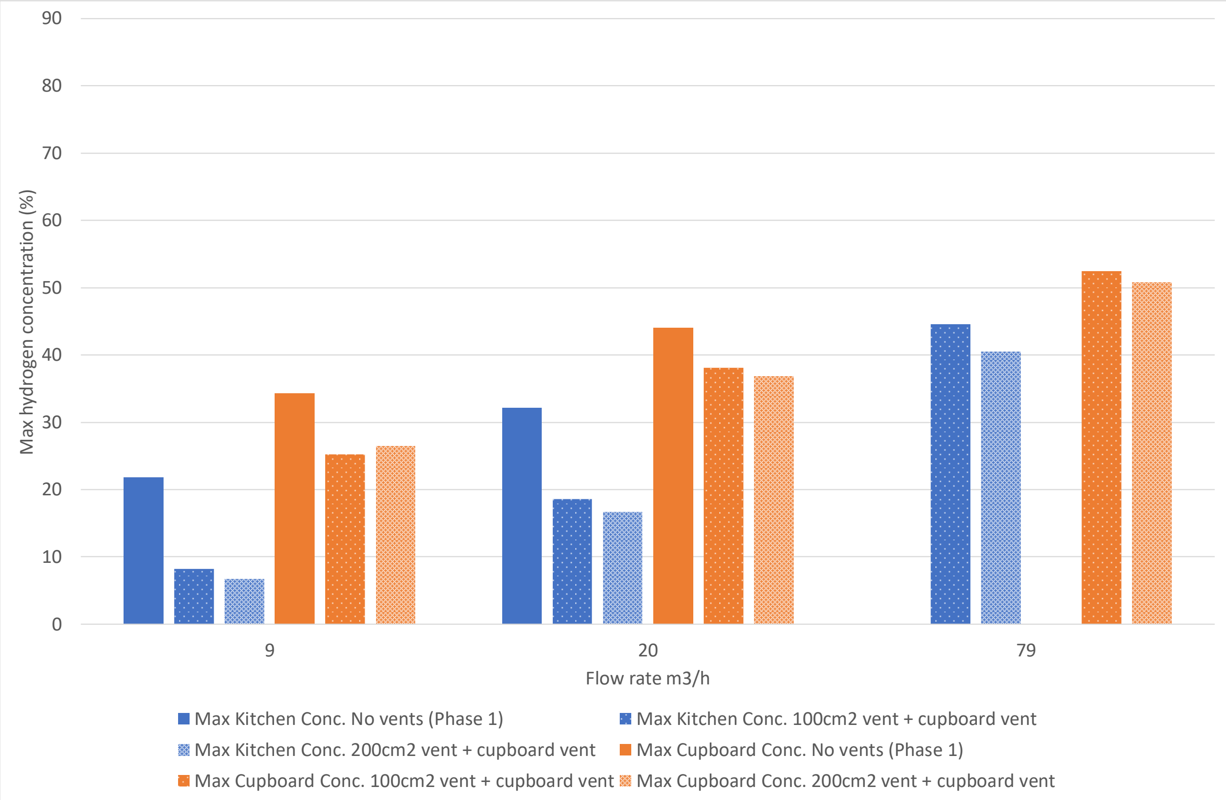


Figure 35: Base cupboard hydrogen injections with no vents (Phase 1) 100 cm^2 and 200 cm^2 ceiling vents and cupboard vents (Phase 2)

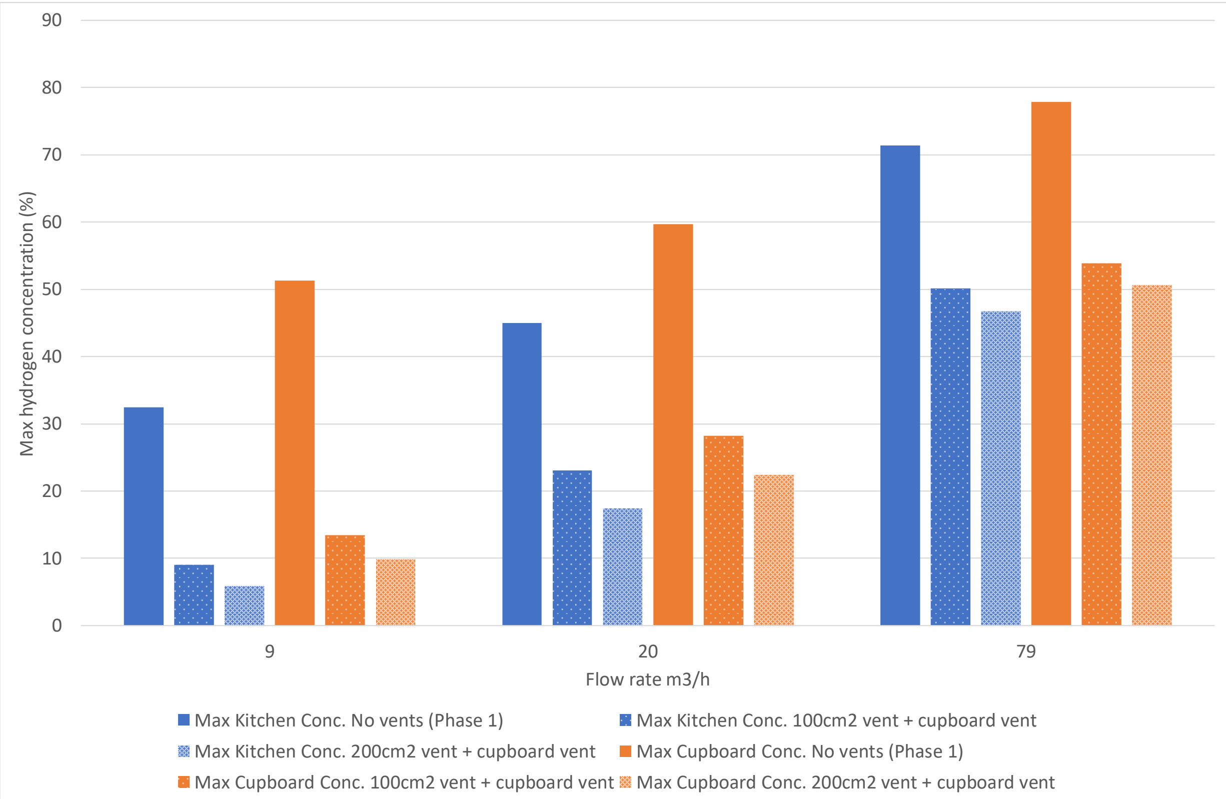


Figure 36: Boiler cupboard hydrogen injections with no vents (Phase 1) 100 cm^2 and 200 cm^2 ceiling vents and cupboard vents (Phase 2)

Using tests of the same flow rate (67 kW or 20 m^3/h), further comparison was made between the different ventilation scenarios to assess maximum hydrogen concentration in the kitchen at low, mid and high level, as well as the maximum hydrogen concentration measured in the cupboard space for the base and boiler cupboards (Figures 37 and 39). Gas inventory was then calculated for the kitchen and whole house for each scenario to understand how the different ventilation scenarios affected the total amount of hydrogen present in the house (Figures 38 and 40).

When comparing the effect of the different ventilation scenarios on a leak of the same magnitude, there was a difference in effectiveness of each solution depending on whether the injection took place in the boiler or base cupboard.

For the base cupboard the lowest gas inventory and lowest kitchen concentrations were observed with just the 200 cm^2 ceiling vent. Adding a cupboard vent lowered the cupboard concentration but resulted in higher kitchen and total house hydrogen inventory, and maximum concentrations (when compared to just the ceiling vent).

In contrast, for the boiler cupboard the lowest gas inventory and kitchen concentrations were observed when both the 200 cm^2 ceiling vent and cupboard vents were in place. This is likely due to the leak being at height, meaning the gas was removed from the space as it was released.

The intention was to extend this to include phase 1 data however, the phase 2 tests had been carried out at slightly different flow rates and therefore detailed analysis of this nature would have been misleading. As such the figures below report only phase 2 data.

Inclusion of a ceiling vent also served to reduce the ground to first floor ceiling void concentrations (above the kitchen) to below 5% for all tests; even with injection rates up to 264 kW (hydrogen). In phase 1, maximum concentrations of approximately 60% had been recorded during the highest injection rates.

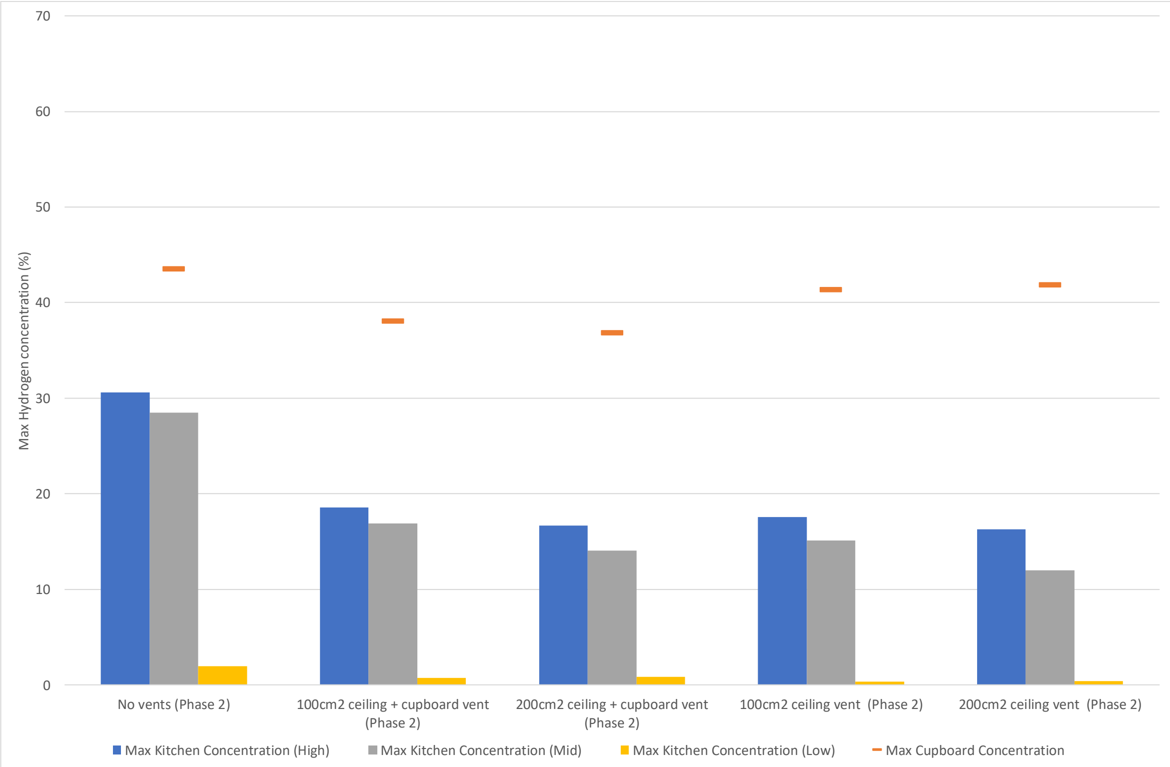


Figure 37: Hydrogen concentrations at low, mid and high level in the kitchen compared to cupboard concentrations for each ventilation scenario at flow rates of 20 m^3/h into the base cupboard

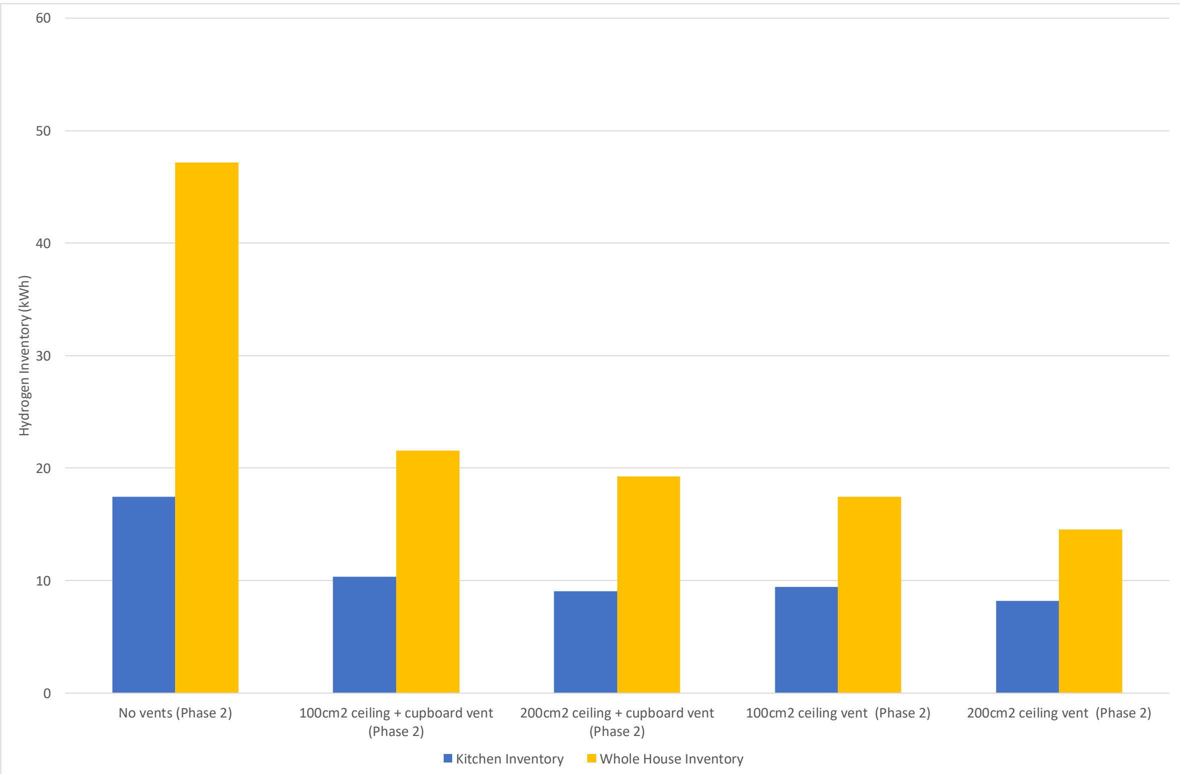


Figure 38: Kitchen and whole house hydrogen inventory for each ventilation scenario for injections into the base cupboard at 20 m^3/h

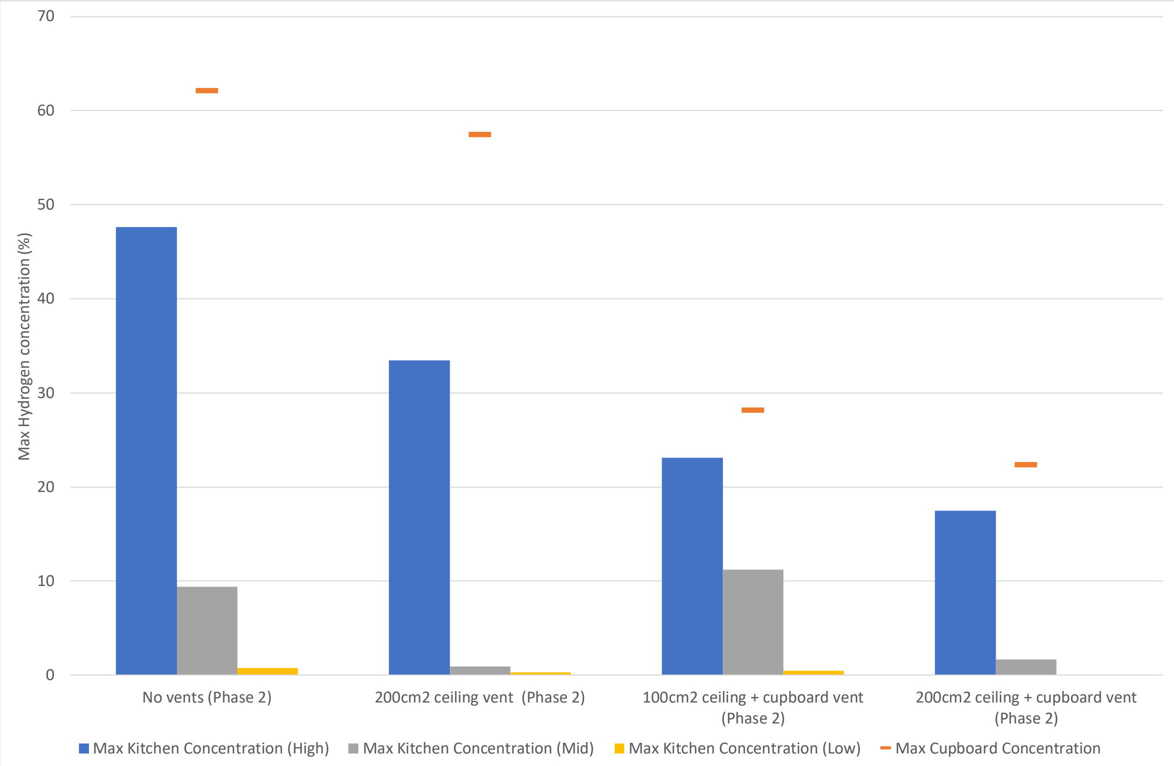


Figure 39: Hydrogen concentrations at low, mid and high level in the kitchen compared to boiler cupboard concentrations for flow rates of 20 m^3/h into the boiler cupboard

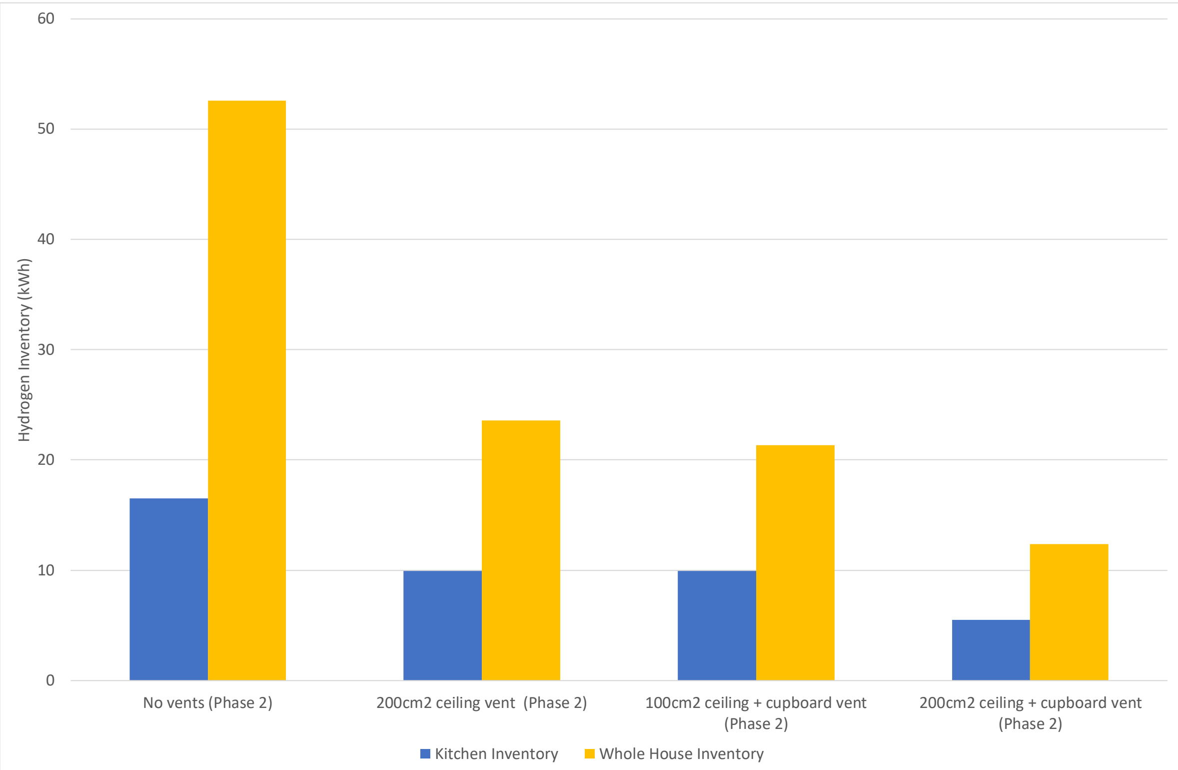


Figure 40: Kitchen and whole house hydrogen inventory for each ventilation scenario for injections into the boiler cupboard at 20 m^3/h

6.2. Basement ventilation

Tests were carried out in the basement to assess the effect of a 200 and 400 cm^2 air brick in the external wall of the property on the maximum hydrogen concentration observed in the basement for a range of leak rates (9 to 79 m^3/h or 30 to 264 kW). Phase 1 tests were included for comparison to a scenario in which no ventilation was added.

