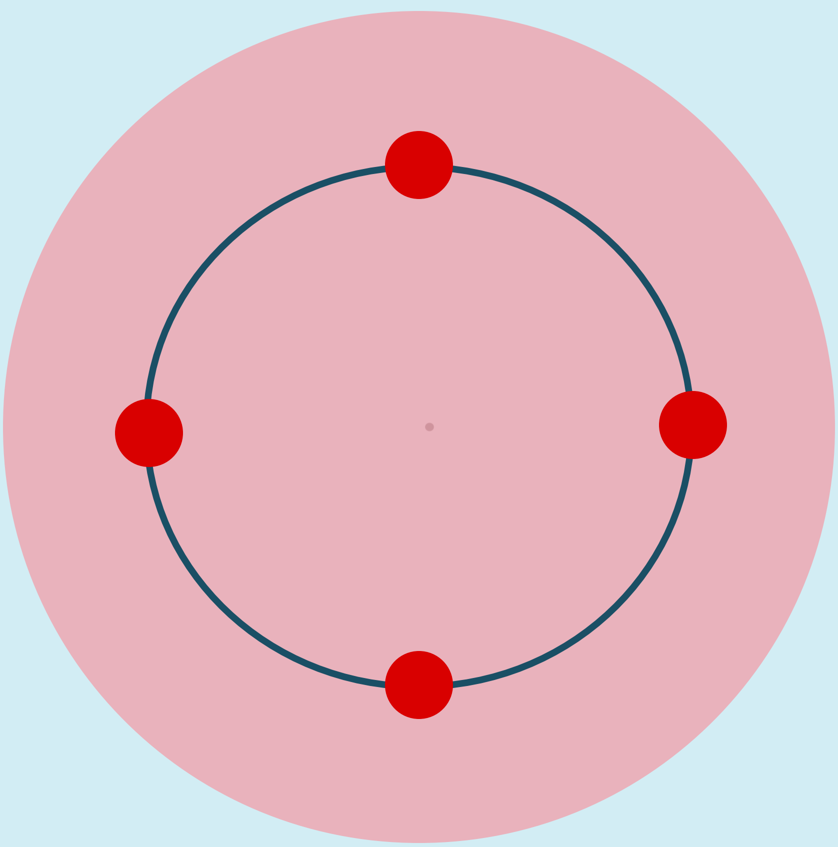
Hy4Heat

Department for Business, Energy & Industrial Strategy

WORK PACKAGE 7

Domestic hydrogen purge procedures



Domestic hydrogen purge procedures

Final Report

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Executive Summary

The aim of this project was to review the current purge standards for UK domestic installations, in particular IGEM/UP/1B, and carry out experiments to assess the validity of those standards for use in hydrogen in order to understand and recommend safe purge practices for hydrogen in a domestic environment.

This report provides the results and conclusions relating to the relative safety of purging domestic installations to hydrogen compared to Natural Gas and the implications of releasing any purged gas into an enclosed volume representing a small room.

The two high-level findings from this work are:

- changeover to hydrogen will result in an increased risk of flammability inside the installation pipework
- changeover to hydrogen will result in a reduced risk of a build-up of flammable gas in any room where purging occurs.

This work recognises a number of important differences between hydrogen and methane. Hydrogen is more flammable than methane in air, particularly at high concentrations.

Hydrogen can maintain a flame at 4%, but does not support general three dimensional deflagration until about 8.5%. Above about 18%, given increased obstruction within the combustion zone, or passage of the flame along a pipe the deflagration can transition to detonation. The flame speed suddenly increases to ~2000m/s. It is very important to avoid this situation although the inventory in a domestic pipe is low. This risk of detonation can occur at concentrations up to 59% and the risk of deflagration remains to 75 %.

Methane behaves very differently to this with a range of deflagration of about 4.8 to 16% and a detonation range only marginally narrower. Initiating detonation is however much more difficult with methane.

The risks with hydrogen are associated with a wide range of flammability, with methane the risks are smaller and mainly in lower concentrations of gas in air. Because of this it is particularly important to ensure hydrogen pipes are appropriately purged.

The first stage of work carried out was to measure the ease and effectiveness of purging domestic installations from air to hydrogen. Over 80 purge tests were carried out on 29 different installations and scenarios all comprising pipes ≤ 35 mm diameter and volumes ≤ 35 litres including gas meters. A standard isolating valve with integral 1 mm test point (1mmTP) was used for the majority of the purge tests. This set a consistent purge rate and allowed a qualitative real time measurement of the hydrogen concentration of the displaced gas to be made providing a very reliable method of assessing the time taken and effectiveness of each purge.

- It was possible to purge all installation components and pipes in all orientations tested, even at slow purge speeds.
- An installation with branches was always successfully purged if each branch was individually purged using a 1mmTP.
- It was only possible to retain air in the installation in disused branches that were not separately purged. The most significant of these is the case when the branch runs downwards from the supply pipe.
- A part purged system that is left with both hydrogen and air appears to homogenise to a uniform mix over a matter of hours.
- The volume of hydrogen displaced during the purge process was in the order of 1-2 litres before > 95% concentration was reached.

During the purge first pure air was released from the 1mmTP, then the transition zone where a mixture of air and fuel gas was released, finally pure hydrogen was released as the purge was completed. The size of the transition zone was in the order of 1-3 litres of a flammable gas mix. The transition zone was always clearly indicated demonstrating only a limited amount of mixing of the hydrogen and air. This limited mixing is due to the very low Reynolds numbers in the pipeline during the purge. Hydrogen flowing in a 35 mm pipe displacing air leaving a 1mmTP will travel at a speed of 0.04 m^{-1} giving a calculated Reynolds number of just 13.1. Mixing is limited by this laminar flow but it is supplemented with buoyancy effects if the pipe is running upwards.

Therefore, although the volume of flammable mixture inside the installation pipework is increased by a transition to hydrogen, this volume accounts for a portion of the pipework and will have a varying concentration along the length of the pipework.

The second stage of work examined the effects of releasing purged hydrogen into rooms. The experiments examined extreme conditions of purging 100% hydrogen into an enclosed space representing a small kitchen.

In all 27 test releases, ranging from 2 to 53 litres were carried out. The 53 litre volume is the absolute maximum release that could occur derived from 1.5 times the maximum 35 litre domestic installation volume released as 100% hydrogen. In reality this will not happen if procedures are followed. The hydrogen releases were all 100% concentration of hydrogen, release points were either at the top, middle of base of the room. The majority of releases also used an open hose rather than the 1mmTP to limit the mixing through turbulent effects. Key findings for releasing hydrogen into the closed chamber are:

- Releases of 2-5 litres, similar to those seen in the installation purge tests resulted in very low concentrations of hydrogen, <4000 PPM.
- A high flow release of hydrogen mixed more quickly in the atmosphere than a slow flow release. Release through a 1mmTP created additional turbulence and mixing at the point of release lowering hydrogen concentrations.
- A release of hydrogen at the bottom of the chamber mixed more quickly in the atmosphere than a release at the top of the chamber, lowering hydrogen concentrations.
- The tests confirmed findings reported in the literature that hydrogen released into closed spaces disperses throughout the complete volume. Factors that sped up the mixing processes were turbulence from buoyancy effects, high flow rates, and ventilation.
- Ventilation of the enclosed space greatly increased mixing of the gases, and the speed of dissipation of the hydrogen into the atmosphere.

The likelihood of a build up of flammable gas in the enclosed volume representing the room is reduced for hydrogen when compared to Natural Gas.

This report has examined the IGEM/UP/1B standard for use with hydrogen. The most significant change that is suggested is the practice of lighting the purged gas to identify the presence of the fuel gas. The increased flammability of hydrogen suggests that this should be avoided. A separate means of confirming that a high concentration of hydrogen is present is therefore recommended prior to attempting to light appliances. Steer Energy are working to develop a passive gas concentration indicator to provide a clear indication of the purge progress and completion.

All of the work presented here followed the process of direct purging as dictated by IGEM/UP/1B. None of the results showed challenges to the efficiency of direct purging so no recommendation is made to move to indirect purging. Indirect purging carries additional hazards from taking inert gases into the domestic environment. These additional risks need to be quantified before recommending indirect purging especially when comparing to the ease and effectiveness of direct purging presented here. As explained in the main text even with the relatively low flow produced by the

1mmTP the hydrogen purged very cleanly with an abrupt end transition both from air to hydrogen and hydrogen to air.

It would also be useful to extend this work to explore purging in commercial and larger installations. This would involve reviewing the suitability of the IGE/UP/1 standard for hydrogen.

Recommendations for domestic installations are that a purge point, such as the 1mmTP used in this work is installed in each leg of the installation. This provides a means of isolation for each appliance and a means of purging the network. The 1mmTP also creates turbulence at the release point if the purged gas is to be released into the room. The position of the 1mmTP should not be within 1 m of the ceiling in the room to increase dispersion of purged gases.

