Energy Storage Component Research & Feasibility

Study Scheme

HyHouse

Safety Issues Surrounding Hydrogen as an Energy Storage Vector

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HyHouse - 30233

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1 Key Project Achievements and Outcomes

The work undertaken throughout this project has successfully demonstrated the potential of hydrogen as a fuel source as a safe replacement for natural gas. Hydrogen is an environmentally benign fuel in that it produces no carbon dioxide emissions when combusted. As a result, replacing natural gas (essentially methane) with hydrogen could provide a low carbon option for heating and hot water in our homes and businesses; as well as providing a more environmentally friendly way of operating motor vehicles and fuelling industry. This project has been extremely useful in demonstrating to the gas industry that hydrogen does not inherently offer risks over and above other flammable gases, for example Natural Gas, LPG or Town Gas; all flammable gases need appropriate engineering.

1.1 Premise

Before a widespread roll-out of hydrogen is possible, the risks associated with a small low pressure leak, as sometimes occurs in a domestic environment, must be understood to remove the general fear that hydrogen is significantly more dangerous as a fuel than the natural gas currently used. The project consisted of a series of low rate gas leak simulations by which 5 test gases were injected into a property at rates between 8 and 64kW and the concentrations and distribution of those gases throughout the house was measured. This was complimented by several high rate releases to simulate a leaking hydrogen vehicle or gas main, using 100% hydrogen and 100% natural gas, at injection rates of 200kW. The following test gases were used:

- 100% Natural Gas
- 100% Hydrogen
- 3% v/v Hydrogen (97% NG)
- 10% v/v Hydrogen (90% NG)
- Town gas (50% Hydrogen, 25% CO_2 and 25% natural gas)

Overall 122 tests were completed; 112 low rate releases up to 64kW and 10 high rate releases at 200kW. These were carried out in the property (a two storey farmhouse) at three levels of air tightness to simulate different ages of construction up to Energy Saving Trust (EST) best practice of ~3m^3/h/m^2 (at 50Pa air pressure). The simulations were carried out at various locations to represent a range of leaks in the living room, kitchen and cupboard under the stairs.

The calorific value of hydrogen is only about 1/3rd of natural gas (~3.25kWh/Nm^3 compared to ~10.8kWh/Nm^3), but as the density is only about 1/8th, (~0.083kg/Nm^3 compared to 0.7kg/Nm^3) the leakage from the same orifice (perhaps in a defective pipe) expressed as kW are broadly similar. This phenomenon (well known in the gas industry) is expressed numerically via the Wobbe Index (WI) and the WI for hydrogen at 45 is only slightly less that of natural gas of about 51.

1.2 Low rate Simulations

At all gas injection rates (8 to 64kW) and all levels of air tightness, stratification of the flammable gas was observed in the downstairs rooms from low concentrations at floor height to higher concentrations at ceiling height. Stratification did not occur upstairs, where gas concentrations at lower, middle and upper sample points were similar to those observed at ceiling height in the room below. Concentrations observed at the lower and middle sample points downstairs were often at or only just above background conditions.

Upstairs equilibrium concentrations of both hydrogen and natural gas at 64kW injection and at three different levels of house sealing are reported in the table below. It can be seen that the hydrogen concentrations are very much less than expected by simple ratio of injection volume.

Table 1: Hydrogen to natural gas ratio

Gas	% gas property as found (phase 1)	% gas after 1st seal (phase 2)	% gas after 2nd seal (phase 3)
Hydrogen (H_2)	4.3%	7.1%	8.7%
Methane (NG)	3.2%	5.5%	5.5%
Ratio H_2/NG (v/v)	136%	129%	158%
Ratio of inputs (v/v)	340%		
Ratio predicted by density theory (v/v)	173%		

The most significant mechanism within the property was the chimney effect by which the lower density of the injected gas caused it to rise. Although (as said above) approximately three times the volume of hydrogen is required when compared to natural gas to carry the same energy content, the concentrations reached within the property were not three times as high for hydrogen. This is because of the buoyant nature and high diffusivity of hydrogen. Certainly at higher levels of air permeability; when the property was less air tight and thus more ‘leaky’, the injected gas dispersed rapidly after gas injection stopped without additional ventilation (e.g. no air moving equipment was required).

It is also particularly important to note the concentration of the two flammable gases relative to their stoichiometric mixture i.e. the perfect gas concentration for total combustion and their lower (LFL) and upper (UFL) flammability limits.

Table 2: Flammability Limits

	LFL %		UFL %	% stoichiometric
Hydrogen	Ignited upwards	4	75	30
	Ignited horizontally	6		
	Ignited downwards	9		
Natural Gas	4.4		15 to 17	10
Propane	2.1		9 to 10	4

The collected data shows that a 64kW leak (~6.4Nm^3/h of natural gas or 20Nm^3/h of hydrogen) results in flammable concentrations of both natural gas and hydrogen. Concentrations of natural gas (methane) are over half stoichiometric concentration, however in comparison, hydrogen was only a third of stoichiometric conditions. Although both gases are at flammable concentrations, if ignited, it is likely that the methane would result in greater damage.

The situation in the cupboard is somewhat different in that gas concentrations were much higher than those observed in the rest of the property and in some instances exceeded the upper flammable limit for methane but were within the flammability range of hydrogen. However, due to its lower CV the actual energy content of the volume of gas available in this space was modest; 2.2kWh in a 1m^3 cupboard at 20%, and so damage done to the whole of the property in the event of an ignition would likely be manageable. It is theoretically possible that the concentration within the cupboard could be high enough to cause local detonation, but realistically the door is likely to fly open (and/or off its hinges) and so offer even less resistance to a hydrogen flame front than a window and provide immediate and effective pressure relief into a low hydrogen concentration area, thereby mitigating the fire. Nonetheless this would be an interesting area for further study.

The following statement has been offered in light of the results from this study:

The trials indicate that in the house as a whole, the risks of a significant fire and explosion and the subsequent impact on the health of a householder following a significant leak (<64kW) of either hydrogen, natural gas or a natural gas and hydrogen mixture are similar.

In confined spaces it is possible to envisage gas concentrations which lie above the UFL of natural gas but are still highly flammable for hydrogen. Fortunately the energy content of these small spaces is inherently low but the matter still needs investigation.

1.3 High Rate Simulations

When considering a leak from a hydrogen car, (with a hydrogen tank of ~70l at 700bar), the test work showed that if the hydrogen leaked into a relatively confined space (e.g. a garage with adjoining doors to the property closed), then hydrogen concentrations within the garage can be significant. Concentrations within the rest of the property were comparable to those experienced during the low rate experiments.

Stratification of the gas appears to be strong and thus additional ventilation in the roof space would likely reduce the risk associated with a gas leak. Similarly, gas detection interlocked with the power supply to switch off appliances that may be within the space (e.g. a fridge freezer) could mitigate the source of ignition if a leak were to occur.

The leaking gas main tests resulted in surprisingly low gas concentrations detected within the test property. More specifically, gas was only evident upstairs. It is hypothesised that this is as a result of the gas moving within the internal wall spaces instead of through the floor downstairs which was covered in a heavy carpet. It is also suggested that as the pipe into which the gas was injected was perforated, the majority of the gas escaped through the soil external to the property and thus concentrations within the house were limited.

Overall, the collected data has enabled the following aspects to be considered in terms of mitigating the risk associated with future use of hydrogen within domestic properties:

- The requirement for gas alarms which may or may not be interlocked with automatic gas shut-off and ventilation
- Use of automatic excess flow shut-off valves to detect significant gas leaks and disconnect the supply
- Increased ventilation mitigating the risk from a leak
- Definitive marking of location of buried/hidden gas pipes
- Enhanced odourisation to lower detection thresholds

2 Summary of Funding and Timescales

The project was funded through the Energy Storage Component Research and Feasibility Study Scheme. Funding was received from DECC, internally from Kiwa, Scottish and Southern Energy (SSE) and multiple interested parties including, Air Liquide, IGEM, AMEC, BCGA, SGN and National Grid.

Originally the project was due to commence in September 2013 and be completed by the end of December 2014. However, due to technical issues with the analysers which required parts to be returned to the USA for repair, a three month extension was provided for the test programme to the end of March 2015.

3 Summary of Project Issues

One of the most important aspects of the project was the reliability and accuracy of the gas analysers. Although both analysers were fully calibrated at the beginning and end of every test, there was significant drift in the methane reading over the test period. This was also evident on the CO_2 sensor but to a lesser extent. This was corrected for during the data analysis process, therefore the data presented in this report is accurate, robust and comparable. However, it made on-site review of the data very difficult. The hydrogen sensor was less problematic; a small zero offset was corrected for in the data processing procedure.

The hydrogen sensor in analyser A developed a fault at the end of phase 1 and had to be returned to the manufacturer for repair. This resulted in the sensor having to be sent to the USA and the test work had to be suspended until the faulty sensor was returned. This resulted in a 3 month delay in the testing schedule.

Whilst waiting for the hydrogen sensor to be returned, the test house was broken into and doors and windows damaged. Although the gas injection equipment was untouched there was structural damage to the property in the form of broken doors and windows. The house was repaired and pressure tested before phase 2 and before the test work continued.

A further difficulty was the remote nature of the property. Although this was beneficial in terms of ensuring the potential for damage to external properties was minimised, it did lead to access difficulties in poor weather conditions throughout the winter months. The significant travelling required to attend site also meant careful planning was required to maintain personnel on site to complete the testing schedule as well as ensuring working hours were kept reasonable. There were also safety aspects to consider with remote working including numbers of staff on site, first aid training and emergency procedures. These were all carefully considered (including structured risk assessments) and appropriate measures were put in place to ensure staff safety.

4 Dissemination

The results of this project have already been disseminated to a wide audience and have provided reassurance to members of the gas industry that the potential risks of distributing 100% hydrogen or low concentration mixtures of hydrogen and natural gas are no more significant than when distributing 100% natural gas. To date, the test work and findings have been disseminated at the following events:

- University College London – Now in discussions as to how to progress studies on the wider use of hydrogen in towns and as a fuel.

- IGEM - Now considering Hydrogen as ‘just another flammable gas’ and believe it should be part of the IGEM fuel portfolio.
- Network Innovation Conference 2014 (Aberdeen) - Considerable interest from all of the gas utilities regarding the safety aspects of Hydrogen:
    - Wales & West
    - Scotia Gas Networks
    - Northern Gas networks
    - National Grid Transmission
    - National Grid Distribution
- Northern Gas Networks – NGN have placed a contract with Kiwa Gastec to investigate all aspects of the possible conversion of Leeds to 100% hydrogen. The so-called Leeds21 project.
- Presentation to the Yorkshire branch of IGEM
- Presentation to the HHIC conference on future gas quality

5 Proposals for Next Steps

This project has provided a real insight into the risks associated with hydrogen as a fuel gas, demonstrating that although concentrations of hydrogen from a leak are higher than methane; the characteristics of the gases within a standard domestic setting are remarkably similar and the risk is no greater when considering a leak of hydrogen compared to natural gas. This work has shown ways of mitigating risks associated with hydrogen and also how potentially dangerous situations can be avoided.

A potential follow on from this work, now that the likely concentrations of each test gas is understood, is to investigate the impact/damage capacity of explosions of these concentrations within an enclosed space, as may be experienced in a domestic setting. The same fuel gases would be used as in the HyHouse project (100% natural gas, 100% hydrogen, 10% hydrogen, 3% hydrogen and town gas) allowing direct cross correlation between the studies.

Another possible avenue for further work is the need for odourisation of hydrogen if it were used as a fuel gas. Due to the large volume changes induced by hydrogen, it is foreseeable that hydrogen leaks will be much more readily detected by smell (similar to natural gas).

When considering hydrogen vehicles, there is significant scope to carry out further work on safety aspects of filling stations (garage forecourts). This has already been noted by industry members following the HyHouse project, and discussions are in place to formulate a work programme to investigate the concentrations of hydrogen which could occur in the event of a hydrogen leak from a dispenser on a forecourt. As with the HyHouse work, the results would be made publically available and will influence safety regulations surrounding forecourt environments, hydrogen dispensing methods and garage construction/alteration to accommodate hydrogen filling dispensers.

In addition, to aid the deployment of hydrogen into the market it is suggested that work could be carried out to test the types of fittings used within a hydrogen system. The results would be made public and would offer information on the safety aspects of different types of joint for use in DSEAR (Dangerous Substances and Explosive Atmospheres Regulations) and ATEX (controlling explosive atmospheres) calculations.

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Summary Technical Report

1 Introduction and Background

In recent years it has become popular to think of electricity as the sole green energy vector of the future, with significant automotive and heating advancements using electricity as their fuel source. Although this combats the 'at point of use' emissions of carbon dioxide and other polluting substances, particularly when considering vehicle emissions, it does not resolve the significant emissions and inefficient operation of central power generation, operating on a supply and demand basis.

Electricity accounts for approximately 18% of the UK final energy consumption[1], but it cannot be easily stored and thus successful management and supply is highly complex. Over recent years the increasing use of renewable sources has added to this complexity because renewable sources, particularly wind energy, are often unpredictable and sporadic, making successful integration into the existing grid network very difficult. Renewable generation increased to 15% in 2013 from 11% in 2012[1]; mainly as a result of increased on and off shore wind capacity and solar photovoltaics. Unfortunately however, as is becoming increasingly publicised, wind farms are effectively being 'turned off' at times of high output, as the electricity grid is unable to effectively utilise the additional capacity from wind generation. This is hugely undesirable and costly but ultimately very difficult to overcome as the grid must be controlled so that demand is always satisfied.

In addition, it has become apparent over recent years that the vast quantities of natural gas used for domestic and commercial seasonal heating, as well as by UK industry, cannot be easily replaced on grounds of cost and engineering practicality. Gas accounted for approximately 32% of the final fuel used by consumers in the UK in 2013, with utilisation within power generation, industry, and commercial and domestic properties. Of the approximate 851TWh demand, about 40% was used within the domestic sector;[2] primarily for space and water heating.

In the UK's drive towards decarbonising its energy infrastructure, it is increasingly accepted that there is probably no single, simple solution. One of the key issues is energy storage; rising levels of renewable generation stock will increasingly be curtailed by periods of high production and low demand. If the "renewable" electricity generated during these periods could be effectively stored and then used when required, this would represent a major step forward.

A possible solution to the above difficulties is the utilisation of hydrogen within the existing energy infrastructure. Hydrogen is increasingly expected to play a key role in delivering low

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[1] Digest of United Kingdom Energy Statistics 2014, Department of Energy and Climate Change, A National Statistics Publication; 2014.

[2] Digest of United Kingdom Energy Statistics 2014, Department of Energy and Climate Change, A National Statistics Publication; 2014.

cost green energy, due to its ability to be generated, stored and consumed within different time frames. In its simplest form this involves replacing natural gas with hydrogen in the existing low pressure natural gas infrastructure.

As hydrogen can be stored, there is full separation of generation and use/demand. It can be generated from renewable energies as and when these are available, or from Steam Methane Reformation with carbon capture, and can be stored underground or in steel spheres at modest cost. It can also be easily transported and once produced can be used in a number of ways, coupling established technologies with low environmental impact at point of use. The hydrogen economy has long been discussed as a clean energy ideal. Furthermore it has the potential to be rolled out incrementally, in parallel with and complementary to, other low carbon energy initiatives. It is suggested that hydrogen could be generated (using electrolysis) from renewable electricity e.g. wind turbines, and then used in a variety of complementary ways – for example:

- Mixed with methane and injected into the current natural gas distribution network at low or high percentages
- Distributed in local gas networks as 100% hydrogen – effectively replacing natural gas
- Compressed and bottled or stored, for resale for a variety of uses such as transport

1.1 Hydrogen

Hydrogen gas is a colourless, odourless gas with a density of 0.085kg/m^3 (at 1 Bar and 15°C) making it the lightest of all elements. Its low density means the gas is highly diffusive and buoyant and mixes rapidly with air when released[3]. Diffusion rates of hydrogen in air are influenced by atmospheric turbulence and space constraints and are approximately 4 times greater than air in air. In many ways this buoyancy is favourable, with any hydrogen leaks dispersing without difficulties, particularly when considering gas escape into a 'leaky' building; e.g. an aged dwelling. However, the rapid mixing and rising of hydrogen with air also creates flammable mixtures very quickly as the flammability range of hydrogen is wide at 4 to 75% concentration in air. As will be explained below, the concept of 'flammability' is much more complex than for natural gas and especially at low concentrations only half the hydrogen present may be consumed. Pure hydrogen oxygen flames are almost invisible to the naked eye and this means detection of burning hydrogen can be difficult.

The flammability range is the range of concentrations at which a gas will burn if an ignition source is introduced. Every flammable gas has a lower and upper limit of flammability beyond which the gas is either too lean or too rich to burn (there is too little or too much fuel compared to available air). For natural gas comprised mainly of methane, this range is between 5 and 15% concentration, with stoichiometric conditions at approximately 10%. For hydrogen the flammability range is much more complex (as discussed below) with

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[3] www.hysafe.org/downloads/997/brhs_ch1_fundamentals-version1_0_1.pdf.

stoichiometric conditions at approximately 30%. Stoichiometric conditions are the perfect theoretical mixture for complete combustion, where all fuel is converted to useful energy.

For natural gas, if an ignition source is introduced to a gas concentration at 5% or above (until approximately 15%) the gas will ignite (the lower flammability limit (LFL) for natural gas is 5%). However, unlike natural gas, the lower flammability limit (LFL) of hydrogen is complex with different flame characteristics at different concentrations.

- At approximately 4% concentration hydrogen combustion will produce only an upward flame
- At approximately 6% a horizontal flame will also be produced
- A downward flame is then introduced at approximately 9% concentration

However, although hydrogen deflagration is possible at low concentrations as discussed above, it is unlikely that detonation would occur with concentration below 18% and then detonation is only likely with a commercial detonator. It is between approximately 20 and 40% (near stoichiometric conditions) that there is a significant risk of explosion as the ignition energy required at these concentrations is very low compared to natural gas. This is discussed in further detail later in the report.

Hydrogen is an environmentally benign energy source; it contains no carbon and therefore does not produce carbon dioxide or carbon monoxide when burnt; in fact the only by-product of combustion of hydrogen is water. Currently the largest cause of death and ill health associated with the gas industry is carbon monoxide poisoning. In this context hydrogen reduces the risk of fatalities from faulty appliances.

Hydrogen has a lower calorific value than natural gas at approximately 12MJ/m^3 compared to approximately 39MJ/m^3 for natural gas (comprised primarily of methane). This means that to provide the same amount of energy, or the required amount of energy to an appliance, a greater volume of hydrogen is required in comparison to natural gas (approximately three times as much). It was hypothesised that the significantly increased volume of hydrogen required for the same energy input would result in much higher (potentially 3x) concentrations of hydrogen being reached within the property during a leak. However, as a result of the much lower density of hydrogen it was also hypothesised that dispersion would be quicker and thus the dangers of hydrogen may not be as significant as possibly predicted.

Hydrogen can be generated by Steam Methane Reforming (SMR) from Natural Gas with Carbon Capture and Storage (CCS), or by electrolysis with low carbon electricity such as wind, amongst other methods. It also has multiple end uses in conventional applications. This means it is flexible in its application and therefore capable of providing an energy storage solution with significant capacity.

2 Project Objectives and Methodology

Demonstrating the safety of hydrogen is clearly a prerequisite for progressing with the widespread use of hydrogen in homes and transport. This project builds on a number of studies in which hydrogen, and methane and hydrogen mixtures, have been injected into enclosures. The outcomes from this project aim to advance knowledge on hydrogen safety, with the results placed in the public domain. Of particular relevance is investigation of the implications of small or modest leaks (2 to 64kW) that do occur occasionally within a domestic setting and to investigate whether these leaks are more or less hazardous with natural gas, hydrogen, or a hydrogen methane mixture. Also of interest is the result of larger scale leaks (~200kW) as would be experienced if a hydrogen vehicle was to fail or a gas supply main (external to the property) were to leak.

A series of gas leaks have been simulated within a property at three levels of air tightness to simulate different ages of construction, from aged, to new build meeting the Energy Saving Trust (EST) best practice air tightness figure of $3m^3/h/m^2$ (or as close to this as possible). The simulations were carried out at various locations within the building to represent a range of appliances such as a boiler, cooker or gas fire. The leak rates were selected to be representative of those likely within a domestic setting up to 64kW, as it is expected that flow limiters will be present if hydrogen were to be utilised as a fuel gas.

The movement and dispersion of the gases around the property have been investigated, as well as the concentrations achieved at varying leak rates and air tightness rates. The collected data has also enabled the following aspects to be considered in terms of mitigating the risk associated with future use of hydrogen within the gas industry:

- Use of automatic excess flow shut-off valves to detect significant gas leaks and disconnect the supply
- The requirement for gas alarms which may or may not be interlocked with automatic gas shut-off and ventilation
- Increased ventilation mitigating the risk from a leak
- Definitive marking of location of buried/hidden gas pipes
- Enhanced odourisation to lower detection thresholds

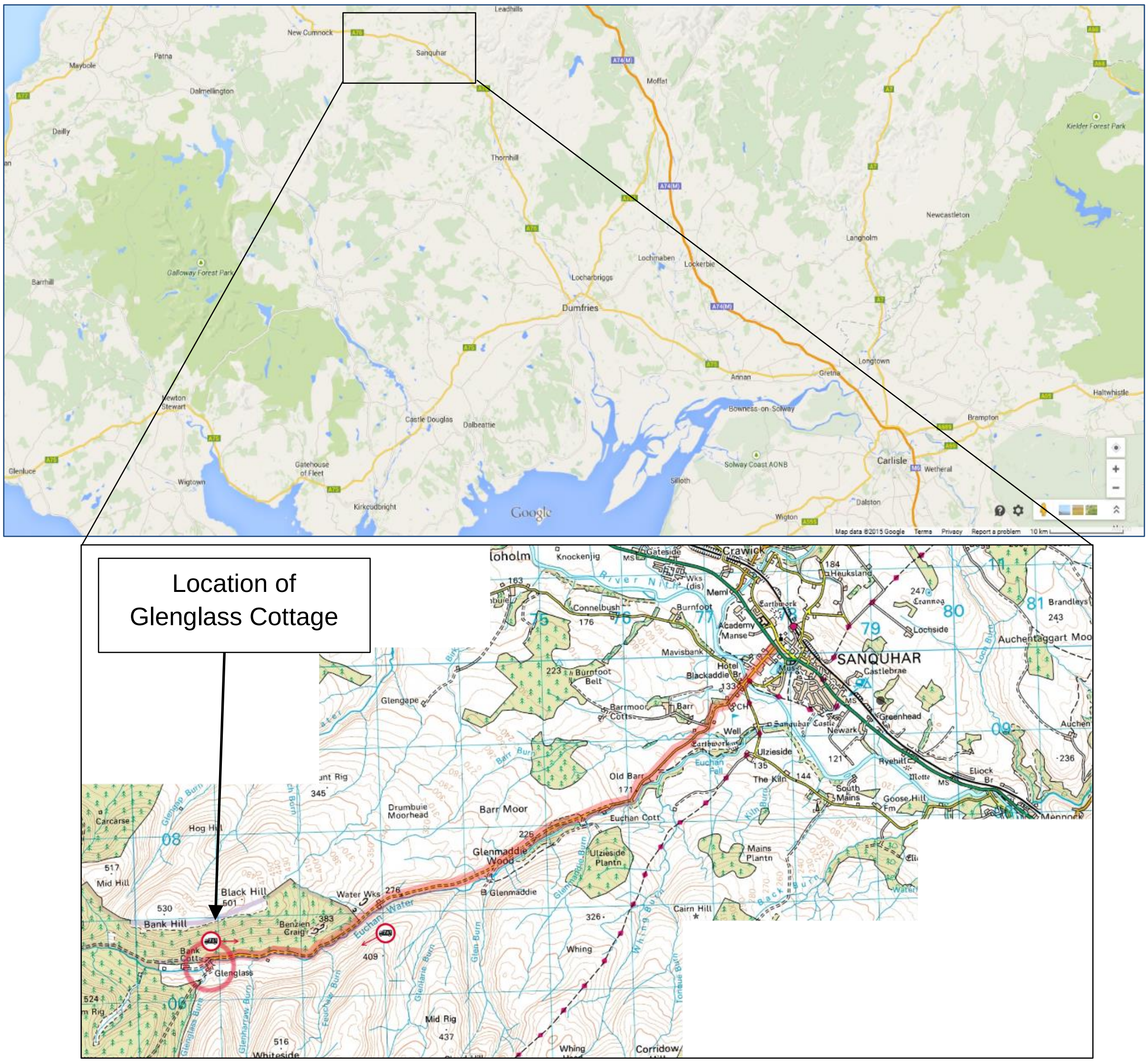
The project has been supported by a number of industry bodies and all aspects of the project methodology have been discussed and reviewed by a steering committee including the following bodies:

- AMEC
- Scotia Gas Networks (SGN)
- Scottish and Southern Energy (SSE)
- Atkins (technical advisor to DECC)
- National Grid
- Air Liquide
- British Compressed Gases Association (BCGA)

- Health and Safety Executive (HSE)
- Institute of Gas Engineers & Managers (IGEM)
- UK Fuel Cell Association (UKFCHA)

2.1 Test Site

The test work was carried out at Glenglass Cottage; a remote property in the Dumfries and Galloway region of Scotland, near the town of Sanquhar.



Location of Glenglass Cottage

Figure 1: Location map of test site[4]

The property was approximately 330m above sea level[5] with one neighbouring dwelling approximately 270m away. The building was a rendered solid stone structure with slate tile roof. Internally the walls were plaster board and skimmed with finishing plaster. It is thought that the original property was constructed with suspended wooden floors and single glazing,

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[4] https://www.google.co.uk/maps

[5] Ordnance Survey Explorer Map 328, Sanquhar & New Cumnock, Muirkirk & Moniaive, 2006

as is now evident in the living room and dining room on the ground floor. Evidence suggests that the property was then extended to encompass a kitchen and bathroom with solid concrete floors, and two bedrooms within the roof space. There was also a lean-to on the rear of the kitchen, again with solid concrete floors and single glazing.


Cottage Location
Front Elevation
Side Elevation
Rear Elevation
Lean-to

Figure 2: Glenglass Cottage

Access to the property was via a long single track road which, although this caused some difficulties in adverse weather conditions, did add to the isolation and thus suitability of the property for the required test work.

2.2 Test Methodology

The project aim was to assess the risk associated with an accidental leak from 5 fuel gas mixtures which may be experienced in a domestic setting through DIY accidents or faulty appliances.

The gas leaks were simulated using 5 test gases. These were injected at known flow rates into the property at 3 locations; kitchen, living room and under stairs cupboard. Samples of the air within the property were taken from 5 rooms at low, medium and high height and the concentration of gas within the air analysed using gas analysers. The test gases were as follows:

- 100% Natural Gas
- 100% Hydrogen
- 3% v/v Hydrogen (97% NG)
- 10% v/v Hydrogen (90% NG)
- Town gas (50% Hydrogen, 25% CO_2 and 25% natural gas)

Clearly it was important to understand the characteristics of the gas currently used in the gas distribution system, therefore the reference gas was compressed natural gas. This is largely methane but also contains other hydrocarbons (butane, propane, ethane), non-combustibles (nitrogen, helium, CO_2 water) and sulphurous compounds. For comparison 100% hydrogen was used to carry out analysis of complete gas replacement within the national grid.

It was also considered important to test natural gas/hydrogen mixtures as industry bodies have suggested injecting small amounts of hydrogen to natural gas would be a feasible alternative to 100% replacement. In Germany the natural gas network has been successfully substituted with 2% hydrogen in certain areas which has been achieved without significant changes to appliances or the distribution network[6]. This process has been further extended during the initial months of 2015 with additional power to gas capacity being installed by RWE Deutschland in Ibbenburen[7] expected to go into operation in the first half of 2015.

Similarly it was considered interesting to trial Town Gas, which was the main fuel gas until the 1960's when offshore natural gas reserves began to be significantly exploited[8]. Town Gas was originally made by distillation of coal and contained typically 50 to 65% hydrogen, 20-30% methane and the balance carbon monoxide and carbon dioxide. Because Town Gas contained carbon monoxide (CO) the overall death rate associated with its use was high and exaggerated by suicide; but the risk of fire and explosion was acceptable and is currently good in the Far East. To reduce the risk in these experiments the carbon monoxide was replaced by carbon dioxide which is far less dangerous to human health but has broadly similar characteristics.