Figure 41 shows the maximum basement concentration measured at each flow rate for each ventilation scenario. Unlike the cupboard tests discussed above, the basement showed more erratic results with two of the 200 cm^2 vent tests resulting in higher maximum hydrogen concentrations than tests in which no vents were present. At the highest flow rate, the measured concentrations show more expected results, with increasing vent areas resulting in reducing maximum gas concentration.

To understand the effect of ventilation on the stratification of the gas within the basement space the maximum hydrogen concentration measured at the low, mid and high sensors were plotted for each ventilation scenario and for each leak rate (Figures 42–44). The gas inventory (kWh) for the basement space and whole house has been included for comparison. In all tests, the largest vent area resulted in the lowest gas inventory in the basement and throughout the while house.

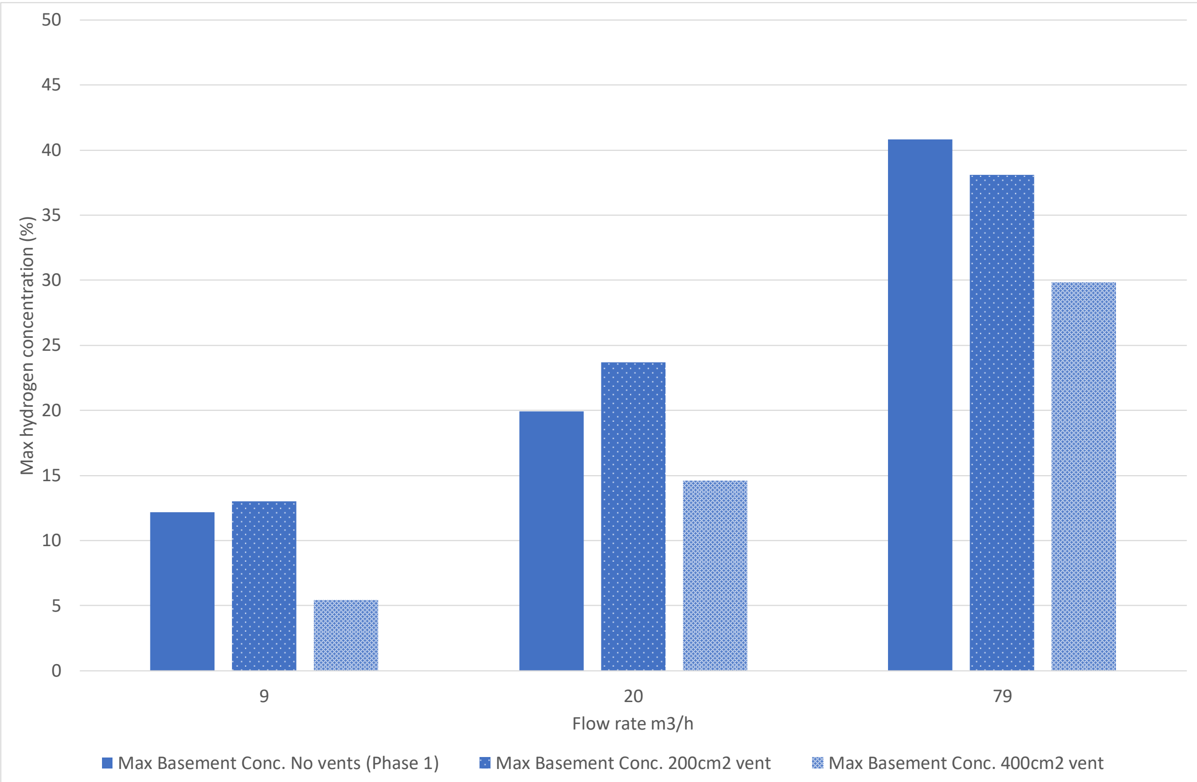


Figure 41: Basement hydrogen injections with no vents (Phase 1) and 200 cm^2 and 400 cm^2 wall vents (Phase 2)

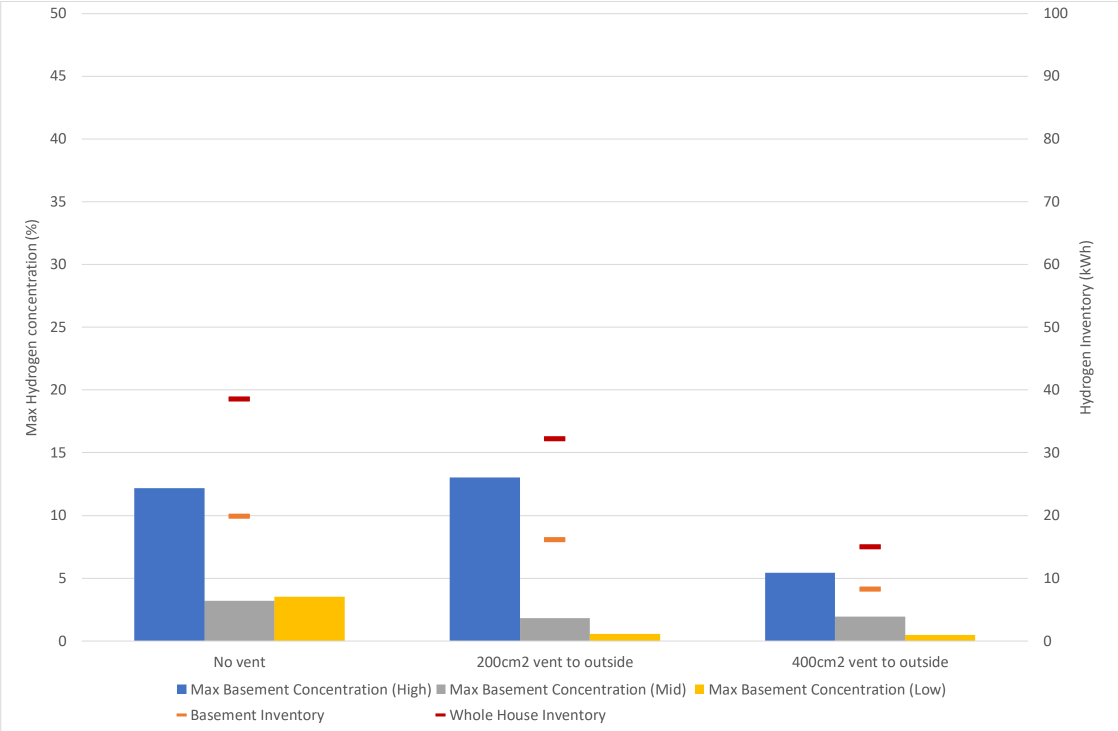


Figure 42: Basement maximum hydrogen concentrations and inventory – 9 m³/h (30 kW)

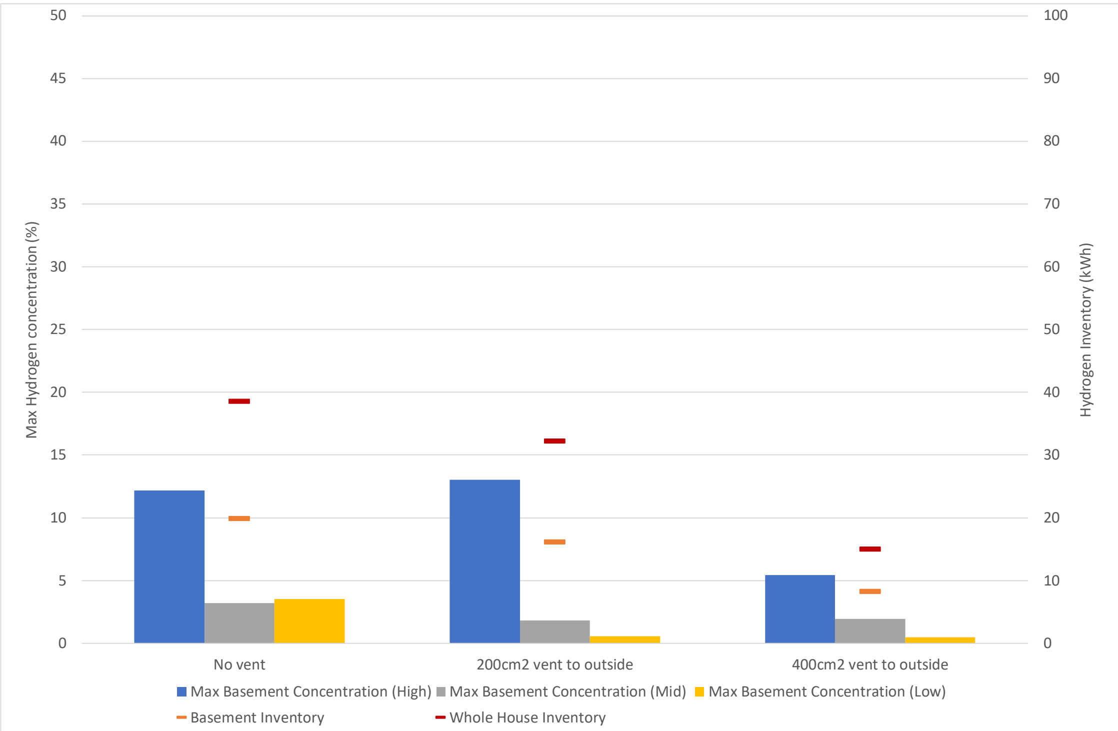


Figure 43: Basement maximum hydrogen concentrations and inventory – 20 m³/h (67 kW)

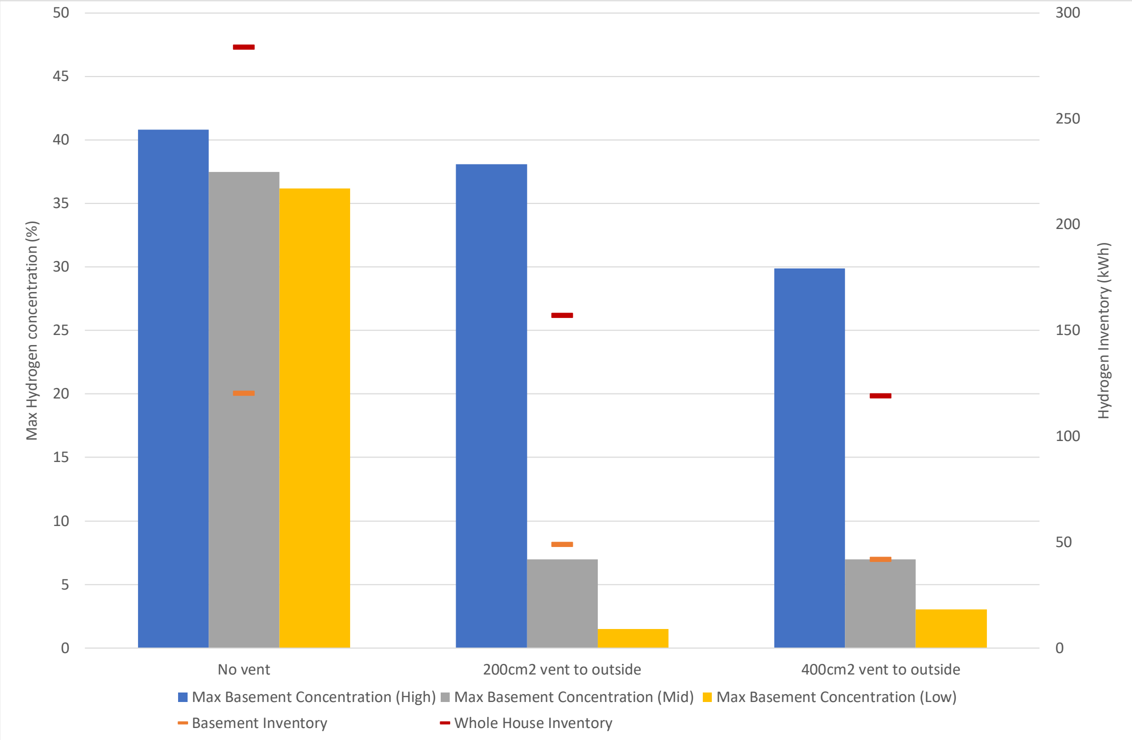


Figure 44: Basement maximum hydrogen concentrations and inventory – 79 m^3/h (264 kW)

6.3. The effect of room ventilation on hydrogen concentrations

The data was further analysed to quantify the beneficial effects of increased ventilation on reducing hydrogen concentration after a leak. This section is designed to consider the minimum vent area that particular rooms within the test house would require to prevent hydrogen accumulating to such a degree as to disproportionately increase the risk of injury compared to a similar leak of natural gas, within and around the same room. Such calculations are not required for the QRA as this is based upon a current evidence-based profile of the as occupied Air Change Rate (ACH) of UK housing stock. The QRA only considered the effect of excess flow valves.

Further test work to investigate the initial findings discussed herein would be of benefit.

6.3.1. The effect of leak size on hydrogen concentration.

Tables 3 and 4 below show the hydrogen concentration at the high, mid and low sampling points in the kitchen arising from holes of three different sizes, 3.6, 5.1 and 7.2 mm diameter; equivalent to nominal hydrogen leak rates of approximately 5, 9 and 18 m^3/h respectively from a pipe at 20 mbarg. All escapes were created within the kitchen base cupboard and the kitchen door was closed for each test. The 7.2 mm hole (~18.4 m^3/h) allows the largest leak permitted by the excess flow valve recommended by Hy4Heat.

Table 3 shows results with no additional ventilation. Table 4 shows results with a 100mm diameter (area $80cm^2$) wall vent installed over the interior kitchen door.

There is a direct correlation between GIA concentration and severity of damage during a deflagration event; with higher concentrations usually resulting in more severe consequences. This is explored in detail in the Hy4Heat Gas Ignition and Explosion Assessment report [7]. However, to provide context to the concentrations observed in these experiments, the tables below have been colour coded to denote likely severity of an ignition event. The colours are summarised below:

Table 2: Colour key for Tables 3 and 4

Concentration	Colour	Effect of deflagration	Local damage
>30 %	Bright red	Very high local flame speed	If restrained high local overpressure, but damage also dependent upon inventory.
30-23%	Pink	High local flame speed	Will depend upon size of cloud and its ability to expand for example into barely flammable zone below
23-15%	Orange	Moderate flame speed	Somewhat more severe than Nat Gas
15-8.5%	Yellow	Flame speed similar to Nat Gas	Expansion ratio much reduced. Local damage equivalent to Nat Gas
<8.5%	Green	Flash fire.	No overpressure.

Table 3: Kitchen hydrogen concentrations reached from base cupboard leaks without wall ventilation

Release point	Hole Size	Kitchen High	Kitchen Mid	Kitchen Low	Living High	Living Mid	Upstairs High	Upstairs Mid	Cupboard High	Cupboard Mid	Cupboard Low
Kitchen base cupboard	3.6	10.75	9.55	1.83	2.69	1.37	1.28	1.22	22.04	22.84	4.87
Kitchen base cupboard	5.1	21.96	19.96	2.51	3.29	2.98	3.35	3.22	33.10	34.31	13.25
Kitchen base cupboard	7.2	32.22	30.08	2.60	6.42	4.31	4.91	4.70	43.17	44.17	23.40

Table 4: Kitchen hydrogen concentrations reached from base cupboard leaks with additional ventilation

Release point	Hole Size	Kitchen High	Kitchen Mid	Kitchen Low	Living High	Living Mid	Upstairs High	Upstairs Mid	Cupboard High	Cupboard Mid	Cupboard Low
Kitchen base cupboard with 100mm WALL vent	3.6	6.23	5.12	0.48	1.55	1.42	1.74	1.68	19.22	17.39	3.57
Kitchen base cupboard with 100mm WALL vent	5.1	14.31	12.02	1.41	2.78	3.46	4.12	3.95	28.15	24.92	9.36
Kitchen base cupboard with 100mm WALL vent	7.2	20.31	17.04	1.15	3.08	3.35	4.85	4.64	39.81	39.64	15.82

The results show that the inclusion of a 100mm diameter (area 80cm^2) wall vent produced a significant reduction in hydrogen concentrations at high and mid-level within the room. Effectively those from the 7.2mm hole i.e. above 30% (red) and those from the 5.1mm hole i.e. above 15% (orange) concentrations, have been reduced to about ~60% of their original (unventilated) values. For the largest leak, hydrogen concentrations fell from about 31% to 19%; the mid-scale leak 20% to 13%, and for the smallest leak 10% to 6% GIA concentration.

It has been shown in [34] that GIA concentration has a direct correlation with flame speed and therefore overpressures in the event of an ignition. Therefore, a reduction in concentration such as those shown above, should reduce the likely damage associated with any deflagration or explosion. Increased ventilation of a room or house also reduces hydrogen inventory (Figure 40) which in turn is likely to reduce damage.

There is a subtlety here depending upon the size of any cupboard (or other small, vented compartment). As discussed elsewhere appliances within such compartments should be ventilated according the Building Regulations ADJ [32] to ensure there is no excessive accumulation within the compartment. In practice this is only likely to redistribute the hydrogen into the room and not materially affect inventory. However the ventilation of a room either into the house or (better) directly to outside will materially reduce the total inventory.

For context, if the kitchen inventory is considered as was described in section 5.4, each horizontal band would consist of 340 g of hydrogen at 50% v/v and 200 g at 30% v/v.

6.3.2. The effect of leak location on resultant hydrogen concentrations

Table 5 shows hydrogen concentration from a nominal escape of 18 m^3/h (~64 kW or ~7.2 mm hole at 20 mbarg; and the maximum leak permitted by the excess flow valve recommended by Hy4Heat) from four locations (kitchen door closed) with one repeat result with the kitchen door open.

Table 5: Hygrogen concentrations from low level releases (colour coded as per Table 2)

Release point	Hole Size	Kitchen High	Kitchen Mid	Kitchen Low	Living High	Living Mid	Upstairs High	Upstairs Mid	Cupboard High	Cupboard Mid	Cupboard Low
Wall cupboard DC	7.2	52.7	19.8	1.1	12.2	2.5	6.1	5.8	70.2	72.3	73.9
Base cupboard DC	7.2	32.2	30.1	2.6	6.4	4.3	4.9	4.7	43.2	44.2	23.4
Behind base cupboard DC	7.2	34.5	32.5	2.7	10.2	5.9	7.0	6.9	48.0	45.9	19.1
Undersink cupboard DC	7.2	37.7	37.4	11.2	12.4	7.1	8.1	7.8	49.5	46.4	5.6
Boiler cupboard DC	7.0	45.0	9.9	1.1	7.2	2.2	3.2	3.0	58.6	59.7	42.6
Boiler cupboard D OPEN	7.0	38.9	1.7	0.9	3.9	0.7	3.9	3.7	57.5	56.9	42.2

As discussed in detail in section 5, stratification of the gas within the kitchen is strongly influenced by the height of gas release with escapes at height (the wall and boiler cupboard) resulting in higher GIA concentrations than releases from low locations (behind and within base cupboard and undersink cupboard) which produced a more even distribution.