Use of a purge indication device would provide positive feedback of successful purging and would significantly limit the volume of fuel gas ejected during a purge.

This work has demonstrated that release into a well vented room will be sufficient to ensure safe purging however it may be desirable as an alternative to actively vent the purged gas out of a window to a safe outside location using a flexible hose. This could be fitted with a guard to ensure no naked flame is brought close to the pipe discharge point, but no flame arrestor is recommended.

The greatest unknown from this work is to experimentally determine the actual likelihood of ignition of purged fuel gas and the consequence of such ignitions. Informal tests have been carried out under laboratory conditions and whilst ignition is possible it is smooth, unlike the highly explosive incidents (detonation) often anecdotally quoted. It would be of value to devise a test programme that formally investigates the likelihood of ignition in real life scenarios to inform risk assessments. This could also explore how likely it is to reach LFL and LEL in hydrogen in a domestic situation and understand how long the atmosphere remains flammable with the high dispersion rate of hydrogen.

1 Introduction

The aim of the project was to review the current purge standards, in particular IGEM/UP/1B, and carry out experiments to assess the validity of those standards for use in hydrogen in order to understand and recommend safe purge practices for hydrogen in a domestic environment.

1.1 Work packs

The scope of work was derived from the 'Domestic pipework purging – briefing note' given to Steer Energy on 9 July 2020. The work was broken up into a number of individual activities to deliver the comparative assessment of the risks associated with purging natural gas installations and hydrogen installations. The project work packs are as follows:

- WP1: Review purging standards and practice
- WP2: Desk based risk assessment
- WP3: Experimental work
    - Stage 1 purging installations
    - Stage 2 purging into confined spaces
- WP4: Statement regarding regulations
- WP5: Reporting and project management

2 WP1 Review of purging standard and practices

This first work pack aimed to explore current practices for purging gas appliances and installations and review relevant standards. The work was extended to take guidance from other industries and reported incidents. Appliance manufacturers were contacted to examine how purging could be carried out through individual devices. A survey of gas engineers was proposed as an additional source of information regarding common professional practices.

2.1 Relevant standards

The IGEM family of standards for purging sit under IGE/UP/1. There are three separate standards which can be used in specific instances. IGE/UP/1A applies to small industrial and commercial installations, IGEM/UP/1B targets domestic installations and IGM/UP/1C applies to meter installations.

All of these standards have an algorithm which dictates where each standard can be used, it should be noted that the algorithms in the standards are inconsistent with each other relating to LPG installations. LPG is out of scope for this project and so does not impact the work.

IGE/UP/1 Edition 2 deals with all aspects of strength testing, tightness testing and direct purging of selected 1st, 2nd and 3rd family gases. For example, for NG, it covers pipework downstream of the emergency control valve (ECV) of maximum operating pressure (MOP) not exceeding 16 bar. This standard can be used for domestic installations if desired.

IGE/UP/1A Edition 2 +A: 2005 deals with strength testing, tightness testing and direct purging of small, low pressure industrial and commercial natural gas installations. Volume not exceeding 1 m^3 and diameter not exceeding 150 mm, of MOP (and operating pressure (OP)) not exceeding 40 mbar and supply MOP not exceeding 75 mbar.

IGEM/UP/1B Edition 3 +A: 2012 deals with tightness testing/direct purging of small Liquefied Petroleum Gas and Air, NG and LPG installations. Volume not exceeding 0.035 m^3, capacity not exceeding 16 m^3h^{-1}, diameter not exceeding 35 mm, OP not exceeding 21 mbar and supply MOP not exceeding 2 bar.

IGEM/UP/1C deals with strength testing, tightness testing and direct purging of meter installations (as defined in IGEM/G/1), containing either Natural Gas (NG) or liquefied petroleum gas (LPG), of volume not exceeding 1 m^3 and MOP not exceeding 7 bar.

Of the standards, IGE/UP/1 and IGEM/UP/1B are most relevant to this project.

Associated guidance documents include:

- Domestic Gas Safety On Site Guide - The Domestic Gas Safety On Site Guide has been reviewed by IGEM to ensure the information within the booklet is in line with the current standards and promote safe working practices
- Corgi Direct’s Essential Gas Safety; Domestic. - The Essential Gas Safety book also often references the British Standards Institute, IGEM and Liquid Gas UK.

These associated standards give an insight into recommended current practices and interpretation of the relevant standards in particular the IGEM/UP/1B standard.

2.1.1 Purge details from IGEM/UP/1B Edition 3

IGEM/UP/1B Edition 3 details the series of activities leading up to and within the purge process. Importantly, the standard is for LPG, LPG and air mixtures, and natural gas installations. Domestic installations are always below 0.035 m^3.

There are few differences in purging procedures for the different gases covered in the standard. The main difference is the purge point and whether the gas is ignited. LPG/LPG and air both require purging through a burner with ignition of the purge gas occurring as quickly as possible. Natural gas also requires ignition through a burner but only when the installation is greater than 0.02 m^3 in volume. When a natural gas installation is equal to or less than 0.02 m^3, it is also permissible to loosen a fitting and not ignite the purge, but both methods are applicable below 0.02 m^3.

Other than the loosened nut on lower volume, natural gas installations, there is only one difference between the three gas types listed. For LPG, there is a possibility that there is no meter in the installation. This would mean the relevant person would have to judge a complete purge.

The purge process is addressed in section 6 of the standard and involves three basic activities:

1. Carry out let by test in the isolation valve and a tightness test on the pipework
2. Calculate the purge volume
3. Carry out the purge

Calculation of the purge volume is carried out according to table 5 of the standard, replicated here for information.

Type of installation		Purge volume (PV)
Meter Designation	Pipework Diameter	
U6, G4, E6	≤ 28 mm	0.01 m^3
U6, G4, E6, U16, G10	> 28 mm ≤ 35 mm	1.5 IV

Where IV = installation volume

This is important as it means that for many cases the pipework volume does not have to be calculated. Calculation only needs to be made only when the system is likely to be large in volume, when a U16 or G10 meter is present or pipework greater than 28 mm diameter is present. In the case where a formal calculation does not need to be made, there are situations where the total volume in the pipework and meter is greater than the 0.01m^3 designated purge volume. This could be the case in a single pipe run let alone the complete installation. The later stages of purging including ignition will be carried out with flammable air and gas mixtures upstream of the appliance.

Once the volume is estimated or calculated the purge process can be carried out. A meter reading is first taken then two options are provided for the purge the selection depends upon the installation volume. For volumes between 0.035 m^3 than 0.02 m^3 purging is first carried out on an appliance with an open burner. The gas is ignited from the burner as soon as possible. The same process is permitted for purge volumes less than 0.02 m^3 it is also permitted to loosen a fitting to purge the gas and confirm presence of gas by smell.

The attempt to light the gas as soon as possible means it is expected that a partial mix of air and natural gas will be passing through the burner as ignition is attempted. This very much relies on the control of the flame and that it will not pass back into the appliance supply line.

The process is repeated on the particular pipe until the correct volume of gas is indicated on the meter. Every branch is purged one at a time and a stable flame established on each appliance.

It is unclear if each branch requires a full purge volume to be passed through the meter, the gas fitter survey suggests that professional practice is to purge only until stable flame is achieved on all appliances and not carry out a full system purge from each point.

2.1.2 Details from IGE/UP/1

IGE/UP/1 is the umbrella standard sitting above individual purge standards such as IGEM/UP/1B. It is a much more detailed standard that can be used for domestic settings if desired or required by some individual feature of the system. It also deals with installations across a wide range of volumes and pressures so is much wider reaching. This standard has therefore many more stringent rules for tightness testing and purging. The installation may require to be split up into individual test sections and ring main installations isolating.

The simplifications of the IGEM/UP/1B standard are not included in the complete IGE/UP/1 standard. Tightness testing incudes individual calculations of:

- the installation volume,
- the test pressure,
- maximum permitted leak rate,
- and test tightness duration.

In addition, appliance isolation valves also require testing.

Purging for all but the simplest systems requires a written procedure for the operation detailing the number of supervisors and full details of the processes. A permit to work system is required for some operations and full site work precautions followed as expected in an industrial setting.

Vent stacks and flame arrestors are mentioned in section 6.4.3 which may be very undesirable for hydrogen systems.

Section 6.4.10 carves out some simplifications for small volumes of pipework, under 0.02 m^3, allowing purging into a well-ventilated internal area without purge stack or flare. This cannot be carried out if the system includes a diaphragm meter and gas monitoring is required.

Verification of purge velocity is required using a volume meter or rate of flow meter.

Calculations need to be carried out for:

- purge volume
- minimum purge flow rate
- purge time

Table 12 is of particular interest as it details minimum purge flow rates and velocities for different nominal pipe diameters. The first three rows of this table are pertinent to domestic systems as they are for nominal pipe diameters of 20, 25 and 32 mm which are close to the internal diameters of 22, 28 and 35 mm copper tube. Sections of table 12 are repeated here for information.