The test work consisted of three phases equating to the three different levels of air tightness. At each condition the low rate, domestic leak simulations were carried out using a range of kW inputs from 8 to 64kW; these equate to gas flow rates of 39.5 to 316l/minute of hydrogen and 12.6 to 101l/minute of natural gas. The gas injection was carried out for 2 hours during phase 1 and 2.5 hours during phases 2 and 3. The longer injection was carried out after feedback from the steering committee after phase 1 that although the

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[6] http://www.itm-power.com/news-item/injection-of-hydrogen-into-the-german-gas-distribution-grid

[7] http://www.itm-power.com/news-item/rwe-power-to-gas-system-delivered

[8] http://en.wikipedia.org/wiki/Coal_gas

hydrogen concentrations were seen to reach a plateau , the natural gas levels were indicating that peak concentrations had not been reached. The longer injection times were thus used as a compromise between trying to achieve the peak achievable concentrations and using a financially viable quantity of gas within the time constraints of the project.

During the second phase of test work, additional high rate releases were carried out to simulate a leak from a vehicle or from an external leaking gas main. The vehicle simulations were carried out using 100% hydrogen as would be used in a hydrogen car/van/minibus etc. The leaking main experiments were carried out using 100% hydrogen and 100% Natural Gas, e.g. comparing the current situation with future scenarios. These tests consisted of much higher kW injections with gas flow rates of 1000l/minute of hydrogen and 300l/minute of natural gas, but were much shorter in duration with injection times of 48 minutes and 60 minutes for the vehicle and gas main respectively.

2.2.1 Test Cabin & Equipment

The property was acquired by SSE, a partner in the project, and works took place to develop the test site during the spring/summer of 2014. A test cabin was erected 50m from the property which housed the test engineers and sampling equipment. The cabin was protected by a row of meter square sandbags to act as a blast shield in case of an accident and the cabin was tethered to the ground using 8mm wire rope and helical ground anchors. Alongside the test cabin a venting stack, span and zero gas cage and rig enclosure were erected.

Figure 3: Test Site

Three rigs were constructed in and around the cabin consisting of test gas injection, sampling and exhaust gas rigs. The test gases and the injection rig were located externally to the cabin; the injection rotameters were connected to the test gas packs and were used to control the flow rate and mixture of the test gases injected into the property.

Figure 4: Test gas injection rig

Within the cabin, the sampling panel measured the flow rates taken from the individual rooms within the property. This ensured all sample points were operating as expected and could identify leaks or blockages if they were to occur. The sample points from this panel were then connected to the exhaust gas rig through which each pipe was connected to a solenoid valve controlled by a computer programme. These valves operated in turn to sample the required points from the house throughout the test period (discussed in further detail below).

Figure 5: Internal rigs

From the cabin, a trench was dug to the property into which the test gas supply pipe and the 15 sampling lines were buried. The test gases were delivered to the property in a 32mm plastic gas pipe before changing to 28mm copper pipework for distribution throughout the house. The copper pipe was earthed to ensure no static electricity was present from the gas transfer through the plastic pipe.

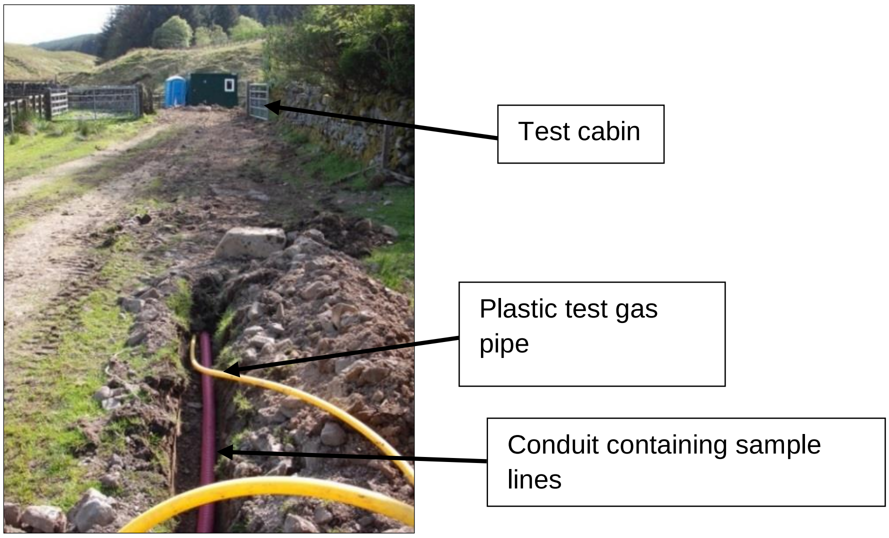

Figure 6: Pipe trench containing test gas delivery pipe and sample lines

The gas injection pipe and sample lines entered the property through the wall adjacent to the front door. From here the copper gas pipe ran into the kitchen, living room and under stairs cupboard where a manual ball valve in each room controlled the release of gas as shown on the plan below.

Figure 7: House plan showing injection locations

The 15 sample lines were distributed throughout the house and positioned at low (~30cm from the floor), middle and high (~30cm below ceiling) height in the following rooms; each sample point contained flash back protection:

- Kitchen
- Living room
- Dining Room (was originally a downstairs bedroom when the property was occupied but named Dining Room for ease of identification)
- Bedroom 1
- Bedroom 2

The following images show the gas injection and sample points:


Kitchen
Hallway (under stairs)
Lounge

Figure 8: Gas injection points

Figure 9: Room sample points

Before test work could take place in the property, all sources of ignition had to be removed. Therefore the electricity and telephone supply to the house were disconnected and the electricity was re-routed from the transmission pole to the test cabin. The property windows were also coated in blast-proof film. The equipment was commissioned using low rate injections of CO_2 before test work took place.

2.2.2 Test Procedures – Low Rate Release

The test work followed set procedures and strict safety precautions. Personal gas alarms were issued to onsite personnel and no electronic equipment was permitted within or near the property whilst test work was taking place.

The house was set up before each test to ensure consistent conditions. The internal doors were open and set in position using door wedges and markers. All windows and the door between the lean-to and kitchen was closed. The sample points were checked and the gas injection valve set depending on the test taking place. The front and back door of the property were locked and the surrounding area was checked for people and livestock before the test engineers took position in the test cabin. The property was surrounded by warning signs and ‘danger’ tape and the access road blocked by a gate and further warning signs.

Gas was injected into the property at set rates as per the table below.

Table 3: Gas injection rates

Gas Leakage Rate (kW)				**8**	**16**	**32**	**64**
Gas Injection Rate	CH_4	CO_2	H_2	(l/min)	(l/min)	(l/min)	(l/min)
Gas Composition 1				12.6	25.3	50.6	101.2
100% Natural Gas	100			12.6	25.3	50.6	101.2
		0					
			0				
Gas Composition 2				12.9	25.8	51.6	103.3
3% Hydrogen / 97% Natural Gas	97			12.5	25.0	50.1	100.2
		0					
			3	0.4	0.8	1.5	3.1
Gas Composition 3				13.6	27.1	54.3	108.5
10% Hydrogen / 90% Natural Gas	90			12.2	24.4	48.8	97.7
		0					
			10	1.4	2.7	5.4	10.9
Gas Composition 4				30.9	61.7	123.4	246.9
50% Hydrogen / 25% Natural Gas /	25			7.7	15.4	30.9	61.7
25% CO_2		25		7.7	15.4	30.9	61.7
			50	15.4	30.9	61.7	123.4
Gas Composition 5				39.5	79.0	157.9	315.8
100% Hydrogen	0						
		0					
			100	39.5	79.0	157.9	315.8

The original test work was going to include 2 and 4kW injection rates, however when these were trialled in the first stages of the experiment, no gas was detected in the property and therefore it was not considered beneficial to use this rate subsequently. 64kW injections were not carried out in the cupboard due to the confined nature of the area, however, 32kW injections were completed in the cupboard space.

To allow comparison to current ATEX and DSEAR documentation the leakage rates have been compared to an approximate hole size when considering gas delivery of 20mbar. These are shown in the table below. Note that the hole size for hydrogen and natural gas are very similar.

Further explanation regarding the method used to calculate the hole size can be found in section 7.

Table 4: Leak rates and equivalent hole size

Energy (kW)	Gas Mixture	Circular hole ϕ (mm)
8	100% Hydrogen	2.4
	100% Natural Gas	2.3
	3% Hydrogen	2.3
	10% Hydrogen	2.3
	Town Gas	3.5
16	100% Hydrogen	3.4
	100% Natural Gas	3.2
	3% Hydrogen	3.2
	10% Hydrogen	3.2
	Town Gas	5.0
32	100% Hydrogen	4.8
	100% Natural Gas	4.5
	3% Hydrogen	4.5
	10% Hydrogen	4.6
	Town Gas	7.1
64	100% Hydrogen	6.7
	100% Natural Gas	6.4
	3% Hydrogen	6.4
	10% Hydrogen	6.5
	Town Gas	10.0

The gas injection was controlled using two-stage regulators and flow rotameters and was carried out for up to 2.5 hours. Air from within the property was sampled through the 15 sample lines using a negative pressure principle created using two compressors connected to the venting stack at the cabin. These compressors were set to operate at 6 bar into the chimney and this caused a suction effect drawing air from the house and through the gas analysers within the cabin.

Figure 10: Compressors and vent stack

The sample lines entered 15 solenoid valves within the cabin which were controlled by a computer programme. The analysers were set to sample 9 points apart so when analyser A was reading sample point 1, analyser B was reading sample point 9. The programme cycled through each of the sample points, opening each one in turn so each sample point was monitored by both analysers. Sample 16 was air taken from within the test cabin to provide reference conditions.

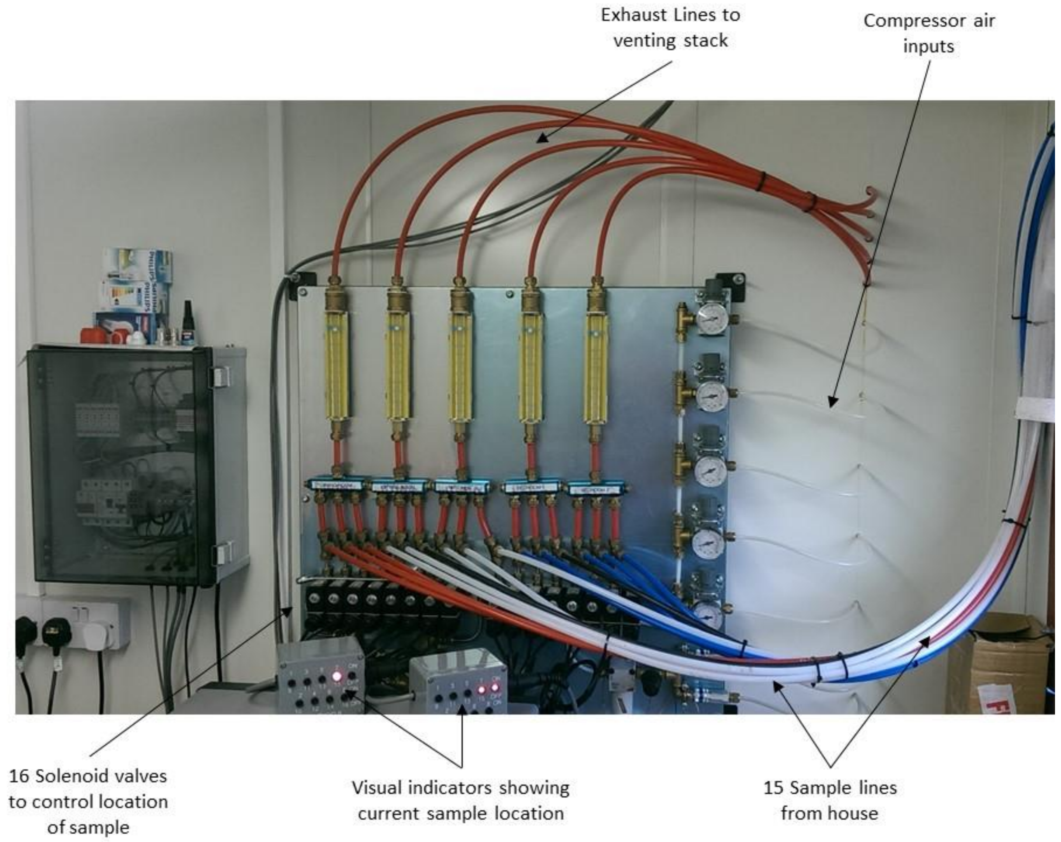

Figure 11: Control Solenoids

The sample interval was set so that the analysers could sample each point for long enough to reach a stable condition (approximately 1.5 minutes) before readings were taken and logged every 5 seconds for 30 seconds. Once the gas had passed through the analysers it was vented through the exhaust stack. Data logging started before gas injection began and continued until the house was fully vented to background conditions. Data from each sample point was logged and saved automatically.

Table 5: Sample Line References

Pipe Reference Number	Location
1	Dining Upper
2	Dining Middle
3	Dining Lower
4	Living Upper
5	Living Middle
6	Living Lower
7	Kitchen Upper
8	Kitchen Middle
9	Kitchen Lower
10	Bed 1 Upper
11	Bed 1 Middle
12	Bed 1 Lower
13	Bed 2 Upper
14	Bed 2 Middle
15	Bed 2 Lower
16	Cabin Air

At the end of the injection period gas flow into the property was stopped and monitoring continued for at least 30 minutes to allow the gas within the house to disperse, before the property was manually vented. Venting was carried out in two stages. First both the front and back doors, and two downstairs windows (in living room and dining room) were opened from the outside. Once levels within the downstairs of the property had reached less than 20% of the LEL, the upstairs Velux windows in Bedroom 2 and the stairwell were opened using pull cords from the base of the stairs. Once levels upstairs had decreased to less than 20%LEL the final window was opened manually in Bedroom 1. The house was then left to ventilate fully and monitored until background levels were observed before being set up for the next test.

The gas analysers were calibrated at the start and end of each test using zero and span gases. The zero gas was 100% nitrogen and the span gas consisted of 10% concentrations of methane, hydrogen and CO_2 (balance nitrogen). The zero and span drifts, which varied between each test, were logged and used for corrections through the data processing stage.

2.2.3 Air Tightness

The test work was carried out in three phases at three different levels of air tightness within the property. The first phase was ‘as built’ which equated to an air tightness of 9.85m^3/h/m^2. This is representative of a large proportion of the UK housing stock and complies with the minimum standards under 2010 building regulations of 10m^3/h/m^2. The test work was carried out in the property with no alterations except those required to remove sources of ignition and installation of the test apparatus.

On completion of Phase 1, the house was sealed using temporary sealing methods such as tape, plastic sheeting, decorators caulk, silicones and adhesives. The following list provides an example of the sealing measures carried out (not exhaustive):

- External floor vents boarded and sealed with sealant
- Wall to ceiling joint filled – all rooms
- Window frames filled – all rooms
- Chimneys in Dining Room, Living room and Bedroom 1 sealed using plastic sheeting
- Cupboard (containing chimney and hot water cylinder) in Bedroom 1 sealed using plastic sheeting
- Window vent in lean-to sealed
- External wall vent covered and sealed in Lean-to
- Any significant holes within the walls of all rooms were sealed

Figure 12: Examples of sealing measures after phase 1 and before phase 2

Another air tightness test was then carried out and the property achieved 6.64m^3/h/m^2. This was representative of new builds potentially aiming for a Code for Sustainable Homes Code 3 where a 25% improvement in Emission Rate is required compared to current building regulations[9]. Phase two test work then took place following the procedures detailed above. In addition to the low rate simulations, the high rate releases were also carried out during phase two. This is discussed in section 2.2.5 below.

Following the completion of Phase 2 a second set of sealing measures were carried out before the onset of Phase 3. These included:

- Covering the floor in Dining Room, Living Room and downstairs hallway in plastic sheets
- Covering downstairs windows with plastic sheets
- Sealing all plug sockets
- Sealing all skirting to wall joints

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[9] Code for Sustainable Homes, A step-change in sustainable home building practice, Communities and Local Government, December 2006.

Figure 13: Examples of sealing measures after phase 2 and before phase 3

A further air tightness test was carried out and the property achieved 3.46m^3/h/m^2. This is comparable to the EST best practice figures and may be representative of properties aiming to meet zero carbon homes or Code Levels 5 and 6 where air tightness is required to be 3m^3/h/m^2 or better[10]. A third set of gas injections were then carried out.

2.2.4 Low Rate Release Test Programme

At each air tightness 36 tests were required (although some stages had additional tests due to repeats being needed).

Phase 1 consisted of some lower injection rates than phases 2 and 3 as prior to this, it was unknown how the gases would disperse in the property and the concentrations which would be reached. It was found that releases under 8kW were almost undetectable, therefore it was decided that subsequent phases should consist of a greater number of higher release rates to be able to understand the characteristics of the gas once within the property. A single 8kW injection of each gas mix was carried out into the kitchen as a comparison across the phases to identify if greater air tightness meant concentrations within the property were higher at low levels of gas injection. The tests carried out are shown below:

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[10] A practical guide to building airtight dwellings, NHBC Foundation, June 2009.

Table 6: Gas releases in Phase 1 (kW and location)

Location	100% NG Inject for 2 hours	10% H; 90% NG Inject for 2 hours	3% H; 97% NG Inject for 2 hours	Town Gas (50%H; 25% NG; 25%CO_2) Inject for 2 hours	100% H Inject for 2 hours
Kitchen	2, 8, 16, 32, 64				
Living room	8, 64				
Under stairs	8, 16, 32				
Kitchen		8, 16, 32, 64			
Living room		8			
Under stairs		8			
Kitchen			8, 16, 32, 64		
Living room			8		
Under stairs			8		
Kitchen				8, 16, 32, 64	
Living room				8	
Under stairs				8	
Kitchen					2, 8, 16, 32, 64
Living room					8, 64
Under stairs					8, 16, 32

Table 7: Gas releases in Phase 2 & 3 (kW and location)

Location	100% NG Inject for 2.5 hours	10% H; 90% NG Inject for 2.5 hours	3% H; 97% NG Inject for 2.5 hours	Town Gas (50%H; 25% NG; 25%CO_2) Inject for 2.5 hours	100% H Inject for 2.5 hours
Kitchen	8, 16, 32, 64				
Living room	32, 64				
Under stairs	16, 32				
Kitchen		8, 16, 32, 64			
Living room		32			
Under stairs		32			
Kitchen			8, 16, 32, 64		
Living room			32		
Under stairs			32		
Kitchen				8, 16, 32, 64	
Living room				32	
Under stairs				32	
Kitchen					8, 16, 32, 64
Living room					32, 64
Under stairs					16, 32

2.2.5 Test Procedures - High Rate Release

In addition to the low rate releases explained above, a series of high rate, short term releases were also carried out to simulate a leak from a hydrogen vehicle or from a mains gas pipe (external to the property). The test procedures were similar to those used in the low rate releases, however the flow rates used were much greater at 1000l/min of hydrogen and 300l/min of natural gas, and the injection time was much shorter, at 48 minutes for the vehicle simulation and 60 minutes for the leaking main.

The sample points within the property were altered to better measure the areas directly impacted by these releases. For the vehicle simulation additional sample lines were tee'd into the Dining Room and Living room sample lines as shown below:

- Dining Upper, Middle, Lower = Lean-to Upper, Middle, Lower
- Living room Upper, Middle, Lower = Lean-to Upper, Middle, Lower
- Kitchen, Bedroom 1 and Bedroom 2 remained in the original configuration.

For the leaking main simulation the majority of the sample points remained as per the original setup with upper, middle and lower sample points in each room. However, Dining Room and Living room middles were re-plumbed to measure under the corresponding floor.

As for the low rate releases, data logging started before gas injection began and continued until the property had been fully vented at the end of the test. The same logging procedures and venting procedures were carried out as for the low rate release tests.

2.2.6 Safety Aspects

Due to the nature of the gases being injected into the property, safety was of paramount importance to ensure successful completion of the project. A formal risk assessment was carried out, which recommended a number of measures to reduce the risks associated with the test programme.

- The electricity supply to the house was disconnected.
- The telephone line to the house was disconnected.
- 'No smoking' and 'no naked flame' signs were installed around the test site and danger tape around the periphery.
- During Phase 1 of the test work a recruitment company was enlisted to fill the position of site 'look-out' to ensure no individuals passed the test house whilst test work was taking place. However, due to delays in test work as a result of equipment failure this was not continued during Phase 2 and 3 which took place during the winter months. A full risk assessment was carried out before this decision was made and further warning signs and notices put in place before the test work continued.
- Rules were written concerning the flammable gas concentration limits before entry to the house.

- Mobile phones, 2-way radios, and all electrical equipment were banned from the house during testing.

The testing staff all attended an emergency first aid training course and emergency services within the local area were notified of the work taking place. The fire service attended site to carry out a risk assessment before the test work started and on each day of testing the staff on site contacted the fire service on arrival and departure to notify them that work was taking place. The local police were also notified of the experiments.

3 Results and Discussion

A total of 112 low rate tests were carried out over phases 1 to 3. Of these, 4 were repeat tests due to issues with the analysers. A further 10 high rate simulations were carried out; 4 in the lean-to and 6 in the dining room to simulate a vehicle failure and a leaking gas main respectively. The two 100% natural gas releases into the dining room were repeated due to zeroing errors on the analysers.

The raw data was corrected for zero and span drift on the analysers using the reference sample line taken from the cabin air (sample line 16); this correction was carried out before any further data analysis.

Overall a leak from hydrogen displays no greater risk in terms of flammability than a leak from natural gas, or a mixture of natural gas and hydrogen. This is primarily due to the density of hydrogen compared to natural gas – although approximately three times the amount of hydrogen is required to provide the same energy input as natural gas, the significantly lower density means the hydrogen disperses much faster and thus concentrations of hydrogen only reach approximately half of the expected amount. This and the full results are discussed in greater detail below.

3.1 Low Rate Simulations

Gas leak simulations were carried out at three levels of air tightness as shown in the table below. Due to the temporary nature of the sealing measures carried out in the property and the good correlation shown between the positive and negative tests at the start of Phase 1, only positive tests were carried out before Phase 2 and 3 to reduce the risk of the sealing measures failing; e.g. plastic sheeting lifting from floor.

Table 8: Air Tightness Results

	Air Permeability @ 50Pa		
	Phase 1 - Original ($m^3/h/m^2$)	Phase 2 - After 1st Seal ($m^3/h/m^2$)	Phase 3 - After 2nd Seal ($m^3/h/m^2$)
Positive	9.7	6.64	3.46
Negative	9.99		
Average	9.85	6.64	3.46

The test work consisted of analysis of several variables at each air tightness including:

- The maximum concentrations of gas reached within the property; including comparison between the cupboard space and the other rooms within the house

- Concentrations achieved compared to volume of gas injected for the different gases
- Gas distribution throughout the property; including any differences between the upstairs and downstairs
- Energy content of the gas concentrations within the property

3.1.1 Gas Concentrations

The following table shows the peak gas concentrations reached for each gas at each air tightness within the property.

Table 9: Gas concentrations achieved within the property (%)

	H_2		CH_4		CO_2	
Phase	**Max house excluding cupboard %**	**Max cupboard %**	**Max house excluding cupboard %**	**Max cupboard %**	**Max house excluding cupboard %**	**Max cupboard %**
1	6.5 – 7.0	18.2	4.0 – 5.5	15.8	2.9	2.7
2	10.0 – 10.5	19.3	7.0 – 7.5	13.5 – 15.0	2.7	5.7
3	12.0 – 12.5	22.1	6.5 – 7.5	15.0 – 17.5	3.1	6.4

These figures show the peak concentrations observed at a single sample point within the property during the test work at each phase. In all phases the highest concentration was observed at the point of injection and this was exacerbated when injection took place within the cupboard due to the confined nature of the space. However, once injection stopped, dispersion from within the cupboard space to the rest of the property was rapid.

Excluding the cupboard space, the highest concentrations were observed at the upper sample point in the room of injection, with very similar concentrations observed at the upper sensors in the other downstairs rooms and all of the sample points in the bedrooms. The dispersion of gas is discussed in further detail below.

As discussed in section 1.1 different gases have varying characteristics when considering flammability. Natural gas (methane) has a flammability range of 5% to 15% concentration; this increases to 4% to 75% for hydrogen. This means if the property reaches a concentration between these limits the gas/air mixture within the property will combust (or at least offers the risk of combustion) if a source of ignition is introduced, e.g. the spark from an operating light switch.

Damage and fatalities caused by the ignition of gas is a direct result of the overpressure shockwave (shockwave above normal atmospheric pressure) caused by the ignition. For methane, the most potentially damaging conditions are at approximately 10% concentrations (stoichiometric concentrations) with studies by Zhang et al. (2014) showing higher overpressures observed at gas concentrations of 9.5% (see Figure 14 below)[11]. Also significant is the size of the area in which the gas/air mixture is held and into which a source of ignition is introduced. The maximum overpressure from the explosion wave is reached quickly after detonation due to the chemical reaction energy of ignition. Over time, this energy reduces as more energy in the form of heat is given off than is present in the reaction, until the explosion process is over. The sound wave from the explosion travels outwards from the source of ignition, at a faster speed than the flame front. If held in a container (or room) the sound wave will reflect off the surfaces and potentially interact with the flame front causing further reduction in energy. This means in smaller containers the explosion process is over quicker and dominated by chemical energy, therefore overpressure is higher (and consequently more damaging) in smaller containers.

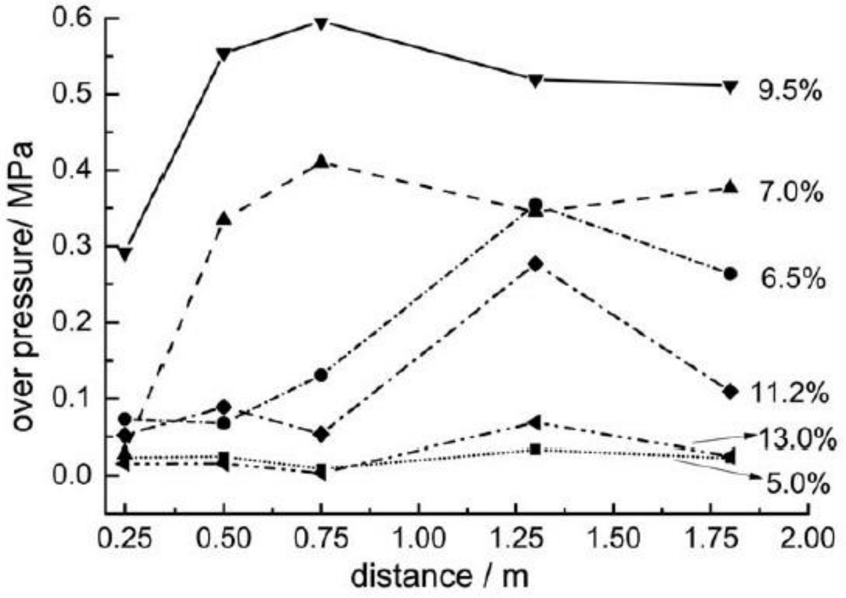

Figure 4. Explosion overpressure for methane/air mixture at different compositions.

Figure 14: Explosion overpressure at various methane/air concentrations. Bo Zhang et el. 2014.

Hydrogen reacts slightly differently at different concentrations with only very low overpressure deflagration between 4% and 9%, where the buoyancy of the gas will only allow for an upward (4%) and horizontal (6%) propagation of flame[12]. At 9% hydrogen

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[11] Explosion and flame characteristics of methane/air mixtures in a large-scale vessel; Zhang et al, 2014.

[12] Effect of the concentration distribution on the gaseous deflagration propagation in the case of hydrogen/oxygen mixture; Sochet et al, Journal of Loss Prevention in the Process Industries, Elsevier, 2006.

flames can also propagate downwards. Hydrogen has a higher laminar burning velocity than methane which directly affects the pressure generation from the flame front after ignition, this can be further accelerated by turbulence of the flame front caused by obstacles within the space[13]. Hydrogen does not reach its stoichiometric mixture until approximately 30%v/v.

In certain conditions deflagration will transition to detonation. The speed of the flame front increases as it moves away from point of ignition. As the reaction of hydrogen and oxygen is so quick and thus the flame speed is so fast, in some situations the flame front overtakes the sound wave and thus deflagration moves to detonation. This is most likely to occur when the hydrogen / air mixture is in a pipe, or at much larger scale in a tunnel. The transition from deflagration to detonation is akin to moving from cordite to TNT.

How the transition from deflagration to detonation (DDT) occurs is generally acknowledged as a very complex subject. The paper On Detonation Dynamics in Hydrogen-Air-Steam Mixtures, Theory and Application is a good overview[14]. In essence DDT either requires an explosive detonator (as used in munitions) in the midst of the gas cloud, or specific arrangements of geometry and hydrogen concentration. Unconfined or fully relieved hydrogen / air mixtures very rarely detonate.