As the height of the location of the leak is increased the convective driving force must decrease, but as hydrogen rarely disperses to heights below the leakage point, the room inventory will also tend to modestly reduce. Release points nearer the ceiling (or effective release points if the leak is within a cupboard) can lead to very high concentrations near the ceiling. However, if the inventory of the whole space is low, this does not always lead to significant increases in overpressure in the event of an ignition. In the H100 FIB tests, hydrogen was leaked into the undersink cupboard producing very high localised concentrations. There is some evidence from the video that as the undersink doors opened there was a localised ignition event of increased speed, however there was little evidence of increased overpressure from the pressure transducers [4].

Anecdotal evidence from individuals within the industry suggests that the majority of gas escapes caused by corrosion and accidental damage (such as mechanical impact) are located near the floor, where there is more damp and the carcass can be more easily accessed. Spontaneous damage to high level pipes is less common. Ease of installation also favours gas pipes at low level.

3rd party damage (during building work) can occur to pipes in all locations but (as explained elsewhere) the presence of the person means the leak is usually dealt with responsibly.

Without any additional ventilation, the leaks from within the kitchen base cupboard resulted in concentrations very similar to both those of the leak behind the cupboard and under the sink. It is therefore reasonable to assume that adding a 100 mm vent (over the door) would produce similar reductions in concentrations for all these low (or moderately low) leak locations.

The results suggest that adding ventilation (or ensuring properties already have appropriate ventilation) could significantly reduce the concentrations (and thus hazard) associated with hydrogen. It should be noted that this was an internal vent, and whose performance would be degraded by a build-up of hydrogen in the house and which would not be subject to the beneficial effects of wind speed. In the following analysis it is assumed any vent is to the outside i.e. is external.

6.4. Quantitative estimates of the equivalent ventilation area

To understand how the appropriate amount of ventilation may be achieved in practice in a 'real' property, it was necessary to quantify the amount of ventilation that was present in the test house with and without the additional vents. In turn this was compared with the free equivalent ventilation areas required by Building Regulations ADF (England and Wales) [6] or regional variant.

The test house was tested for air tightness and found to have an air tightness of 5.58 m^3/h on the basis of the envelope (including basement) and 4.26 m^3/h without the basement. Data was not collected for individual rooms.

It has been well established in this work that the buoyancy of hydrogen generates an effect that drives ventilation in line with expectations that this would occur. Using the steady state hydrogen concentrations and nominal rate of gas injection used in the test work, a simplified version of a two-vent model as described (which assumed air can freely enter the room at floor level), was used to calculate a theoretical vent area within the test house.

When a buoyant gas is released into a room, the pressure profile inside the room with height differs from the air outside. The height at which the pressure in the room equals the atmospheric pressure at that height outside of the room is known as the neutral plane. The difference in height between the neutral plane and the high-level exit vent drives the flow of gas through the vent and hence strongly influences the steady state hydrogen concentration that would be reached.

The level of the neutral plane is discussed for each leak scenario, but it is proposed that this is predominantly defined by the level at which the hydrogen is released and forms a stratified layer. Very little hydrogen disperses to below this plane of leakage. This assumption also requires the incoming air floor vents to be much larger than the high level exit vents. This assumption regarding the position of the neutral plane could become inappropriate as the size of the top vent is increased, (as shown in Figure 35 and Figure 36) but this method of estimating the neutral plane level is thought to be a reasonable approximation for many of the scenarios investigated. The reductions in hydrogen concentration shown by the two sizes of external vents are very much in accord with expectations at the 20 m^3/h injection level. These are reductions in maximum concentrations from 32% to 18% from the base cupboard and 45% to 23% from the tall boiler cupboard.

The model is explained below.

Hydrogen is less dense than air, so a hydrogen/air mixture will create a negative pressure gradient inside a room and exert a positive pressure on the side of a vent in the room.

The pressure on the room side of the vent is equal to the atmospheric air pressure at ground level, minus the air pressure difference between the ground and the neutral plane, and further minus the gas/air mixture pressure difference between the neutral plane and the vent:

$$P_{inside\ vent} = P_{ground} - \rho_{air}\ g\ h_{np} - \rho_{mix}\ g\ (h - h_{np})$$

Where:

P_{ground} is the air pressure at ground level (bar)

ρ_{mix} is the density of the gas/air mixture (kg/m^3)

h_{np} is the height of the neutral plane from the floor (m)

h is the height of vent (m)

g is the acceleration due to gravity (m/s^2)

Using the concentration of hydrogen in the room for each of the base cupboard releases, the density of the gas/air mixture can be calculated and is equal to:

$$\rho_{mix} = V_{air}\rho_{air} + V_{H_2}\rho_{H_2}$$

Where:

V_{air} and V_{H_2} are the volumetric fractions of air and hydrogen, respectively

ρ_{air} and ρ_{H_2} the densities of air and hydrogen respectively (kg/m^3)

The pressure on the outside of the vent acts to oppose the flow of gas/air mixture and is equal to the air pressure at ground level minus the air pressure difference between the ground and the vent:

$$P_{outside\ vent} = P_{ground} - \rho_{air}\, g\, h$$

Where:

ρ_{air} is the density of air (kg/m^3)

This gives a pressure drop across the vent equal to:

$$\Delta P = P_{inside\ vent} - P_{outside\ vent} = g(\rho_{air} - \rho_{mix})\,(h - h_{np})$$

The pressure drop across the vent drives a flow of gas/air mixture through the vent. Assuming that the pressure difference is converted into kinetic energy, the pressure drop across the vent is equal to:

$$\Delta P = \frac{1}{2}\rho_{mix}\, v_{mix}^2$$

Where:

v_{mix} velocity of gas/air mixture through the vent in m/s

ΔP is the pressure drop across the vent (bar)

The volumetric flow rate of gas through the vent is equal to $Q_{mix} = v_{mix} A_{vent}$

Where:

A_{vent} is the vent area in m^2

Q_{mix} is the flow of gas/air mixture through the vent (m^3/s)

Substituting for v_{mix} gives:

$$A_{vent} = Q_{mix}\sqrt{\frac{\rho_{mix}}{2\, g\ (\rho_{air} - \rho_{mix})(h - h_{np})}}$$

At steady state it is assumed that the rate of hydrogen injection (m^3/s) divided by the mixture hydrogen volume fraction is equal to the volumetric flow rate of gas mixture leaving the vent (Q_{mix}). Therefore, given a steady state GIA concentration and a volumetric rate of gas injection, it is possible to calculate the theoretical vent area present. These calculated values were then validated using the actual, known vent area, and were compared to the existing requirements of ADF (England and Wales). Table 6 shows the results of this calculation for three injection rates carried out in the base cupboard.

There are number of uncertainties about the approach, the principle probably being the average height of the average exit vent above the neutral plane. This has been taken in this calculation as

2.00 m. The second is whether the mid height concentration is representative of the mean concentration of hydrogen in the room.

Table 6: Predicted vent sizes based on base cupboard releases

Model to determine intrinsic vent area (predominantly microcracks) of Spadeadam Kitchen					
No additional vents					
Hydrogen hole size	*mm*	*3.6*	*5.1*	*7.2*	
Hydrogen Rate	*m3/h*	*4.59*	*9.21*	*18.36*	
Height of H2 mix layer	*m*	*2.0*	*2.0*	*2.0*	
Measured value at steady state	*%*	*9.5%*	*20.0%*	*30.1%*	
Vent exit flow	*m3/h*	*53.20*	*57.69*	*87.35*	*Mean*
Equivalent area	*cm2*	*75.50*	*53.55*	*62.11*	*63.72*

Model to predict the area of added vent to the above case					
Hydrogen hole size	mm	3.6	5.1	7.2	
Hydrogen Rate	m3/h	4.59	9.21	18.36	
Height of H2 mix layer	m	2.0	2.0	2.0	
Measured value at steady state	%	5.1%	12.0%	17.0%	
Vent exit flow	m3/h	94.4	86.7	130.1	Mean
Equivalent area	cm2	187.5	108.4	133.0	143.0
Predicted added vent area	cm2	111.9	54.8	70.9	79.2

The free vent area as calculated in this work, is the theoretical area that is available to allow hydrogen to escape from the room. It arises from the sum total of all microcracks and real cracks located in the kitchen above the neutral plane. The location of the neutral plane is complex as it is a function of both the height of release of the hydrogen and of ratios of the pressure drops across the ventilation above and below the plane.

In accordance with ADF, it was assumed in this calculation that the kitchen door had a 75 cm^2 undercut and thus together with other air leakage paths that often occur at the floor /wall joints there is no limit on ventilation ingress, i.e. the neutral plane could be at the floor whereupon the height of the 'convective force' is calculated as the difference in height between the clean air / hydrogen air mixture boundary layer, and the mid-point of the top exit vent. It should be further noted that the general ingress of air into the house should not be limiting factor. The volumetric flowrate into and out of the kitchen detailed in Table 6(~50 to 90 m^3) are broadly similar to the ADF ventilation requirements of such a property (80 to 100 m^3/h).

The three successive hydrogen leaks rates permitted three separate calculations resulting in theoretical vent areas of 76, 54 and 62 cm^2 for scenarios in which no ventilation was present. The calculation was then repeated for scenarios in which additional ventilation was present in the form of a 100 mm vent fitted above the door, resulting in theoretical vent areas of 185, 109 and 133 cm^{2}. These calculations were undertaken with no reference to the numerical area of the added vent.

The difference between the unvented and ventilated scenarios thus provides a prediction of the vent size fitted to produce this increase in vent area. For these scenarios and using the mean ventilation areas calculated (63.7 (unvented) and 142.3 (ventilated) cm^2), the predicted vent size was 78.6 cm^2 (at a height of 2.2 m) the actual vent that was fitted was 78.5 cm^2. Clearly this very close agreement is probably coincidental, but it does give the analysis considerable credence.

As a further cross check, it might be thought reasonable to investigate the difference between the calculated free area of the kitchen (un-ventilated) and those that might be calculable from the 50 Pa pressurisation tests of the whole house, but these have very different characteristics. The first is assessing the air tightness of the internal walls, ceilings etc including all the pipes, cables etc that cross these, the second is the external fabric. These therefore are expected to be different.

In light of the importance of this work another series of tests were carried out whereby 100 cm^2 and 200 cm^2 angular vents were taken off the kitchen ceiling and run horizontally almost immediately to outside. There was a substantial fall in hydrogen concentration going from no vent to 100 cm^2 but subsequently little reduction as the vent was increased to 200 cm^2. This demonstrates that there are diminishing returns with increasing outlet vent size as the limitation to flow becomes more strongly associated with the air inlet from under the door, 75 cm^2, and from other low level air entry points.

These data points can also be used within the two-vent model to predict both the absolute value of the leakage area with no vent and by repeating the calculations with observed hydrogen concentrations, the predicted area of the added vent can be evaluated.

Table 7 Reverse prediction of added vent area for three tests. Actual vent added 100cm^2

Experimental conditions	Location of leak	Base cupboard	Base cupboard, including ADJ vents	Base cupboard	Kitchen boiler cupboard	Kitchen boiler cupboard
	Nature of vent	No vent	100cm2	100cm2	No vent	100cm2
Height of H2 mix layer	m	1.4	1.4	1.4	0.5	0.5
Measured value at steady state	%	28.50%	15.10%	16.90%	47.60%	23.10%
Vent exit flow	m3/h	102.5	160.6	145.9	80.2	112.6
Equivalent area	cm2	90.4	210.4	178.9	79.7	190.7
Predicted added vent area	cm2	NA	120	88.5	NA	111

As described above the largest uncertainties arise from the height of the vent above the neutral plane, and the correct concentration. A leak into the base cupboard was taken as creating a neutral plane at 1 m and that from the kitchen boiler cupboard as 1.9 m. These equate to vent heights above the neutral plane of 1.4 m and 0.5 m respectively. Mean concentrations were taken as the mid height concentration for the base cupboard case and the ceiling concentration for the latter, although this is known to be high. These gave predicted areas of added vent of 120, 88.5 and 111 cm^2. These are close to the added vent of 100 cm^2. These tests again demonstrate that despite its simplicity the two-vent model is appropriate for the quantitative assessment of vent size.

6.5. Prediction of effect of requiring ADF 50 cm² vent at 170 cm above floor.

Having determined the efficacy of the simple two vent model (above) it can then be used to determine the effect on hydrogen GIA concentration of adding a 50 cm^2 vent at 170 cm from the floor. Such a vent is recommended by ADF for rooms where there is doubt regarding compliance. The above calculation was thus repeated with the neutral plane at 1 m and vent height of 1.7 m i.e. a driving force resulting from a static head difference of 0.7 m; the results are shown in Table 8.

Table 8: Results of model with 50 cm^2 vent at 1.7 m from floor

Model to determine intrinsic vent area (predominantly microcracks) of Spadeadam Kitchen					
No additional vents					
Hydrogen hole size	mm	3.6	5.1	7.2	
Hydrogen Rate	m3/h	4.59	9.21	18.36	
Height of H2 mix to vent	m	0.7	0.7	0.7	
Measured value at steady state	%	9.5%	20.0%	30.1%	
Vent exit flow	m3/h	53.2	57.6	87.3	Mean
Predicted equivalent vent area	cm2	127	90	104	107
Model to predict the effect of adding 50cm2 of vent upon H2 conc					
Hydrogen hole size	mm	3.6	5.1	7.2	
Hydrogen Rate	m3/h	4.59	9.21	18.36	
Height of H2 mix to vent	m	0.7	0.7	0.7	Mean
Equivalent area plus 50cm2 of vent	cm2	177	140	154	157
Vent exit flow	m3/h	65.3	73.9	105.8	
Predicted value at steady state	%	7.6%	14.5%	22.3%	

The model suggests that for the scenario considered, the inclusion of a 50 cm^2 vent at 0.7 m above cupboard height i.e. 1.7 m from the floor reduces hydrogen concentrations to about ¾ of their original (unventilated) value. It was also shown to reduce the highest average concentration from ~30% (highlighted in red) to ~22% (highlighted in yellow). It is accepted that the choice of an ADF vent area is fortuitous, but it is convenient to utilise a vent area already prescribed in regulation, and which is known to offer good but not excessive ventilation. Even though ¾ might be considered a modest improvement, knowing the rapid increase in flame speed of hydrogen above about 20%, and the limitation of hydrogen flow at 20 m^3/h (or less) this level of protection is useful.

Efforts have been made to increase the complexity of the above model by adding an allowance for restriction of the input air, but such approaches require detailed knowledge of real leaks at floor level as well as real leaks near the ceiling and the number of assumptions required rapidly increases. Because of this, the simplicity of the above approach is preferred. Further work would be very useful in this area, especially as there is trend to reduce ventilation from fabric leaks. It is felt worthy of repeating that recent work by the building industry to reduce ACH should have concentrated upon reducing excessive ventilation associated with poor workmanship, although this has been misinterpreted as reducing the required number of ACH of an occupied property. This is incorrect, it is now accepted effort should be taken to ensure good quantitative compliance with ADF (or local variant) to prevent on the one hand poor internal air quality, or on the other hand excessive heat loss.

External ADF vents are usually specified in the range 350-400 cm^2 for a typical 3 bed property. These are designed to provide as occupied air changes of 0.4 to 0.45 per hour (ACH), or ~80 to 100 m^3/h of air movement. These are substantial values and if the house were fully open plan, would result in average hydrogen concentrations (from the above leakage sets) of 5.4%, 10.3% and 18.6%. Clearly not all houses are open plan, and this rate of air change (m^3/h) would not be available within a single room with the door closed. However, if considered alongside the flow limitation as proposed by Hy4Heat, the fitting of vents would result in reduced hydrogen concentrations within the property if a leak were to occur.

In many (probably the significant majority) homes, boiler installations are within kitchens, utility rooms, bathrooms or sanitary accommodation [35], all of which require increased ventilation - typically to 1 to 1.5 ACH, under ADF. The 100 cm^2 vent data reported above would be more representative of the type of vent to achieve this. This produced approaching a halving of peak hydrogen concentration (see Table 6). This increase in underlying ventilation must reduce the risk from any hydrogen leak. Other common boiler installation locations are garages, sheds or outhouses all of which are likely to be poorly sealed.

To significantly reduce the risk of serious hydrogen explosions, prior to any repurposing, it is recommended any room containing a gas appliance has a 100cm^2 vent. Detailed work sheets will need to be compiled to achieve this.

6.6. Other effects

A critical aspect that has not been included in this analysis is the effect of weather, particularly wind on the effectiveness of ventilation to remove gas from the property.

In windy conditions it has been demonstrated by various studies [31, 4] that if the wind is in the opposing direction to the vent, the release of gas through the vent will actually be inhibited instead of improved, although statistically windy days tend to dilute flammable gas levels. This may explain some of the results seen particularly in the basement tests, where different winds could either increase or decrease hydrogen concentrations.

The Hy4Heat data includes additional weather observations, however these were not available at the time of analysis. It is recommended that understanding the effect of wind on dispersion around and out of a property is investigated as further work to realistically model gas dispersion in the event of a leak. This work should also consider the merits of the industry available models which consider one vent and two vent scenarios when modelling a domestic setting.

A challenge of all the dispersion testing is that the results obtained rely on the size, layout and air tightness of the test houses (or mock-room in the case of H100 testing). One way to attempt to account for these differences is to normalise both the measured gas concentrations and gas escape flow rate with respect to properties of the test houses. This is explored briefly in Appendix 2 and is also suggested as an area for additional work.

7. Conclusions

Risk associated with ignitions of flammable gas concentrations is determined by GIA concentration and inventory, as well as physical characteristics of the space. Greatest risk from deflagration tends to correlate to stoichiometric GIA concentrations which are ~9% and ~29% for methane and hydrogen respectively, however experimental results to quantify the consequences and therefore risk of ignitions above stoichiometric concentrations are limited.

Over 300 experiments have been completed and analysed across a number of projects to understand the dispersion of hydrogen and methane within typical domestic environments, the findings being:

- Comparable maximum GIA concentrations were recorded for hydrogen and methane for tests of the same release rate on an energy basis. Stratification of the dispersing gas was also evident for both gases, with highest concentrations seen at the top of the space. The point of gas release always presented the highest GIA concentrations, and higher gas release rates resulted in the greatest maximum GIA concentrations within the property. When released into a cupboard, localised cupboard GIA concentrations were significant.
- The total gas inventory of the property (on an energy basis) was lower (usually much lower, about half) when a release of hydrogen occurred compared to the equivalent escape of methane, even at the highest flow rates. The highest flow rates (such as the mains failure simulation) led to the greatest gas inventories, with releases into the basement resulting in the highest total property inventory for both gases. This is likely due to the reduced ventilation factors active in the basement and the increased volume of house available for the leaking gas to disperse in to. Releases into a room resulted in the lowest gas inventory when there was no confinement of the escaping gas.
- Void concentrations measured within the property were low and largely below the range of flammability in the majority of test work. The exception to this was the ceiling void between the kitchen and the first floor; however, adding ventilation ducted to outside during phase 2 greatly reduced this. Flammable concentrations were also observed in roof voids and stud wall voids during very high gas release rates, and this was more pronounced for methane than hydrogen.