Nominal pipe diameter to be purged	Minimum purge velocity	Minimum purge flow rate	
mm	$m\ s^{-1}$	$m^3\ min^{-1}$	$m^3\ h^{-1}$
20	0.6	0.01	0.7
25	0.6	0.02	1.0
32	0.6	0.03	1.7

Vent gases should be monitored with detail provided on the various gas properties such as specific gravity, lower and upper flammability limits and the safe purge end points for purges from air to gas (commissioning) and from gas to air (decommissioning), given in terms of percentage volume of gas in air.

It is clear that it is not desirable to follow IGE/UP/1 for domestic systems due to the increased complexity, however there is learning from the umbrella standard to carry forward for consideration during the programme of work. Of particular interest is the minimum purge velocity which suggests a minimum purge velocity of 0.6 ms^{-1}. Such speeds in methane still result in laminar flow regimes but at the upper end, approaching transition flow. In the fullness of time, the IGE/UP/1 standard will have to be amended with hydrogen procedures. It should be noted that the lowest purge velocity routinely used for the experiments was 0.04 ms^{-1} for the 35 mm pipe sections. This value was determined by the 1mmTP used in the experiments and was selected as taking a very conservative approach likely to result in challenging purge scenarios.

2.2 IGEM Hydrogen reference standard

IGEM, funded by Hy4Heat has written a reference standard for low pressure hydrogen utilisation.

The standard contains some very useful information, especially *'Appendix 3 Hydrogen Characteristics'*.

It is useful to refer to elements of this document here, in particular section 8.6.3 which discusses purging. Section 8.6.3.3, 'Effects on procedures using hydrogen', is repeated here for convenience.

"Due to the higher flame speed and wider flammability limits, purging hydrogen is a more hazardous and complex operation than with Natural Gas, for the following reasons:

- *The greater density difference between hydrogen and air may cause increased pocketing and stratification problems*
- *The wider flammability limits of hydrogen may cause greater hazards in the mixing zone at the interface, especially when purging*
- *Hydrogen mixtures may have a greater ignition potential within the pipework system*
- *The properties of hydrogen may prevent the practice of venting smaller systems directly into internal spaces.*

The use of direct purging may still be possible on domestic and small commercial sized systems by applying agreed procedures based around IGEM/UP/1B, but this still needs to be proven.

On larger systems, higher purge velocities may be required to avoid pocketing and stratification problems and to minimize the size of the mixing zone at the interface.

Further work will be required to quantify the requirements for direct purging of hydrogen systems.

It may be necessary to use indirect purging if the changes to direct purging procedures are too involved or impractical to apply. A requirement to use indirect purging could impose challenges and additional costs, particularly on smaller systems.

Installations will require a suitably valved and sealed vent point to be installed at the extremities of the system.

A suitable hose can be connected to the vent point, which will pass the vented gas to a safe outside area where venting can take place using a mobile vent stack incorporating a flame arrestor, test point and a suitable terminal device.

The motive force for the purging process will be supplied by the gas supply pressure (for commissioning) or a suitable air fan (for decommissioning).

> *Equipment used for purging must avoid the generation of ignition sources (including static) and include suitable flame arrestors.*
>
> *All purge equipment will need to be cleared of any residual flammable gas immediately after use."*

The text above covers domestic systems, referred to in IGEM/UP/1B. It also comments on larger systems and the potential need for indirect purging via an inert gas. The work in this document work focusses on domestic systems as covered by the IGEM/UP/1B standard.

Recommendations for larger systems, such as valved vent ports, hoses to carry the purged gas to an outside area, flame arrestors and the need for indirect purging are not discussed here.

It should be noted that a flame arrestor suitable for methane will not necessarily be suitable for hydrogen and may introduce challenges of a closed system preventing the release of energy. The European Industrial Gases Association (EIGA) design document on vent systems states no flame arrestors shall be used for hydrogen vents[1]. This is for large scale industrial installations so may not be fully relevant to small systems.

The purging section of the standard concludes that further research is required to develop and test purging methodology for hydrogen which feeds into the purpose of the programme of work reported in this document.

2.3 Gas industry practices

The standards pertaining to domestic gas purging offer guidance and suggested procedures to trained gas engineers and training facilities. This has led to development of different methods. The majority of these methods will adhere to the standards, while some inevitably deviate in some way. By nature of them being in use currently, all methods are deemed by the engineer to be safe when using Natural Gas. There may be specific situations in which dangerous situations could occur with Natural Gas, and some situations that while safe with Natural Gas, are unsafe with Hydrogen. These particular situations would fall outside those which would be noted when looking only at the methods dictated by the standards.

This section is intended as a brief investigation to explore current practice with methane that may lead to dangerous situations with hydrogen.

Steer Energy contracted a domestic gas engineer to act as a consultant and provide independent information and knowledge based on approximately 25 years of experience in the trade.

A survey was commissioned to provide information on industry practices that are not covered by the standards.

2.3.1 Consultant gas engineer

A local gas engineer was contacted to assist with creating the survey. It was important to frame the questions in a way that would elicit accurate responses from an industry tradesperson. Following this consultation, the questions were altered and tailored to provide the best platform to receive the information.

The consultant gas engineer also provided useful information regarding anecdotal situations and procedures. The information pertinent to safety aspects around the purge process is highlighted below:

- Purge and light/relight operations would only be done as part of a larger job such as after working on the installation or commissioning a new installation. The methodology is not

[1] EIGA Doc 211/17 Hydrogen vent systems for customer applications

generally considered by gas engineers as it is a known process. This is the opinion of one person, a larger sample size would be likely to produce other responses.

- 30 seconds to a minute is the maximum time an engineer is likely to want to wait for a purge but this may be extended for a large system.
- Calculating purge volumes is rarely done, and the purge is done until the smell of gas is detected, then the appliance is lit.
- Usually the primary purge is done by loosening a fitting by the boiler, as this is the largest flow and shortest purge time. Sometimes the hob is used in preference, because although the flow is lower, it can be lit and left alight, allowing the operator to relax, plan.
- Often a separate flame carrying device is used instead of integrated appliance lighting (Bunsen burner or a camping stove).
- Gas fires are unpopular to work on because there are additional tests required such as flue flow tests and associated cleaning.
- The meter should - but is not always - be removed from the house while the pipework is being worked on. This means it would be fully purged with air by the time it is re-inserted. As the downstream pipework remains in place, the gas is less likely to dissipate. The appliance will often initially light from the gas that remains in the pipework, then go out as a large slug of air from the meter is purged. This will be less true for the smaller volume, modern electronic meters than for the old bellows type of meter.
- 30 seconds of running an appliance is a suitable test to ensure it is working and fully purged - this completes two tests in one operation and is a benefit of using the hob to purge.
- Occasionally medium pressure supply is found at domestic properties.
- Branches that are no longer used should be capped immediately next to the supply line. Sometimes however this is not done, and systems can be found with ‘dead legs’.

2.3.2 Gas engineer survey

A survey was drawn up and issued to attendees of the Kiwa Gastec’s domestic gas engineer training course. The questions of the survey are included in Appendix A.

The survey was designed to ensure anonymity for the gas engineers who complete it. Because the aim is to highlight specific procedures that may not match the standards or training manuals, the engineers may be reluctant to highlight things that actually happen in practice.

It is reasonable to assume that due to the number of gas engineers working in the UK, there will be a large variation in the way work is carried out. While this report does not investigate deviations from the standards and the safety implications caused by them, where seen they are noted.

In practice, it is likely that gas engineers currently deviate from the standards when working with Natural Gas, so it is assumed the same will be true when using hydrogen. For this reason, it is important to ensure that these working practices would not lead to an unsafe situation if hydrogen is the gas being used. If any such practices are discovered that would be unsafe with hydrogen, they will be highlighted.

The survey was originally conceived to be released as an online survey but ended up being issued manually to participants of Kiwa’s domestic gas engineer training course.

2.4 Appliance and meter manufacturers’ comments

Steer contacted project partners from WP4 (Domestic Hydrogen Appliances) and WP10 (Meters) of the Hy4Heat programme. This led to numerous discussions relating to the purge process through and for different appliances. Initial emails were sent out on 1 September 2020, and were followed up with discussion meetings for many of the appliance manufacturers.

2.4.1 Worcester Bosch

Worcester Bosch are one of the two boiler manufacturers associated with Hy4Heat programme. Part of their research has investigated gas conditions in the pipework upstream of the boiler and the possibilities of fire passing from the boiler into this pipework. They had found that the air to hydrogen purge process took a long time with stratified flow occurring. CFD studies were carried out that indicated stratified flow conditions in supply pipes. Steer will be attempting to confirm this CFD finding by replicating this experimentally. Worcester Bosch is looking at the possibility of adding flashback arrestors to the installation but this is not currently a recommendation as yet. The flow rate through the appliance when the main burner is unlit is 1 l/hr which is much to slow for a practical purge.