There is evidence from some studies which suggest detonation is possible with concentrations at 11%, however other studies suggest that it is not until approximately 18% when the risk of detonation from hydrogen becomes more significant, for example Molkov[15]. The detonation limits are largely influenced by the size of the area in which the hydrogen is contained. During experimental conditions with hydrogen contained in cylinders, or very confined spaces, it is possible to make the transition from deflagration to detonation at relatively low gas concentrations. However, when considering the scale of the space into which hydrogen is likely to leak in a domestic situation, it is argued that the conditions experienced in an experimental situation may well not occur. The space is much larger and thus the movement from deflagration to detonation requires a greater concentration more comparable to the 18% concentrations. This is supported by studies by Bauwens et al. in which very low overpressures were observed from ignition of hydrogen concentrations below approximately 18% in a vented space[16]. The lack of obstacles such as tightly

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[13] Vented confined explosions involving methane/hydrogen mixtures, Lowesmith et al 2011. International Journal of Hydrogen Energy, 36 (3) pp. 2337-2343.

[14] On Detonation Dynamics in Hydrogen-Air-Steam Mixtures. Theory and Application to Olkiluoto Reactor Building. A. Silde, I. Lindholm VTT Energy, Finland, February 2000 NKS-9. ISBN 87-7893-058-8

[15] Fundamentals of hydrogen safety Engineering 1, Vladimir Molkov, 2012.

[16] Effect of hydrogen concentrations on vented explosion overpressures from lean hydrogen air deflagrations, Bauwens et al, FM Global, Research Division Norwood, MA.

encased pipework or objects within a domestic setting also significantly reduces the risk of detonation in these environments.

At injection rates under 16kW (when injected into the kitchen or living room) as would be expected from a minor leak such as a gas hob and oven, or faulty pipe connection, gas concentrations within the property did not exceed the lower flammability limit (LFL) for natural gas. This was the same for hydrogen injections of 8kW.

For 16kW, 100% hydrogen injections, concentrations did reach the LFL in the room of injection, but only just, and concentrations throughout the rest of the house did not reach LFL until the very end of the injection period. This suggests that flammable concentrations are unlikely to be achieved during short term, low rate releases, even in properties with low air permeability rates (e.g. ~$3m^3/h/m^2$).

The tapestries below display the gas concentrations at each sensor within the property throughout the test period. Each sensor is listed and the darkening colour gradient indicates increasing concentration. For each gas, the various flammability concentrations are marked using indication lines; these are:

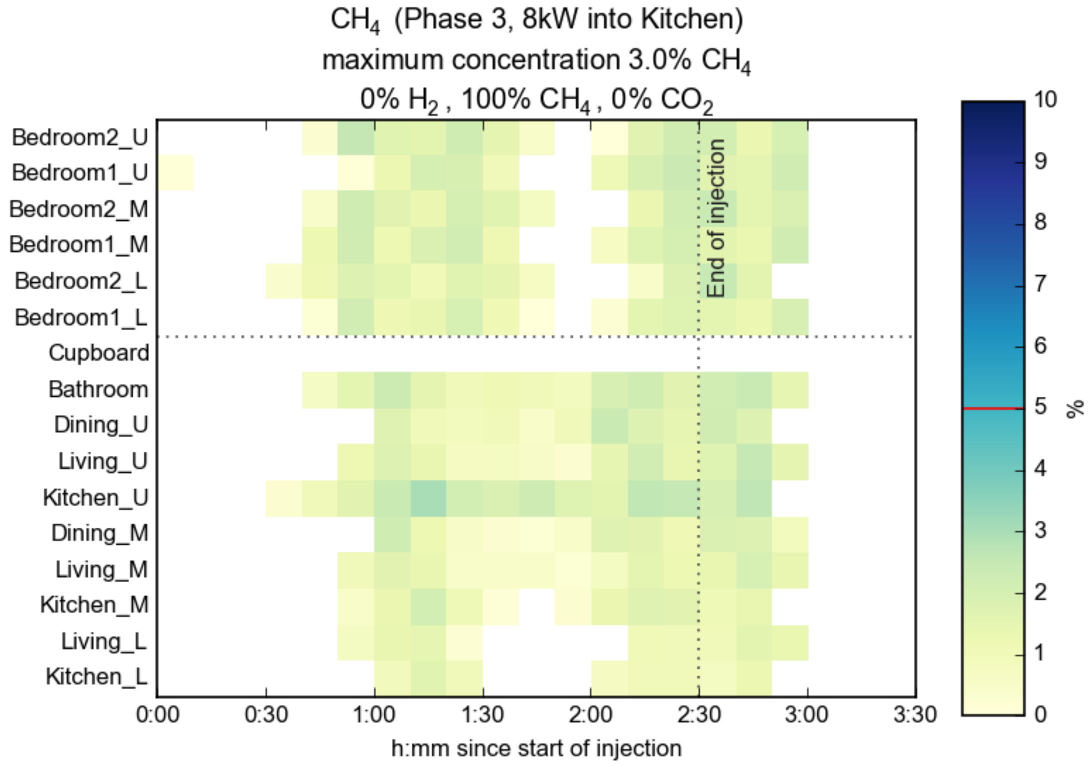
Hydrogen

- Dashed green – 4% (LFL & upwards propagation)
- Dashed blue – 6% (horizontal propagation)
- Solid blue – 9% (downwards propagation)
- Solid black – 18% (possible detonation)

Methane

- Solid red – 5% (LFL)
- Solid black – 10% (Stoichiometric)

The 8kW and 16kW injections are shown for 100% methane and 100% hydrogen injected into the kitchen. It is clear that methane does not reach flammable limits and hydrogen only reaches 4% concentration with the 16kW injection at the end of the injection period during Phase 3. Tapestries for every test can be found in section 9. The blank rows indicate that no sample was taken from this location for this test.



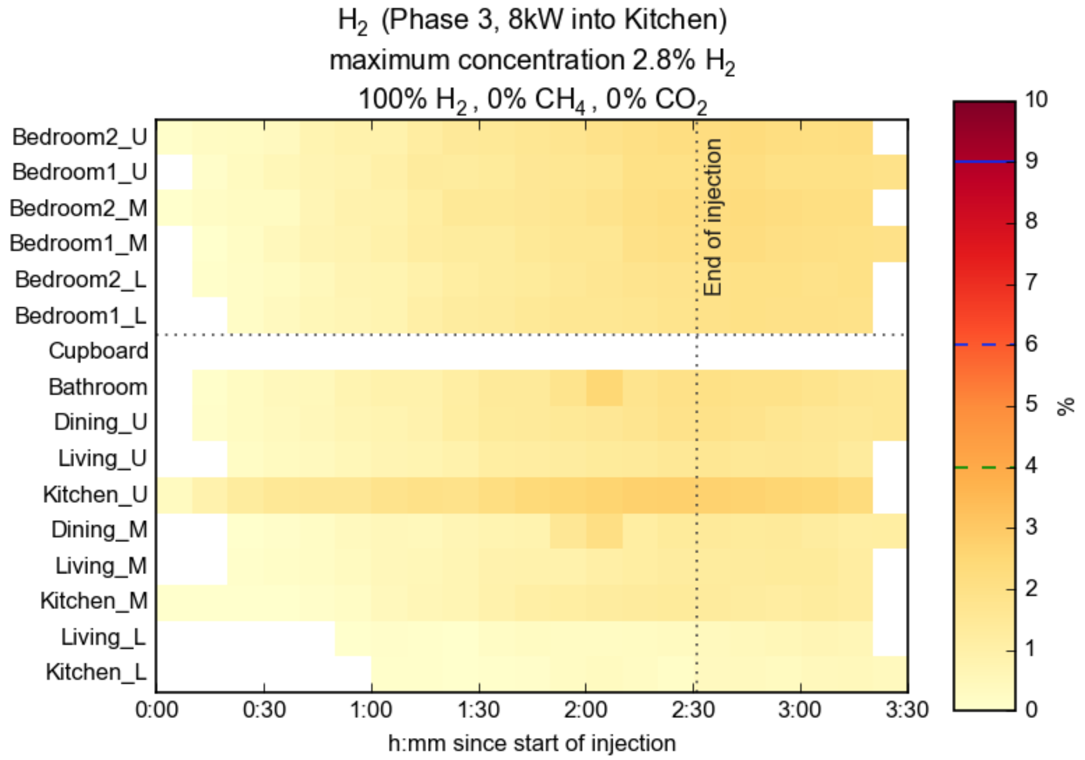
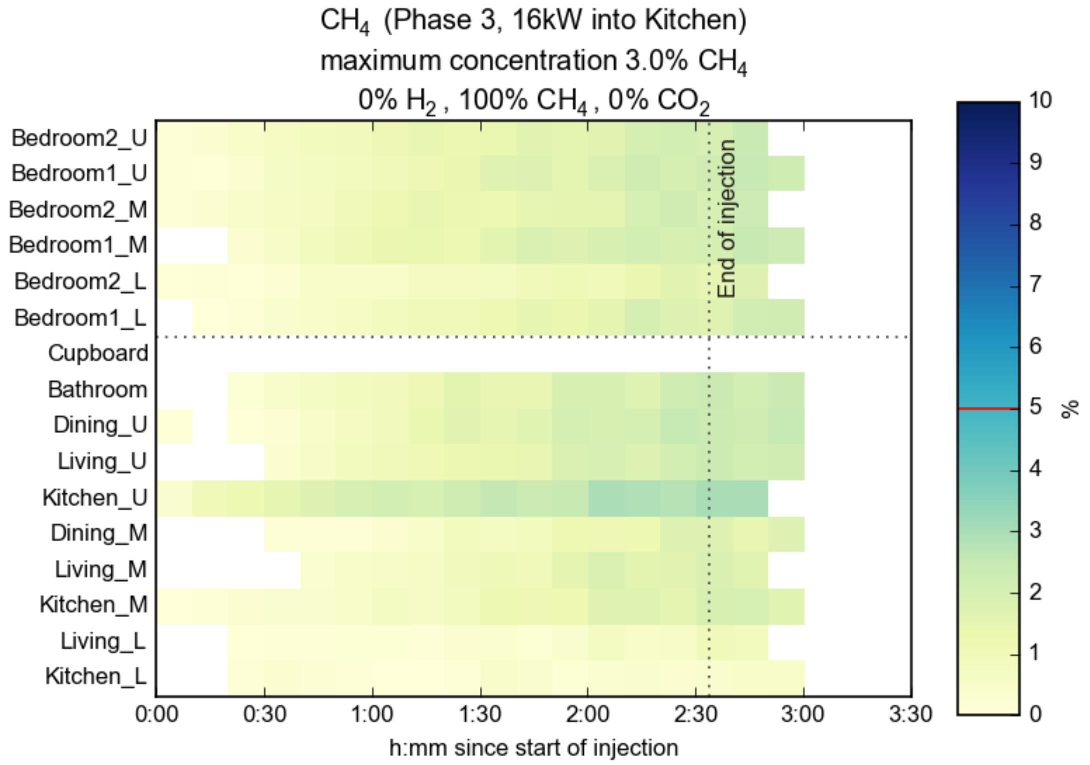


Figure 15: Gas concentrations achieved during phase 3 for 100% methane and 100% hydrogen – 8kW



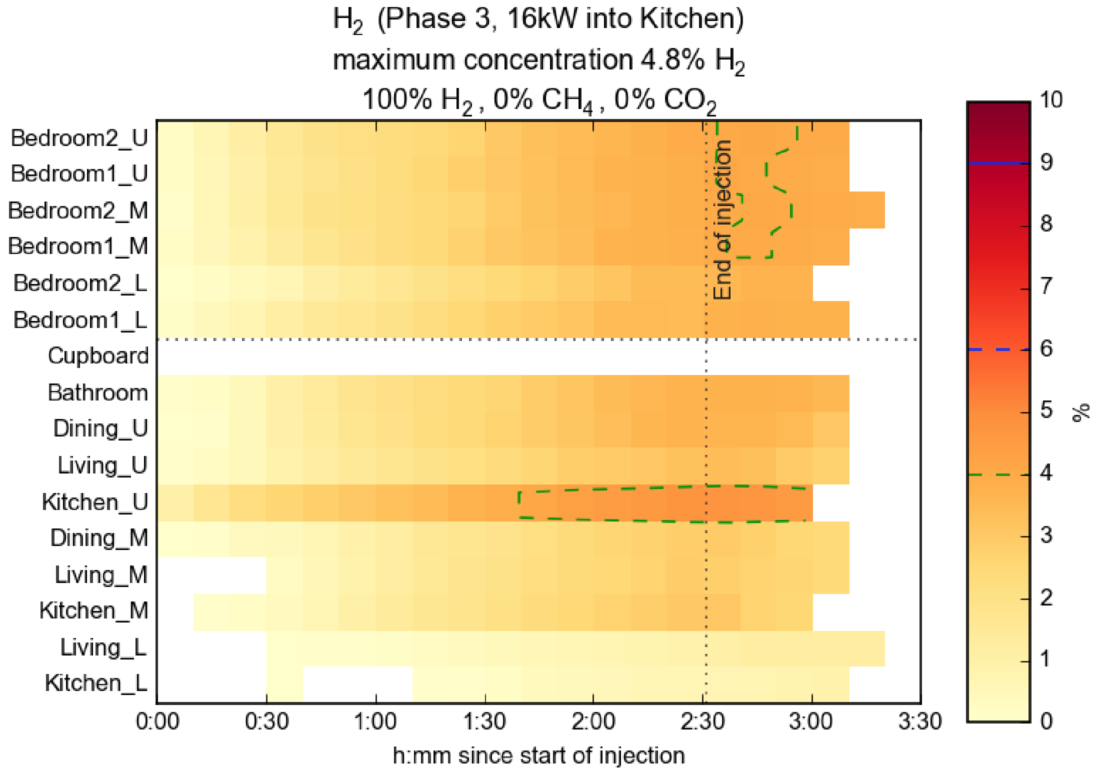
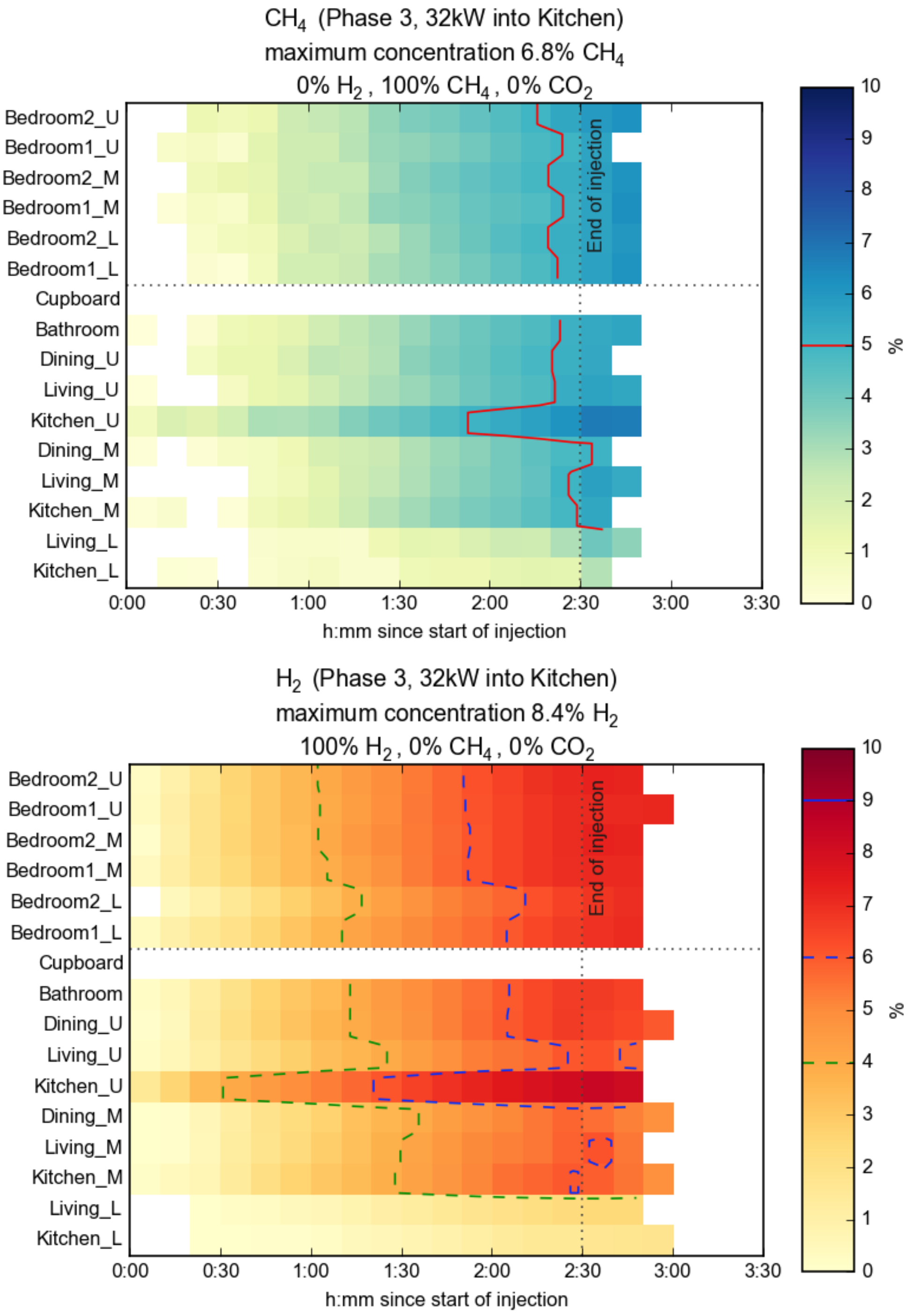


Figure 16: Gas concentrations achieved during phase 3 for 100% methane and 100% hydrogen – 16kW

At leak rates of 32kW, in a well-sealed property (Phase 3), gas concentrations within the property reached approximately 7% for methane and 8% for hydrogen (see below) when injected into a vented space such as the kitchen or living room. This was the same for the 10% and 3% hydrogen/natural gas mixtures, which behaved in a very similar way and reached very similar concentrations to 100% natural gas.

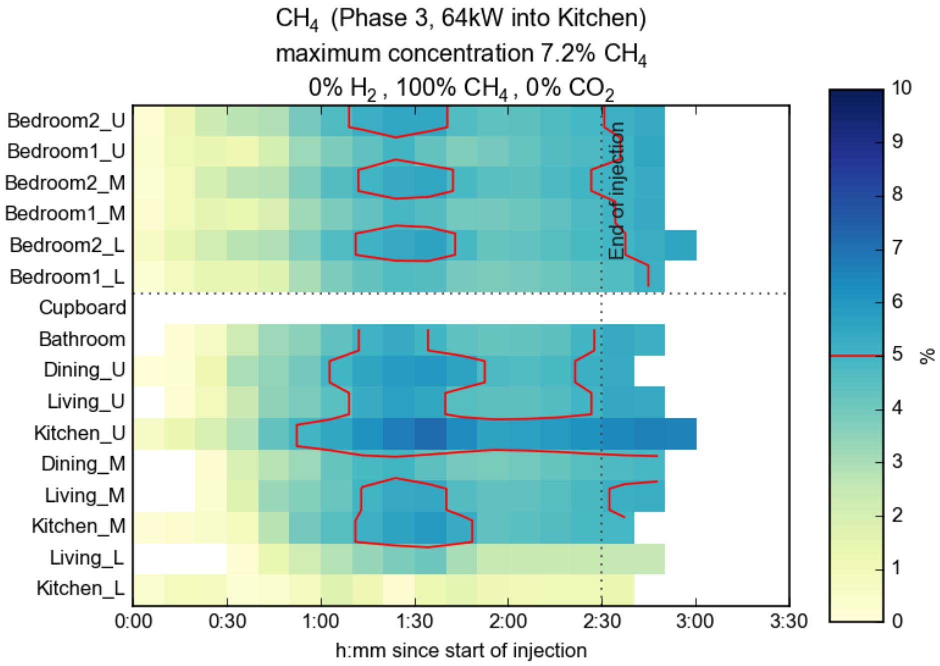


CH_4 (Phase 3, 32kW into Kitchen)
maximum concentration 6.8% CH_4
0% H_2, 100% CH_4, 0% CO_2

H_2 (Phase 3, 32kW into Kitchen)
maximum concentration 8.4% H_2
100% H_2, 0% CH_4, 0% CO_2

Figure 17: Gas concentrations achieved during phase 3 for 100% methane and 100% hydrogen – 32kW

At 64kW, gas concentrations peaked at 12.0–12.5% hydrogen and 6.5–7.5% natural gas as shown in the figures below. At these concentrations there is a risk of deflagration causing damaging overpressure, however the risk is similar for hydrogen and methane.



Note: The section in the middle of the methane tapestry which goes just above, then back below, the LEL is as a result of an adjustment to the zero calibration of the analyser mid-test, rather than any other effect

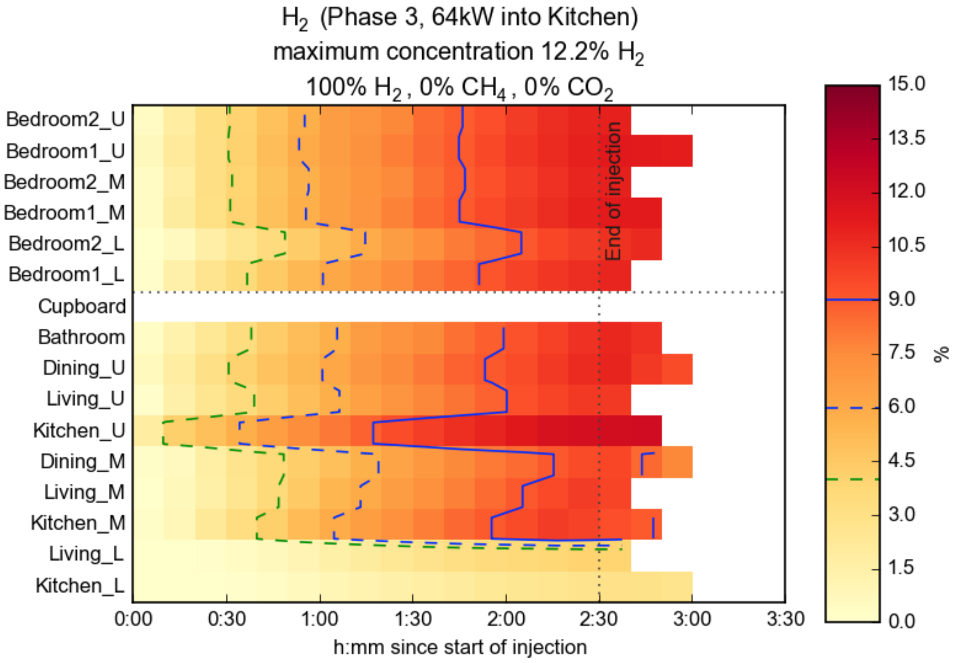
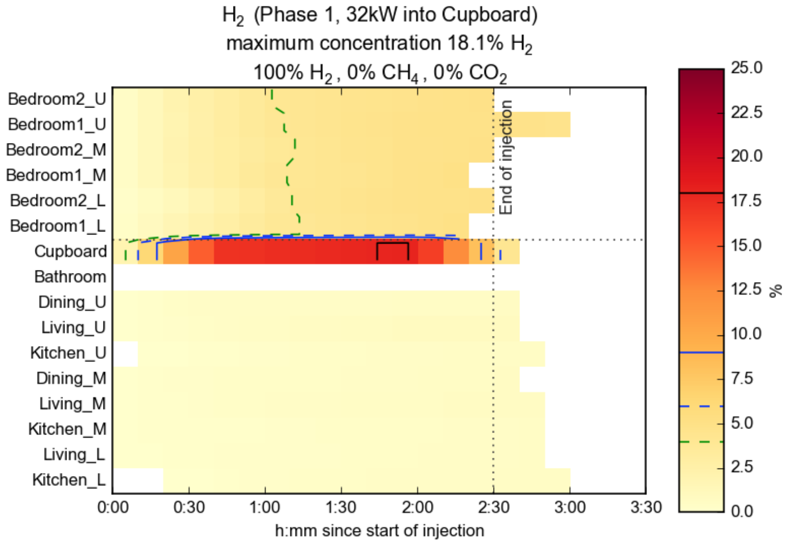
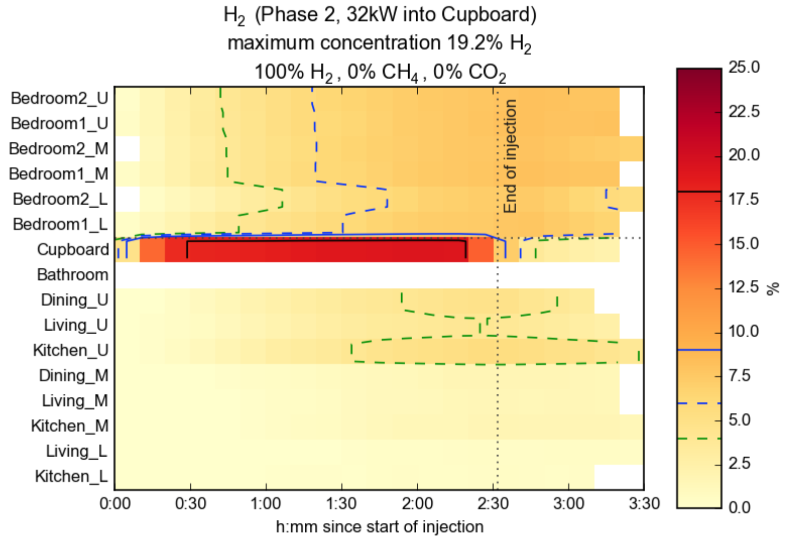


Figure 18: Gas concentrations achieved during phase 3 for 100% methane and 100% hydrogen – 64kW

When considering the cupboard space, concentrations reached during injection were consistently higher than those injected into larger (vented) areas. However, concentrations observed throughout the building varied considerably depending on the air tightness of the property. The tapestries below show concentrations observed during 32kW injections in to the cupboard space for phases 1 to 3 for 100% hydrogen.





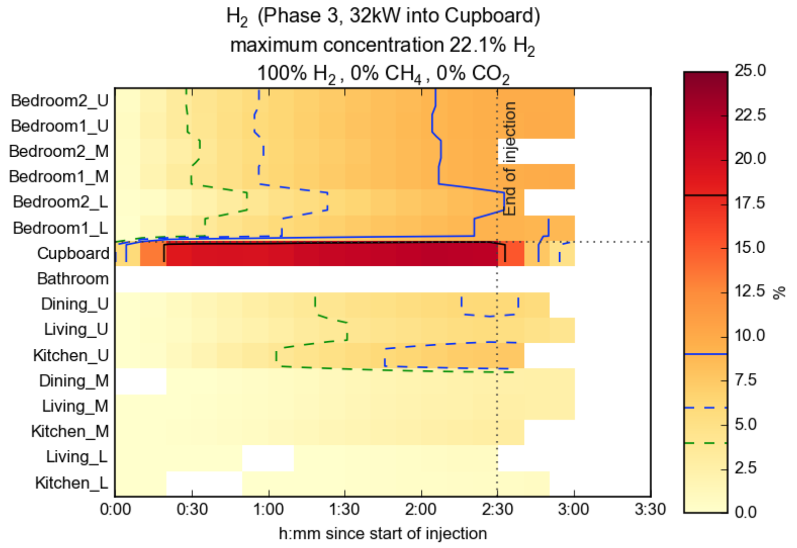


Figure 19: Tapestries of cupboard space – 32kW 100% hydrogen (phases 1 to 3)

In all phases, hydrogen was detected at flammable concentrations throughout the upstairs rooms when injecting into the cupboard. However the time taken to reach flammable concentrations decreased from approximately 1.25 hours in Phase 1 to approximately 40 minutes in Phase 3.

The concentration reached within the property (excluding the cupboard space) was also progressively increased as the house became more air tight; at less than 6% in Phase 1, up to between 9 and 12% in Phase 3. Hydrogen was also detected throughout the downstairs rooms but only reached flammable limits during phases 2 (upward flame propagation only) and 3 (upward and horizontal propagation); and only at the upper sample points in the downstairs rooms.

In the cupboard space (point of injection), concentrations reached a maximum of approximately 20% in all phases (~18% in Phase 1 to ~22% in Phase 3). However, the duration of time for which the cupboard space was above 18% (potential detonation) significantly increased in Phase 2 compared to Phase 1, and again but less marked between Phase 2 and Phase 3. This is denoted by the solid black line in the graphs above; concentrations within the solid black line is a concentration above 18%.