However:

- The height and location of gas release has a marked effect on the maximum GIA concentration recorded in the space; with releases at height resulting in higher maximum GIA concentrations. This was demonstrated through cupboard releases, where injections into 'high' cupboards resulted in higher maximum GIA concentrations at the top of the kitchen than the equivalent release in 'low' cupboards. Gas stratification was also exacerbated when the gas release was from cupboards at height, with a highly concentrated band of gas recorded at ceiling height and much lower GIA concentrations seen within the rest of the space.
- The air tightness of the property had a marked effect on the resulting maximum GIA concentration for the same release rate, with increasing maximum GIA concentrations observed as the air tightness of the property increases. Opening and closing internal doors also served to change the maximum GIA concentrations seen within the room of release, as well as throughout the rest of the property.
- Complex dispersion patterns were observed when the gases were injected into the basement with height and direction of gas release affecting the resulting stratification and inventory of the basement space. Opening or closing the basement door had a marked effect on the maximum GIA concentrations seen in the basement, but when injecting hydrogen, the effect to concentrations within the context of the rest of the house was limited; except at high release rates (>250 kW). Adding ventilation to the basement space had inconsistent affects, although most tests showed a reduction in maximum GIA concentrations with additional ventilation. Complex interactions between ventilation and weather conditions, particularly wind speed and direction are suggested and investigation of this is recommended as further work. The basement releases also had the greatest impact on the maximum GIA concentrations observed in the voids within the property (e.g.

wall and floor cavities), particularly for methane and for both gases at high flow rates where considerable GIA concentrations were observed in voids throughout the rest of the house.

Certain steps could be taken to reduce the maximum GIA concentration:

- Adding ventilation to the cupboards (as per ADJ) and kitchen reduced the maximum GIA concentration measured in the space. For injection rates around 67 kW (20 m^3/h), the resulting maximum kitchen concentrations almost halved when high level vents ducted to outside were added. Total gas inventory within the property also showed significant reductions when ventilation was ducted to outside of the property.
- When gas was injected into the kitchen, opening the internal door reduced the gas inventory (on an energy basis) in that space, and for the majority of tests did not impact the total house gas inventory.
- Ensuring rooms with gas appliances have sufficient ventilation (100cm^2 vent as recommended in Hy4Heat Annex.)

This work recommends that:

- Prior to repurposing to hydrogen visual inspections should be carried out to ensure compliance with Building Regulations J and F England (or local variation) and (when appropriate) other ventilation requirements for specific appliance types as laid down in British Standards or appliance manufacturers installation instructions.
- Hydrogen gas meters should be located externally to the property to reduce the risk from an unrestricted leak (e.g. prior to the gas meter regulator and emergency control valve) as this would occur in open air rather than within the property boundary.
- An excess flow valve or other form of flow restriction should be included in new hydrogen systems to reduce the risk of high flow rate scenarios occurring.

The data above has formed the basis of further modelling and consequence analysis reported separately under WP7.

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Appendix 1 Hole size and flow rate comparison

Hole diameter (mm)	Leak flow rate Q_o (m^3/h) for H_2	Leak rate (m^3/h) Qo for CH_4
0.3	0.03	0.01
0.6	0.13	0.05
0.9	0.30	0.10
1.2	0.53	0.19
1.8	1.18	0.42
2.5	2.28	0.81
2.8	2.87	1.01
3.55	4.61	1.63
4.14	6.26	2.21
4.92	8.85	3.12
5.1	9.51	3.35
5.8	12.29	4.34
6.97	17.75	6.26
7.2	18.94	6.68
7.6	21.11	7.45
8.29	25.11	8.86
8.8	28.30	9.99
9.76	34.81	12.28
10	36.54	12.89
10.6	41.06	14.49
11.2	45.84	16.17
11.8	50.88	17.95
12.4	56.19	19.83
13	61.76	21.79
13.6	67.59	23.85
14.08	72.45	25.56
14.61	78.00	27.52
14.7	78.97	27.86
15	82.22	29.01
15.5	87.80	30.98

Appendix 2 Normalization of GIA concentrations

Here a normalised gas inventory is plotted against a normalised escape rate (Figure 45), which gives an approximately linear relationship for both hydrogen and methane at the scales of escape tested. The specific formulae for calculating the normalised quantities were:

$$\text{Normalised gas inventory} = \frac{\text{Gas inventory in house } (m^3)}{\text{Volume of house } (m^3)}$$

$$= \frac{\sum_{\substack{\text{all} \\ \text{spaces}}} \left[\text{Gas concentration in space } \left(\frac{m^3}{m^3}\right) \times \text{Volume of space } (m^3)\right]}{\text{Volume of house } (m^3)}$$

$$\text{Normalised escape rate} = \frac{\text{Volumetric escape rate } \left(\frac{m^3}{h}\right)}{\begin{array}{c}\text{Volumetric leakage airflow rate} \\ \text{measured during air tightness test}\end{array} \left(\frac{m^3}{h}, \text{at 50Pa}\right)}$$

The gradient of the best fit line for methane is approximately 2.3 times the gradient of the line for hydrogen. However, it should be emphasised this is for a given volumetric escape rate and so for a turbulent escape through the same size hole, hydrogen will escape at a volumetric rate of up to 2.8 times that of methane.

There is good agreement between testing under HyHouse, H100 and Hy4Heat for both hydrogen and methane (Figures 46 and 47, respectively), despite the fact that all these test programmes used different houses (or mock-rooms), with different volumes and different air tightness values. In the Hy4Heat testing, the air tightness of the enclosure (effectively the building) also depended on whether the basement was included.

For the hydrogen tests, when taking account of building volume and air tightness, there is good agreement between the vast majority of HyHouse, H100 and Hy4Heat tests (Figure 46, blue circles, blue and purple squares, and all other symbols, respectively). The values below the best fit at high escape rates are Hy4Heat releases into the boiler cupboard in the kitchen. These have not been included in the fit. It is likely that at these high release rates, the test was terminated before the rest of the house was able to reach steady state (partly due to the high volumes of gas required to sustain the test). If the rest of house was further from steady state then it could be that there were (particularly upstairs) spaces where the concentration was still increasing at the end of the test, which would account for lower inventory across the whole house.

For the methane tests, there was again good agreement between the between testing under HyHouse, H100 and Hy4Heat (Figure 47). The values below the best fit at high escape rates are Hy4Heat releases into the boiler cupboard in the kitchen. Again, these are likely due to the rest of the house not having reached steady state and have not been included in the fit.

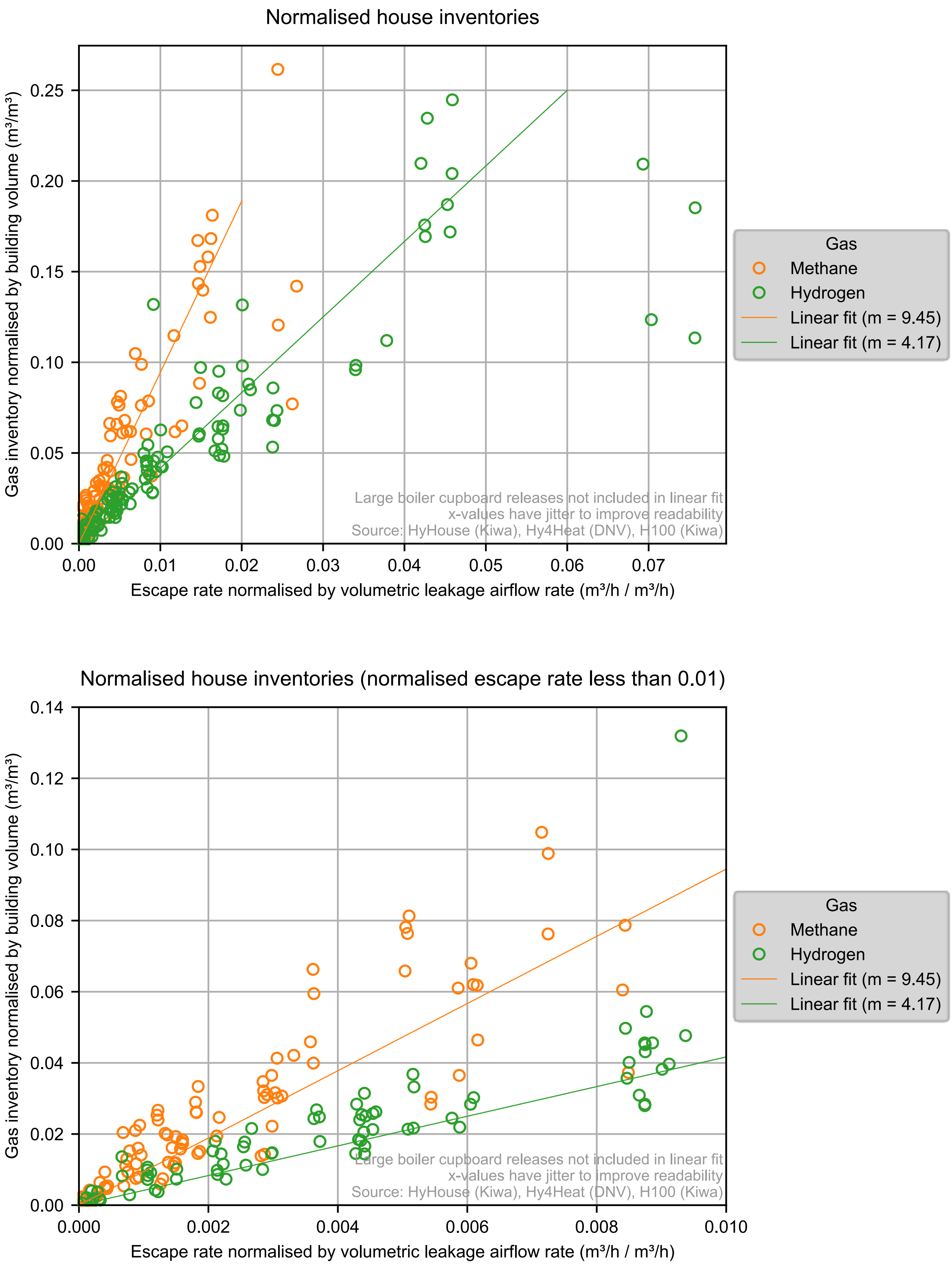
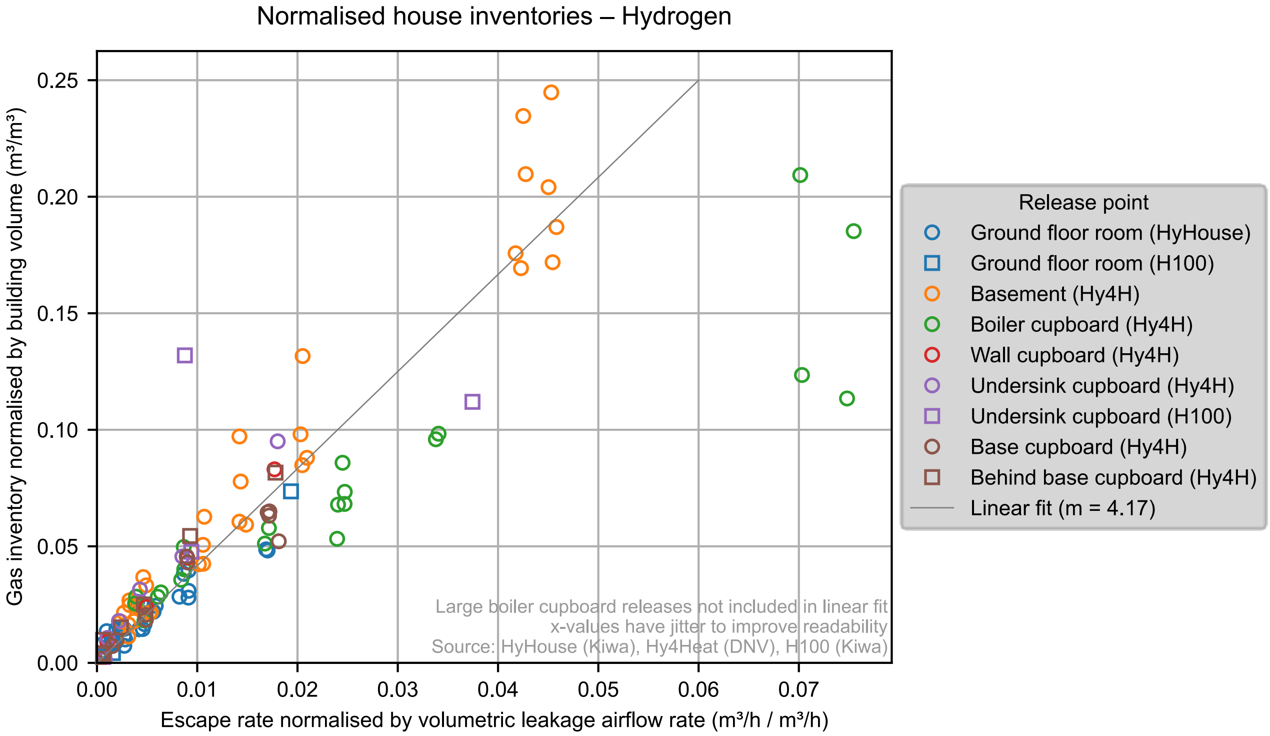


Figure 45: Normalised gas inventory for all hydrogen and methane scenarios (top) and smaller escapes (bottom)



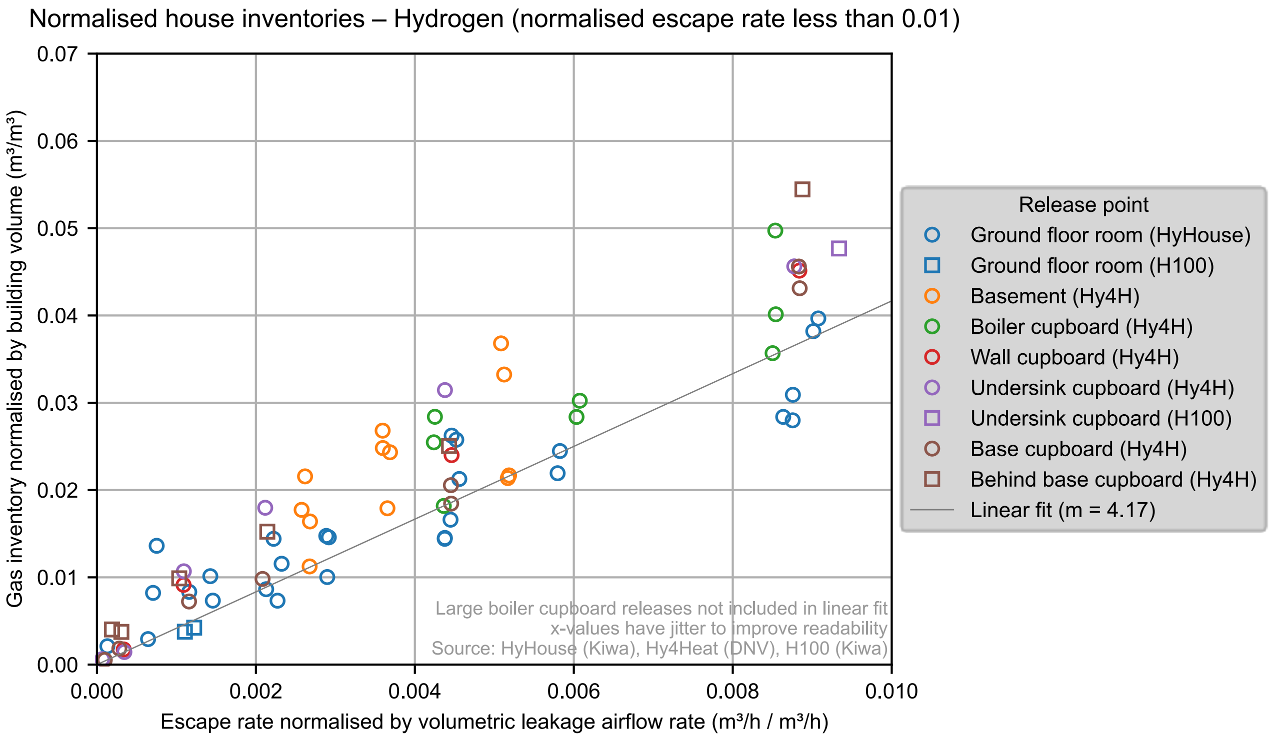
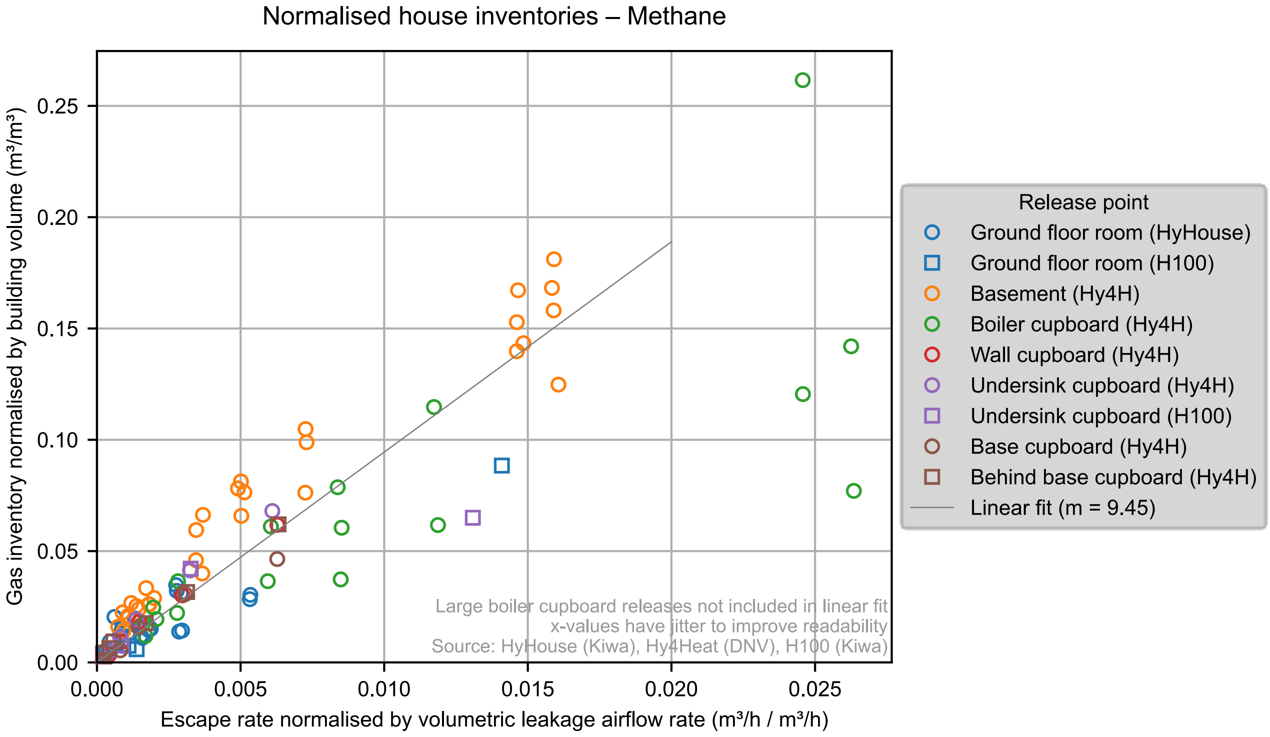


Figure 46: Normalised gas inventory all hydrogen scenarios (top) and smaller escapes (bottom)



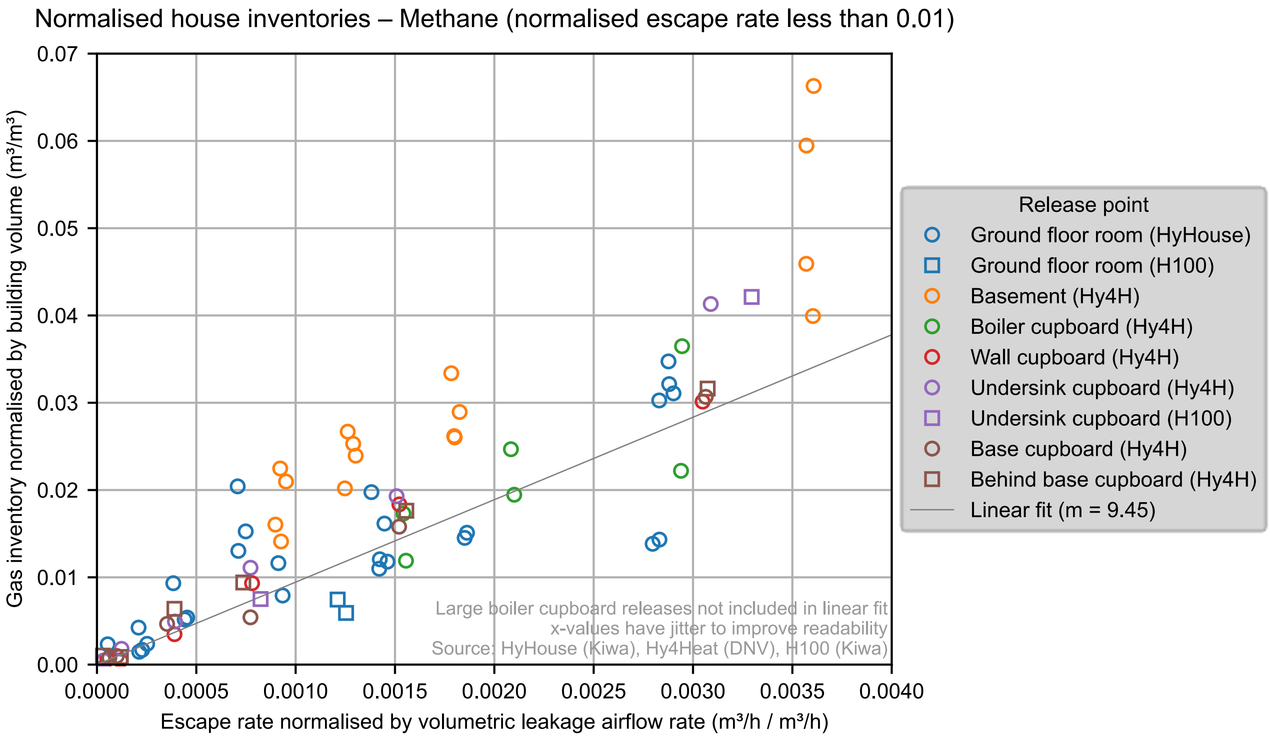


Figure 47: Normalised gas inventory all methane scenarios (top) and smaller escapes (bottom)

Appendix 3 Time to gas in air concentrations

The Hy4Heat dispersion reports completed to date [36] [37] have considered the maximum gas in air (GIA) concentrations reached in a domestic setting in the event of gas escapes of varying severity. These have been used to assess the risk associated with the ignition of comparable escapes of natural gas and hydrogen [38]. Which in turn, has provided evidence to support the development of a safety case for hydrogen for its use in place of natural gas within the UK gas network.