Further discussions were held on 15 September, these were instigated by Worcester Bosch as they were due to install a demonstrator appliance in the HyHouses at DNV Spadeadam. The result of this discussion was that an appliance isolation valve with a 1mmTP be used.

2.4.2 Baxi

The discussion between Steer and Baxi was held on 16 September 2020. Baxi have been involved in hydrogen developments for a number of years, including having members on the steering committee for the PAS4444 standard and working on the HyDeploy project. Baxi include an isolation valve with an integral test point on the appliance. Hydrogen flow through this test point when following the manufacturer’s recommended procedure is approximately 20 l/min.

2.4.3 Clean burner system (CBS) consortium

The CBS consortium comprise the burner manufacturer and two fire manufacturers, Focal Point Fires and Legend Fires. They are supported by the University of Leeds and Birmingham Burners. A discussion has been held between Steer and CBS on 24 September. The outcome of this discussion was that it is unlikely that the fires will be suitable purge points for the upstream pipework. A range of questions clarifying this are being passed from CBS to the specific appliance manufacturers.

2.4.4 MeteRSit

Steer held an informative discussion meeting with MeteRSit on 9 September. MeteRSit are producing a static meter which has a straight through pipe construction. The meter uses micro flow sensing technology to measure the flow of gas. The dimensions for the pipework inside the meter are identical for methane and for hydrogen and a dual gas meter is proposed in the future.

MeteRSit use a purge volume of 2x IV for their experiments, however this is agreed to be a conservative approach to purging. They have also used nitrogen as an inert buffer between air and hydrogen to reduce experimental risks. The meter has an auto-shutoff facility which is set to trigger if 120% of maximum flow is registered for 10 seconds. This value provides a guide to the end cut-off limit for gas flow should this be required for high velocity purging of pipework.

The most significant point of the discussion was that the meter is a static meter with measurement technology based on straight through pipe configuration. This meter doesn’t have the different chambers of a mechanical meter which would act as individual vessels each requiring a minimum purge flow to displace all the air during a purge to hydrogen.

2.4.5 Enertek

Steer held a meeting with Enertek International, representing HyFires, HyCookers consortiums looking at domestic cookers and fires and commercial cookers and air heaters. Enertek didn’t have purging as part of their work scope but they did have to purge appliances prior to testing in the lab. This purge was carried out in a lab environment and not the domestic environment.

Of the appliances discussed:

- Fires have intermittent pilot lights; a spark lights the pilot which either lights or doesn't light. No issues of burn back through the injectors have been noted but their work has not explicitly considered burn back as a focus. Fires were not seen at risk of this by Enertek due to very small volumes of gas feeding pilot lights.
- During commissioning, some of the hobs have delivered a 'crack' on ignition, indicating burn back into the appliance on lighting for the first time. This crack was identified as being due to the gas supply to the appliance not being 100% hydrogen but containing a small amount of air resulting in a flammable gas mix in the appliance pipes. This was not a regular event, only happening during commissioning but it was noted by the engineer carrying out the work.
- Ovens and grills were noted as potentially problematic in the same fashion as a hob.
- It was noted that the burner volume varies with appliance type.
- The appliance may start with 100% air in the burner from the control to the burner head as hydrogen will have dispersed over time (say if left for a week). Appliance design addresses this by providing time to purge the appliance from the gas valve to the burner to assure 100% fuel gas up to the burner.
- There is no requirement on a manufacturer to make the appliance robust to supply with anything but 100% fuel mix.

The discussion identified that no specific work was known to have been done to identify the likelihood of burn back through the control valve when the appliance is supplied with a mixture of air and hydrogen.

2.4.6 Appliance and meter conclusions

It is not desirable to purge through many of the appliances, due to slow flow rates through unlit appliances. Currently it is permitted in certain cases to loosen a fitting to permit greater purge flow, the preferred recommendation is to be the installation of an appliance isolation valve with an integral 1mmTP. The 1mmTP gives a controlled and repeatable purge flow rate of known value adjacent to all appliances. The hydrogen meters being developed are straight through pipework without the separate chambers of a bellows meter, these make purge operations simpler due to the lack separate chambers to be purged. The maximum likely flow rate in the hydrogen systems will be determined by the high flow cut off, this is set to 120% of maximum flow.

2.5 Additional information

Steer Energy carried out a brief investigation into current hydrogen usage, and safety considerations in other countries and other industries. One of the principal aims was to find procedures for purging, along with reasoning and safety cases.

2.5.1 Other countries

Hydrogen as a source of energy to provide heat is not unique to the United Kingdom. The European Hydrogen Backbone project aims to use Europe's existing energy infrastructure in conjunction with newly constructed hydrogen pipelines to transport hydrogen to 10 countries around Europe.[2] These countries will all be experimenting with utilising hydrogen in the domestic environment over the coming decade.

Other countries experimenting with hydrogen include USA, Australia, China, Japan and more. Japan was planning to fuel the 2020 Olympics with hydrogen. This has been postponed, currently until July 2021, due to the Covid-19 pandemic.

[2] European Hydrogen Backbone, July 2020

The pan-European Hydrogen Incidents and Accidents Database (HIAD)[3] currently contains details of 592 incidents and accidents involving hydrogen. A cursory search was carried out but none of the events involved network fed hydrogen.

HyLAW[4] was an EU project which ran from January 2017 to December 2018. It has a large database concerning many aspects of hydrogen use, transport and storage. No significant information on purging was found.

No information or standards specifically relating to domestic system purging were found during this brief search.

2.5.2 Other industry practices

Hydrogen is already widely used in other industries. Applications most similar to domestic heating are the use of hydrogen as a coolant and as a searching gas. Many modern large electrical generators use hydrogen gas as a rotor coolant at a pressure of around 4 bar. The main advantages are hydrogen's low density, leading to lower windage loss than for air, and its high thermal conductivity and specific heat capacity, resulting in reduced cooler sizes. As a searching gas, the environmental impact of hydrogen release is lower than many other gases. Manufacturing plants often use hydrogen to detect leaks in their systems. This may contribute to the commonly held falsehood that hydrogen gas is particularly searching, and will leak where other gases would not.

Reviewing documents from these industries allows us to study some of the practices and procedures already used in industry.

Different purge methods apply to different scenarios. These are:

- Indirect gas purge, using an intermediate inert gas such as carbon dioxide or nitrogen
- Direct gas purge (as currently done with Natural Gas in domestic situations)
- Pressurising-venting cycle purge (normally used to dilute until a desired concentration of flammable gas is met)
- Vacuum purging (the installation has all the gas removed before re-pressurisation)

This project only examines direct flowing gas purges, but other options may need to be considered if this method is found to be unsuitable for hydrogen.

Hydrogen has a low ignition energy and a wide flammability range. Some guidelines, including OSHA's 2016 safety bulletin on hydrogen gas purging, state concentrations above 10% volume in air are immediately dangerous[5]. This is above the lower flammability limit of 4.5%.

Hydrogen is the lightest known gas. It is believed that stratification can occur within pipelines. Information clarifying whether hydrogen will effectively remove heavier gases in small bore pipework has not been found.

Regarding flaring, hydrogen will produce a colourless flame and will be at a higher flame speed. For the purpose of Steer Energy's investigation, if any flaring becomes part of the purging process, these behaviours should be taken into account.

In *Dispersion of Gaseous Hydrogen Clouds: A Note to First Responders* [6], it is noted that hydrogen burns invisibly to the naked eye unless additives are included. There is also little sensation of heat when in close proximity to the flames, due to low infrared radiation. Flame visibility could be addressed through inclusion of additives or nozzle design, but without mitigation these factors mean

[3] https://odin.jrc.ec.europa.eu/giada/
[4] https://www.hylaw.eu/database
[5] www.totalsafety.com/insights/osha-releases-safety-bulletin-on-hydrogen-gas-purging
[6] 'Dispersion of Gaseous Hydrogen Clouds: A Note to First Responders' https://h2tools.org/sites/default/files/dispersion.pdf

that inadvertent flame contact could be more likely than with Natural Gas. Ultraviolet radiation is high, so UV overexposure, leading to sunburn-like effects, are also possible.

It is generally considered safer to burn Natural Gas than to release it to the atmosphere. While Natural Gas is lighter than air, it takes time to dissipate, and will tend to accumulate. Hydrogen is substantially lighter than air and will dissipate upwards quickly so assuming there is no cover above, a given volume is less likely to accumulate and create an explosive atmosphere.

Current procedures for purging of Natural Gas mandate that volumes larger than 0.02 m^3 are burned. If these procedures are sustained for hydrogen, there may be safety risks associated with flaring of hydrogen away from expected flame points, and at flow rates larger than those expected at domestic appliances.