The tapestries below show the same data but for 100% natural gas injections (32kW into the cupboard).

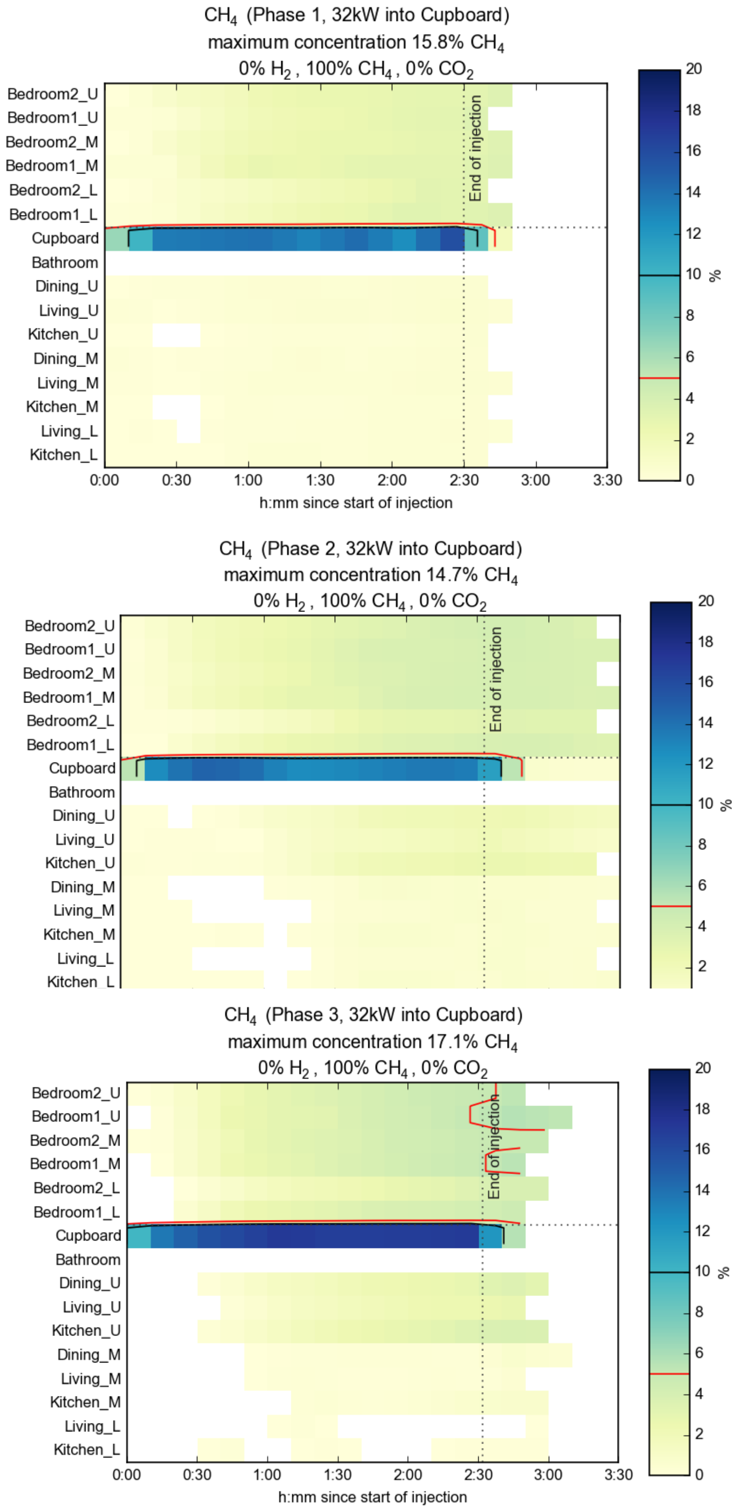


Figure 20: Tapestries of cupboard space – 32kW 100% Natural Gas (phases 1 to 3)

Similar to the hydrogen simulations, natural gas was detected throughout the upstairs rooms during injection into the cupboard and to a lesser extent throughout the downstairs rooms particularly the upper sample points. Flammable concentrations (above 5%) were observed in the bedrooms during phase 3, but never in the downstairs rooms. The data suggests that flammable gas concentrations were only observed in the property (excluding the cupboard space) during Phase 3.

In the cupboard space concentrations very quickly reach the LFL and within 15 minutes of injection, concentrations are at stoichiometric conditions and thus would produce the highest overpressure if ignited. Throughout the whole test period concentrations above 10% are recorded within the cupboard space and in Phase 3 exceed the UFL.

The risk of fire or detonation for methane and hydrogen is greatly increased when considering injection into confined spaces such as a cupboard as can be seen from the concentrations achieved in the above tests. The implications of this in terms of relative risk associated with specific gases is a very important area of consideration as the flame characteristics of hydrogen are very different to those of methane. Ventilation requirements should be considered so that concentrations cannot reach significant values, or if this is not possible, the availability to isolate sparking devices in this type of space should be applied. If hydrogen was to be rolled out as a widespread fuel it is essential that the risk of confined space ignitions is understood; this is suggested as an area in which further investigation is required.

3.1.2 Town Gas Concentrations

The 3% and 10% hydrogen/natural gas mixtures behaved in a very similar way to 100% natural gas, however, the Town Gas was slightly different in the fact that gas was injected at 50% hydrogen, 25% natural gas and 25% CO_2, and these proportions remained evident when observing the concentrations reached within the property; as shown in the example graph below showing gas concentrations in the kitchen.

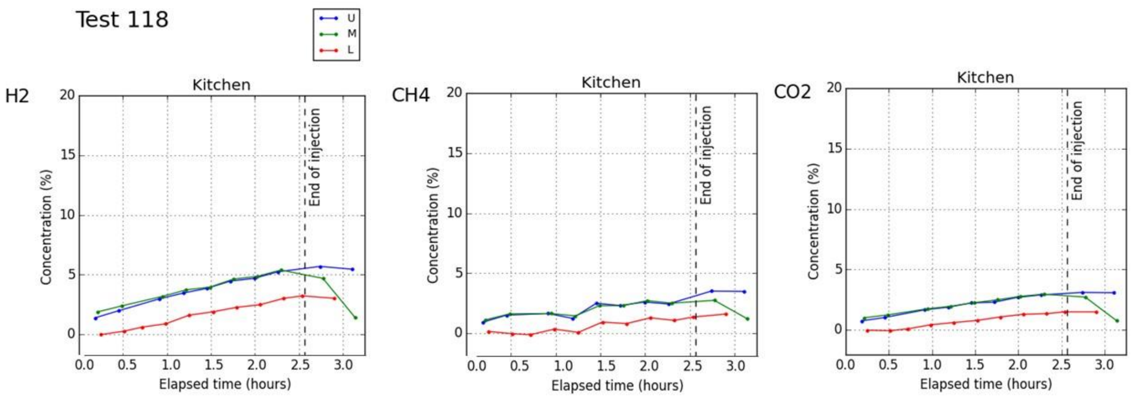


Figure 21: Example graphs to show percentage of each gas during the 64kW Town Gas injection in the kitchen

As both hydrogen and methane are flammable gases, it was decided that for the analysis of Town Gas, the gases should not be split to show methane and hydrogen separately, but were combined to provide a total 'flammable gas' concentration observed within the house.

At 64kW gas injection during Phase 3 (highest release rate and most air tight), concentrations of approximately 9% were observed; this is within the flammability limits of both hydrogen and methane.

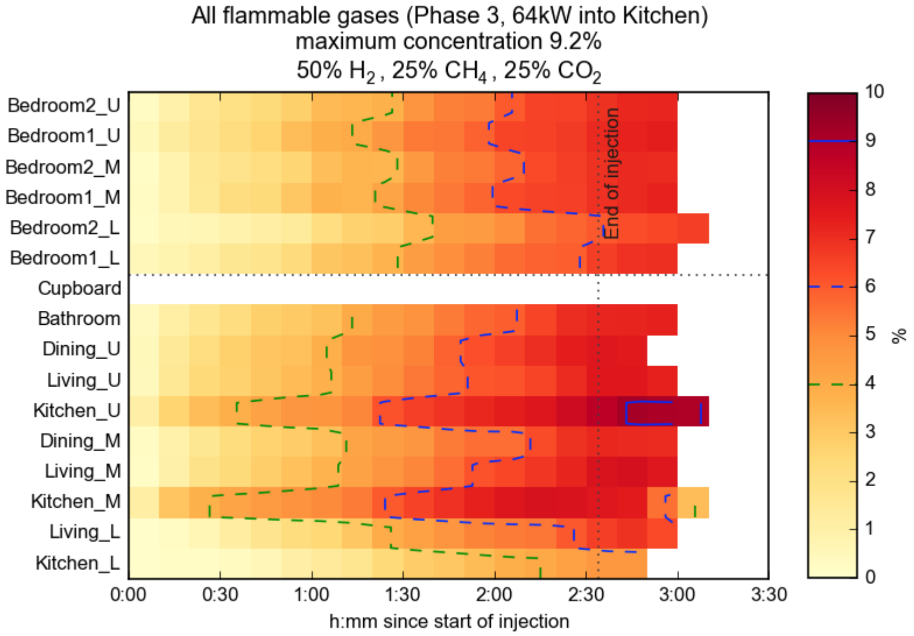
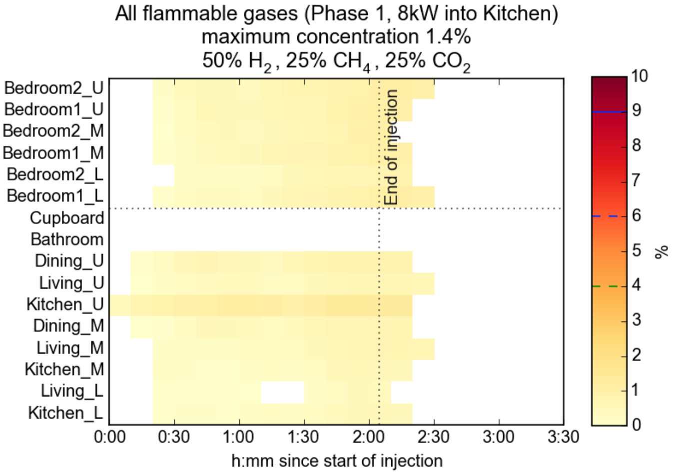
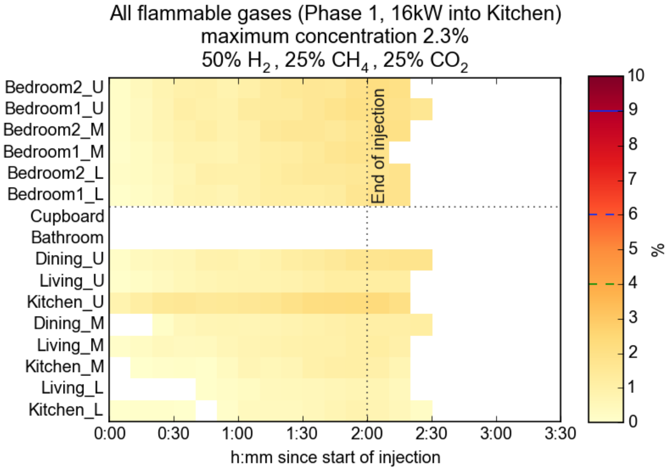


Figure 22: Tapestry for Town Gas showing combined gas concentrations (64kW, phase 3)

Stratification can clearly be seen in this figure, with highest concentration reached at the upper sample point in the kitchen (point of injection) and less gas detected at the lower sample points in any of the rooms. The time in which concentrations reached flammable limits can also clearly be identified, with flammable concentrations observed within the kitchen within approximately 30 minutes. This increased to approximately 1:15 upstairs (Bed 1 upper).

To allow better comparison with natural gas and hydrogen, the following figures show the combined concentration of flammable gases for a variety of tests throughout the programme. During Phase 1, flammable gas concentrations were not observed with injections of Town Gas up to 32kW, with peak concentrations of 3.6% during the 32kW injection into the kitchen (Phase 1). The 8, 16 and 32kW injections in phase 1 are shown below.





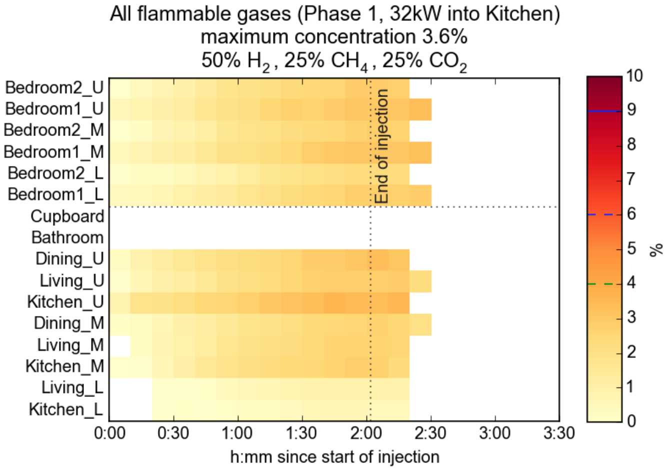


Figure 23: Tapestries of Phase 1 Town Gas Concentrations 8 to 32kW

At 32kW during Phase 2 and Phase 3, concentrations within the flammable limits of hydrogen and methane were observed. The concentrations achieved were slightly lower than the comparable tests of 100% hydrogen and 100% natural gas, with concentrations between 4.5% and 6% observed for Town Gas and concentrations of between 7% and 8.5% for hydrogen and natural gas.

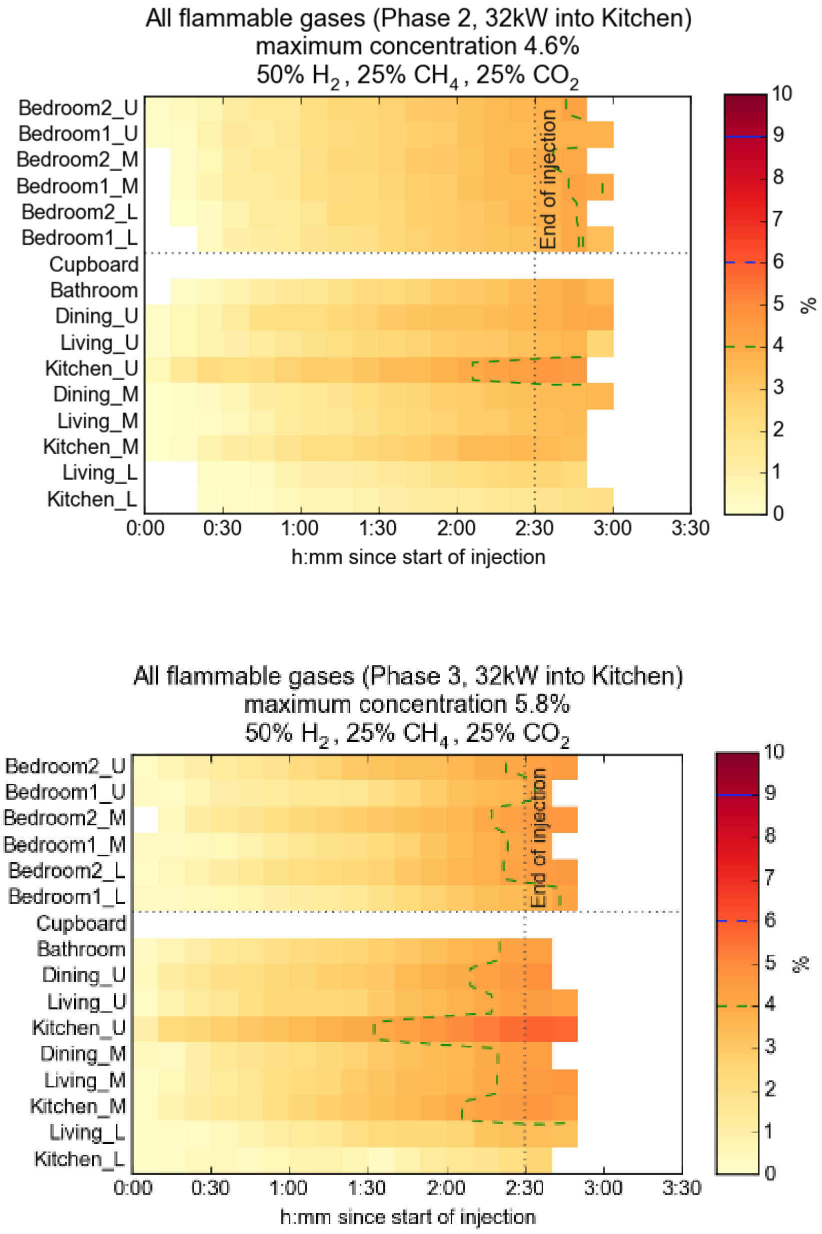


Figure 24: Tapestries of 32kW Town Gas Injections Phase 2 and 3

For Town Gas injections into the cupboard space, concentrations of flammable gases up to approximately 6% to 8% were observed in upstairs rooms and between 4% and 6% at the upper sample points in the downstairs rooms. Within the cupboard space concentrations rapidly reach 9% (after approximately 15 minutes) and peak at approximately 15%, this is within the flammability range of both hydrogen and methane and concentrations remain at this level throughout the test.

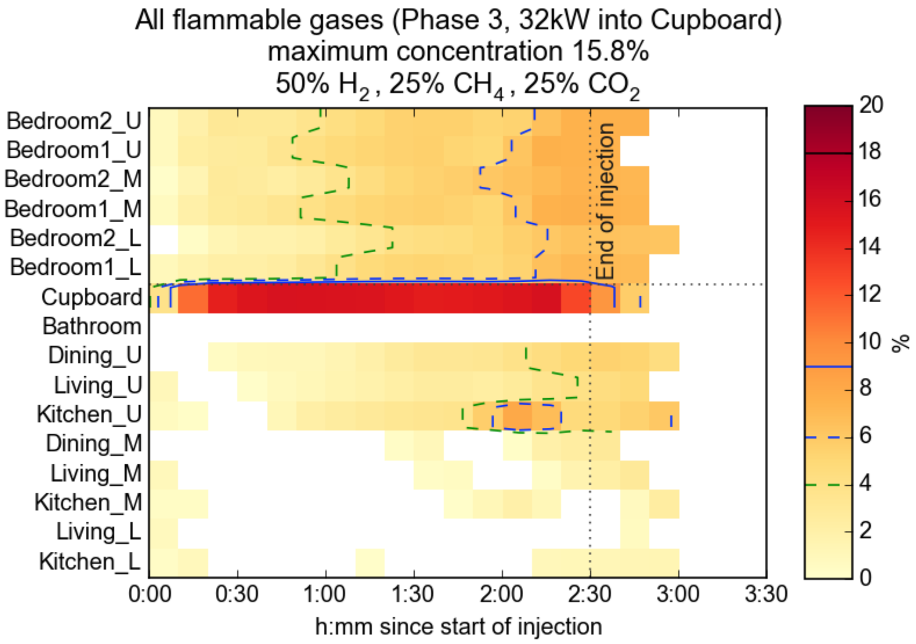


Figure 25: Tapestry of 32kW Town Gas injection into cupboard space (Phase 3)

It is suggested that the ignition characteristics of hydrogen, natural gas and Town Gas is further investigated at the concentrations observed throughout this test programme. Thus providing a quantifiable way of determining which gas would be more hazardous and pose greatest risk if ignited in a domestic situation at concentrations as observed in this study. This is proposed as an area of further study.

3.1.3 Predicting Gas Concentrations

It was thought useful to determine whether it was possible to predict the concentration that a gas would reach when injected at a certain leak rate e.g. 64kW, into a house of a known air tightness.

The following figures show the maximum gas concentrations from all low rate simulations normalised using the air leakage data for the phase in question. Both the maximum average house gas concentrations (red points) and the maximum spot readings, excluding data from the cupboard (blue points) are shown. Where mixtures of gases were injected, the gases are considered separately and their individual injection rates have been used.

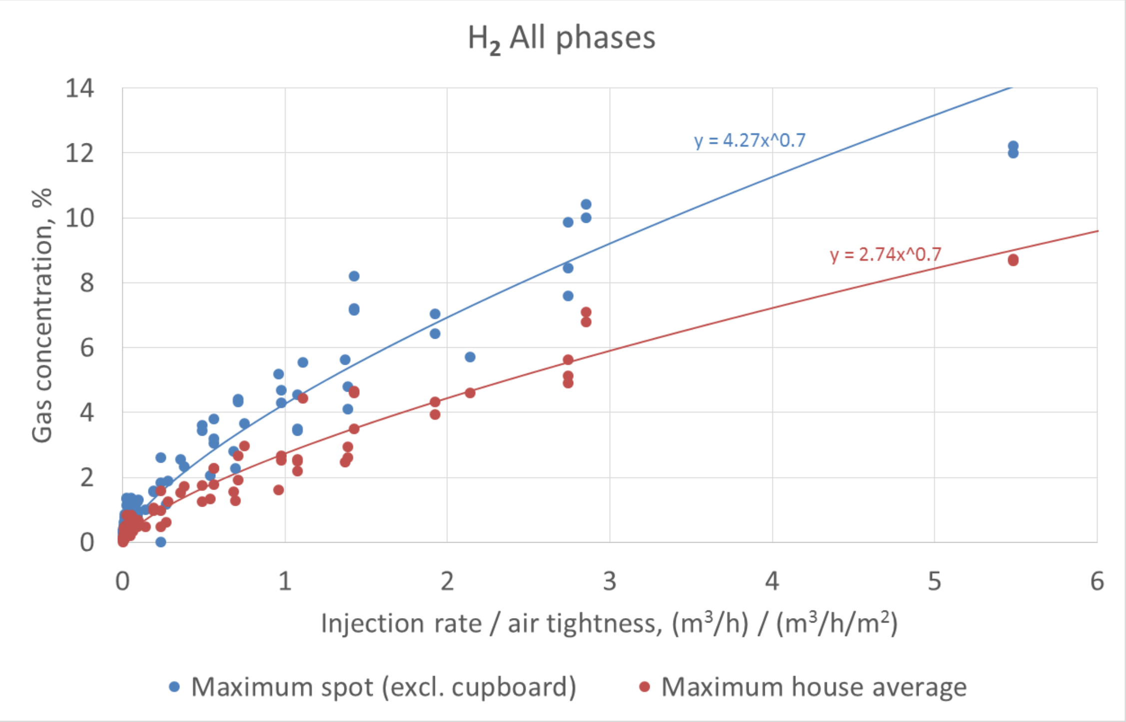


Figure 26: Comparison of maximum hydrogen concentrations reached, normalised using air leakage data

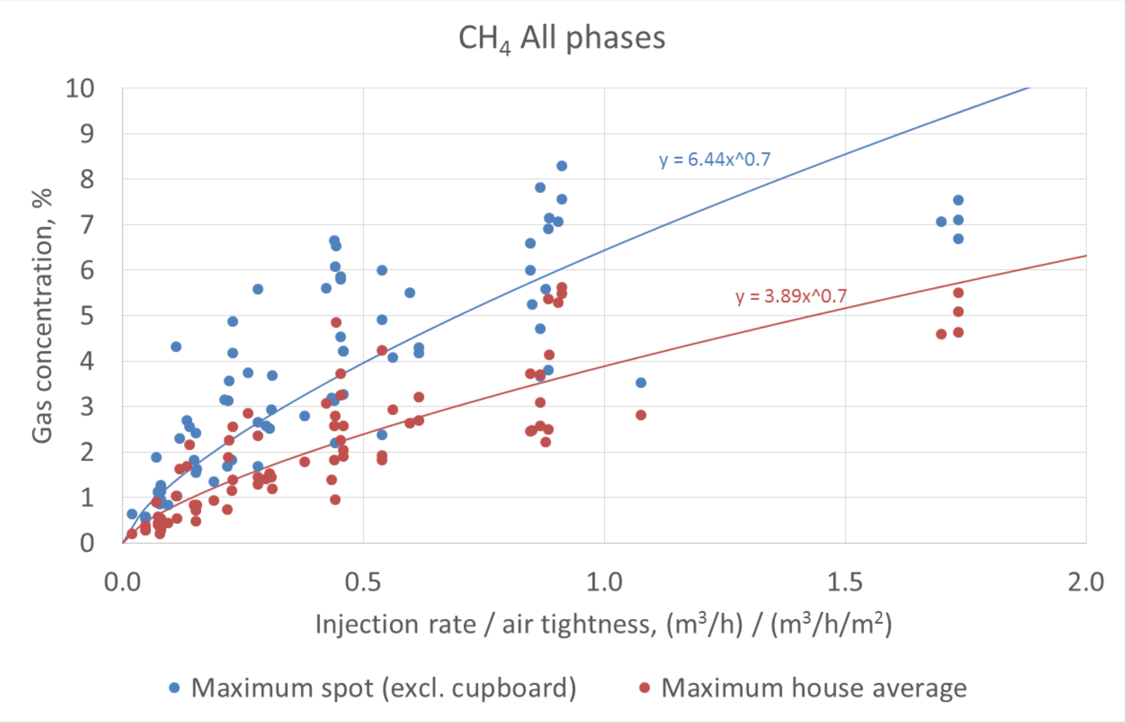


Figure 27: Comparison of maximum methane concentrations reached, normalised using air leakage data

It can be seen that there is a clear correlation for the hydrogen data, and a fair correlation for the methane data, reflecting their differing uncertainties (see Section 3.4). Preliminary analysis using a density model suggested a power curve relationship with an exponent of approximately 0.7. Therefore, similar best fit curves were fitted to the data and their equations are shown on the graphs.

This suggests that it is possible to predict the concentrations of each gas which will be achieved (both the house average and maximum spot concentrations) at a given air tightness. This could be a useful tool for developers and can also be used to determine the ventilation requirements to reduce concentrations to safe levels within a property of a given air tightness.

For a given hole size, hydrogen is expected to leak at just over three times the rate of methane, but (from the graphs), hydrogen is assumed to reach only ~1.6 times the concentrations of methane at these rates. In terms of energy content in the house, this is around 52% of the methane energy content. The graphs show the maximum spot concentrations of either gas were higher than the average house concentrations, by a factor of (on average) between 1.5 and 1.7.

3.1.4 Gas Distribution

For the low rate leak simulations, the same distribution of gases were shown throughout the entire test programme, independent of where the injection took place, e.g. injection into the kitchen, living room or cupboard; and independent of the gas mixture being injected.

Significant gas stratification was shown in the downstairs rooms, particularly when considering 100% hydrogen injections, with increasing definition at higher injection rates and thus higher gas concentrations.

It is suggested that this stratification occurs as a result of the density of the injected gas and the air movements within the space. The injected gas has a lower density than the air into which it is being injected, therefore it rises. The change in density between the internal and external space leads to the ‘chimney (or stack) effect’ whereby air is drawn inwards and upwards from outside, creating a movement of air within the property resulting in stratification. This driving force is far less apparent upstairs and the concentration within the upstairs rooms is uniform when injecting at low concentrations within the downstairs rooms. This effect was seen most prominently at 64kW and 32kW injection rates as shown below. However stratification was evident at all levels of air tightness.

Studies by Lowesmith et al. during which hydrogen gas mixtures were injected vertically into a container to simulate gas release into a single room, also showed this clear stratification. In this study each horizontal plane showed the same concentration with low concentrations observed at low level[17]. As the percentage of hydrogen within the gas mixtures was increased, a larger volume of the gas was injected into the container in a similar way as within the HyHouse experiment. This led to a higher gas concentration, however, due to the significant buoyancy of hydrogen, concentrations were lower than may be expected. This concept in relationship to HyHouse is discussed further below.

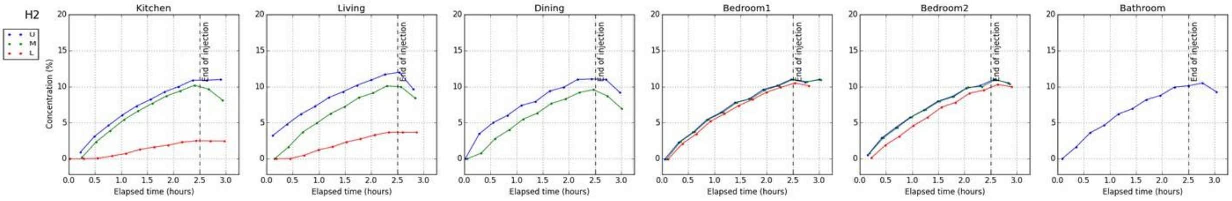


Figure 28: Evidence of gas stratification – 64kW 100% hydrogen injected into Living Room
(downstairs rooms – the left 3 figures and right most figure; upstairs rooms the 4th and 5th figure, with the colours blue, green and red indicating high, medium and low level, respectively)

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[17] Lowesmith, B.J, Hankinson. G, Spataru. C and Stobbart. M. 2009. Gas build-up in a domestic property following releases of methane/hydrogen mixtures. International Journal of Hydrogen Energy, 34 (14), pp. 5932-5939.