One aspect of the hydrogen safety case not considered to date, is the rate at which gas accumulations occur. More specifically, how quickly a hydrogen leak reaches a flammable concentration, compared to a similar leak of natural gas.

Further analysis was carried out on the dataset collected under Work Package 7 of the Hy4Heat programme, to determine the time at which measured GIA concentrations first exceeded certain concentrations. The analysis was carried out for hydrogen and methane at comparable energy release rates, to enable direct comparison of time to a set concentration. The concentrations were as follows:

- **1%** - There is a legal requirement in the UK under the Gas Safety (Management) Regulations 1996 (GS(M)R) [39], that gas distributed to homes and businesses is odorised. The level of odorisation must ensure that gas escapes of 1% are easily detectable by smell as a gas leak [40]. 1% equates to approximately 20% of the lower flammable limit (LFL) of both hydrogen and natural gas. It is at this level that buildings are evacuated in the event of a gas leak.
- **4.5%** - The LFL at which only upward flame propagation occurs, for hydrogen is between 4 and 5% GIA [41]. At this concentration the gas would ignite if a source of ignition were present, however would be unlikely to lead to full deflagration within the space (flame likely constrained to within the vicinity of the ignition source). In contrast, natural gas has full flame propagation in all directions at approximately 5% [41].
- **8%** - Full flame propagation (in all directions) occurs in hydrogen concentrations of above 8% GIA [42]. At this GIA concentration, methane is approaching stoichiometric conditions, an ignition of which is likely to have more severe consequences than that of an equivalent concentration of hydrogen [38].

This analysis has only considered the following:

- The room in which the gas release took place, which for all tests was the kitchen.
- The effect of release height, e.g. the difference in time to measured concentrations for escapes at low (lower kitchen cupboards) and high (wall cupboard) level
- Time to measured concentration at different heights in the room, e.g. low, mid and high-level sampling points.

Further detail regarding experimental set up and data collection is included in the project data report [43].

This summary report presents the results of this further analysis.

1. Methodology

The analysis considered gas releases in kitchen cupboards; and assessed time to the specified concentrations within the kitchen space. Although sensors were located throughout the house, these have not been included. Gas injections in the basement have also been excluded. Comparable methane and hydrogen injections (on an energy basis) took place in the following cupboard locations:

- Wall cupboard (high level injection)
- Base cupboard (low level injection)
- Behind base cupboard (low level injection)
- Undersink cupboard (low level injection)
- Boiler cupboard (high level injection)

A python script was written to extract the time where the measured concentration at each sample point, for each test, first equalled or exceeded the specified concentration (1, 4.5 or 8%). The critical assumptions and uncertainties are given below.

1.1. Determining the test start time

To calculate the time taken to reach each specified concentration, the test start time had to be determined from the raw data. Each test had a different gas injection profile due to the manual nature of the experiments, and in many of the tests there was a degree of ‘set up’ time at the start. This resulted in fluctuations of gas pressure meaning that it was not possible to rely on the presence of gas pressure alone to determine test start time. Instead, the test was said to have started when the gas outlet (“Release”) pressure was above a certain threshold value for a certain time. The default condition was a pressure of 0.01 barg for 2 minutes.

This method removed the set-up period, but in the limited number of situations where the initial set up period did not take place, it may have resulted in an underestimation of the injection time (<5 mins). However, when considering the uncertainty of the sampling measurements (discussed below) and that the uncertainties are applicable to both gases; the ability to determine patterns of gas accumulation and trends between natural gas and hydrogen remained unaffected.

1.2. Granularity of gas sampling

The gas sampling regime involved analysing a sample from one location and recording the result, before moving on to the next location. There was an eight-minute period between each data point from a sample location, resulting in an eight-minute window prior to each value where the concentration was not known.

Given this limitation in the data, when measuring the time for a rising gas concentration to first exceed a certain value, it can be said to have happened any time in the 8-minute period prior to when that value was recorded. For example, if 0% was measured at the sampling interval 8 minutes into the test and 1% was measured at the sampling interval 16 minutes into the test, then 1% could have been reached at any point between 8 and 16 minutes into the test. This sampling uncertainty is shown by error bars on the graphs below.

1.3. Residence time in sample line

The time taken for gas to travel from the sample point to the analyser resulted in a slight delay in the concentration measurement, this is known as the “residence time”. The residence time was not known; however, it is not thought to be large as the analysers were close to the sampling points.

Given the above uncertainties, it is impossible to provide an absolute value for when a specific concentration was reached. However, trends in the data and comparison between hydrogen and methane can be clearly shown.

1.4. Gas flow rates

The tests were designed to inject both gases at approximately the same rate of energy release (in kW). Table 9 shows the approximate energy release rates for injections into the wall, base, undersink cupboard and behind the base cupboard.

Table 9 Energy release rates for all locations other than boiler cupboard

Methane		Hydrogen	
kW	m^3/h	kW	m^3/h
0.4	0.04	0.4	0.13
1	0.1	1	0.3
4	0.4	4	1.2
8	0.8	7	2.2
17	1.6	15	4.6
34	3.2	31	9.2
67	6.4	62	18.4

For ease of visualisation, jitter has been added to the different series on the graphs in Section 2. The points on the graph are centred around the values in Table 9.

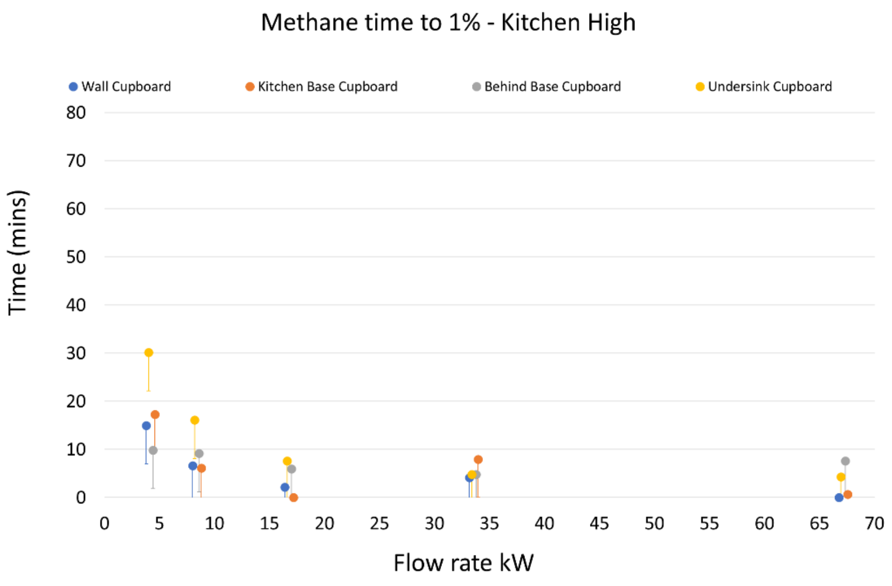
The release rates for injection into the boiler cupboard are shown in Table 10

Table 10: Energy release rates into boiler cupboard

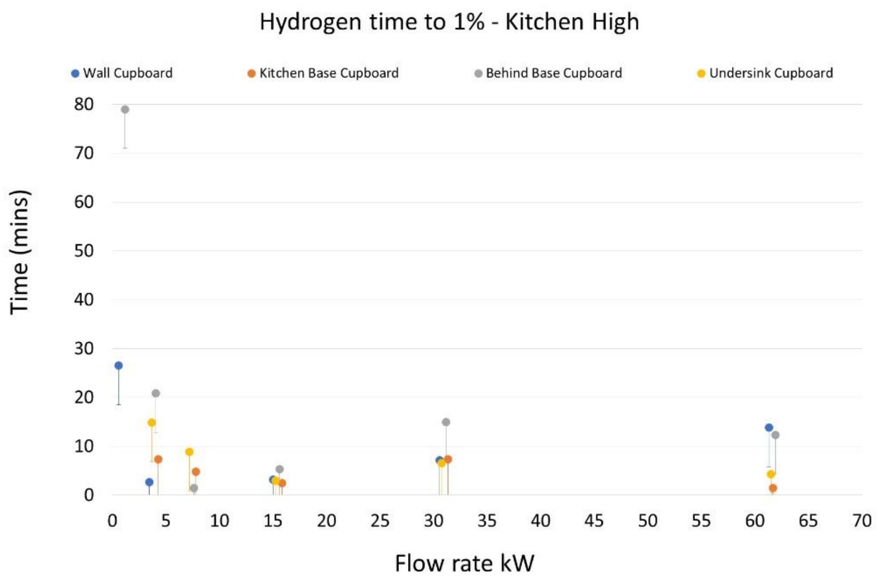
Methane		Hydrogen	
kW	m^3/h	kW	m^3/h
17	1.6	15	4.5
23	2.2	21	6.3
33	3.1	30	8.9
65	6.2	60	17.9
92	8.8	85	25.3

130	12.4	119	35.5
267	25.5	245	73.0
288	27.5	264	78.6

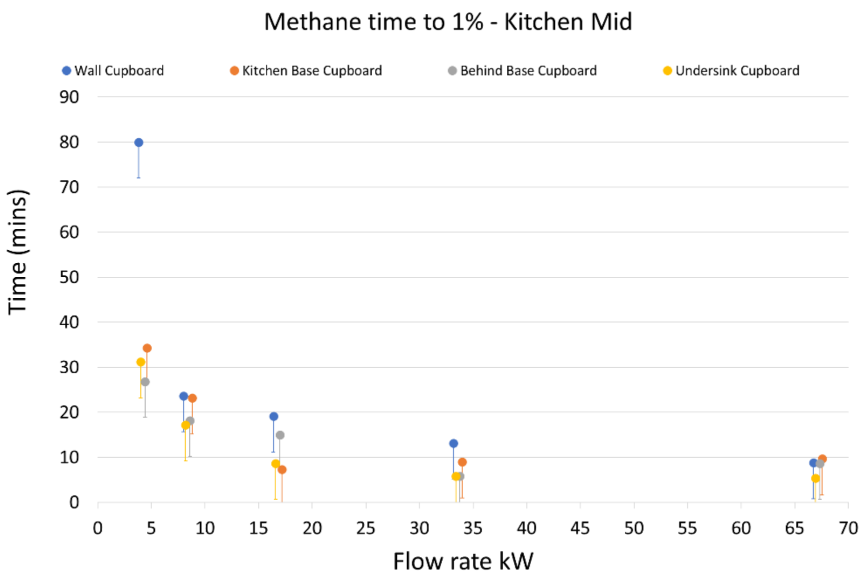
2. Results

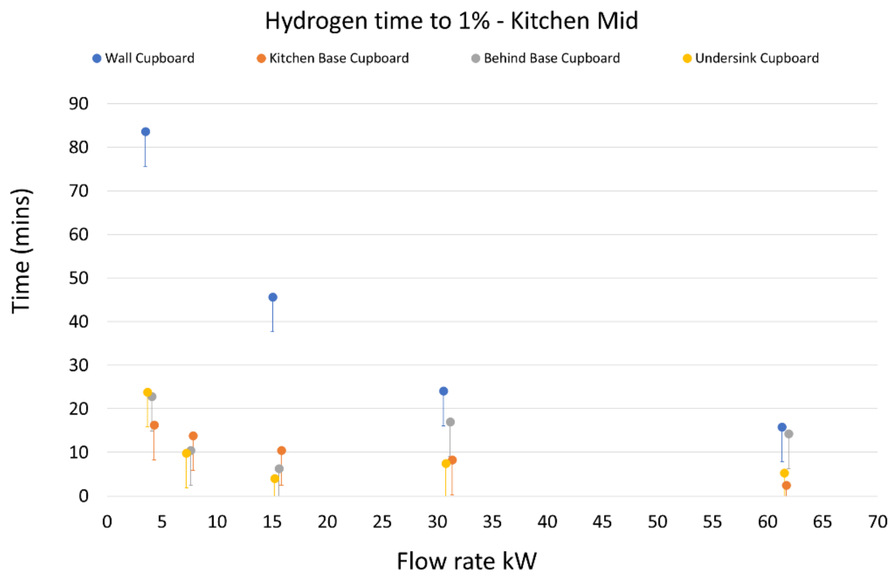


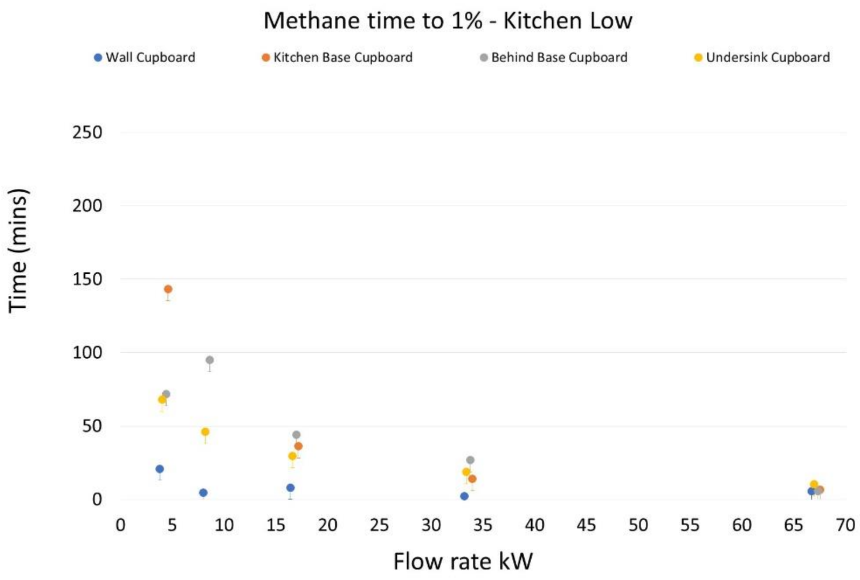
Methane time to 1% - Kitchen High
Wall Cupboard
Kitchen Base Cupboard
Behind Base Cupboard
Undersink Cupboard
Time (mins)
80
70
60
50
40
30
20
10
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70
Flow rate kW

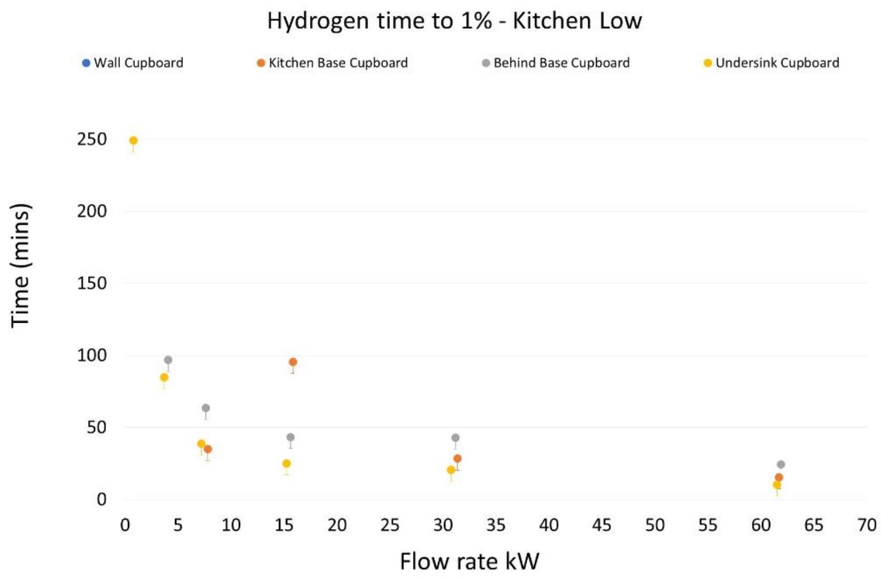


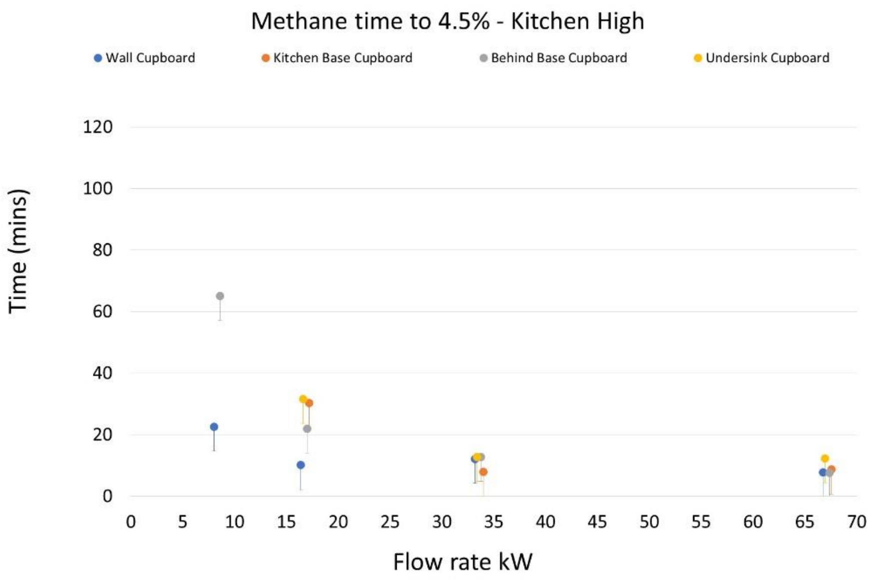
Hydrogen time to 1% - Kitchen High
Wall Cupboard
Kitchen Base Cupboard
Behind Base Cupboard
Undersink Cupboard
Time (mins)
80
70
60
50
40
30
20
10
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70
Flow rate kW