In *The Importance of Purging Hydrogen Piping and Equipment*, by *Hydrogen Tools*[7] it is noted that a common practice with purging Natural Gas is to loosen a fitting to depressurise. Other research has highlighted that the loosened fitting is also often used for the entire purge for Natural Gas domestic installations. This is specifically advised against for hydrogen, due to the much lower ignition energy. With hydrogen, possible ignition sources include the tools, the fitting or the operator. These are generally not considered ignition sources for Natural Gas as the energy is not high enough to ignite. This is stated for industrial use, where the pressure and volume of the gases in use are substantially higher than in domestic systems. The ignition conditions are similar however, so this point may be valid for domestic systems.

Hydrogen Tools also advises purging with an inert gas to avoid the mixing of hydrogen and air. It is however noted that in piping less than 2 inch bore, air can be purged with hydrogen. This is pertinent to domestic systems, where all piping will be less than this size range. Safety considerations specified are ensuring the hydrogen is vented to a safe area and that the piping is strong enough to withstand a deflagration. The former point could be mitigated in a domestic environment by ensuring there is no overhead containment, especially with an energy source. The pipe strength will be dictated by the legacy pipework. Due to the large variety of possibilities and age range of domestic systems, it may be prudent to assume that at least some of the pipework would not withstand such an event. It would therefore be better to avoid the situation where a deflagration event is possible.

2.6 Review conclusions

The most relevant conclusions that can be drawn from the review of standards and practices are:

- Current standards suggest attempting to light the purge gases as a method of identifying the presence of flammable gas during a purge. This poses an unknown risk of flame burning back into the supply pipework due to flammable mixtures being present in the pipework at this time.
- Suggested minimum flow speed as per the IGE UP/1 standard are 0.6 ms^{-1} for all domestic sized pipe diameters. This requires larger flow speeds than may be achieved if purging through some appliances. The test programme here employed slower speeds to provide a conservative response.
- Current industry practice is to purge as quickly as possible. This will be done using appliances or by opening fittings as permitted. A change to purging through a 1mmTP will result in slower purge flows and may meet resistance from operatives. This can be covered in the re-training in conversion to hydrogen.
- The 1mmTPs were designed for pressure measurement and not for flow of gas. The test port size is, however designed to limit the flow of gas from a system to a point where the

[7] 'Importance of Purging Hydrogen Piping and Equipment' https://h2tools.org/lessons/lessons-learned-corner/importance-purging-hydrogen-piping-and-equipment

smell of the gas would be detected prior to a dangerous build-up of gas occurring in a property should the sealing plug be left out. A change of the test point orifice size may compromise this design safety requirement. At the moment the work here indicates that the 1mmTP is adequate for effective purging. Any desire to speed up the process will need to take this into consideration.

3 WP2 Identification of likely risks

This desk-based study aimed to identify and understand likely risks when purging to hydrogen. The risk discussion was based around the differences in physical properties between hydrogen, methane and air in relation to the purge processes.

3.1 Differences in gas properties and behaviour

Table 1 gives details of relevant physical properties of hydrogen, methane and air. These properties are included as a background to the risk identification.

Property	Air	Methane	Hydrogen	Units
Density[8]	1.226	0.68	0.0852	Kg / m^3
Absolute dynamic viscosity[9]	1.80×10^{-5}	1.08×10^{-5}	8.7×10^{-6}	Pa.s
LEL[10]	N/A	5	18.3	% by Vol.
UEL	N/A	14.3	59	% by Vol.
LFL[11]	N/A	4.4	4	% by Vol.
UFL	N/A	15	77	% by Vol.
Ignition energy[12]	N/A	0.28 / 0.3	0.011 / 0.017	mJ
Gross Calorific Value[13]	N/A	39.8	12.7	MJ / m^3
Wobbe Index[14]	N/A	53.28	48.23	MJ / Nm^3
Diffusion coefficient in air	N/A	0.16×10^{-4}	0.61×10^{-4}	$m^2 s^{-1}$

Table 1: Comparison of the physical properties of air, methane and hydrogen

The table of properties indicates the causes of some of the differences in gas behaviour which are based around key property differences.

Methane is a fossil fuel that contributes to carbon emissions and is a significant greenhouse gas in its own right. Transferring to green hydrogen can significantly contribute to achieving zero emssions.

3.1.1 Relevant differences in gas behaviour

Density: hydrogen has a much lower density than both methane and air, the result of this is that hydrogen can become trapped in enclosed spaces above inlets and outlets. In the case of large closed vessels and sections of piping, this could make purging from these encloses spaces challenging in an industrial setting. Conversely the heavier density of air could result in pockets of air becoming trapped in lower portions of pipework and vessels.

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[8] Calculated at 15 Deg C and 1 atm from https://www.engineeringtoolbox.com/gas-density-d_158.html
[9] Calculated at 15 Deg C and 1 atm from https://www.engineeringtoolbox.com/gases-absolute-dynamic-viscosity-d_1888.html
[10] https://en.wikipedia.org/wiki/Flammability_limit
[11] BOC Safety Data Sheet
[12] http://www.euratex.co.uk/110411020.pdf
[13] https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html
[14] https://en.wikipedia.org/wiki/Wobbe_index

Diffusion coefficient: The diffusion coefficient of hydrogen in air is approximately four times that for methane in air this means that hydrogen is likely to disperse much more quickly than methane in a ventilated volume.

Flammability: Flammability is one of the most significant differences between hydrogen and methane. The lower limits of flammability (LFL) is comparable between hydrogen and methane, however the upper limit of flammability (UFL) is much higher for hydrogen than methane. Coupled with the lower ignition energy this makes hydrogen much more likely to be ignited in the presence of air and the flame propagate more freely than in the similar methane system. There is however a large amount of prior art for blended gases in the form of town gas which was approximately 50% hydrogen and had a 44% UFL.

Viscosity: The lower viscosity of hydrogen means that hydrogen flows more freely than methane or air. Hydrogen is sometimes referred to as more slippery and this gives a good impression of its behaviour. In pipework, hydrogen will flow more smoothly and with less frictional resistance. The Reynolds number is over 6 times lower for hydrogen than methane for given volumetric flow conditions. The conditions in domestic installations are such that laminar flow is to be expected. The experimental study sought to identify any scenarios where highly laminar stratified flow could occur, resulting in hydrogen bypassing air in domestic installations during purging scenarios, leaving pockets of air behind.

Leak flow: Leak flow in hydrogen is much larger than in air or methane for equivalent hole type leaks. Work carried out by Steer Energy has already demonstrated that the volumetric leak flow of hydrogen from hole type leak geometries is 2.8 times that for methane.[15] This means that flow from nozzles and test points during purging operations will be greater in hydrogen than in air or methane. This change in flow was used to great effect during these experiments to identify the transition from air or methane to hydrogen.

3.2 Installation infrastructure

A domestic gas installation comprises a number of different components. Categorising these components allows them to be addressed in turn. Components can be loosely grouped into two categories, inline components and end points. Inline components include: meters, regulators, horizontal and vertical pipe runs, U-sections and tees. End points include: boilers, hobs, fires and other points of use. End points also include disused branches which may pose the most likely chance of trapped air in a given system.

3.2.1 Installation infrastructure most likely to cause purging challenges

Large cavities, such as those found in diaphragm meters are expected to pose the greatest challenge to the removal of air from a system. The hydrogen meters are proposed and developed in conjunction with the Hy4Heat project are based on thermal mass and ultrasonic measurement. These meters employ straight through pipework and chambers and as such pose a much lower risk than diaphragm meters of retaining any pockets of air when purging to hydrogen. Diaphragm meters are not expected to be used in conjunction with hydrogen, however the use of a non-standard meter may be a fault condition during installation.

Unused branches are other installation elements that may provide the opportunity for trapped pockets of air in the system. The experiments examined these scenarios as possible challenge points.

3.2.2 Installation infrastructure affecting the purge

The end points in the installation, such as appliances and test ports immediately before appliances will affect the purge. If the purge is to be carried out through the appliance then that particular appliance will dictate the purge flow. Discussions with appliance manufacturers, reported in section

[15] Hy4Heat Work Package 7 – Lot 1 Final Report

2.4, have shown that not all appliances are suited to being used to purge the upstream pipework and so although the flow though some appliances will be relevant, this can only be used as a guide to the experiments. A range of quoted flows from different appliances are given in the table below as a guide to the experiments.

Discussions on industry practice reported in section 2.3 indicated that current practice is a mix of using appliances and opening fittings to achieve the purge.