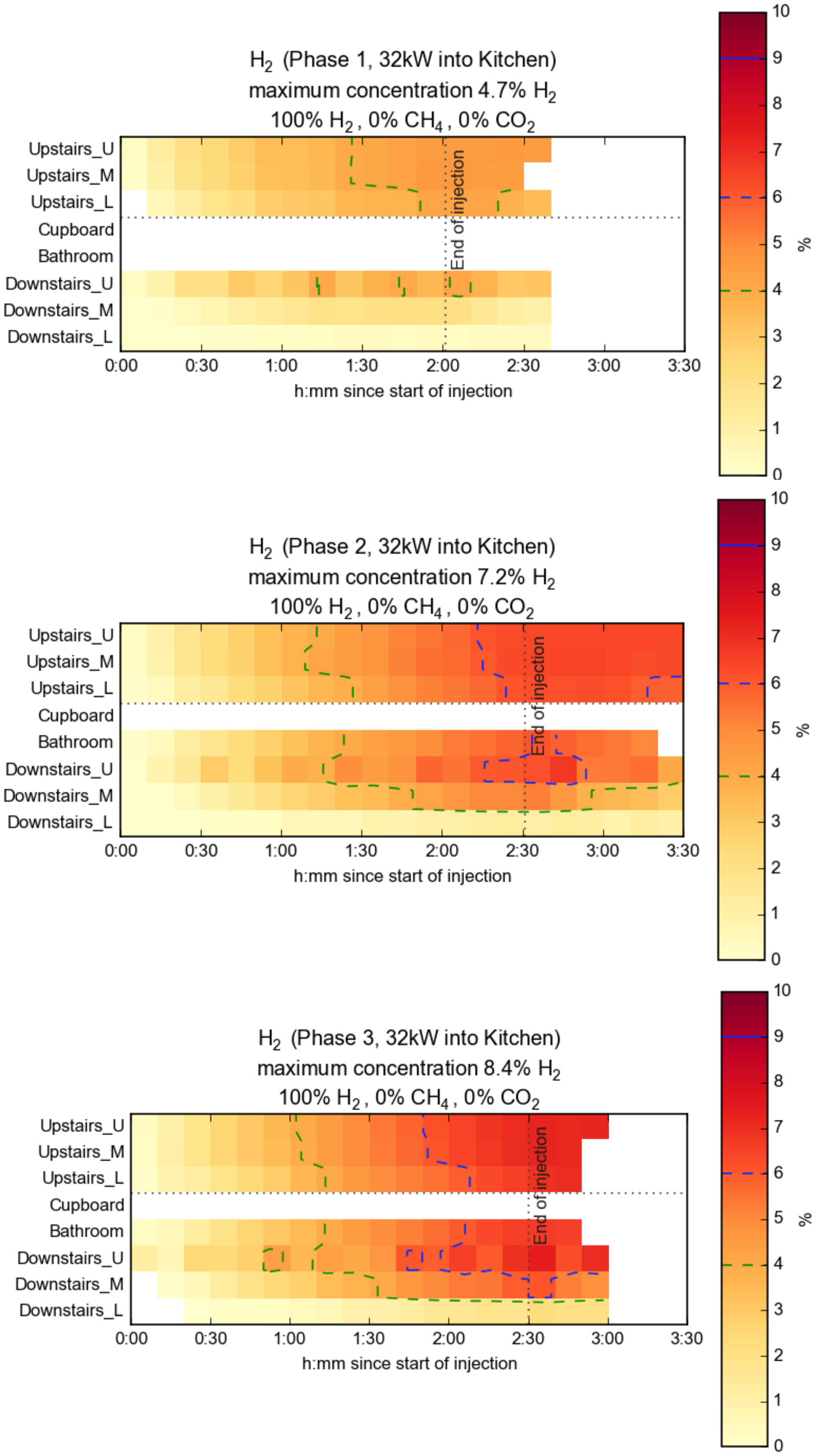


Figure 29: Evidence of gas stratification – 100% hydrogen, 32kW, Phase 1, 2 and 3

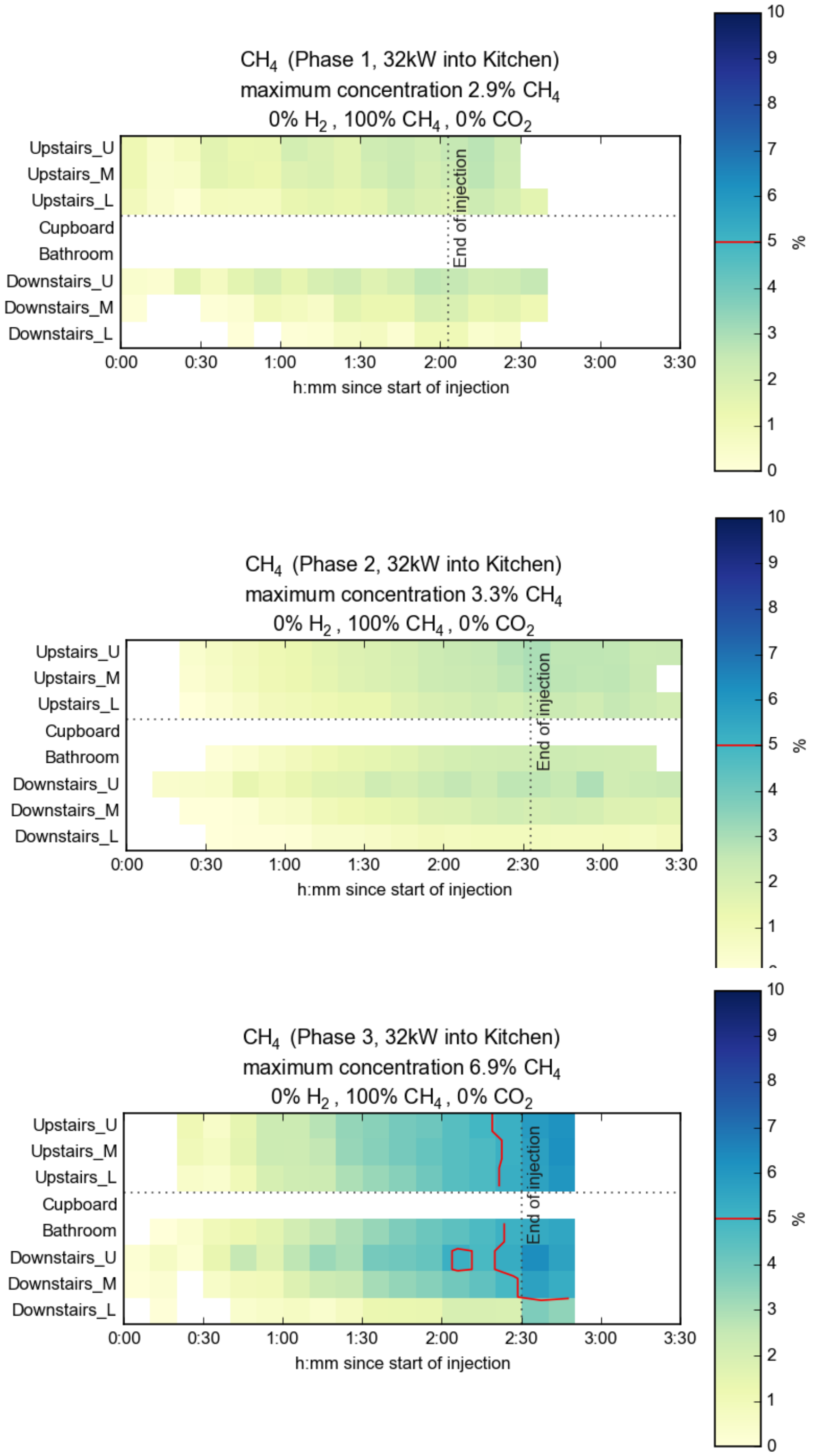


Figure 30: Evidence of gas stratification – 100% natural gas, 32kW, Phase 1, 2 and 3

The 3% and 10% hydrogen/natural gas mixtures behaved in a very similar way to 100% natural gas.

The buoyant nature of hydrogen means that it tends to collect at the highest point; it is therefore suggested that ventilation into the roof space, (in the form of a small vent in the bedrooms), should be enough to mitigate any significant risk from a hydrogen leak. When the property was in its original state, dispersion was fast and concentrations only reached ~7%. This obviously has implications when considering building regulations and ventilation rates, and if hydrogen is utilised as a fuel source the need for ventilation versus the need for air tightness would need to be carefully considered. However, it is suggested that the reduction in emissions from utilising hydrogen as a fuel, may be more beneficial than increasing air tightness further, particularly if the latter risks increased condensation and uncomfortable living conditions for the occupants.

3.1.5 Enumeration of Gas Volumes and Energy Content at Equilibrium

As indicated above one of the most significant findings when considering the concentrations reached within the property is the peak volume of gas reached during the test periods. The lower calorific value of hydrogen results in approximately 340% of the volume of hydrogen being injected for the same energy content compared to natural gas (methane). This would suggest that around three times the concentration of hydrogen would be expected within the property compared to natural gas. However, this did not occur due to the significantly lower density of hydrogen gas. Using density theory (as described in section 8) it is suggested that concentrations of hydrogen would be approximately 173% that of natural gas. However, in reality the observed typical figures are 136% at the property as found (at an air tightness of 9.85m^3/h/m^2), up to 158% in the property at phase 3 (air tightness 3.46m^3/h/m^2). This is shown in the table below.

Table 10: Hydrogen to natural gas ratios

Gas	Typical % gas property as found (phase 1)	Typical % gas after 1st seal (phase 2)	Typical % gas after 2nd seal (phase 3)
Hydrogen	4.3%	7.1%	8.7%
Methane	3.2%	5.5%	5.5%*
Ratio H_2/NG	136%	129%	158%
Ratio of inputs	340%		
Ratio predicted by density theory	173%		

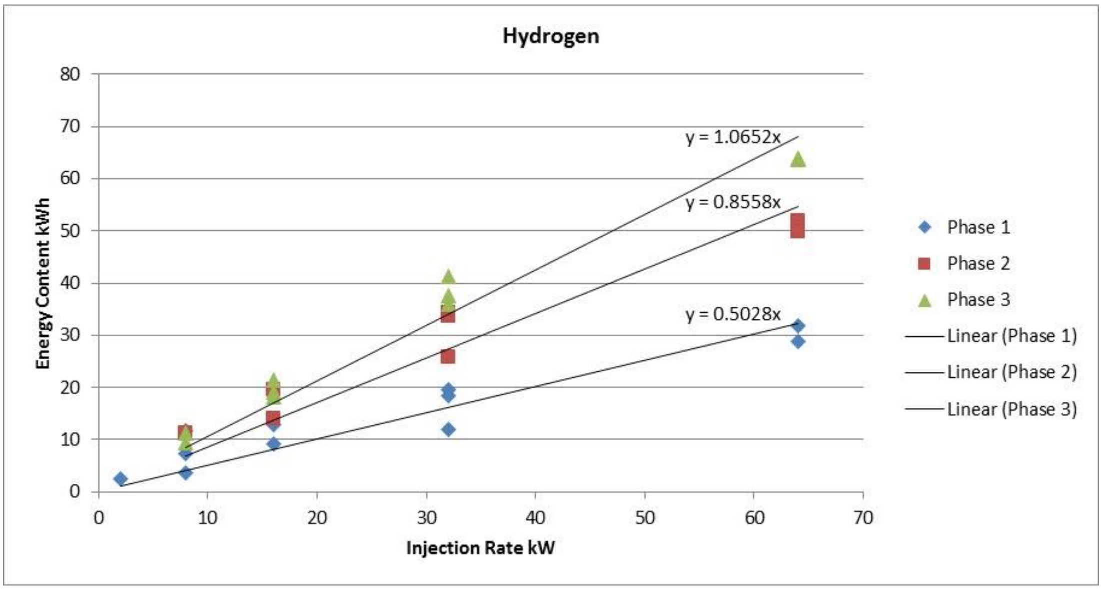
* This figure is lower than may be expected based on the ratios of the results from the earlier phases. Assuming the methane increases in the same way that hydrogen does from phase 2 to 3, we would expect a peak concentration within the range of 6.5% to 7%.

The rapid dispersion of both gases, but particularly hydrogen, means significantly less gas remains in the property than would be expected. The outcome of this dispersion means that the actual energy contained within the gas in the property is also less than may be expected. This is enumerated below.

When considering hydrogen, the maximum volume achieved (during low rate releases) was during the 64kW injection during Phase 3 (into the Living Room). Even during this test the energy content available within the gas at the end of the test period was 64kWh, out of a potential 160kWh injected into the property. This means only 40% of the available energy was actually retained in the property at the greatest air tightness and highest injection rate. Conversely, the energy contained in the natural gas equates to approximately 129kWh, approximately 80% of the available energy (potential 160kWh) at 64kW injection in Phase 3 (into the Living Room).

During Phase 1, the 64kW injections resulted in approximately 30kWh and 68kWh of energy within the property for hydrogen and methane respectively. This suggests, when considering leaks of the same magnitude, or hole size, there is approximately twice the energy contained within the property when considering natural gas compared to hydrogen. At lower injection rates the resultant energy within the property obviously decreases; however the ratio between hydrogen and methane remains consistent.

The following figures show the energy content of the property at each injection rate for hydrogen and methane. The results for the 100% natural gas and the 97% & 90% natural gas/hydrogen mixtures have been combined as the mixtures appear to show very similar characteristics to the 100% natural gas tests. It should be noted that these are indicative figures only and apply to the specific conditions observed within the property during the test work. There are further limiting factors such as wind conditions, and analyser error which contribute to the uncertainty of these figures and thus it should be stressed that they are not definitive.



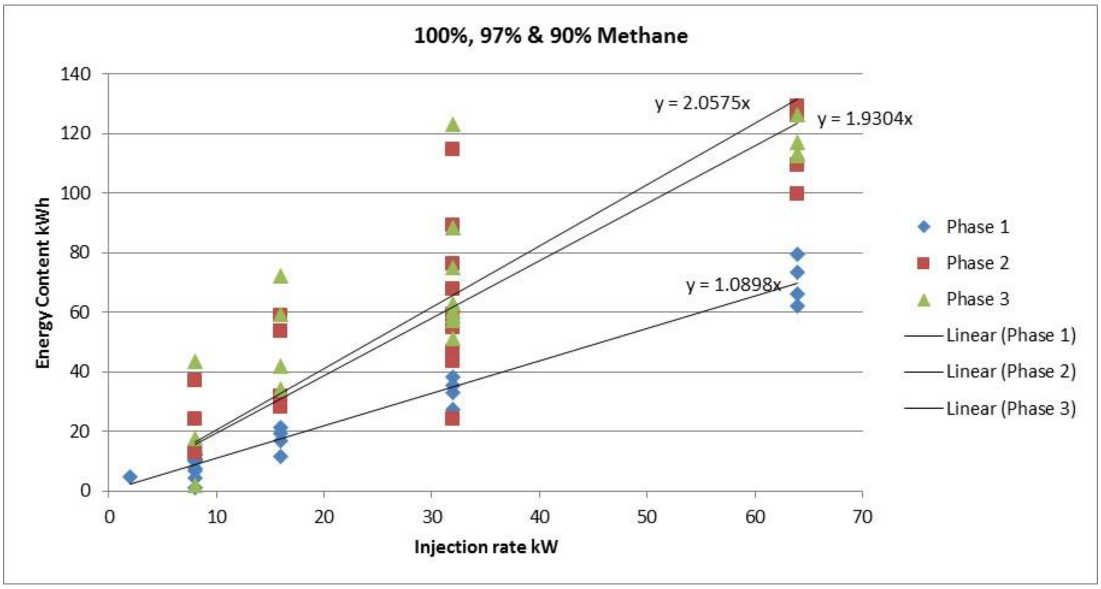


Figure 31: Graphs to show energy content achieved in the property at different injection rates

3.2 High Rate Simulations

In addition to the low rate releases; two high rate simulations were carried out to simulate a leak from a hydrogen vehicle and a leaking gas main external to the property.

3.2.1 Hydrogen Vehicle

The hydrogen vehicle test consisted of a 200kW leak simulated by injecting 100% hydrogen at 1000l/minute for 48 minutes into the lean-to. This was sized to simulate a failure in the low pressure side of a hydrogen vehicle with a flow limiter set to 200kW. As a vehicle fuel tank has a finite volume it was calculated that after 48 minutes the contents of the fuel store would have been exhausted.

The test was carried out four times; twice with the door between the lean-to and the kitchen closed and twice with the door open. After initial analysis the data was considered very consistent and as such the two tests under each condition were combined to increase the data set for the test. The results displaying gas concentration are shown below. As with the low rate releases the tapestries show the concentrations measured at each of the active sample points, with increasing colour intensity showing increasing concentrations. The various flammable limits are marked as per the tapestries in section 3.1.1 above.

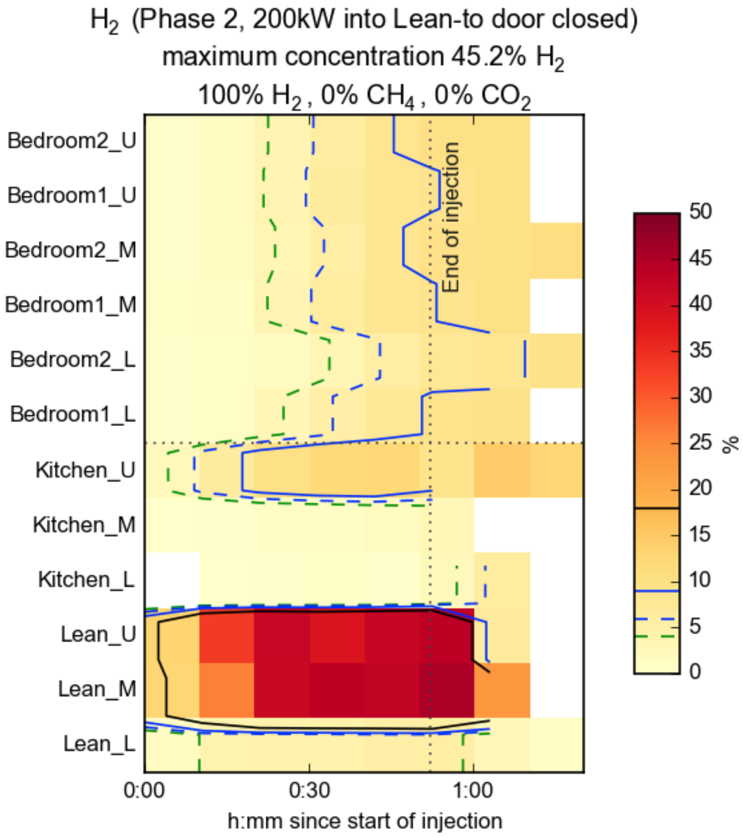


Figure 32: Vehicle simulation – Door closed

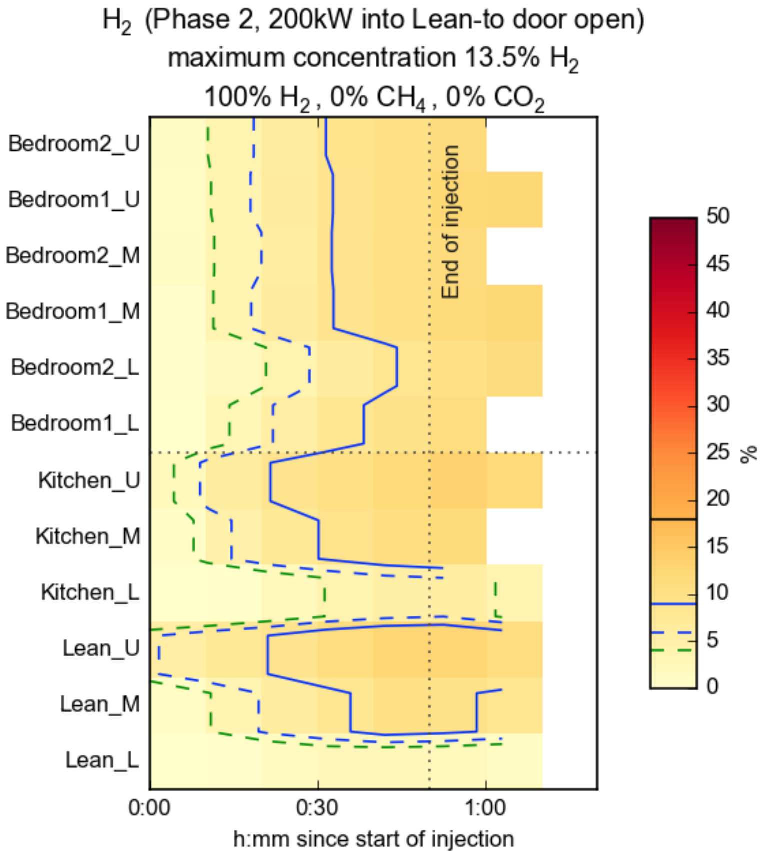


Figure 33: Vehicle simulation – Door open

The following table shows the peak hydrogen concentrations reached in the property during tests with the door open and closed.

Table 11: Peak hydrogen concentrations reached during leaking vehicle simulations

Kitchen Door	Lean-to	House	Kitchen	Bedrooms
Open	13.3%	13.5%	13.3%	12.0%
Closed	45.8%	13.6%	12.5%	10.0%

It is clear to see that when the door was closed the highest concentration was observed in the lean-to (~45%) and was significant in terms of risk of explosion. However, the time for which this concentration was observed was limited, as once the leak had stopped (in effect, the vehicle fuel tank was empty) and ventilation was introduced to the space, the hydrogen rapidly dispersed as it had done during the low rate releases.

Concentrations within the rest of the property during both door open and door closed tests were comparable to those observed at 64kW injections, with concentrations at the upper sample point in the kitchen similar to those measured in the bedrooms (~12% during the low releases compared to ~13% during the vehicle simulation).

With the door open, obvious stratification was observed in both the lean-to and kitchen with all sample points detecting a concentration of hydrogen; however with the door closed hydrogen was only detected at the upper sample point in the kitchen. This is shown in the figures below.

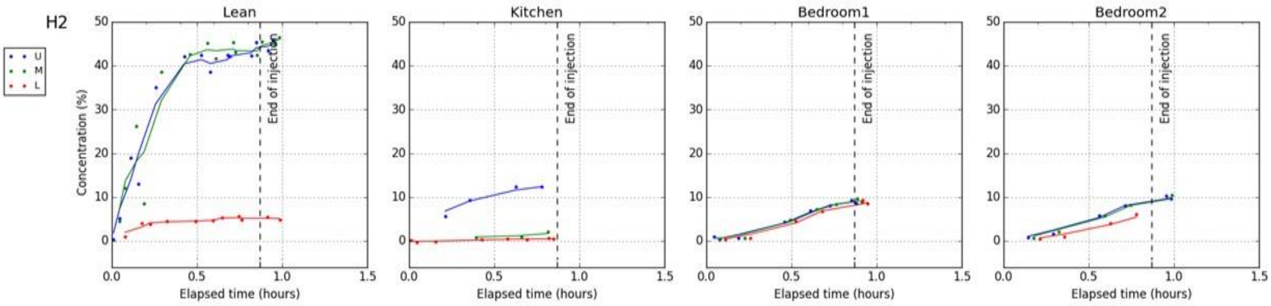


Figure 34: Evidence of stratification – Door Closed

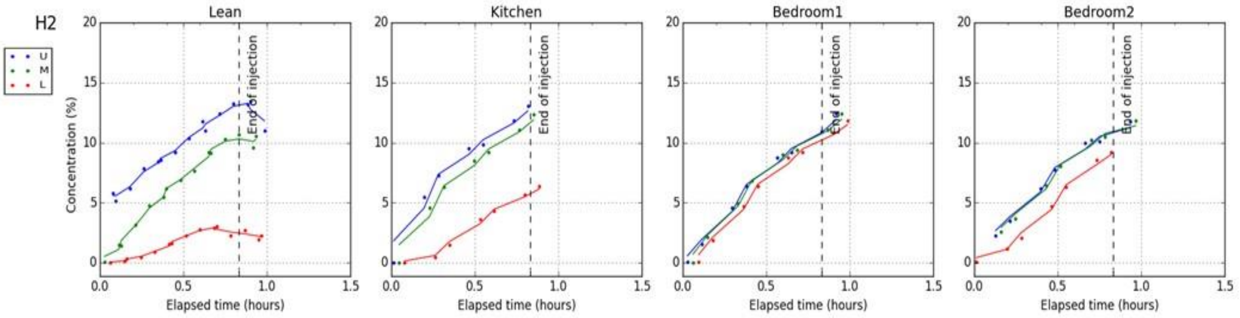


Figure 35: Evidence of stratification – Door Open [Note different scale to Figure above]

The concentrations reached in this test work are significant and raise the question as to how hydrogen cars should be garaged and the safety aspects surrounding their storage in an enclosed space. There is a risk of explosion in this setting when considering a spark from a refrigerator/freezer or other regular switching appliance located in the garage space and serious consideration should be given to recommending an interlock between an ATEX approved hydrogen sensor and master switch. For example, this could be placed in between an appliance plug and the wall mounted socket, isolating the appliance in the event of a hydrogen leak.

Consideration of the required ventilation of a garage space when considering the storage of hydrogen vehicles would also be recommended. Stratification shows that the same buoyancy effect is operating at these levels as was shown in the property, therefore ceiling or roof vents within a garage space may significantly reduce the risk of high concentrations of hydrogen being achieved if a vehicle were to leak, as the gas would disperse through this ventilation before dangerous levels were achieved.

This is further supported by studies by Swain et al, during which hydrogen leaks were simulated using helium in a garage space with ventilation located at different positions. Throughout these experiments it was found that vents near the top of the enclosure allowed hydrogen to escape effectively as long as vents were also present near the base of the enclosure to allow fresh air into the space and thus replace the hydrogen as it escaped[18]. These studies also further supported the accumulation of hydrogen at ceiling height and the presence of stratification as observed throughout the HyHouse experiments.

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[18] Proceedings of the 2000 DOE Hydrogen Program Review, NREL/CP-570-28890. Dispersion of Hydrogen Clouds, Michael R. Swain, Eric S. Grilliot, Matthew N. Swain. University of Miami.

3.3 Leaking Main

The leaking main consisted of simulated 200kW leaks of 100% hydrogen (1000l/minute) and 100% natural gas (300l/minute) into a duct that entered the property under the Dining Room as shown in the simple schematic below.