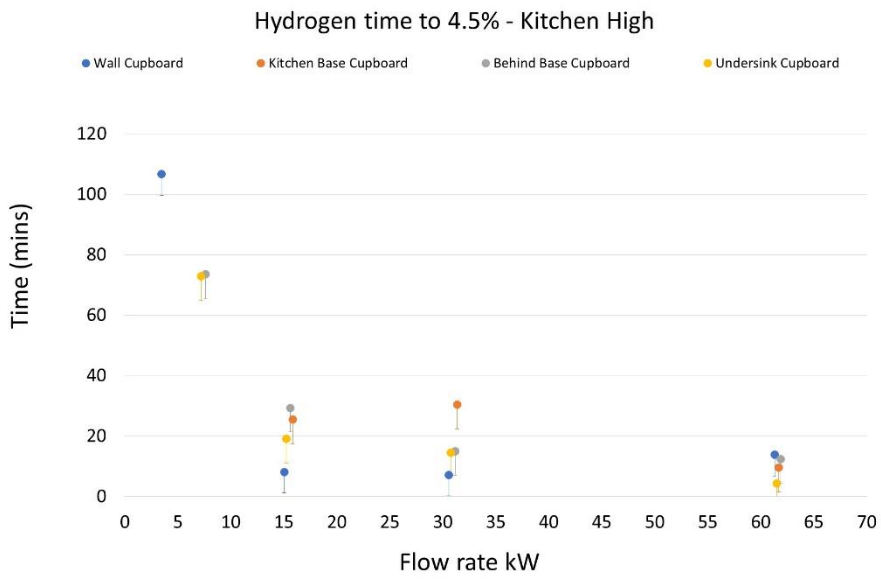

Methane time to 1% - Kitchen Mid
Wall Cupboard
Kitchen Base Cupboard
Behind Base Cupboard
Undersink Cupboard
Time (mins)
90
80
70
60
50
40
30
20
10
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70
Flow rate kW

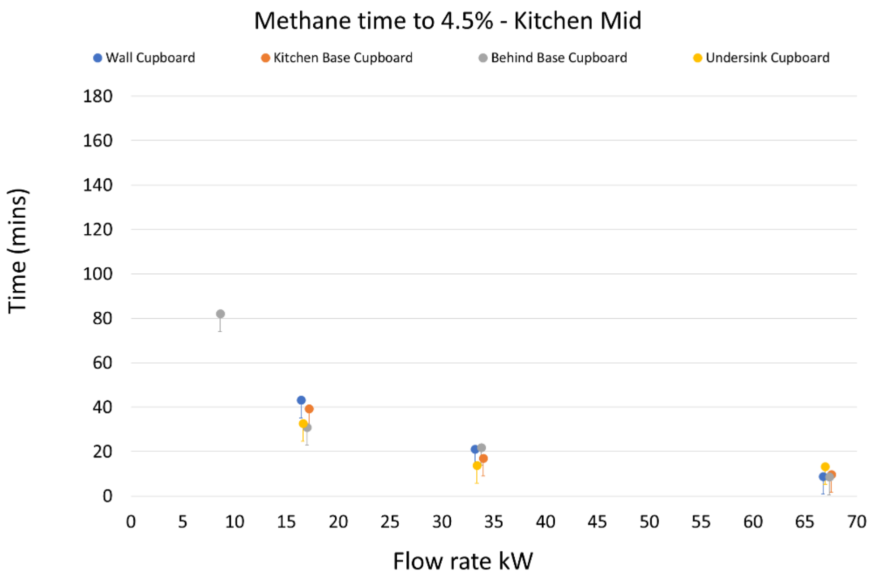

Hydrogen time to 1% - Kitchen Mid
Wall Cupboard
Kitchen Base Cupboard
Behind Base Cupboard
Undersink Cupboard
Time (mins)
90
80
70
60
50
40
30
20
10
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70
Flow rate kW

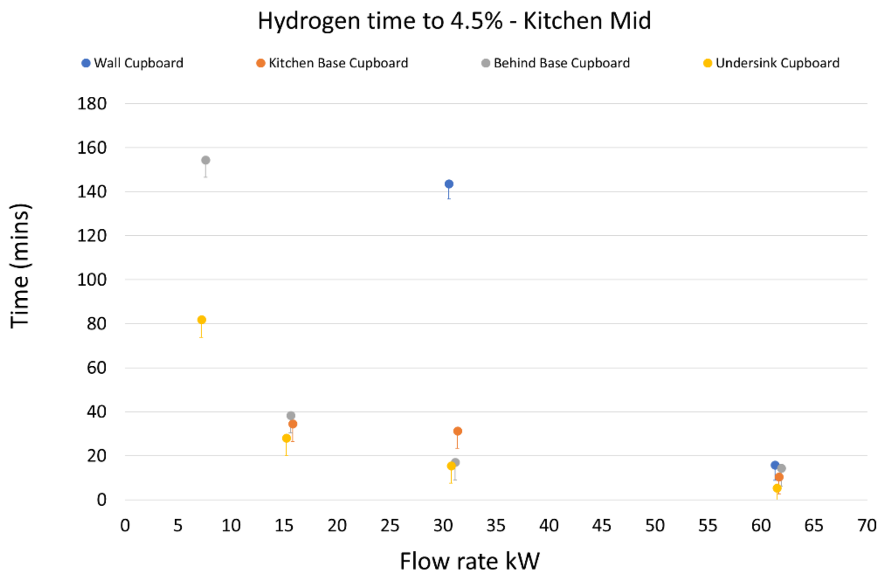

Methane time to 1% - Kitchen Low
Wall Cupboard
Kitchen Base Cupboard
Behind Base Cupboard
Undersink Cupboard
Time (mins)
250
200
150
100
50
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70
Flow rate kW

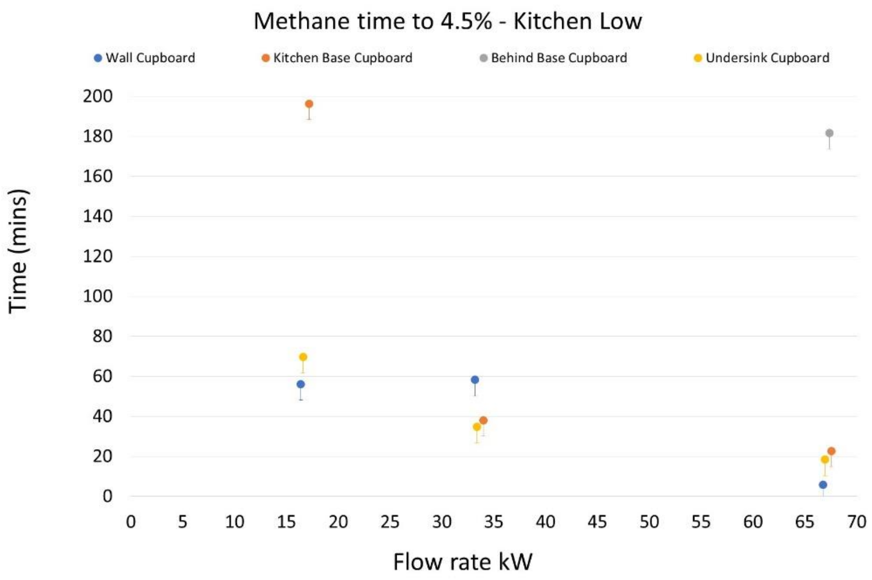

Hydrogen time to 1% - Kitchen Low
Wall Cupboard
Kitchen Base Cupboard
Behind Base Cupboard
Undersink Cupboard
Time (mins)
250
200
150
100
50
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70
Flow rate kW

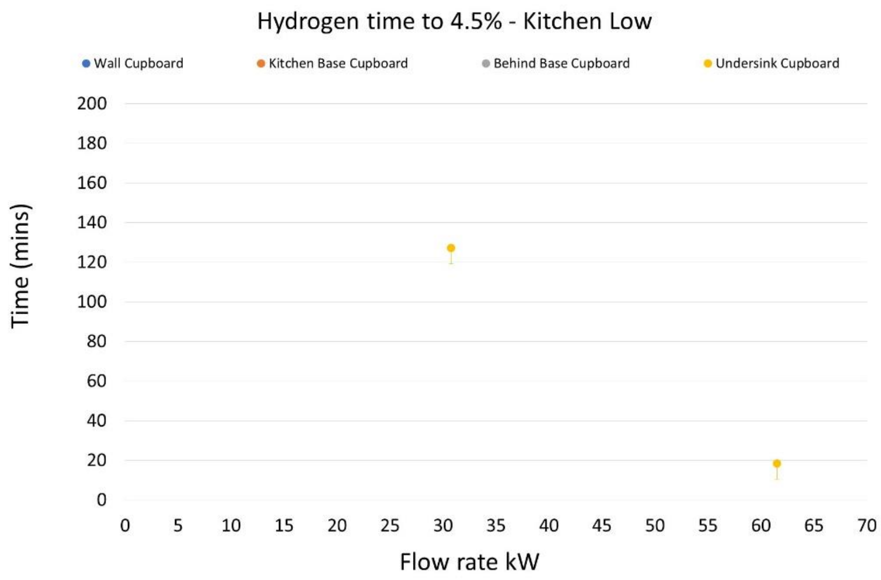

Methane time to 4.5% - Kitchen High
Wall Cupboard
Kitchen Base Cupboard
Behind Base Cupboard
Undersink Cupboard
Time (mins)
Flow rate kW

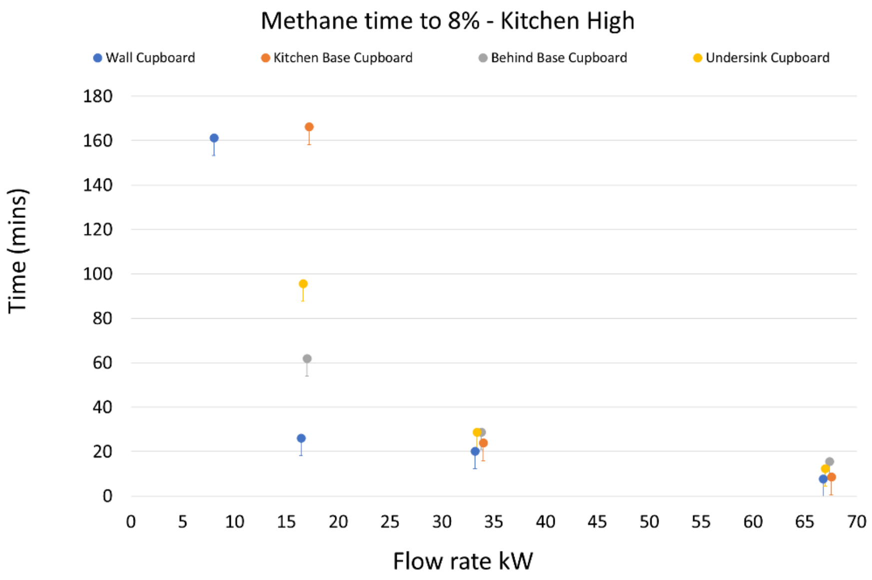

Hydrogen time to 4.5% - Kitchen High
Wall Cupboard
Kitchen Base Cupboard
Behind Base Cupboard
Undersink Cupboard
Time (mins)
Flow rate kW

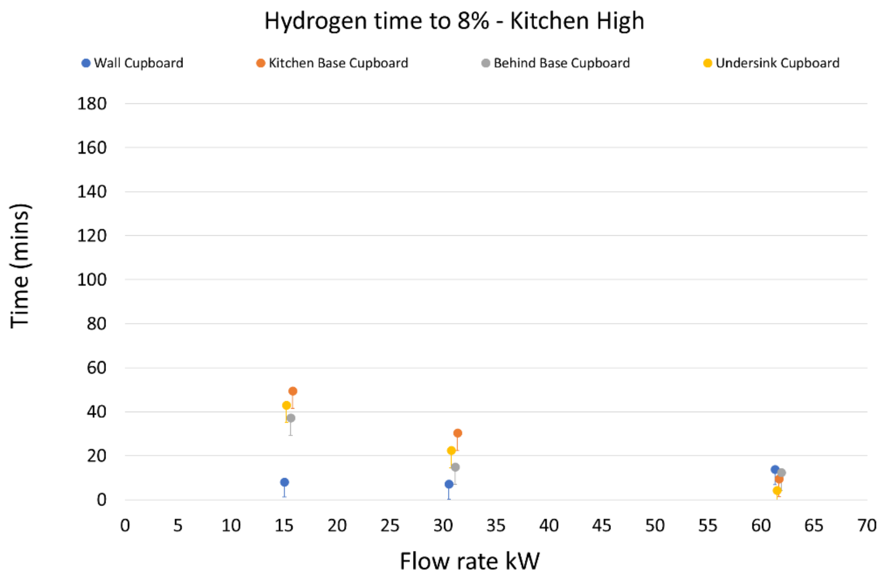

Methane time to 4.5% - Kitchen Mid
Wall Cupboard
Kitchen Base Cupboard
Behind Base Cupboard
Undersink Cupboard
Time (mins)
Flow rate kW

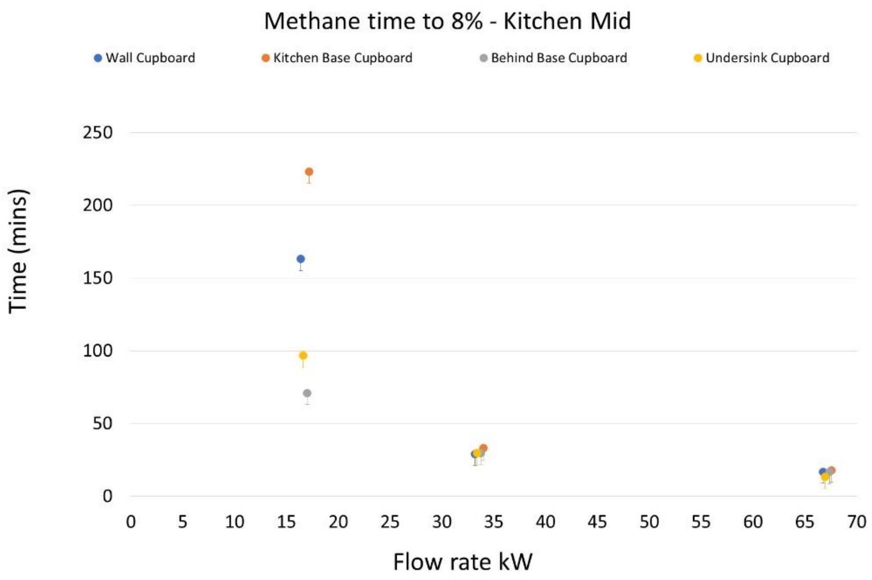

Hydrogen time to 4.5% - Kitchen Mid
Wall Cupboard
Kitchen Base Cupboard
Behind Base Cupboard
Undersink Cupboard
Time (mins)
Flow rate kW

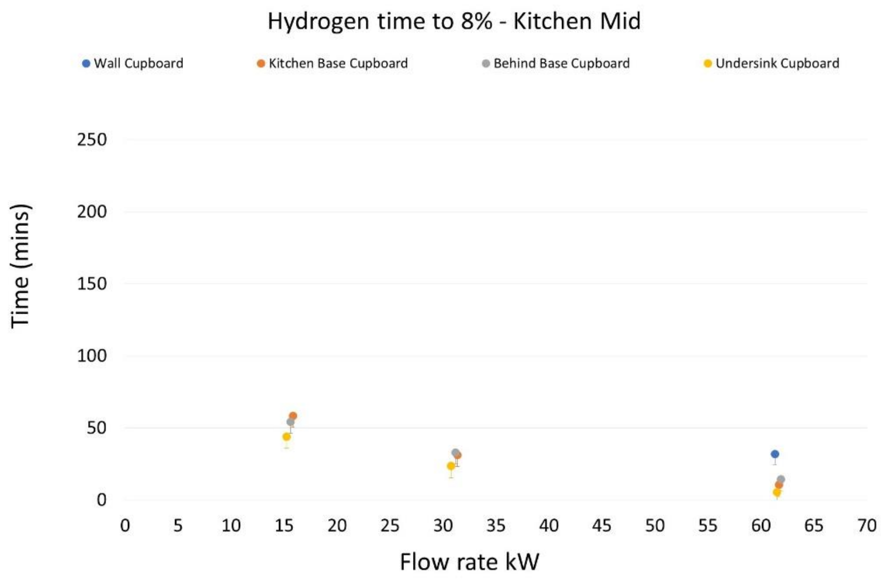

Methane time to 4.5% - Kitchen Low
Wall Cupboard
Kitchen Base Cupboard
Behind Base Cupboard
Undersink Cupboard
Time (mins)
Flow rate kW

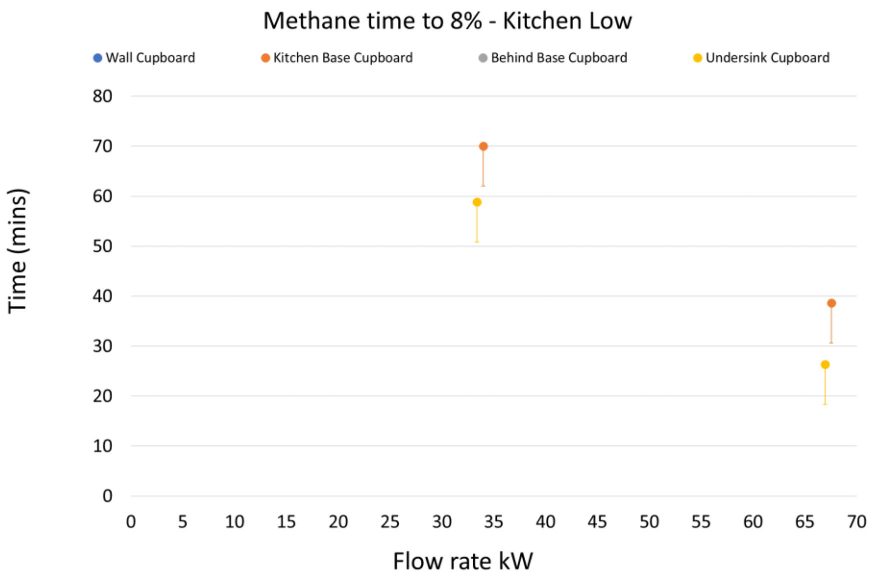

Hydrogen time to 4.5% - Kitchen Low
Wall Cupboard
Kitchen Base Cupboard
Behind Base Cupboard
Undersink Cupboard
Time (mins)
Flow rate kW