Appliance	Flow (m^3/hr)	Flow (l/min)
Large hob burner (3 kW)	0.268	4.47
Small hob burner (1 kW)	0.095	1.58
Small hob burner, low (0.33 kW)	0.031	0.52
Boiler (30 kW)	3.24	54

Table 2: Representative gas flows from appliance data

During a discussion on 15 September 2020 between Steer, the Hy4Heat team and Worcester Bosch, it was decided to recommend the installation of isolation valves with test ports (see Figure 1), immediately upstream of individual appliances. This removes uncertainties surrounding the practice of ‘loosening a fitting’ adjacent to an appliance to purge a section of the installation. It provides a known leak size and hence repeatable purge flows and it also allows the purged gas to be piped out of the building if desired. All of the experiments on installation purging have therefore been carried out using one such 1mmTP.

Figure 1: 1mmTP Isolation valve with test port

3.3 Purge operation scenarios

Purge scenarios – three were posed in the briefing note:

- Methane to hydrogen
- Air to hydrogen
- Air / hydrogen mix to hydrogen

The last two are the most important as they represent operational processes during day-to-day operation with a pure hydrogen supply. They also represent the most dangerous event in the installation as there will be a flammable mix of gases present in the installation pipes during the purge operation.

The purge from air/hydrogen mix to pure hydrogen represents a scenario that is likely to be also seen during a purge from pure air to hydrogen. The risks of these two scenarios are therefore very similar.

When a purge from methane to hydrogen is being carried out, this is most likely to happen through hydrogen ready meters and appliances so these should be the reference for the setup of the experimental work. The methane to hydrogen changeover process is also likely to be carried out in conjunction with gas supply network activities and staff. These staff are likely to be specifically trained for this purpose so more familiar with hydrogen in the first instance than engineers commissioning gas appliances on a day-to-day basis.

The purge from air to hydrogen poses the greatest change in density and so is likely to be the most significant operation during the experiments.

3.4 Fault conditions

The test programme included examining some possible fault conditions. This was not expected to be an exhaustive list of possibilities. Fault conditions included:

- Mistakes in the gas changeover process leading to larger than expected gas releases
- Stopping the purge part way through the exercise leaving a mix of gas in the installation
- Purging through the wrong type of appliance / test port leading to faster than expected gas releases
- Purging through the wrong type of meter
- Purging into a closed, non-ventilated room

The fault conditions investigated extremes of what could occur leading to inefficient purges and unsafe conditions in the installation pipes.

3.5 Risk identification conclusions

The main risk identification conclusions are:

- Following current standards and attempting to light the purged gas as a means of detecting the presence of the purge gas is likely to result in the attempt to light appliances or burners when being fed from supply pipes containing a flammable mix. This practice should be avoided.
- Unknown branches in the installation could lead to pockets of the primary gas, in particular air becoming trapped in a dead branch. This poses the most significant risk of a flammable mix being left in the installation after the purge process is completed.
- Purges involving hydrogen/air pose the most risk, this is due to flammable mixes being present in the pipework during the purge.

4 WP3 Stage 1 Installation purging experiments

There were two major elements making up the programme of work. The first was an investigation into the behaviour of the gas inside the installation. The second element was an investigation into how any gas released during the purge would behave and settle in a room-like enclosure. The first element aimed to trial a number of scenarios for different installation shapes and sizes and to investigate the various conditions likely to prove challenging to completely purge.

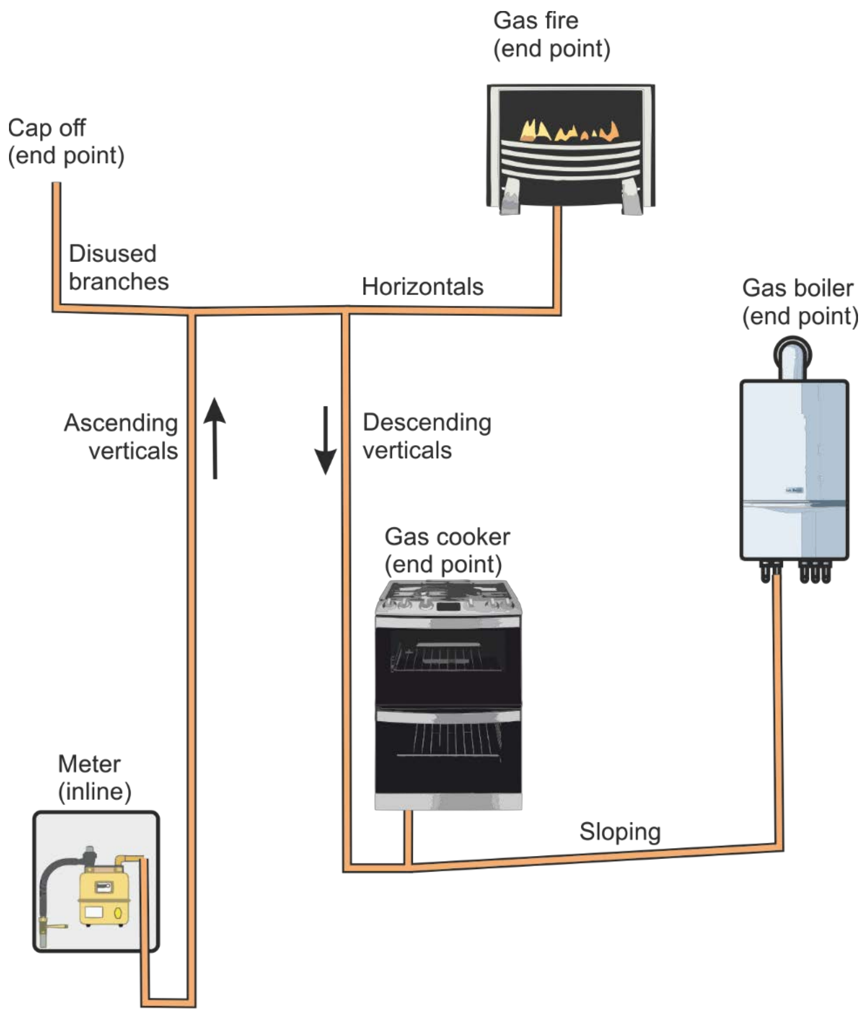


Figure 2: Installation components

Elements in scope for the project were the installation pipe sections and the inline meter. Appliances were out of scope. Referring to Figure 2 indicates the main installation components for the investigation. These were: horizontal pipes, sloping pipes, ascending verticals and descending verticals. Finally, branches, including blanked off tees were investigated as these were identified as components likely to pose the greatest challenge to a complete purge. Examples of each component were taken in turn, placed in different orientations and the ease of purging measured. Pipe sizes used for the experiments ranged from 15 mm to 35 mm but all sections were not needed for all orientations. Options for pipe orientations considered in the experiments were horizontal, sloping up, sloping down, vertically ascending and vertically descending. A branch configuration was then used with blank sections.

A set of investigations were carried out early in the project to investigate likely challenges with purging at very low flow rates. This exploration allowed the formal test process to be developed.

4.1 Experimental philosophy

There are over 20 million homes that are supplied by the gas network in the UK. Each of those homes has the potential for a unique installation of pipework, fixtures, fittings and appliances. It would be impractical to test all of these installations. Instead, individual components have been tested with the aim to identify mechanisms that trap the original gas when purging to a secondary gas. The most hazardous of these purge scenarios is a transition from air to hydrogen, the initial gas being air and the purging gas being hydrogen. Once hydrogen is placed into the installation a portion of that installation is potentially flammable and/or explosive. Only when the hydrogen to air proportion is > 75% throughout the installation do we have a safe system.

The experiments therefore examined purging of simple installation components, then drawn conclusions about general installations based upon the results of those simple installation component experiments. With each experiment, a range of questions are posed, questions such as:

- Does this process lead to flammable gas mixtures?
- How long will flammable gas mixtures be present in the system?
- Does the process conclude with flammable gas mixtures in the system, i.e. is air trapped in the system?

The programme of experiments was designed to seek out unsafe conditions in the systems under test and determine the most likely processes leading to those unsafe conditions. In the case of the domestic pipe installation the experiments aimed to measure the time and volumes required to purge from one gas to a separate gas in the installation.

The experiments actively sought to find systems and purge processes where air is reliably trapped in the installation leading to a flammable mix remaining after the purge process is completed.

The simplest scenario is a horizontal pipe filled with air, as illustrated in Figure 3, being purged to hydrogen.

Figure 3: Pipe section before purging

In the ideal case, the hydrogen enters the pipe and displaces the air with minimal mixing of the two gases. Illustrated in Figure 4.