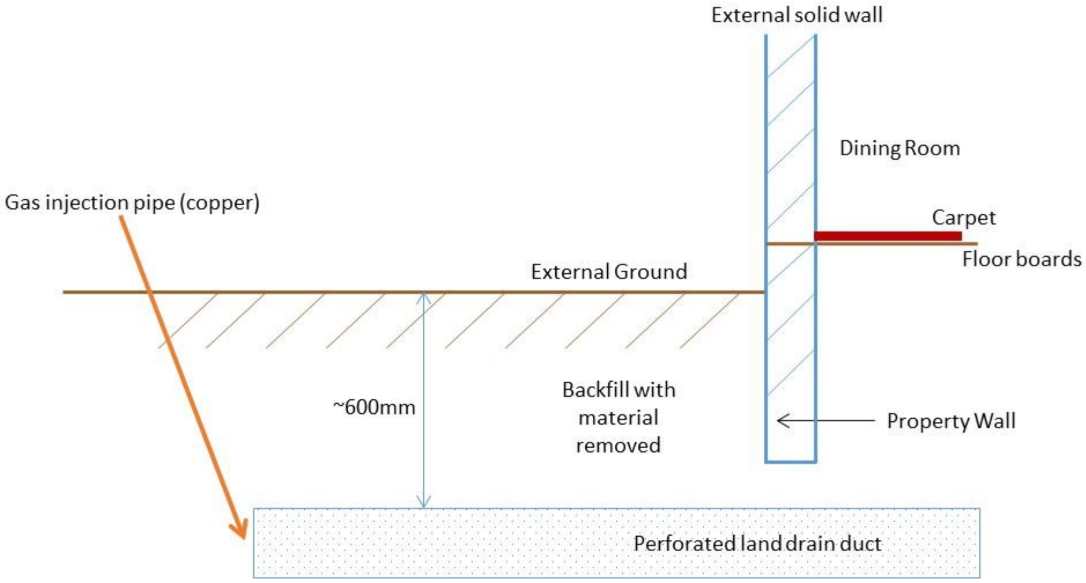

Figure 36: Schematic of leaking main simulation

The test was carried out twice with hydrogen and four times with natural gas (two repeat tests). As a result of analyser failure the data obtained for the natural gas simulations were not of sufficient quality to obtain quantifiable results, and therefore the natural gas simulations have been omitted from this report. The data for the hydrogen experiments was considered very consistent and so the tests were combined to increase the data set for the test (similar to the vehicle simulations above). The results are shown below:

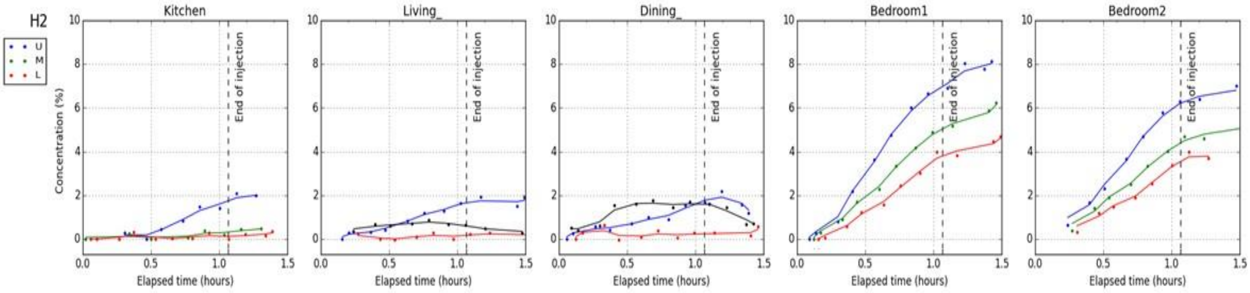

Figure 37: Combined results of hydrogen leaking main simulations

One of the most striking results of the leaking main experiments was the fact that unlike the low rate releases where stratification was observed throughout the ground floor of the property and not upstairs; the leaking main showed very little gas present in downstairs rooms (<2%) and significant stratification in both bedrooms. The dining room was carpeted and smoke tests carried out during the air tightness testing showed a good seal between the carpet and the skirting throughout the room. As a result, when the gas was injected under the floor, instead of rising through the floorboards and into the downstairs rooms, it is suggested that it travelled underneath the floorboards, through the internal wall cavities and was then released into the upstairs rooms - almost as if it was being injected upstairs. This led to the stratification effect in the bedrooms, caused by the same ‘chimney effect’ as discussed above during the low rate releases for downstairs.

The maximum concentrations reached during the leaking main simulations were far lower than expected (see figure below) and it is suggested that this was a result of the gas dispersing through the ground external to the property before entry under the dining room. Again, as with all of the test work, the hydrogen was shown to rise and thus collect at the highest point. However, concentrations reached were limited and would not be expected to cause significant overpressures if ignited.

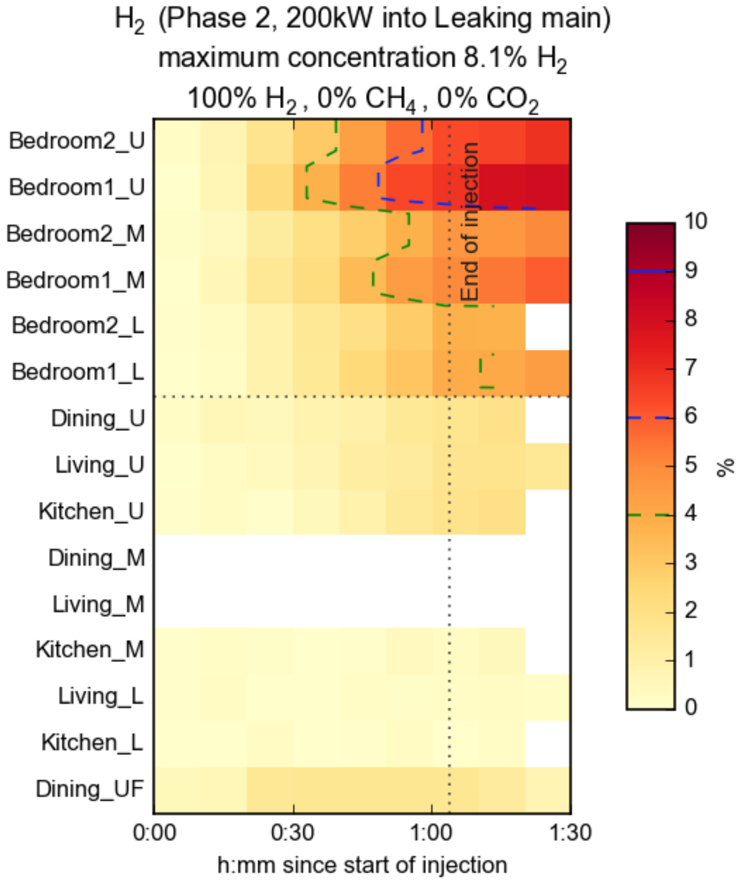

Figure 38: Hydrogen concentrations observed during leaking main simulation

These results support the discussion above, that ventilation within upstairs rooms is likely to mitigate the impact of a hydrogen leak, even if delivered at a high rate as would be expected through a ruptured gas main. This reinforces the need to consider ventilation requirements if hydrogen were to be used as a fuel source.

3.4 Uncertainties

As with all experimental work there is a level of uncertainty with regard to the results obtained. This has been estimated for each phase and is shown below.

The main contributions to uncertainty are considered to be:

1. Uncertainty of the analyser span calibration – the analysers were spanned upon each use, however the span gases were certified with a particular uncertainty and this will in turn affect the measurements made.
2. Uncertainty of the analyser zero calibration – the analysers were zeroed upon each use, however this zero adjustment drifted during each test, so a background measurement of air was made periodically and a linear correction was made to correct for this drift.
3. Uncertainty of the supply rates of the input gases –
    a. the rotameters used to select an input gas flow rate had a particular calibration uncertainty at a set of reference conditions and this in turn affected the measurements made;
    b. due to the nature of the gases there were constant small variations in the flow and also the temperature conditions.
4. Uncorrected effects (such as wind, temperature variation, etc.) – the wind conditions were monitored but corrections have not been made to individual test results
5. Repeatability – any other effects, for example the set-up of the measurement equipment or the conditions in the house being slightly different from test to test

The uncertainty contributions from (1) and (3a) have been estimated from manufacturer and calibration data, or a “Type B” method. The remaining contributions have been collectively estimated via a statistical approach[19], or a “Type A” method.

The relative contributions to uncertainty are expressed in the table below. Some of the contributions to uncertainty differ from test-to-test. This is mostly a reflection of:

a. The fact that the measured values in phase 1 were small, and so although the absolute uncertainty may be the same, the relative uncertainty is larger.

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[19] It was assumed (after graphical analysis - see **Figure 31**) that the average gas concentration in the house responded linearly according to the injection rate of that gas. The average deviation from the best fit line was then used to estimate the variation from test-to-test.

b. The performance issues experienced with the methane analysers in phases 2 and 3, which increased both the absolute and relative uncertainty.

Table 12: Relative contributions to uncertainty for each phase of the test work[20]

Contribution	Hydrogen			Methane		
	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3
(1) Uncertainty of the analyser span calibration	5% relative	5% relative	5% relative	5% relative	5% relative	5% relative
(3a) Uncertainty of the supply rates of the input gases	4% relative	4% relative	4% relative	4% relative	4% relative	4% relative
All other effects	27% relative	16% relative	12% relative	12% relative	29% relative	29% relative
Combined uncertainty	28% relative	17% relative	14% relative	14% relative	30% relative	30% relative

These equate to the absolute uncertainties given in Table 13.

Table 13: Absolute uncertainties for each phase of the test work[20]

Contribution	Hydrogen			Methane		
	Phase 1	Phase 2	Phase 3	Phase 1	Phase 2	Phase 3
Absolute uncertainty in percentage points	1.1%	1.2%	1.2%	0.4%	1.8%	1.8%

These figures reflect the uncertainty of any particular test result (e.g. final gas concentration). When, in this report, more than one test result has been considered in the drawing of a conclusion, the uncertainty will be reduced.

It is clear that as the experimental work progressed the level of uncertainty for methane increased and this was due to the decreased performance of the analysers.

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[20] (at k = 2 coverage factor)

4 Implication of Findings

Whilst a gas network retains its mechanical integrity (i.e. is leak tight) the risk to the general public is independent of the gas being transported. However, this study has shown that, when leaks occur, the risks associated with hydrogen are comparable to those associated with a leak from natural gas (at the conditions observed at Glenglass Cottage). This means that with attention to the specific characteristics of hydrogen it can be considered to be ‘just another flammable gas’.

Overall, concentrations of hydrogen within the test property under simulated leakage conditions were not as high as were originally expected. The low calorific value of hydrogen meant that approximately 340%v/v of hydrogen was injected compared to natural gas to obtain the same energy input. However, importantly, concentrations within the property did not reflect this. It can be theorised that this was a direct result of the buoyancy effect of hydrogen and suggests that generally (in a standard domestic setting) a low rate leak of hydrogen gas will easily disperse before dangerous concentrations are reached. The only exception to this is a sudden and high rate release such as that resulting from damage to the fuel system of a hydrogen vehicle; however with certain actions even the risk from this could be reduced.

The most significant aspect of the gas leaks detected throughout this study is the ‘chimney (or stack) effect’, where the injection of gas of a lower density than the air creates a movement of air into the property and thus the gas rises. This is especially pronounced with hydrogen because the very low density of hydrogen compared to air means the gas rises quickly and accumulates in the highest place; in the case of Glenglass, at ceiling height downstairs and in the upstairs bedrooms. It is suggested that to mitigate the effect of this process, ceiling vents which are either open to the roof void or ducted to outside could be fitted to any property in which hydrogen was to be used

Ventilation and positioning of ventilation has also been shown to be of significant importance in a garage situation in which a hydrogen vehicle is stored. Concentrations from a hydrogen vehicle appear to be significant if the space into which the leak occurs is sealed off from the rest of the property. Ventilation at ceiling and floor height is likely to reduce the accumulation of high concentrations within the garage space.

The data also presents stratification as prominent, with hydrogen concentrations highest at the top of the room. If ceiling ventilation were present, the risk from hydrogen accumulation is likely to be greatly reduced. It is also suggested that in garage settings, a hydrogen sensor (at the highest point) could be interlocked with a flame proof master shut-off switch which would electrically isolate any appliances before flammable concentrations of hydrogen occurred. Thus reducing the risk of accidental ignition from an appliance such as a fridge/freezer.

Another implication lies with gas detection. Overall, detection is paramount in gas safety, with the current natural gas odourised with mercaptans which contains sulphur compounds.

Humans are highly receptive to the smell of mercaptan. If 100% hydrogen were to be used as a fuel it would be necessary to introduce an odorant to aid detection. However, so far odourisation has not been favoured by the hydrogen industry as the compounds within the current odorisers lead to problems in fuel cells.

5 Next Steps and Future Scope

This project has provided a real insight into the risks associated with hydrogen as a fuel gas, implying that although concentrations of hydrogen from a leak are somewhat higher than methane; the characteristics of the gases within a standard domestic setting are remarkably similar and the risk is no greater when considering a leak of hydrogen compared to natural gas. This work has shown ways of mitigating risks associated with hydrogen and also how potentially dangerous situations can be avoided.

An obvious follow on from this work, now that the likely concentrations of each test gas is understood, is to investigate the impact/damage capacity of explosions of these concentrations within an enclosed space, as may be experienced in a domestic setting. The same fuel gases would be used as in this experiment (100% natural gas, 100% hydrogen, 10% hydrogen, 3% hydrogen and Town Gas) allowing direct cross correlation between the studies.

Another possible avenue for further work is the need for odourisation of hydrogen if it were used as a fuel gas. Due to the large volume changes induced by hydrogen, it is foreseeable that hydrogen leaks would be much more readily detected by smell. It is suggested that further work in this area is essential before the roll out of hydrogen can be fully considered.

When considering hydrogen vehicles, there is significant scope to carry out further work on safety aspects of filling stations (garage forecourts). This has already been noted by industry members following the HyHouse project and discussions are continuing to formulate a work package which investigates the concentrations of hydrogen reached in a forecourt situation in the event of a hydrogen leak from a dispenser. As with the HyHouse work, the results would be made publically available and could be used to influence safety regulations surrounding forecourt environments, hydrogen dispensing methods and garage construction/alteration to accommodate hydrogen filling dispensers.

In addition, to aid the deployment of hydrogen it is suggested that work could be carried out to test the types of fittings used within a hydrogen system. The use of mechanical fittings is often deprecated with hydrogen because it is a very small molecule, often used at pressure and leaks can be volumetrically large. Kiwa suggest that a test programme in which joints of varying type are made, unmade and stressed (both with vibration and external flame to assess the risks and likelihood of leaks from such fittings. The results would be made public and would offer information on the safety aspects of these types of joint for use in DSEAR (Dangerous Substances and Explosive Atmospheres Regulations) and ATEX (controlling explosive atmospheres) calculations.

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7 Appendix 1 – Hole Size Calculations

The calculation of equivalent hole sizes is based on the equation for a small bore orifice:

$$q_m = \frac{\epsilon C}{\sqrt{1-\beta^4}} A \sqrt{2\rho\Delta p}$$

Where: q_m is the mass flow rate through the orifice
A is the size of the orifice
ρ is the density of gas upstream of the orifice
Δp is the pressure difference across the orifice
and the other terms are approximately constant, specific to the scenario

Modelling the hole in a pipe as a small round orifice in a large plate, the equation simplifies, and can be rearranged to:

$$A \approx \frac{\rho\, q_v}{C\sqrt{2\rho\Delta p}}$$

Where: q_v is the volumetric flow rate through the orifice
C is assumed to be 0.7
ϵ is assumed to be 1
β is assumed to be 0

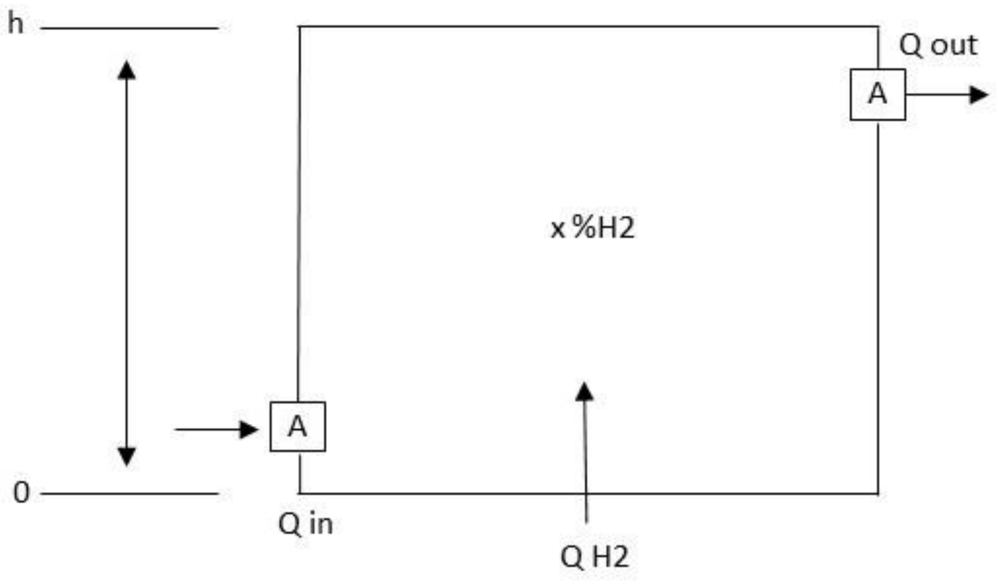
By combining the densities of Hydrogen, Natural Gas and Carbon Dioxide according to their volumetric proportions, the following equivalent circular hole sizes were calculated:

Table 14: Hole Sizes

Energy (kW)	Gas Mixture	Circular hole ϕ (mm)
8	100% Hydrogen	2.4
	100% Natural Gas	2.3
	3% Hydrogen	2.3
	10% Hydrogen	2.3
	Town Gas	3.5
16	100% Hydrogen	3.4
	100% Natural Gas	3.2
	3% Hydrogen	3.2
	10% Hydrogen	3.2
	Town Gas	5.0
32	100% Hydrogen	4.8
	100% Natural Gas	4.5
	3% Hydrogen	4.5
	10% Hydrogen	4.6
	Town Gas	7.1
64	100% Hydrogen	6.7
	100% Natural Gas	6.4
	3% Hydrogen	6.4
	10% Hydrogen	6.5
	Town Gas	10.0

8 Appendix 2 – Density Theory Calculations

To allow comparison between theoretical and actual results, a density (buoyancy) model was used to estimate the concentrations that would be achieved within an enclosed space, (in this experiment, the house). This theory used a simple vented box (as shown below) with known vent sizes to calculate the concentrations that would remain within the space during hydrogen injection. The model assumes the gas within the space is well mixed and at steady state.



The model uses the following steps:

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

9 Appendix 3 – Averaged Tapestry Graphs for All Tests

Please note that the complete data set gathered through the whole experimental programme is available from the authors on request.

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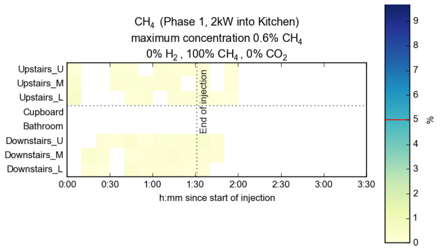
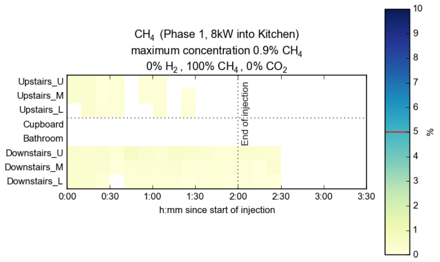

CH4 (Phase 1, 2kW into Kitchen)
maximum concentration 0.6% CH4
0% H2 , 100% CH4 , 0% CO2
Upstairs_U
Upstairs_M
Upstairs_L
Cupboard
Bathroom
Downstairs_U
Downstairs_M
Downstairs_L
End of injection
0:00
0:30
1:00
1:30
2:00
2:30
3:00
3:30
h:mm since start of injection
0
1
2
3
4
5
6
7
8
9
%

2.


CH4 (Phase 1, 8kW into Kitchen)
maximum concentration 0.9% CH4
0% H2 , 100% CH4 , 0% CO2
Upstairs_U
Upstairs_M
Upstairs_L
Cupboard
Bathroom
Downstairs_U
Downstairs_M
Downstairs_L
End of injection
0:00
0:30
1:00
1:30
2:00
2:30
3:00
3:30
h:mm since start of injection
0
1
2
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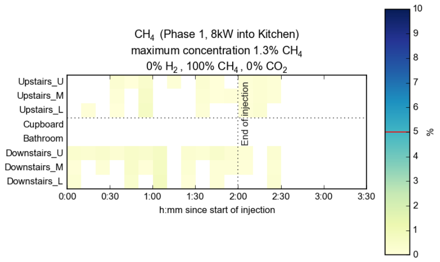
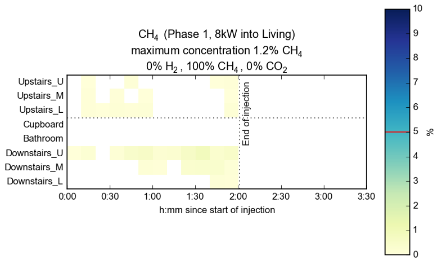
8
9
10
%

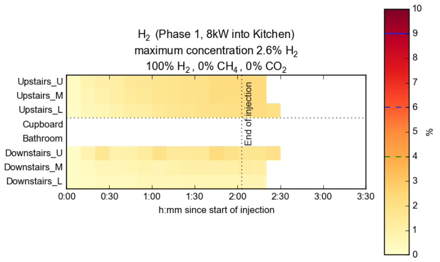
3.


CH4 (Phase 1, 8kW into Kitchen)
maximum concentration 1.3% CH4
0% H2 , 100% CH4 , 0% CO2
Upstairs_U
Upstairs_M
Upstairs_L
Cupboard
Bathroom
Downstairs_U
Downstairs_M
Downstairs_L
End of injection
0:00
0:30
1:00
1:30
2:00
2:30
3:00
3:30
h:mm since start of injection
0
1
2
3
4
5
6
7
8
9
10
%

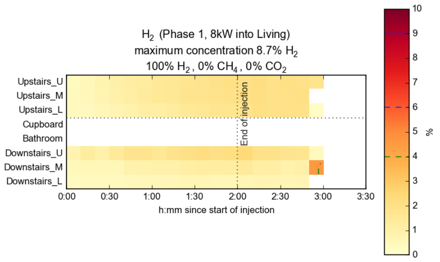
4.


CH4 (Phase 1, 8kW into Living)
maximum concentration 1.2% CH4
0% H2 , 100% CH4 , 0% CO2
Upstairs_U
Upstairs_M
Upstairs_L
Cupboard
Bathroom
Downstairs_U
Downstairs_M
Downstairs_L
End of injection
0:00
0:30
1:00
1:30
2:00
2:30
3:00
3:30
h:mm since start of injection
0
1
2
3
4
5
6
7
8
9
10
%

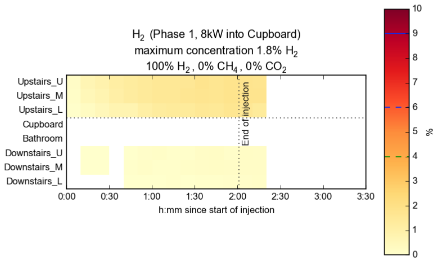
5.


H2 (Phase 1, 8kW into Kitchen)
maximum concentration 2.6% H2
100% H2 , 0% CH4 , 0% CO2
Upstairs_U
Upstairs_M
Upstairs_L
Cupboard
Bathroom
Downstairs_U
Downstairs_M
Downstairs_L
End of injection
0:00
0:30
1:00
1:30
2:00
2:30
3:00
3:30
h:mm since start of injection
0
1
2
3
4
5
6
7
8
9
10
%

6.


H2 (Phase 1, 8kW into Living)
maximum concentration 8.7% H2
100% H2 , 0% CH4 , 0% CO2
Upstairs_U
Upstairs_M
Upstairs_L
Cupboard
Bathroom
Downstairs_U
Downstairs_M
Downstairs_L
End of injection
0:00
0:30
1:00
1:30
2:00
2:30
3:00
3:30
h:mm since start of injection
0
1
2
3
4
5
6
7
8
9
10
%

7.


H2 (Phase 1, 8kW into Cupboard)
maximum concentration 1.8% H2
100% H2 , 0% CH4 , 0% CO2
Upstairs_U
Upstairs_M
Upstairs_L
Cupboard
Bathroom
Downstairs_U
Downstairs_M
Downstairs_L
End of injection
0:00
0:30
1:00
1:30
2:00
2:30
3:00
3:30
h:mm since start of injection
0
1
2
3
4
5
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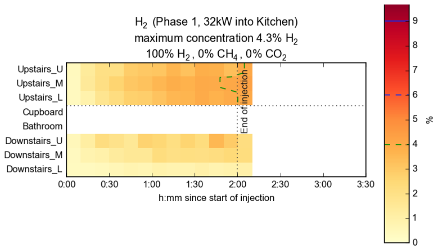
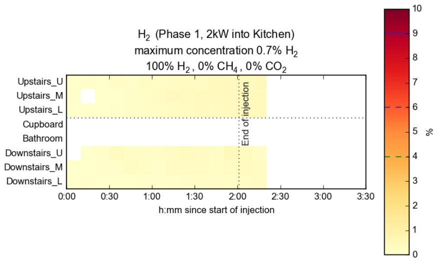
10
%

8.



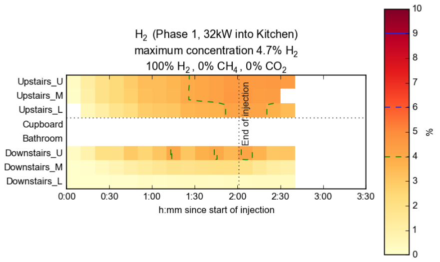
H_2 (Phase 1, 32kW into Kitchen)
maximum concentration 4.3% H_2
100% H_2 , 0% CH_4 , 0% CO_2

9.



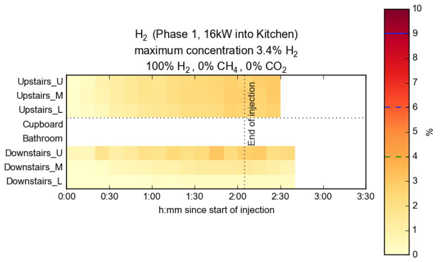
H_2 (Phase 1, 2kW into Kitchen)
maximum concentration 0.7% H_2
100% H_2 , 0% CH_4 , 0% CO_2

10.



H_2 (Phase 1, 32kW into Kitchen)
maximum concentration 4.7% H_2
100% H_2 , 0% CH_4 , 0% CO_2

11.



H_2 (Phase 1, 16kW into Kitchen)
maximum concentration 3.4% H_2
100% H_2 , 0% CH_4 , 0% CO_2

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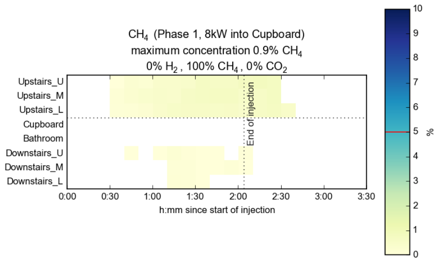
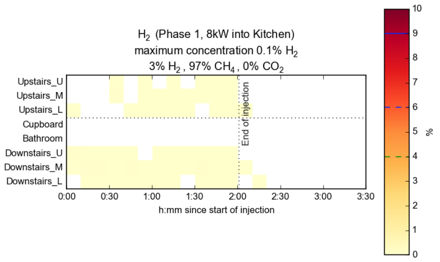


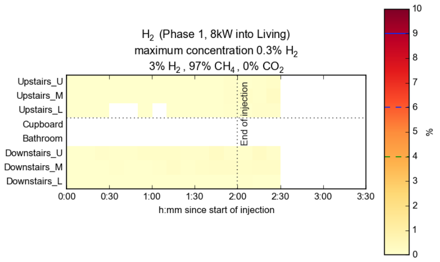
CH_4 (Phase 1, 8kW into Cupboard)
maximum concentration 0.9% CH_4
0% H_2 , 100% CH_4 , 0% CO_2

13.



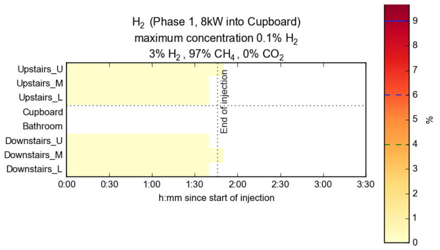
H_2 (Phase 1, 8kW into Kitchen)
maximum concentration 0.1% H_2
3% H_2 , 97% CH_4 , 0% CO_2

14.



H_2 (Phase 1, 8kW into Living)
maximum concentration 0.3% H_2
3% H_2 , 97% CH_4 , 0% CO_2

15.