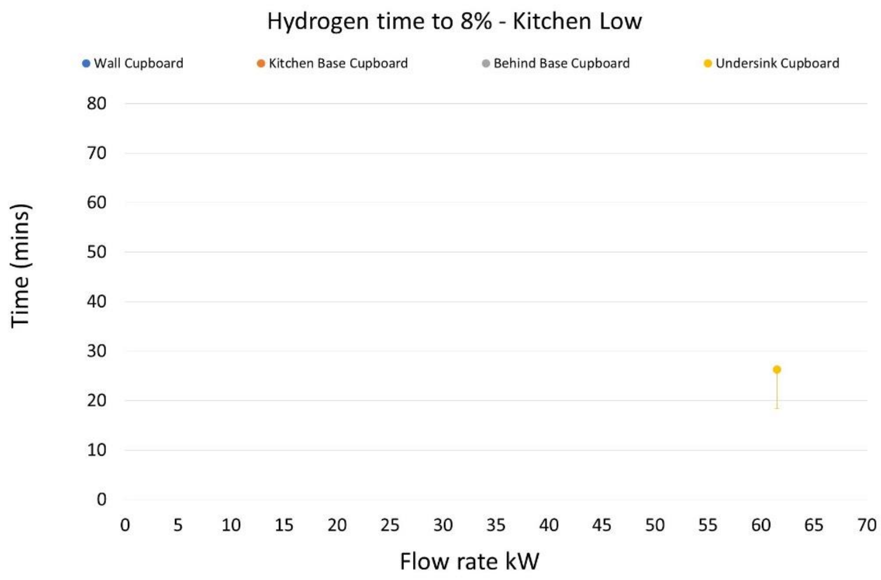

Methane time to 8% - Kitchen High
Wall Cupboard
Kitchen Base Cupboard
Behind Base Cupboard
Undersink Cupboard
Time (mins)
Flow rate kW

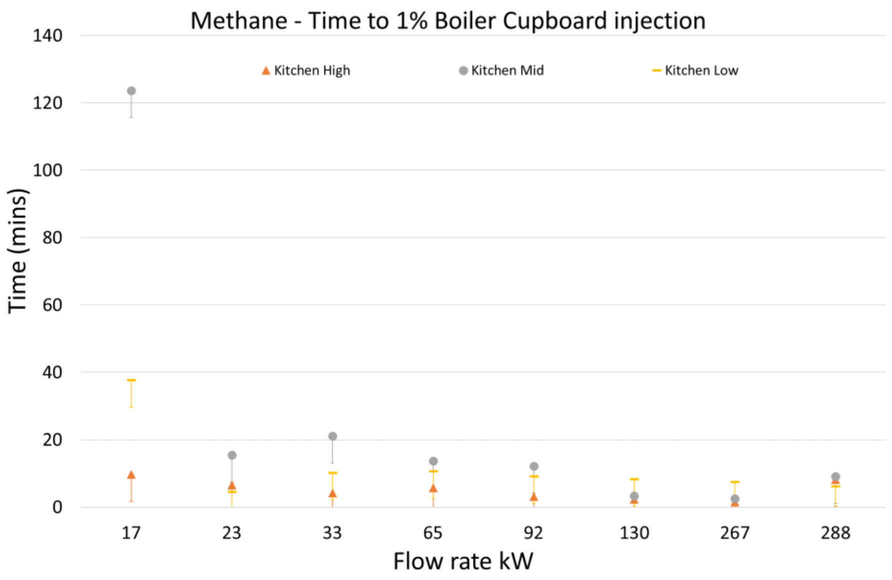

Hydrogen time to 8% - Kitchen High
Wall Cupboard
Kitchen Base Cupboard
Behind Base Cupboard
Undersink Cupboard
Time (mins)
Flow rate kW


Methane time to 8% - Kitchen Mid
Wall Cupboard
Kitchen Base Cupboard
Behind Base Cupboard
Undersink Cupboard
Time (mins)
Flow rate kW

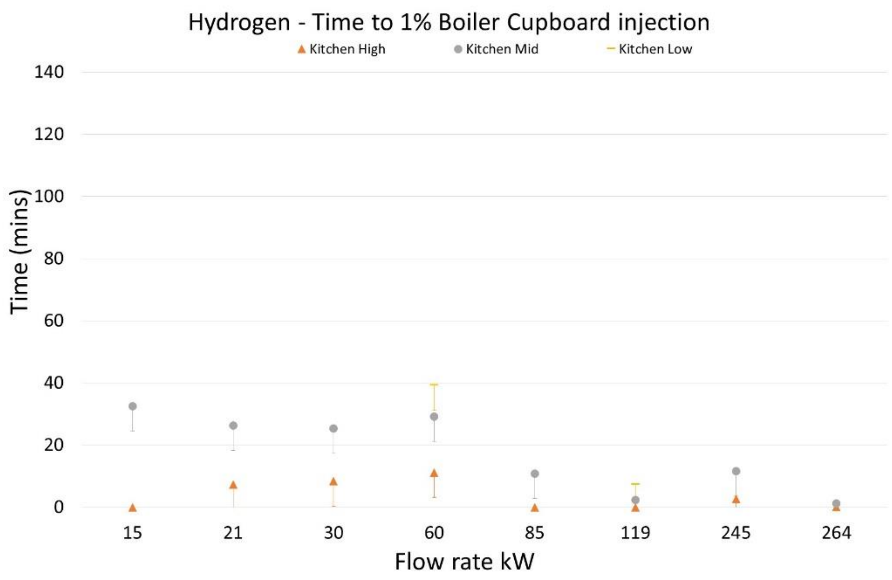

Hydrogen time to 8% - Kitchen Mid
Wall Cupboard
Kitchen Base Cupboard
Behind Base Cupboard
Undersink Cupboard
Time (mins)
Flow rate kW


Methane time to 8% - Kitchen Low
Wall Cupboard
Kitchen Base Cupboard
Behind Base Cupboard
Undersink Cupboard
Time (mins)
Flow rate kW

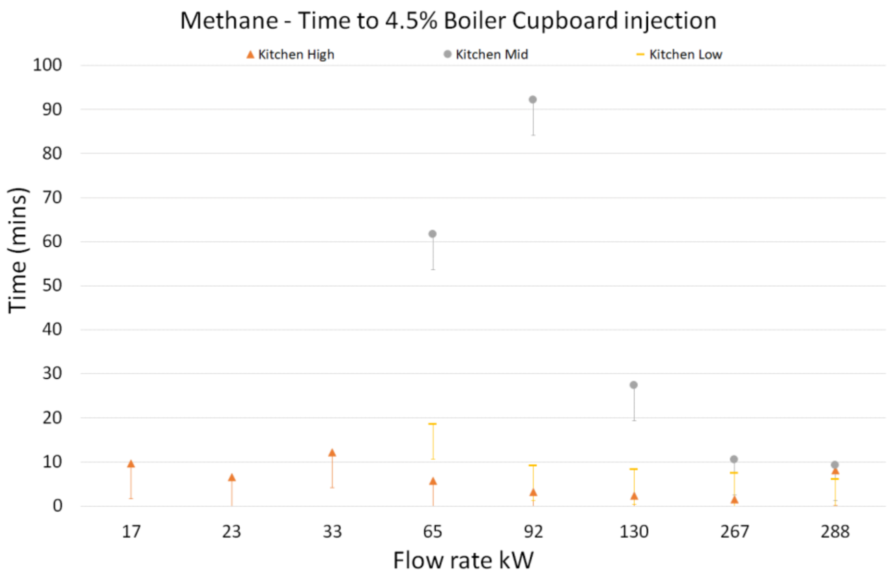

Hydrogen time to 8% - Kitchen Low
Wall Cupboard
Kitchen Base Cupboard
Behind Base Cupboard
Undersink Cupboard
Time (mins)
Flow rate kW



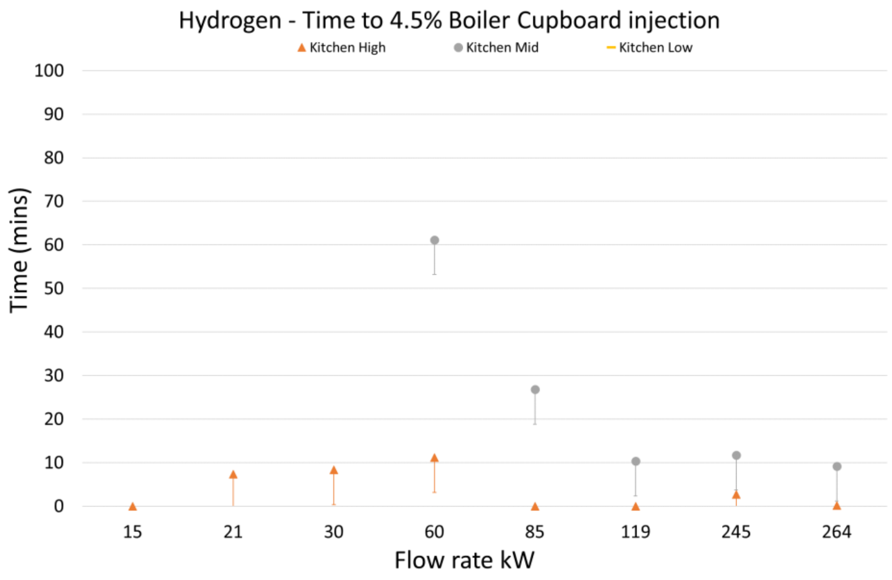
Methane - Time to 1% Boiler Cupboard injection
Kitchen High
Kitchen Mid
Kitchen Low
Time (mins)
140
120
100
80
60
40
20
0
17
23
33
65
92
130
267
288
Flow rate kW



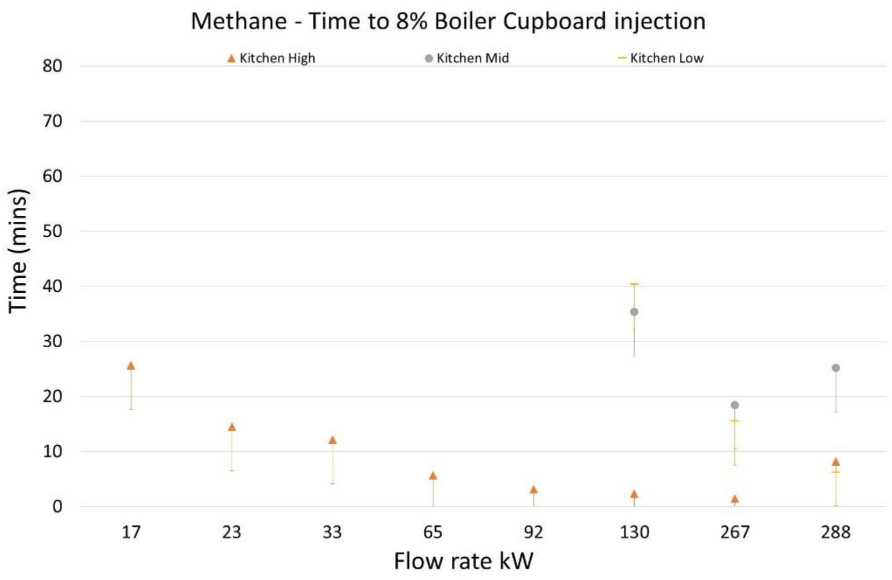
Hydrogen - Time to 1% Boiler Cupboard injection
Kitchen High
Kitchen Mid
Kitchen Low
Time (mins)
140
120
100
80
60
40
20
0
15
21
30
60
85
119
245
264
Flow rate kW

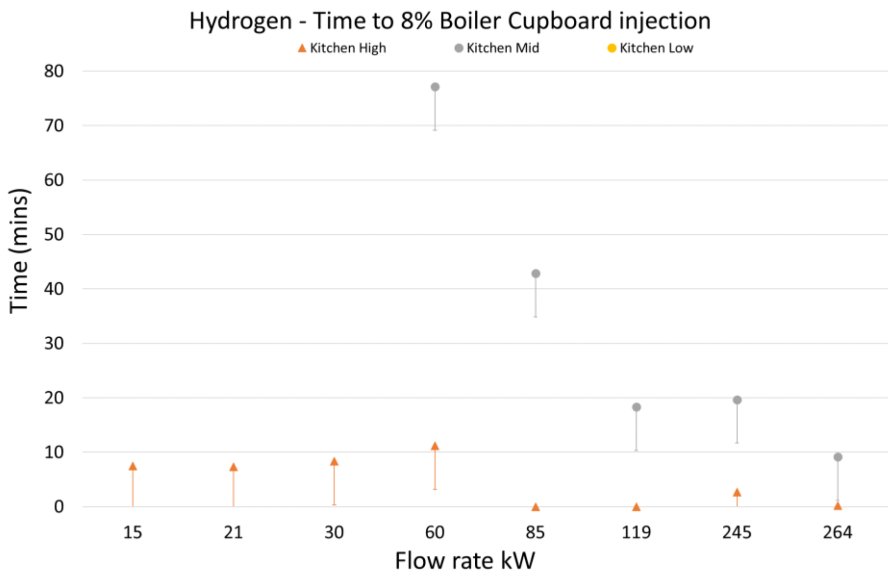


Methane - Time to 4.5% Boiler Cupboard injection
Kitchen High
Kitchen Mid
Kitchen Low
Time (mins)
100
90
80
70
60
50
40
30
20
10
0
17
23
33
65
92
130
267
288
Flow rate kW



Hydrogen - Time to 4.5% Boiler Cupboard injection
Kitchen High
Kitchen Mid
Kitchen Low
Time (mins)
100
90
80
70
60
50
40
30
20
10
0
15
21
30
60
85
119
245
264
Flow rate kW

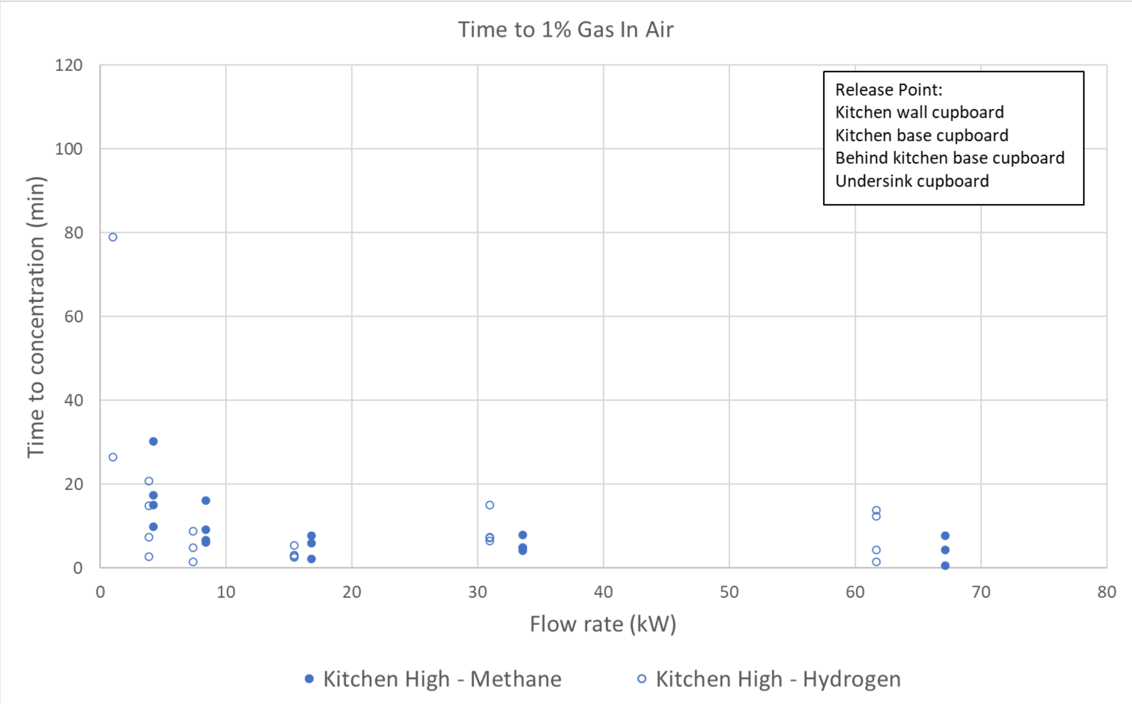

Methane - Time to 8% Boiler Cupboard injection
Kitchen High
Kitchen Mid
Kitchen Low
Time (mins)
0
10
20
30
40
50
60
70
80
17
23
33
65
92
130
267
288
Flow rate kW

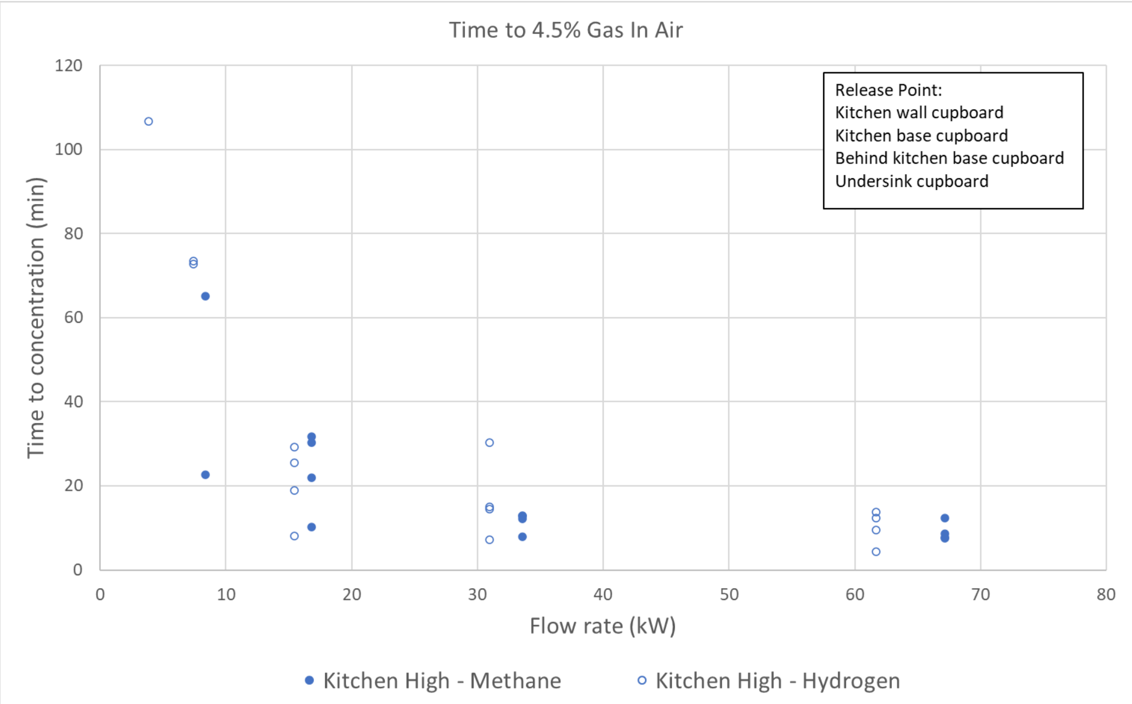

Hydrogen - Time to 8% Boiler Cupboard injection
Kitchen High
Kitchen Mid
Kitchen Low
Time (mins)
0
10
20
30
40
50
60
70
80
15
21
30
60
85
119
245
264
Flow rate kW

2.1. Comparison across injection locations

To aid the identification of overall trends between the two gases, the following graphs compare the time taken to reach the target concentrations for both gases irrespective of injection location (and excluding the boiler cupboard injection). Care should be taken when comparing results from different injection locations as it is known from previous analysis that the dispersion characteristics vary between tests of different release height [36]. However, combining injection locations into one series provides more data points at each release rate, for each sampling point (low, mid and high), and allows general trends to be identified. Each point represents the first time at which the concentration was exceeded as subject to the uncertainty explained in section 1.2.