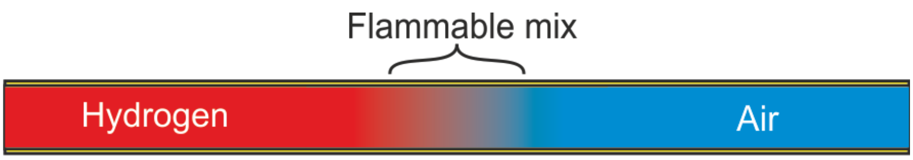


Figure 4: Ideal purge process

There are three distinct sections to the purge, the air component which contains 100% original air, the hydrogen component which contains 100% hydrogen and the portion in the middle where the two gases have mixed to form a flammable mix. This flammable portion represents the portion where the mix is air with between 4% and 75% hydrogen. Where minimal mixing occurs the time where a flammable mix is emitted from the purge point is also minimised. A more realistic purge process for a horizontal pipe is shown in Figure 5 where the lower bulk density of the hydrogen means that the hydrogen rises to the top of the pipe and starts to flow over the air. The result is a larger degree of mixing and a larger volume of flammable mix.

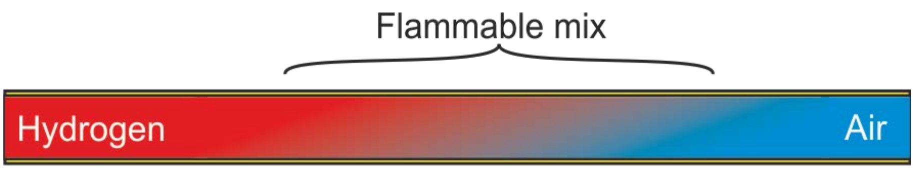


Figure 5: Realistic purge process

The experiments tried to explore conditions where air would be trapped in pipe sections and require a significant purge speed to expel the air. Tests were carried out with pipes horizontal, sloping, vertically flowing up and down. Vertical pipes, in particular were expected to provide the most variation in the purge process. The differences are illustrated in Figure 6, where upward and downward flows are shown.

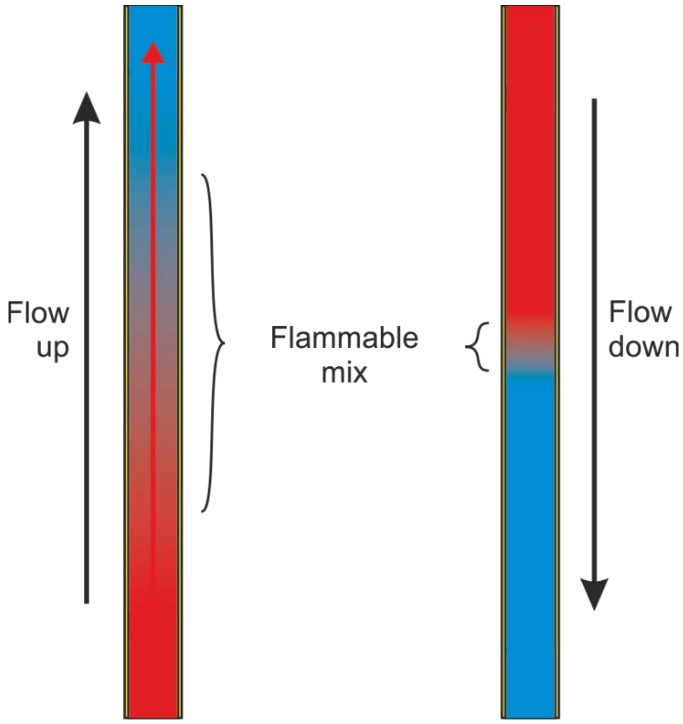


Figure 6: Vertical purge up and down

Bulk density effects cause hydrogen to rise, in the case where hydrogen is flowing downwards this effect tends to keep the hydrogen and air separated except for a small portion at the interface. In the case of upward flowing hydrogen, the bulk effects spread the interface out. Experiments were designed to investigate if a realistic situation occurred where upwardly flowing hydrogen could result in a pocket of air being bypassed during the purge and left in the system. A range of purge speeds were used to assess if this could occur and if so, what speeds would be required to prevent this situation.

In addition to straight sections, branches in the installation were considered in the experiments. Disused branches are considered most likely to result in air being trapped in the installation as it will not be possible to create flow in those systems. The situation illustrated in Figure 7 shows this, the downwards vertical branch results in a situation where the bulk density effect is likely to result in trapped air.

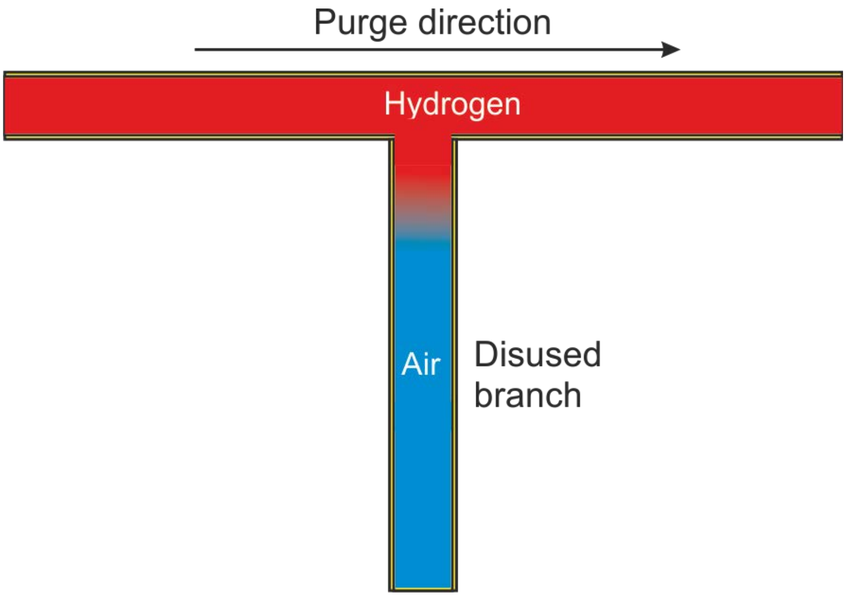


Figure 7: Situation likely to result in trapped air

4.2 Trial investigations

Before planning the formal experiments, a number of initial trials were carried out. These initial investigations were used to inform the formal test programme by identifying pipe layouts and flow speeds that may result in challenges to the purge process. The investigations also explored methods of measuring the purge process that could differentiate between hydrogen, methane and air.

4.2.1 Smoke tests

A range of 'smoke tests' were carried out, where a range of clear pipes were filled with vapour laden air and then purged with hydrogen whilst recording video of the process. Direct observation of the experiments has given a good feel for the ease of purging even under low flow conditions. Laser markers were used to improve the visual investigation. The laser marker can be seen in Figure 8. The left-hand image has the pipe filled with vapour laden air. The vapour is clearly indicated by the complete red line of the laser reflecting off the vapour particles. The right-hand image has the pipe filled with clear hydrogen. The laser can be seen hitting the pipe walls but the line in the middle has now gone.

Figure 8: Laser markers indicating vapour (LHS) and no vapour (RHS)

Purge tests were carried out vertically with gases flowing upwards and downwards, horizontally and sloping. A wide range of gas flows were used, from 0.5 l/m up to 10 l/m and no significant challenges were found in achieving a complete purge.

An example of a horizontal purge in a 40 mm clear pipe are shown in Figure 9. The purge process is shown in the three pictures, as the gas passes from right to left. The red laser light can be seen as lines in the top image. The lines disappear by the bottom image.

Figure 9: Air to hydrogen purge

The smoke tests gave a good indicator of purge behaviour for qualitative results. Investigations included adding elbow sections to the end of the horizontal and sloping pipes to try to trap air into the system. Pipe sizes up to 40 mm internal diameter were tested with flows as low as 0.5 l/m resulting in a 6.7 mm/s flow speed, just 1% of IGE/UP/1 recommended purge speed. No challenges were found in carrying out a complete purge in any of the straight-line purges attempted which was encouraging for the test programme.

4.2.2 Flow tests

The flow tests aimed to use the different flow properties between hydrogen and methane through a known feature such as a 1mmTP. This also was useful as the 1mmTP had been identified by this time as a possible recommended method for generating a reliable controlled purge point from the installation rather than simply loosening a fitting. A system was set up to supply 21 mbar through a standard regulator and fed with hydrogen. The flow of hydrogen fed into the system was measured and this was used to give an indication of the composition of gas exiting the purge point. An early experiment result is shown in Figure 10. There was an early spike as the system, including regulator, was charged to 20 mbar, then the flow dropped to approximately 2 l/min as air was purged from the system. As the air was fully purged and the hydrogen concentration raised to 100%, the flow through the 1mmTP increased to 7 l/min. This property is demonstrated by the annotated screen shot of Figure 10. The main curve sweeps up to a steady state, indicating completed hydrogen purge of the system being tested.