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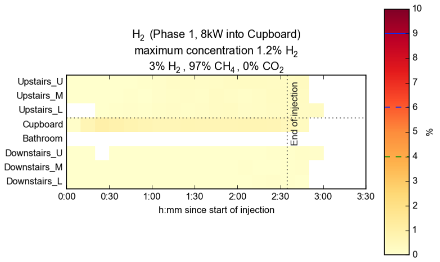

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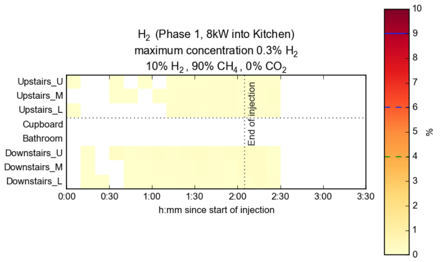

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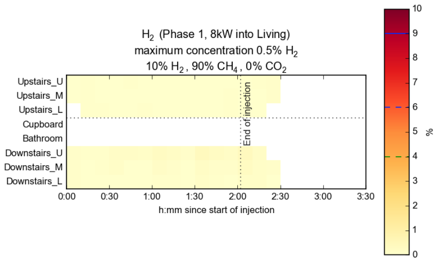

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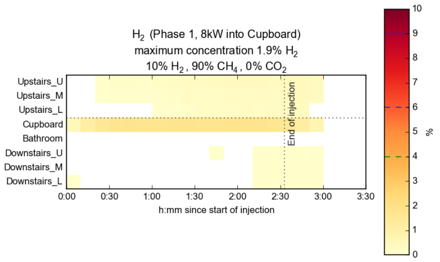

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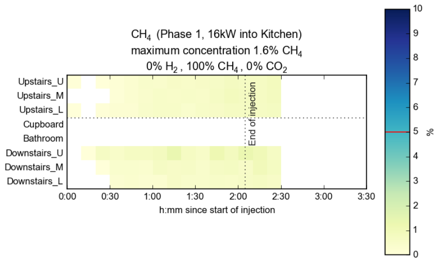

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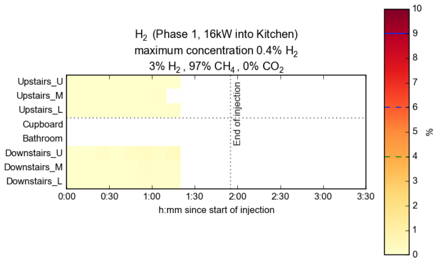

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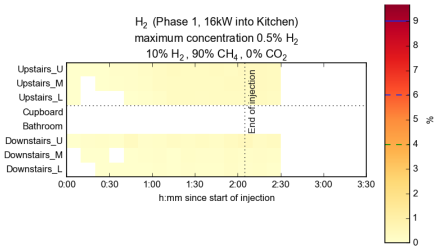

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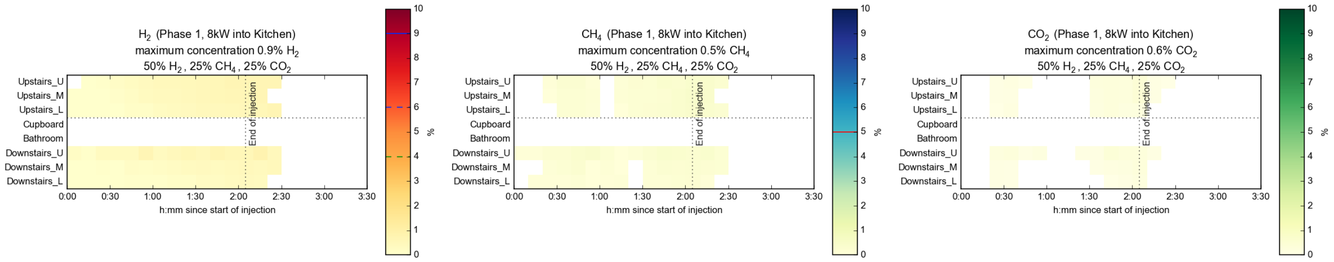

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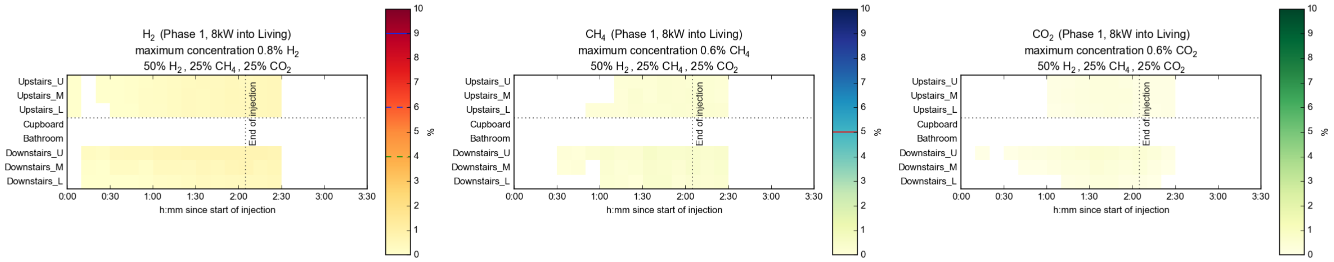

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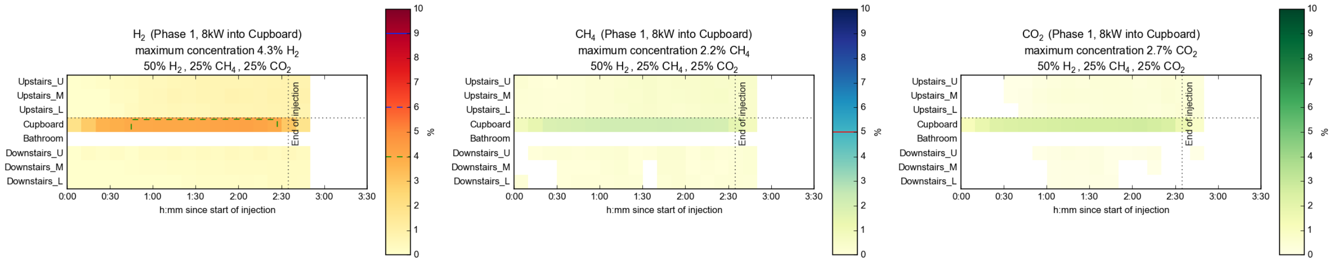

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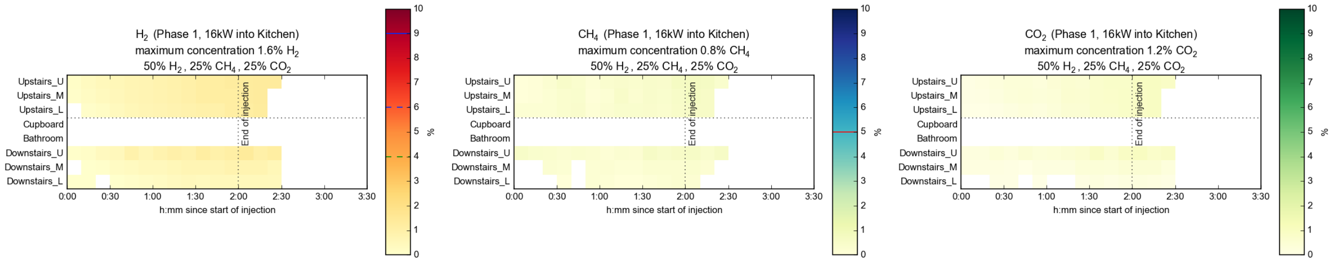

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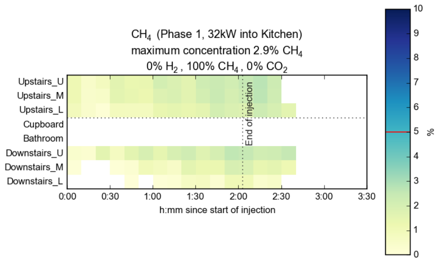

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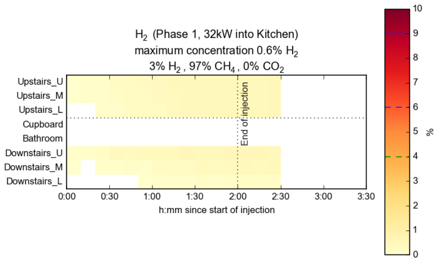

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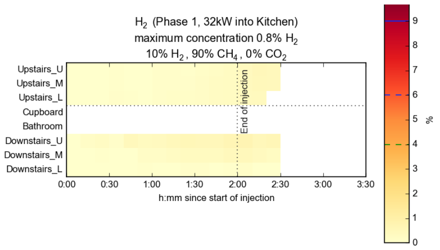

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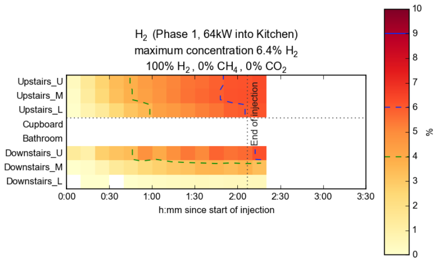

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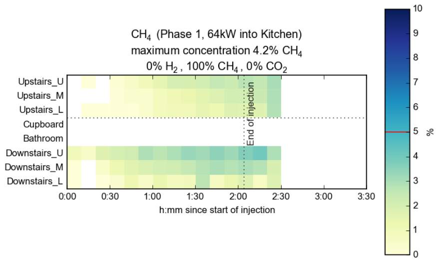

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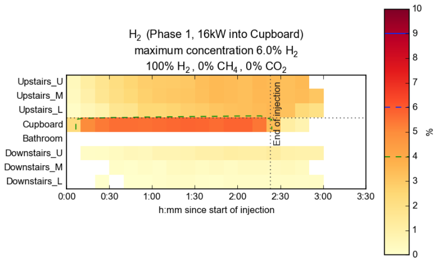

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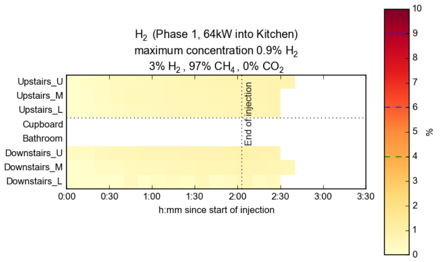

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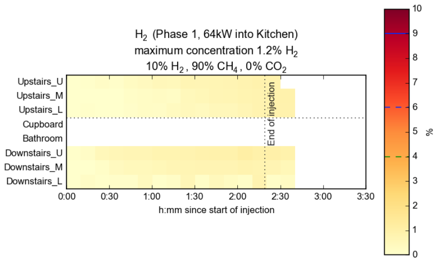

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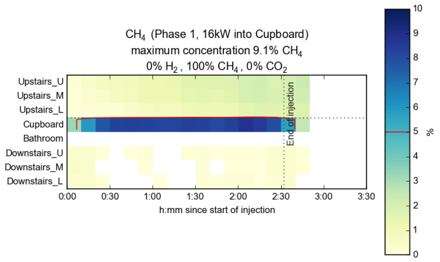

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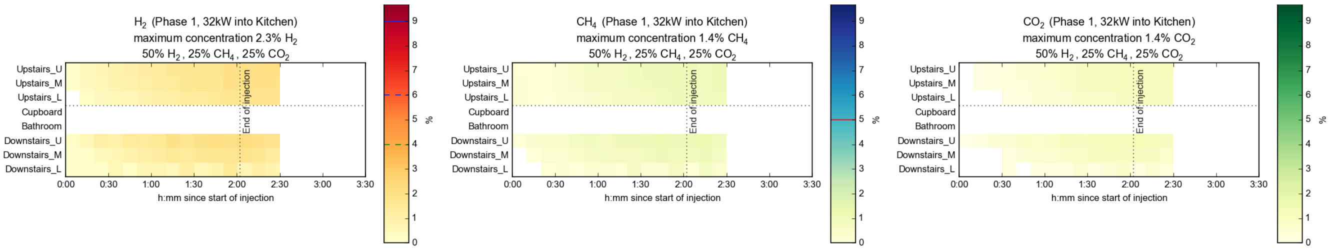

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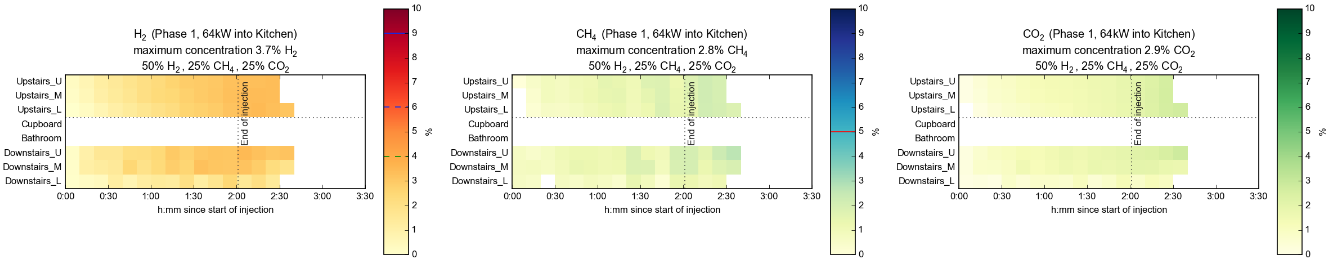

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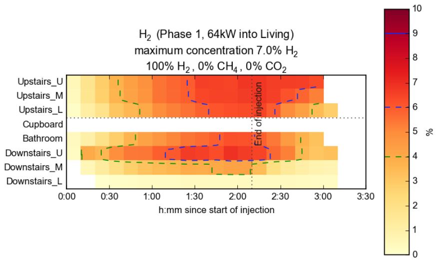

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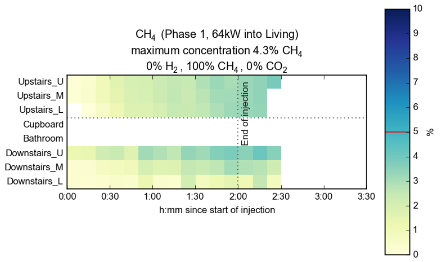

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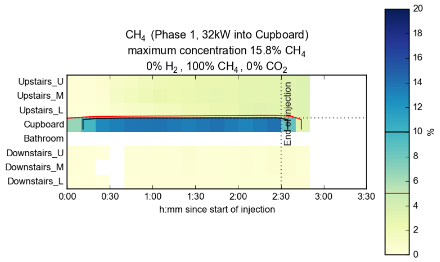

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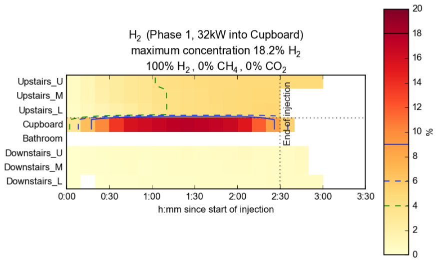

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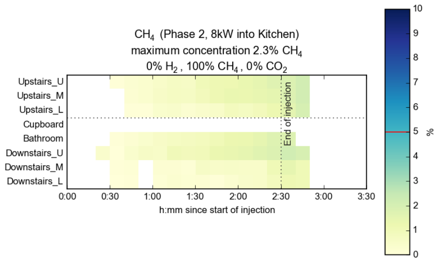

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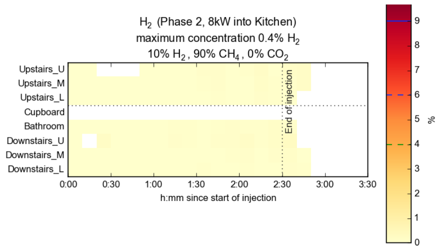

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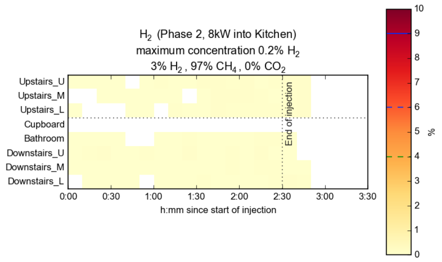

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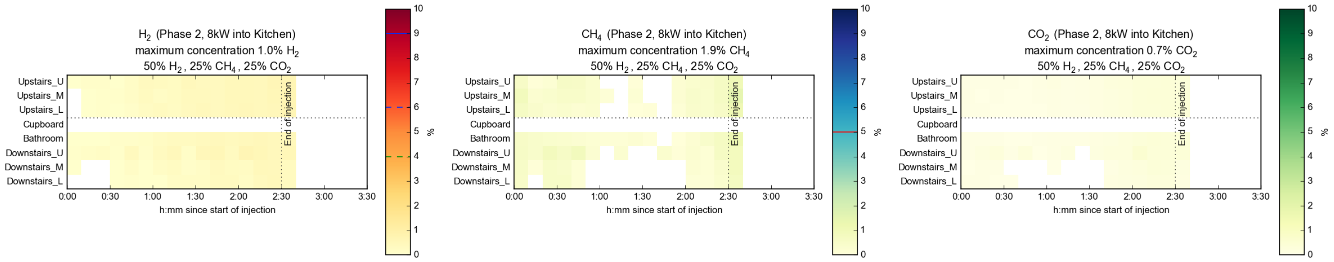

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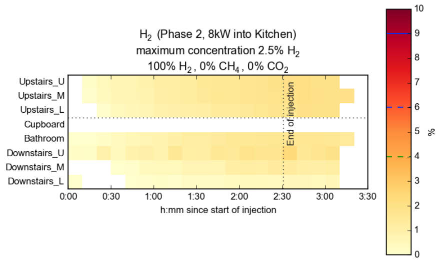

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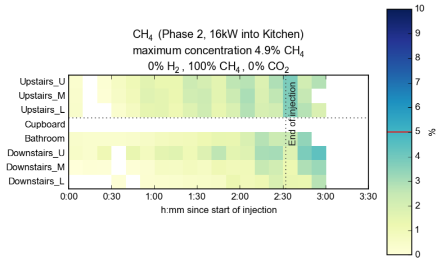

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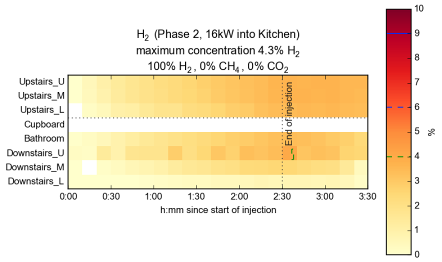

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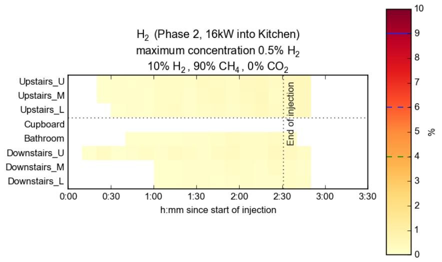

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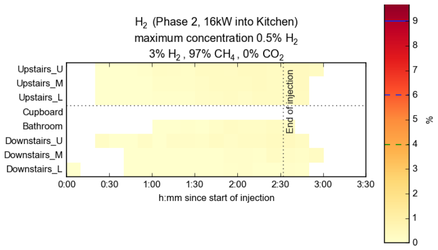

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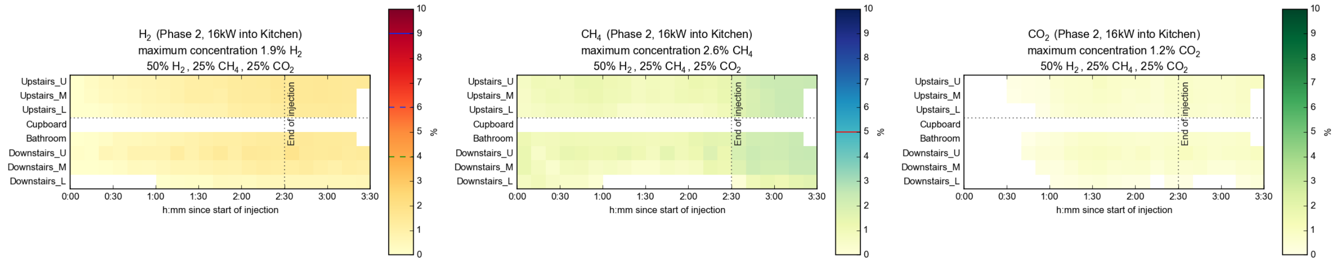

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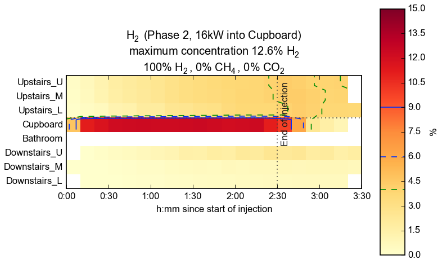

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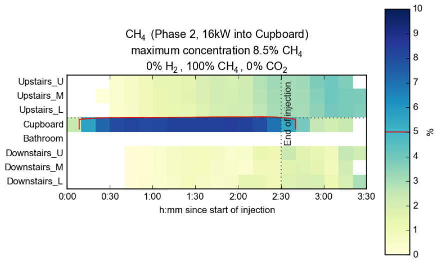

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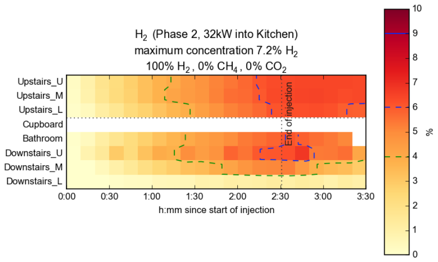

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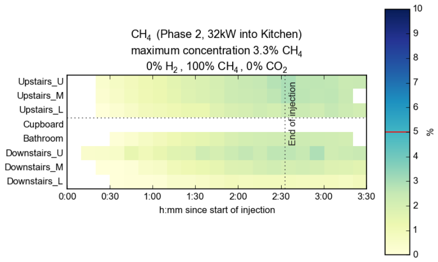

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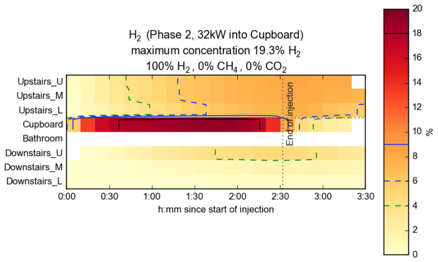

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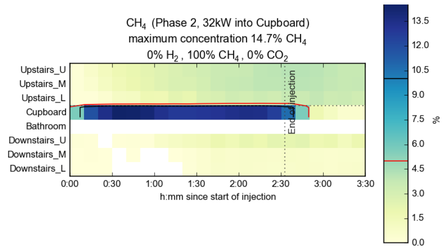

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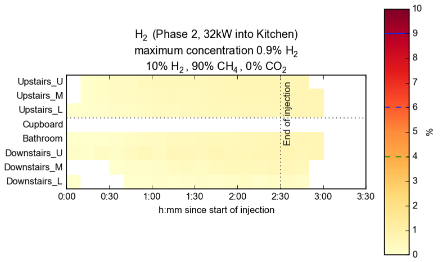

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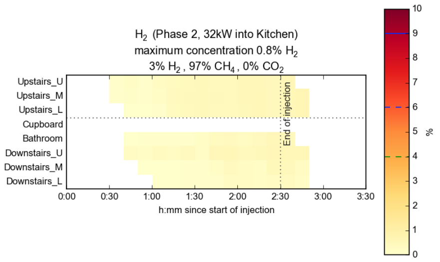

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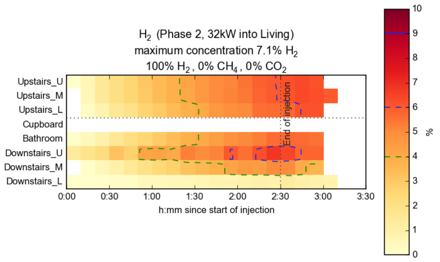

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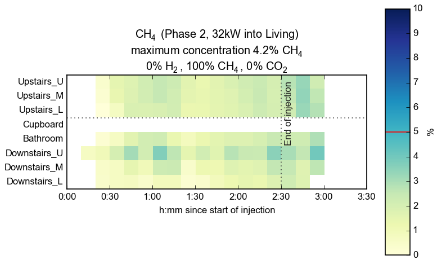

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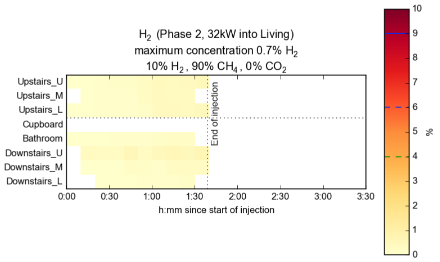

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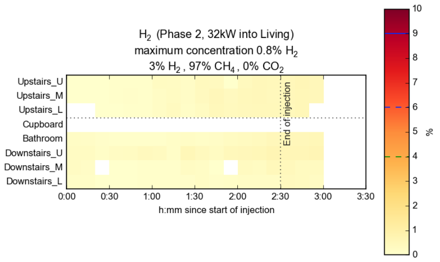

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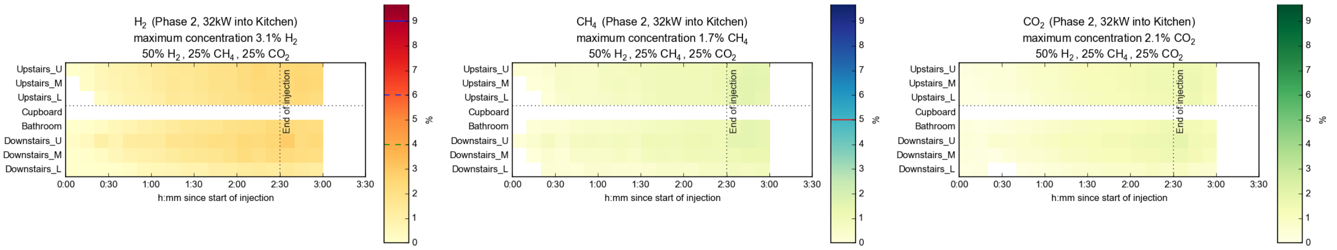

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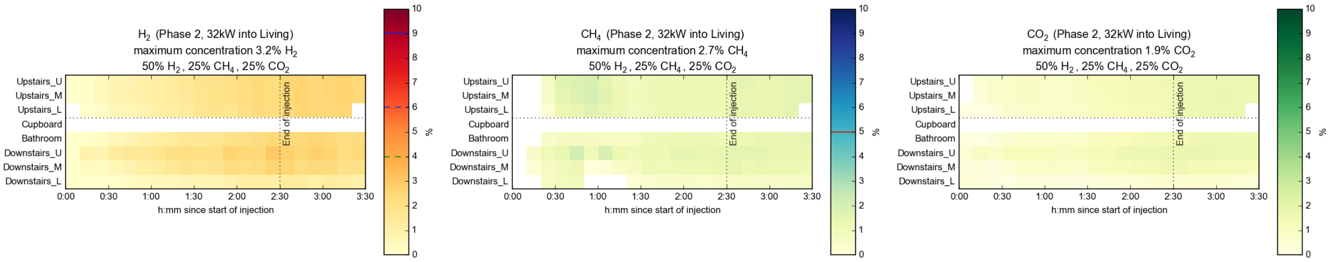

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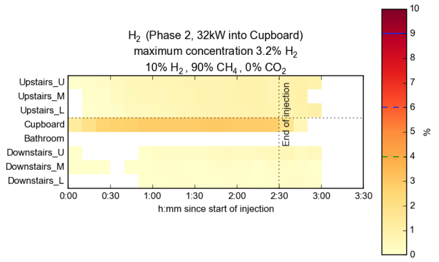

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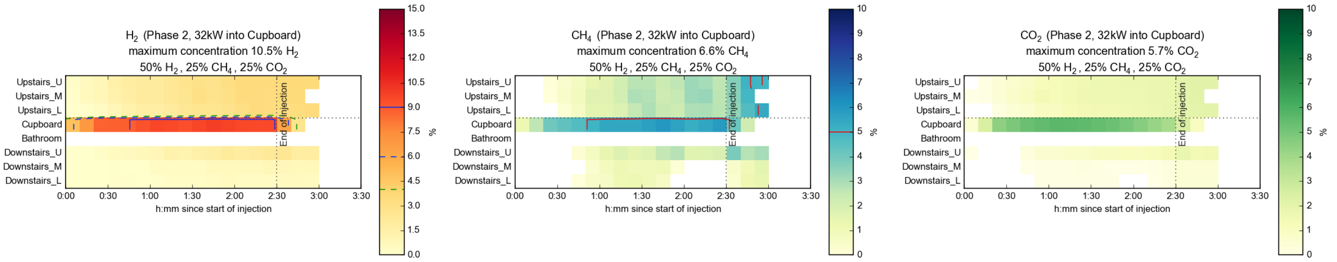

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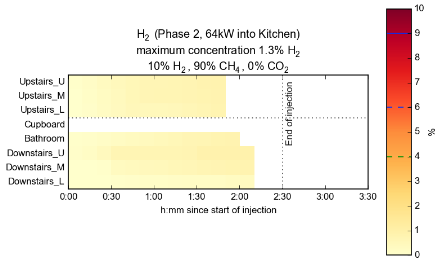

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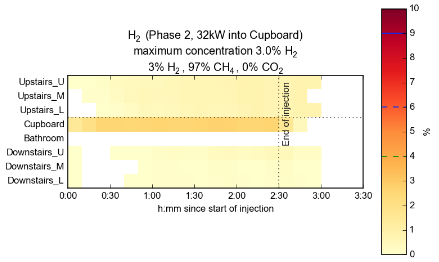

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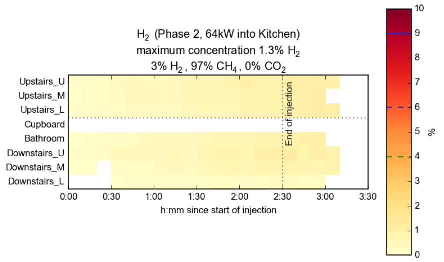

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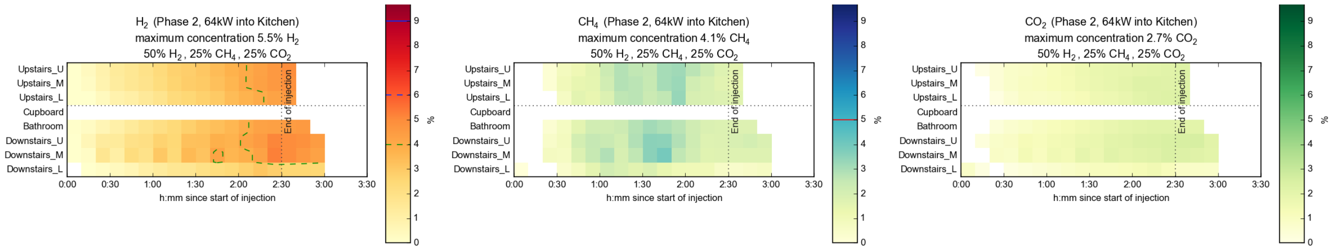
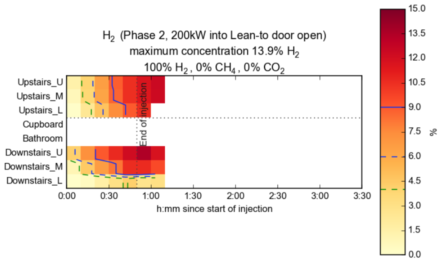


H_2 (Phase 2, 64kW into Kitchen)
maximum concentration 5.5% H_2
50% H_2, 25% CH_4, 25% CO_2

CH_4 (Phase 2, 64kW into Kitchen)
maximum concentration 4.1% CH_4
50% H_2, 25% CH_4, 25% CO_2

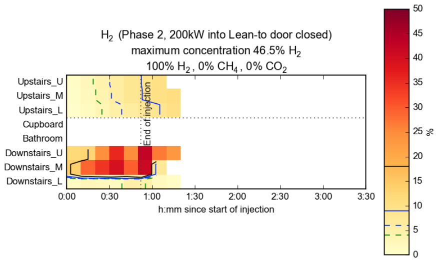
CO_2 (Phase 2, 64kW into Kitchen)
maximum concentration 2.7% CO_2
50% H_2, 25% CH_4, 25% CO_2

72.