2.1.1. Kitchen high point





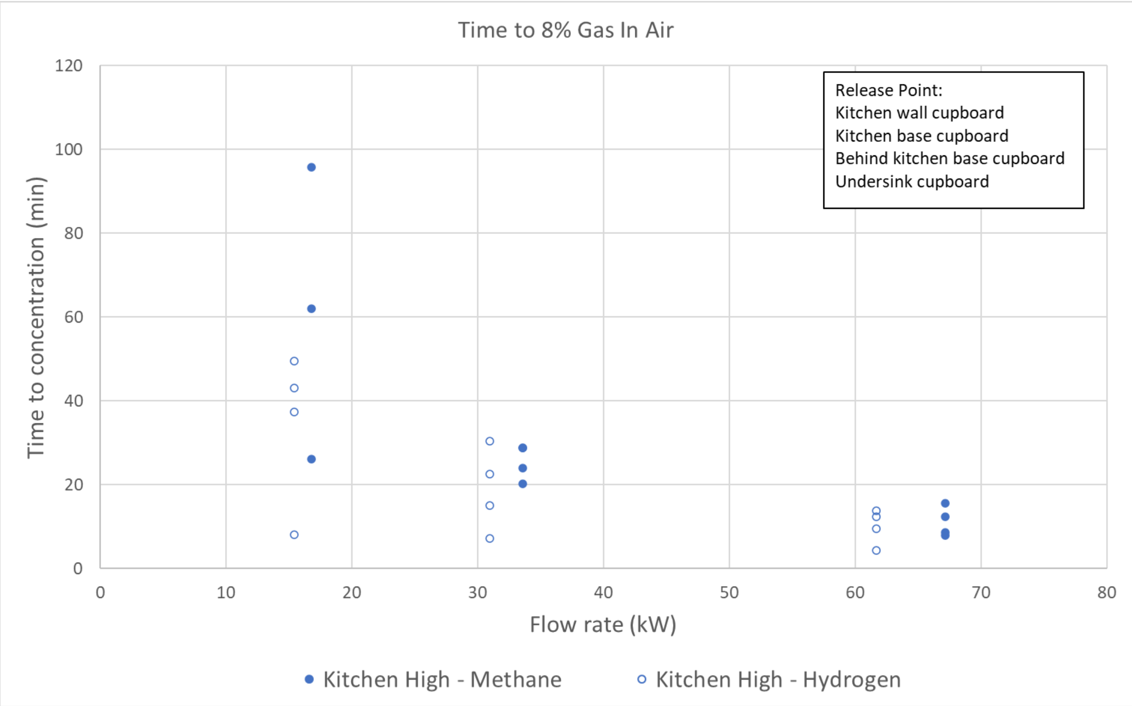
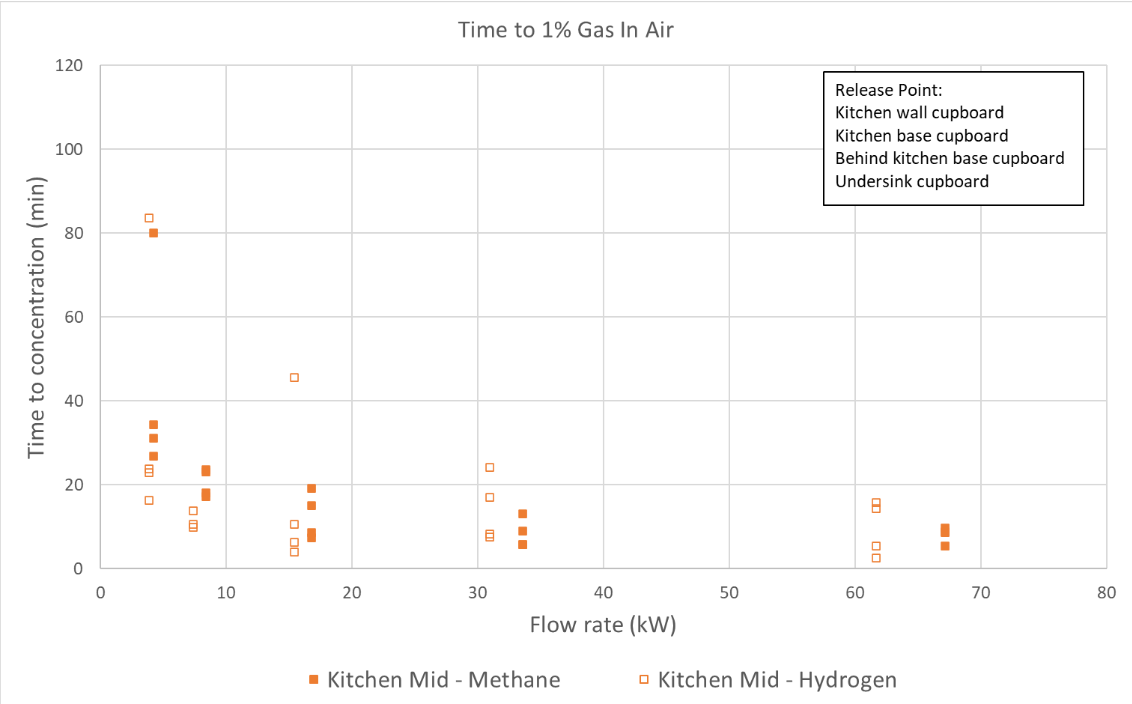


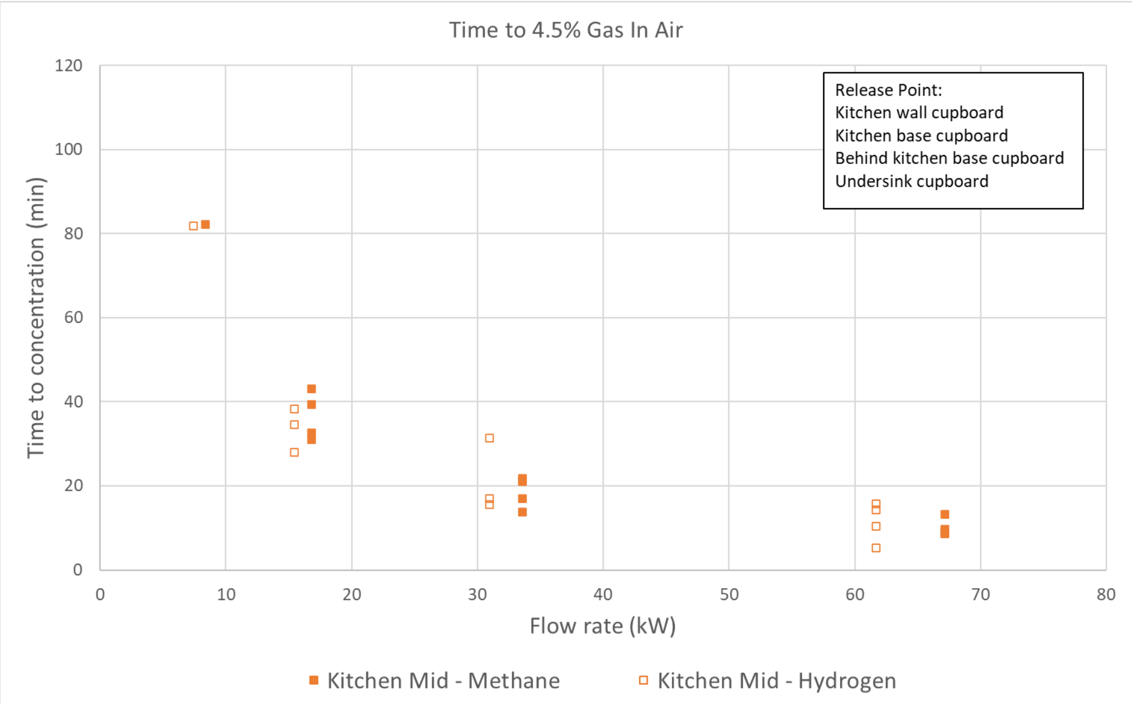
Figure 48 (a, b and c): time to reach 1%, 4.5% and 8% GIA at the top of the kitchen

Figure 48 (a) shows that the kitchen high sampling point reaches 1% GIA quickly for both gases - all but 2 points are less than 20 minutes. Hydrogen may reach 1% concentration slightly sooner at low release rates (<20 kW) than methane, but this is only of the order of 5 minutes and likely within the error of measurement. There is a wider spread (particularly at low flow rates) for the time to reach 4.5% and both gases seem to behave similarly as shown in Figure 48 (b).

Figure 48 (c) has the largest spread of results at low release rates (~15 kW) but shows a trend for hydrogen to reach 8% at the top of the room sooner than methane for medium (~33 kW) to low release rates.

2.1.2. Kitchen mid-point





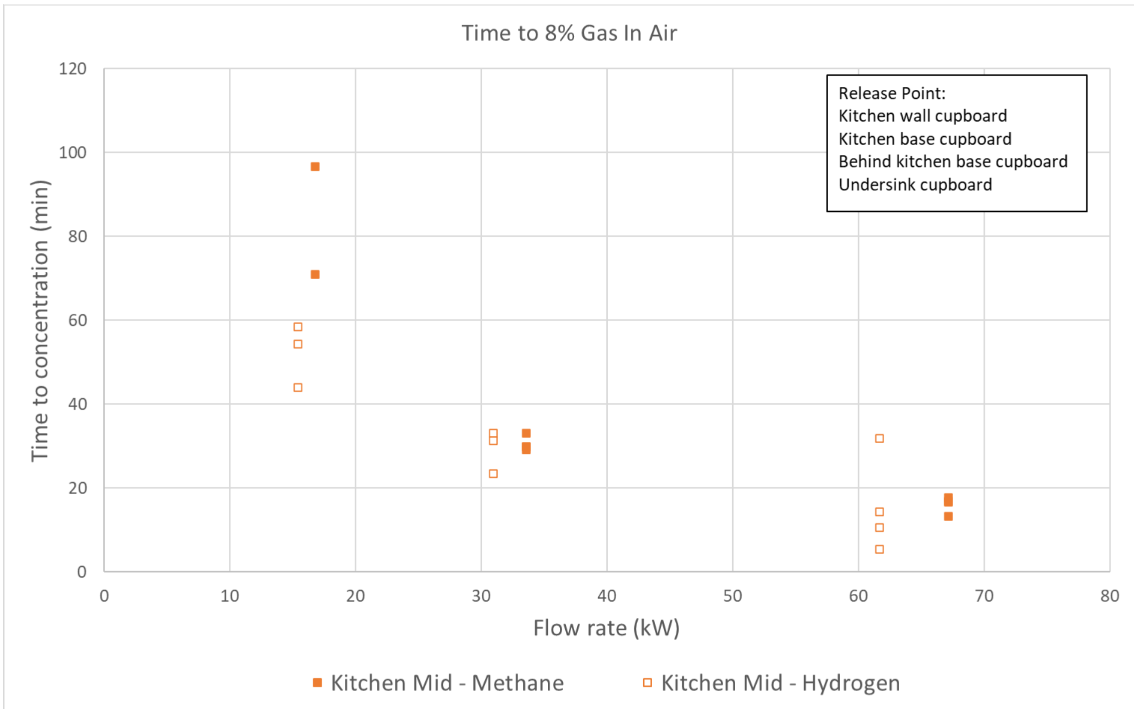
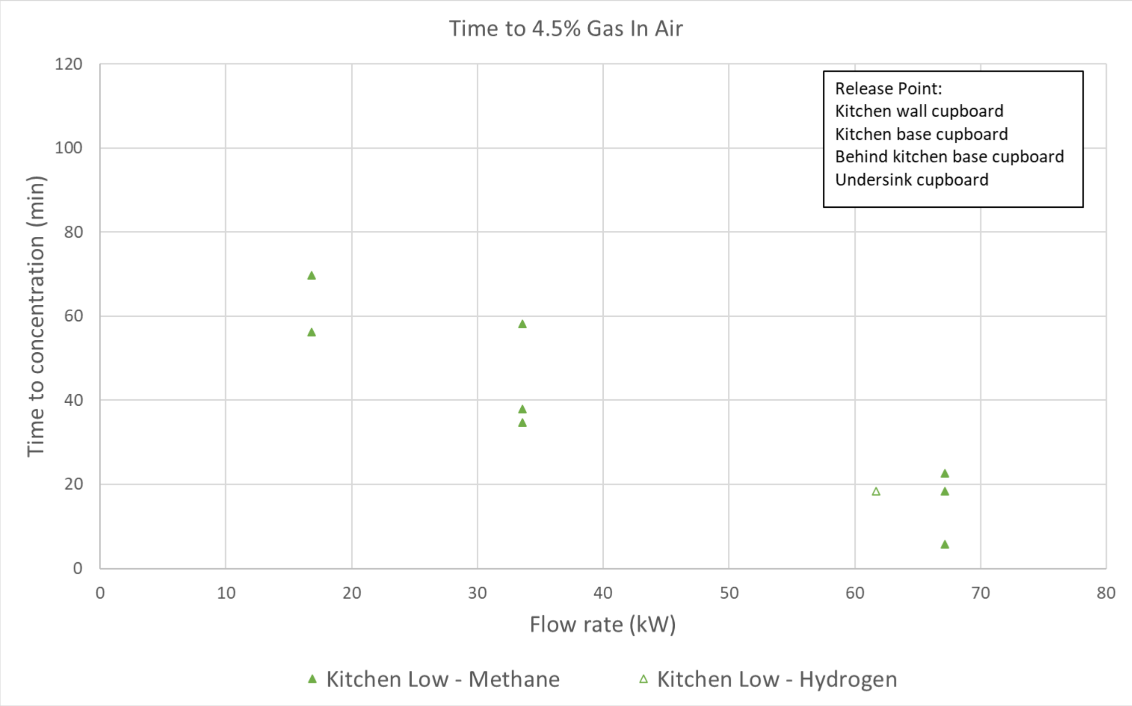


Figure 49 (a, b and c): time to concentrations at the mid-point of the kitchen

Figure 49 (a, b and c) show very similar trends to the high-level sampling point above. For low release rates (<15kW) there is a tendency for hydrogen to reach the target concentration marginally quicker than methane at the midpoint in the room. This is most pronounced at 8%, but care must be taken when considering the error margins present.

2.1.3. Kitchen low point



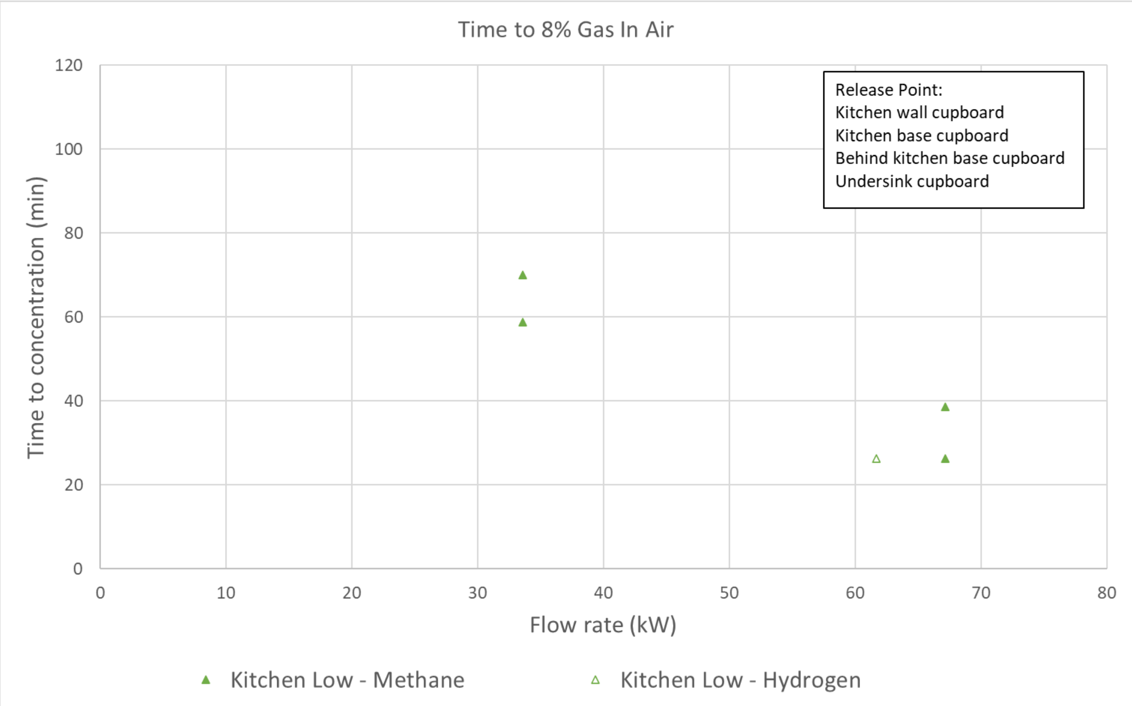


Figure 50 (a, b and c): time to concentrations at low-point of the kitchen

There is considerable spread in the results for the time take to reach 1% at the low point of the room shown in Figure 50(a) with no difference between gases.

Hydrogen never reached 4.5% or 8% GIA concentration at the low point in the room during the test work apart from at the highest level of injection (>61 kW), as may be expected from its buoyancy properties.

3. Findings and conclusions

The following findings have been identified:

- Both gases reach 1% GIA at the top of the room quickly (under 20 minutes for most release rates). Hydrogen may accumulate slightly more quickly at the top of the kitchen than methane, for medium and low release rates, however this difference is well below an order of magnitude.
- Larger rates of gas release result in shorter times to reach target concentrations for both gases.
- For all release rates and for both gases, the kitchen high sampling point was the first to record the target concentrations, i.e. the top of the room reached the target concentrations quicker than the rest of the space.
- For gas escapes below 70 kW:
  - The location of the lower injection points (i.e. into which low cupboard the gas was injected) had limited impact on the time to target concentrations at the high sampling point (kitchen high) when considering tests of the same escape rate. For example, all tests at ~15 kW showed the top of the kitchen had reached 4.5% within ~30 minutes from the start of the test.
  - Injections into the wall cupboard (high injection point) resulted in the top sampling point in the kitchen consistently reaching the target concentration quicker than the same sampling point during low location injections.
  - Time to target concentrations for hydrogen at the mid-point was notably slower for the wall cupboard injections than for the low-level tests. This was not observed to such an extent for methane. This and the previous point support the findings of the existing dispersion reports.
  - Hydrogen was rarely detected at 4.5% or 8% at the low sample point, apart from during the highest release rates (>60 kW). Methane was detected more often at the low sampling point at all concentrations.
- During the hydrogen boiler cupboard releases, 8% GIA was reached at the top of the space within ~10 minutes of the gas injection starting, for all release rates.

For a gas escape of 5 kW or above, 1% GIA was reached at the top of the kitchen within 20 minutes from the start of gas release, with many tests of larger leak rates suggesting 1% is reached almost immediately and certainly within 10 minutes of the gas escape occurring. This applies to both hydrogen and methane. For releases above ~10 kW, 4.5% was easily reached within 40 minutes for both gases (reducing to less than 20 for the large release rates). A similar result was observed for 8% GIA concentrations for injection rates above ~30 kW; however, this time increased for lower injection rates.

As discussed in supporting Hy4Heat WP7 reports [17] [38] larger gas escapes tend to be the result of accidental damage, such as caused by builders or DIY incidents. As such, the times shown in this document are within the reasonable reaction time of people present at the event (e.g. for a person to turn off the ECV, open a window etc.).

Within the limitations of the data, the above analysis has shown there is a tendency for hydrogen to accumulate slightly quicker than methane at the top and mid points in the room during small to medium gas escapes. However, during the initial stages of an escape of this magnitude, the different characteristics of ignitions of hydrogen and methane at the considered concentrations (e.g. 4.5 or 8%) mean there should be no material increase in risk (see section).

The data suggests that behaviour in the event of a gas leak should remain consistent with that of natural gas today. For example, if a gas is detected through an odour, then the gas supply should be isolated (if possible), windows opened, and the property vacated.

4. References

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[2] DNV GL, "Hy4Heat WP7 Lot2 Cupboard level leakage and accumulation data report," Hy4Heat, 2020.

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[4] I. Summerfield, J. Thomas and M. Crowther, "Investigation of the impact of ignition of hydrogen and natural gas accumulations in spaces in dwellings," Kiwa, 2018.

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