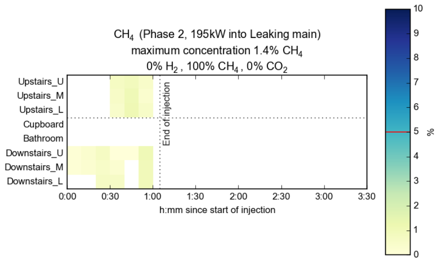
H_2 (Phase 2, 200kW into Lean-to door open)
maximum concentration 13.9% H_2
100% H_2, 0% CH_4, 0% CO_2

73.



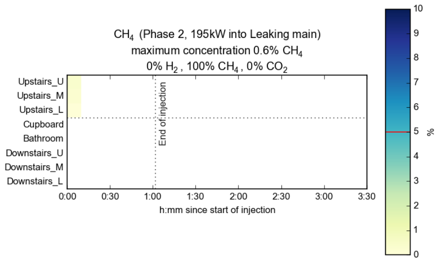
H_2 (Phase 2, 200kW into Lean-to door closed)
maximum concentration 46.5% H_2
100% H_2, 0% CH_4, 0% CO_2

74.



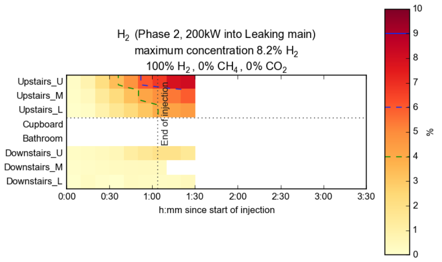
CH_4 (Phase 2, 195kW into Leaking main)
maximum concentration 1.4% CH_4
0% H_2, 100% CH_4, 0% CO_2

75.



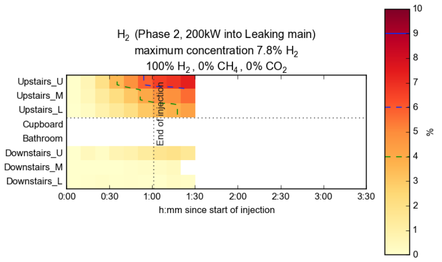
CH_4 (Phase 2, 195kW into Leaking main)
maximum concentration 0.6% CH_4
0% H_2, 100% CH_4, 0% CO_2

76.



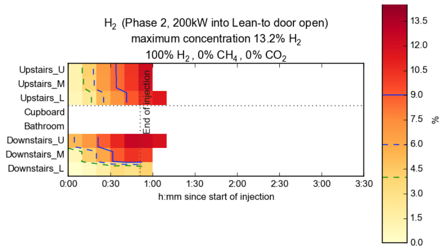
H_2 (Phase 2, 200kW into Leaking main)
maximum concentration 8.2% H_2
100% H_2, 0% CH_4, 0% CO_2

77.



H_2 (Phase 2, 200kW into Leaking main)
maximum concentration 7.8% H_2
100% H_2, 0% CH_4, 0% CO_2

78.



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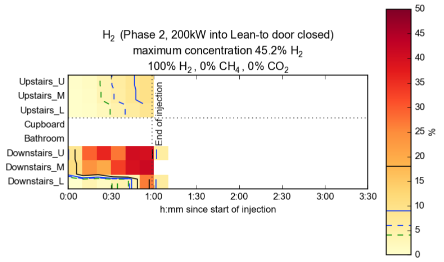

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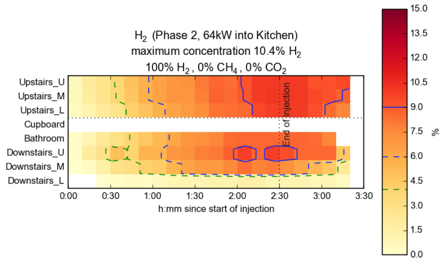

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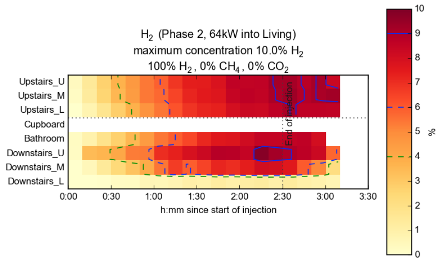

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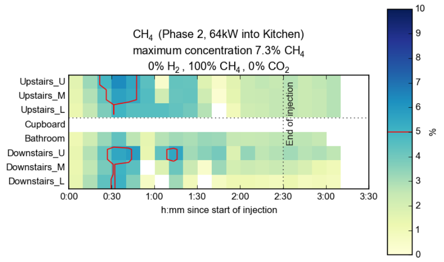

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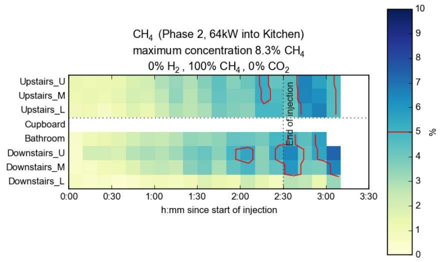

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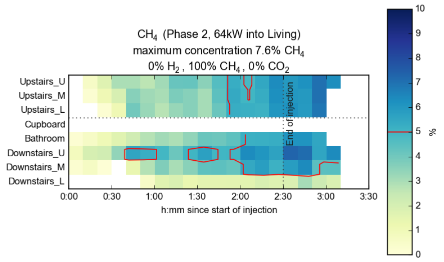

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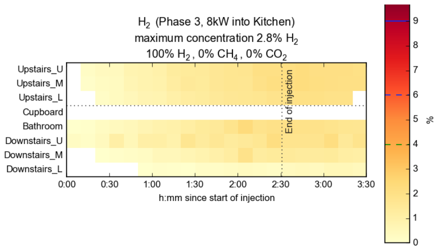

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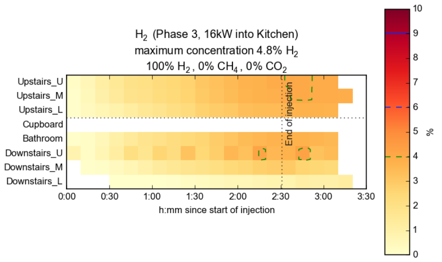

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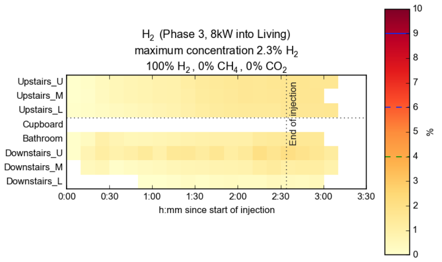

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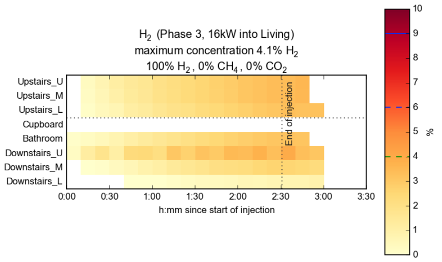

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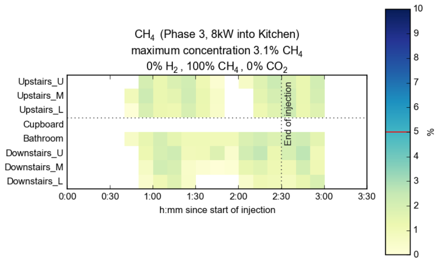

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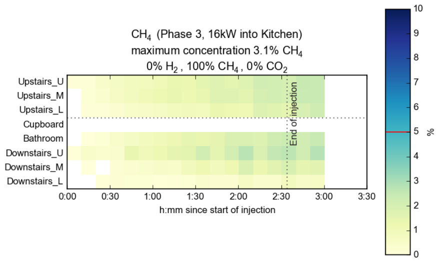

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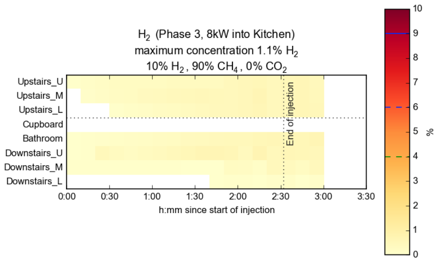

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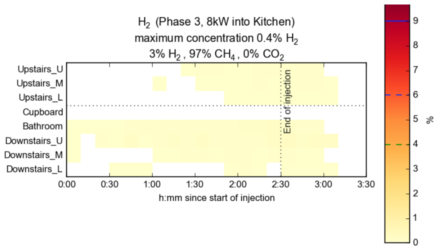

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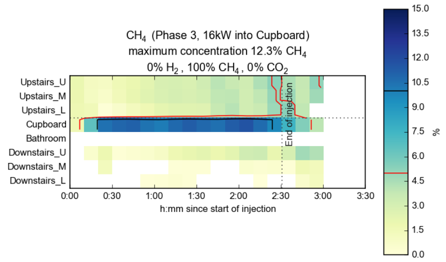

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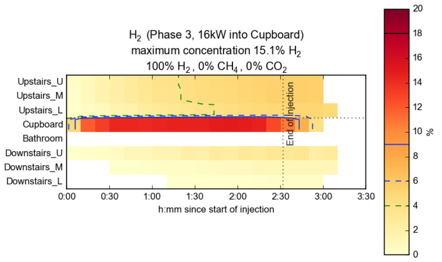

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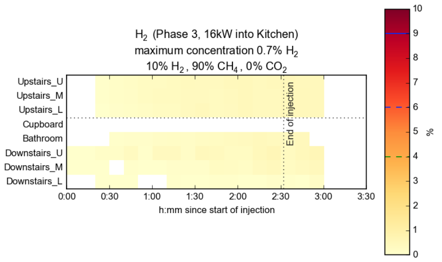

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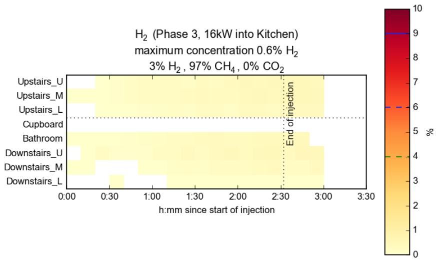

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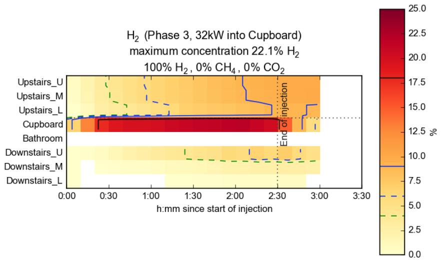

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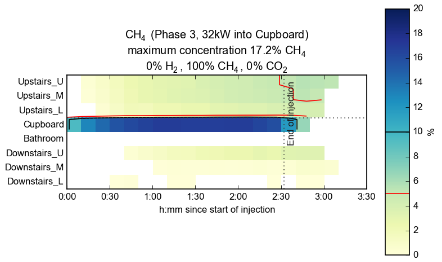

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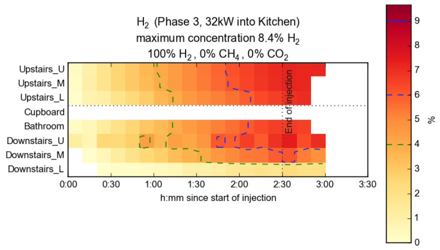

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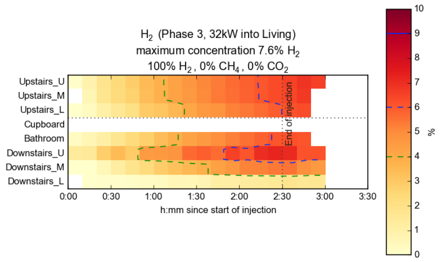

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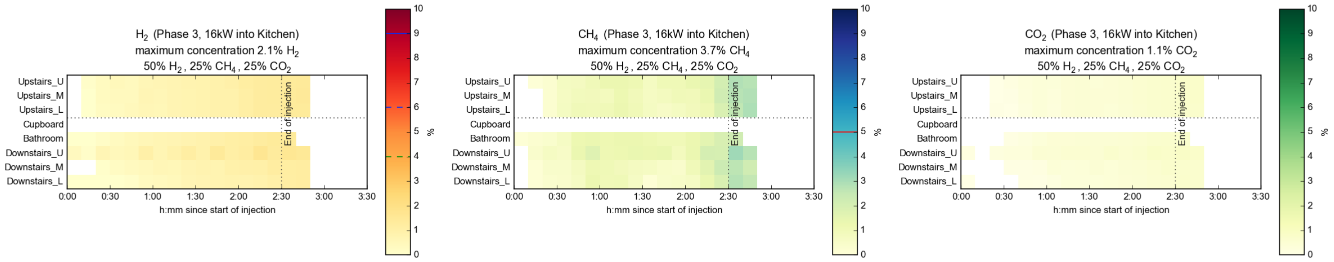

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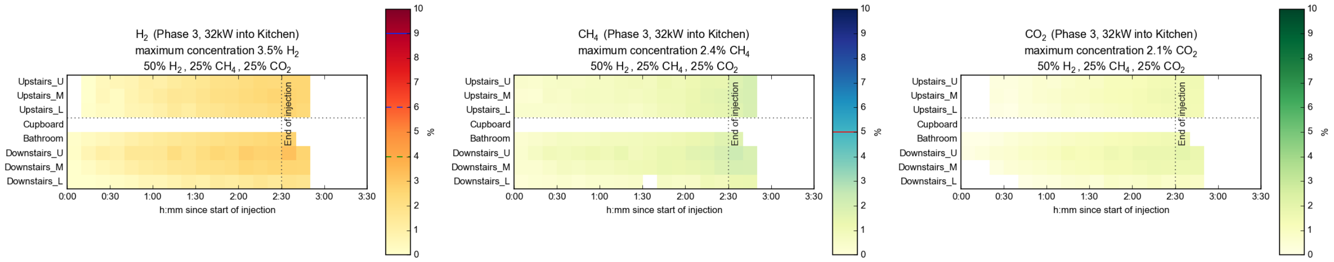

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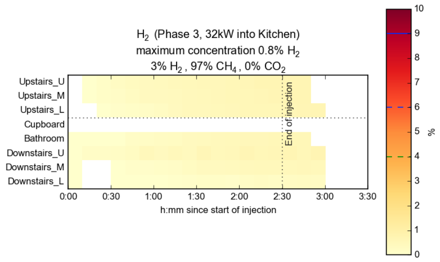
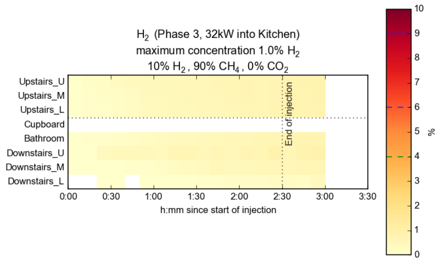
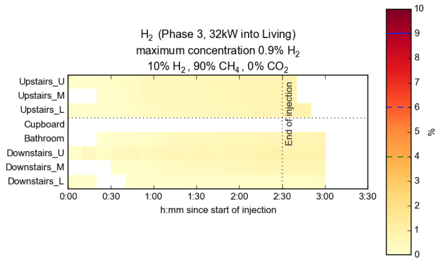


104.



105.



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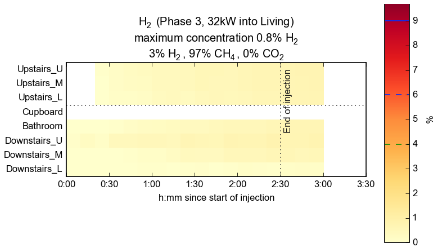
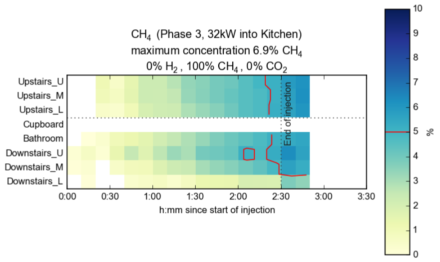
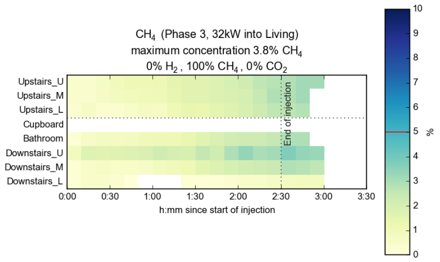


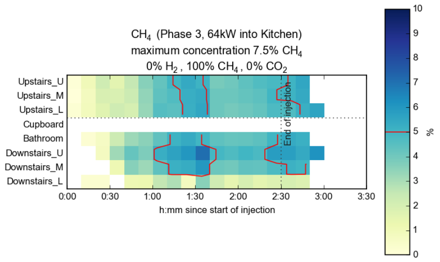
107.



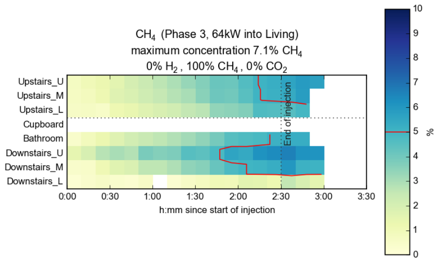
108.



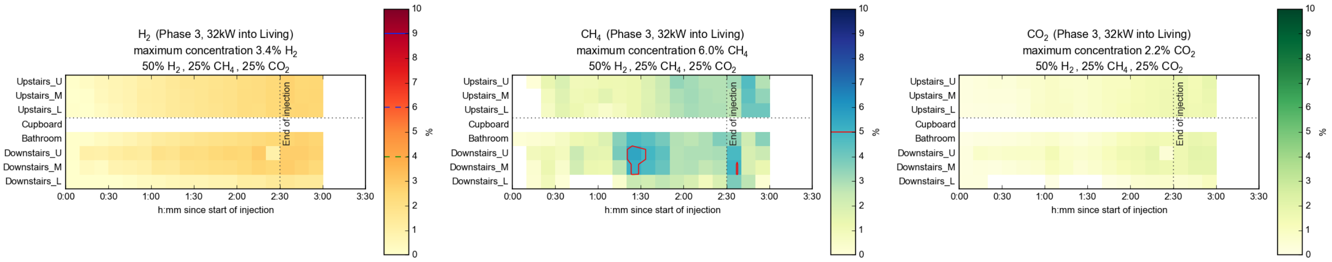
109.



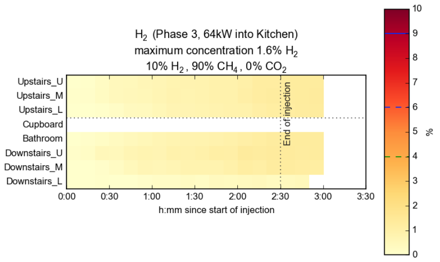
110.



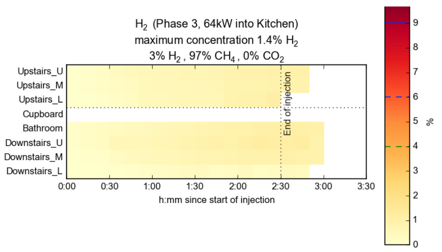
111.



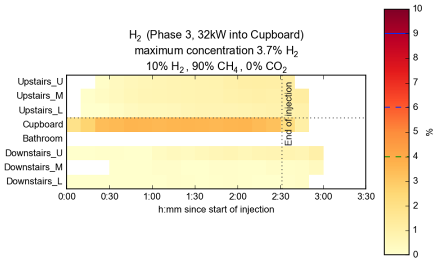
112.



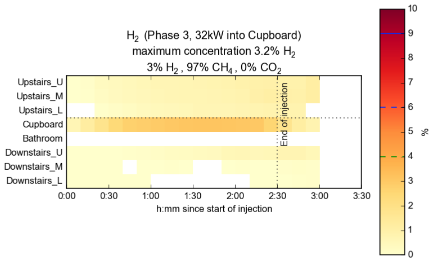
113.



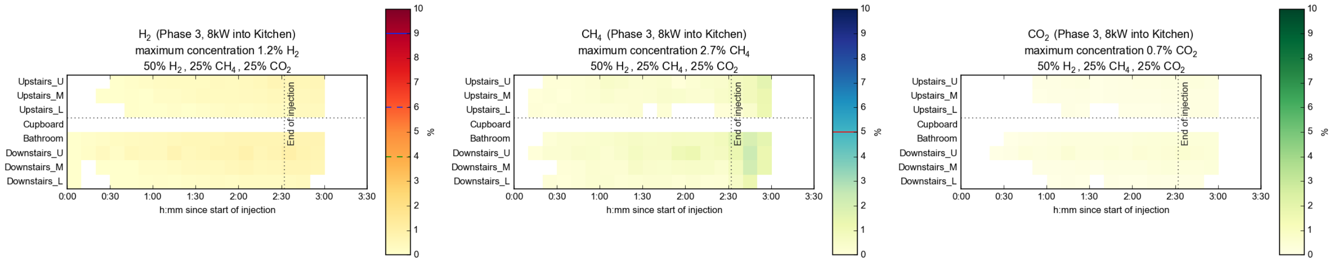
114.



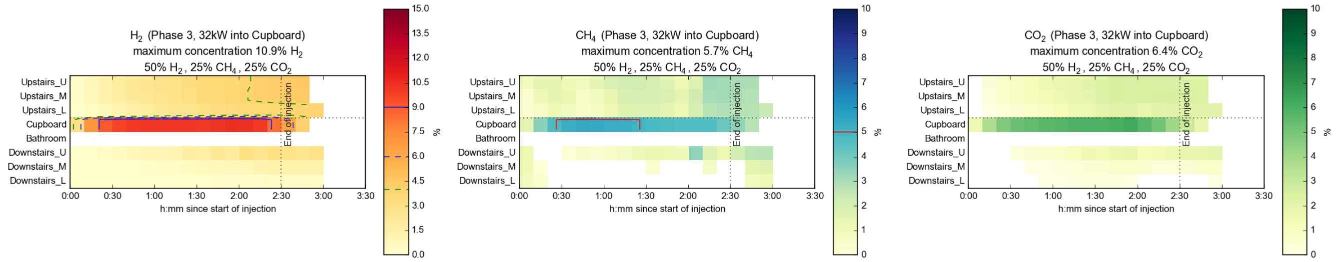
115.



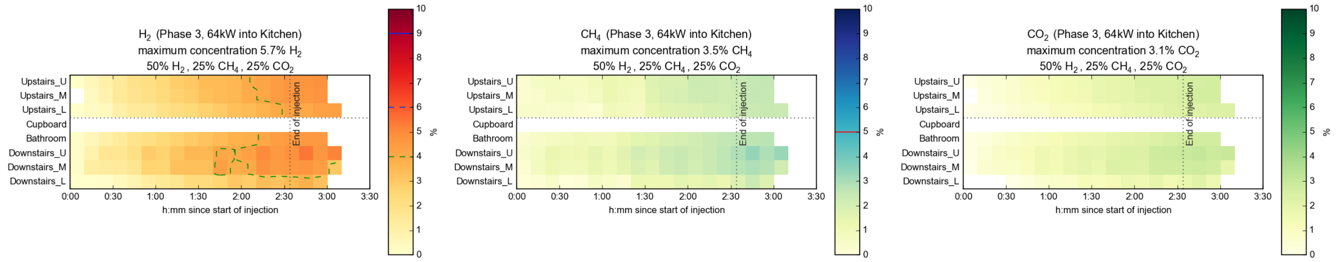
116.



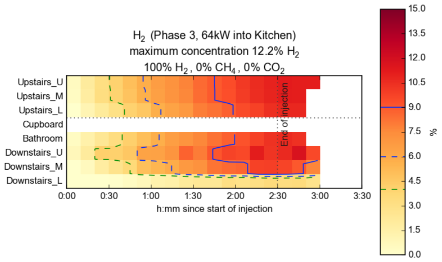
117.



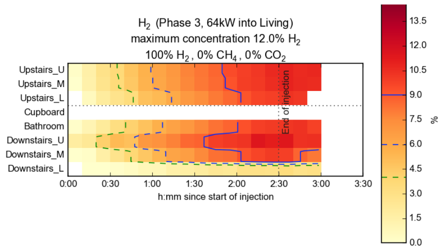
118.



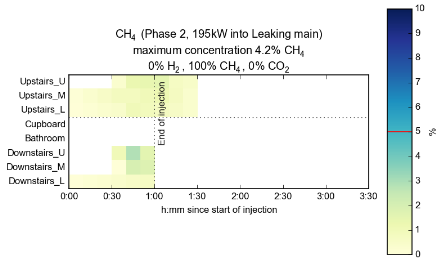
119.



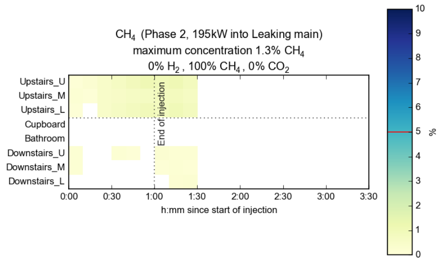
120.


H$_2$ (Phase 3, 64kW into Living)
maximum concentration 12.0% H$_2$
100% H$_2$, 0% CH$_4$, 0% CO$_2$
Upstairs_U
Upstairs_M
Upstairs_L
Cupboard
Bathroom
Downstairs_U
Downstairs_M
Downstairs_L
End of injection
0:00
0:30
1:00
1:30
2:00
2:30
3:00
3:30
h:mm since start of injection
13.5
12.0
10.5
9.0
7.5
6.0
4.5
3.0
1.5
0.0
%

121.


CH$_4$ (Phase 2, 195kW into Leaking main)
maximum concentration 4.2% CH$_4$
0% H$_2$, 100% CH$_4$, 0% CO$_2$
Upstairs_U
Upstairs_M
Upstairs_L
Cupboard
Bathroom
Downstairs_U
Downstairs_M
Downstairs_L
End of injection
0:00
0:30
1:00
1:30
2:00
2:30
3:00
3:30
h:mm since start of injection
10
9
8
7
6
5
4
3
2
1
0
%

122.


CH$_4$ (Phase 2, 195kW into Leaking main)
maximum concentration 1.3% CH$_4$
0% H$_2$, 100% CH$_4$, 0% CO$_2$
Upstairs_U
Upstairs_M
Upstairs_L
Cupboard
Bathroom
Downstairs_U
Downstairs_M
Downstairs_L
End of injection
0:00
0:30
1:00
1:30
2:00
2:30
3:00
3:30
h:mm since start of injection
10
9
8
7
6
5
4
3
2
1
0
%