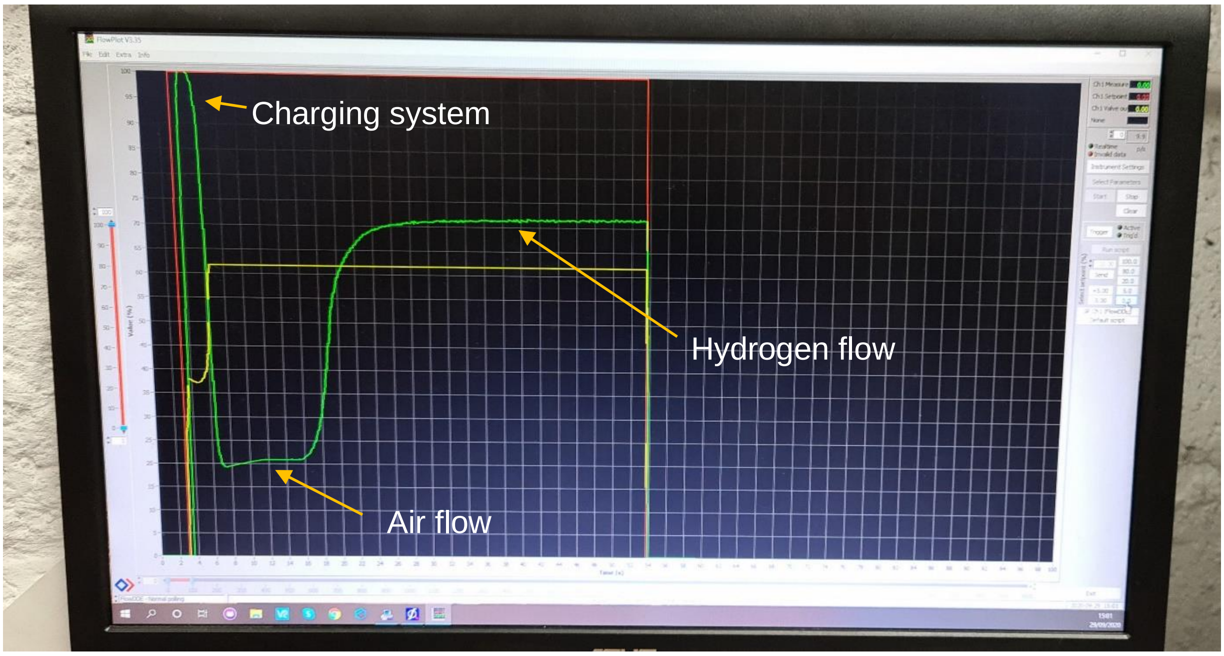


Figure 10: Screen shot of a purge

This difference in flow through a small orifice provides a clear indicator of the density of the gas passing through the orifice. The interdependence between flow and pressure passing through an orifice can be expressed as:

$$Q \propto \sqrt{\frac{\Delta P}{\rho}}$$

Where: Q = Flow

ΔP = Pressure difference across the orifice

ρ = Density of fluid

It is therefore possible to infer the density of the gas exiting the purge point due to the change in this relationship and since the gas is a combination of hydrogen and air it is possible to calculate the percentage of hydrogen and hence completeness of the purge.

This relationship was confirmed by experimental data to provide a reasonable degree of accuracy, certainly enough for qualitative data.

4.3 Formal test programme

The formal test programme was built upon the flow investigations. The formal test measurements are based upon the change in the relationship between the pressure and the flow of the gas exiting the purge point as the gas composition changes.

4.3.1 Experimental equipment

The gas supply from bottle to the pipe was via three step-down regulators from the high-pressure gas supply bottles via a bottle regulator, intermediate regulator and a 21 mbar Sperryn G940M domestic regulator. A crossover valve was used to connect the hydrogen and air lines to the test section. The flush of the air to purge the pipes of hydrogen between tests was provided by compressed air connected to the crossover valve.

The domestic regulator, crossover valve and the purge pipe are shown in Figure 11. The use of the crossover valve isolated the regulator chain and the pressure gauge tee from the test section providing cleaner results for each individual test section. The 1mmTP used for the purging tests is shown in Figure 12, this was placed at the end of the test section. The 1mmTP also included an isolation valve, used to open up the pipework for flushing between tests.

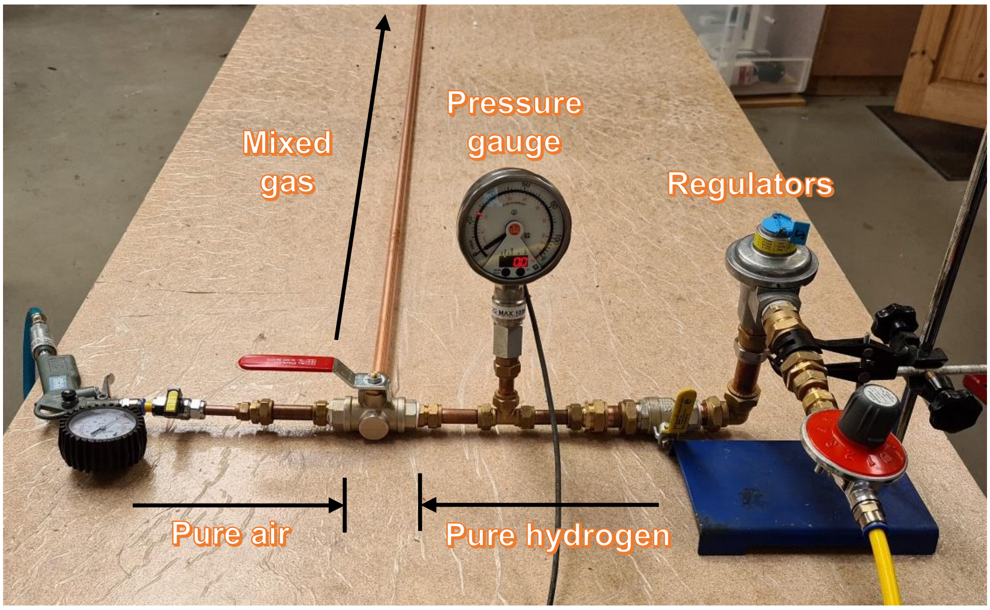


Figure 11: Gas supply with 3-way valve

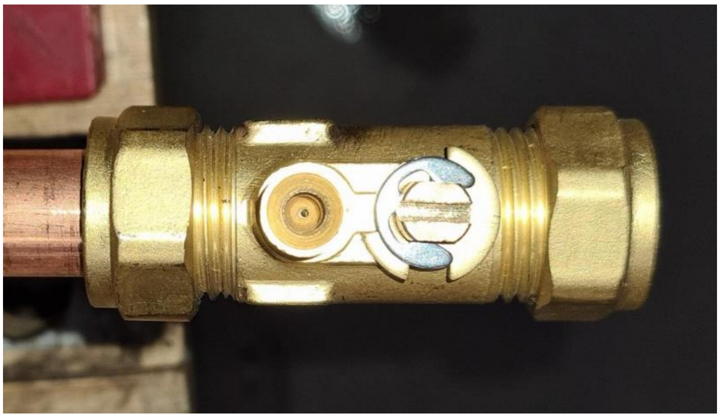


Figure 12: 1mmTP Purge point with detail of 1 mm purge hole

For each test, the flow of the hydrogen supply was logged starting when the changeover valve was switched from the air supply to the hydrogen supply. After changeover, there was an initial spike in the flow as the test section was charged to the 21 mbar test pressure controlled by the regulator. The flow was then determined by gas exiting the purge point. Initially the gas exiting the test port was pure air and the flow rate was just below 2 l/m. The flow rate increased as gas transition occurred from air to hydrogen. Once the flow reached the rate determined by pure hydrogen, just under 7 l/m, the flow was allowed to continue for a short period of steady state before stopping the test. Calculations were then carried out to determine the volume of air purged, the length of the transition from air to hydrogen and the overall purge time and volume.

4.3.2 Example purge result

An example test result is provided below for discussion. A summary of the results is then presented in tabulated form. The full set of tests is provided in Appendix B. The test results are presented in the form of a number of tables and graphs.

The first table of the results provides information about the configuration of the test. This includes the length and diameter of the test pipe. It indicates the orientation of the pipe in relation to flow and provides detail of the installation volume of the test pipe. Finally, details of the speed of flow in the test pipe for the cases when pure air is exiting the purge point and when pure hydrogen is exiting the purge point. This is included to allow the reader to gain an appreciation of the speed of the gas flow in the test section.

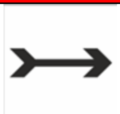
Test #	**001 35mm horizontal test 1**	
Installation configuration	3 m x 35 mm Horizontal	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

Figure 13: Results table #1, system configuration

Four graphs showing the logged results of the test are provided. The first results graph, Figure 14, shows the basic measured flow data and cumulative volume summed from that logged flow. The flow data is the raw data for the test. It commences with the initial spike as the test pipe was charged to 21 mbar when the changeover valve is engaged to start the flow of the purge hydrogen. The two horizontal portions of the flow line correspond to pure air being displaced at the start of the test (approx. 2 l/m) and pure hydrogen being displaced at the end of the test (approx. 7 l/m).

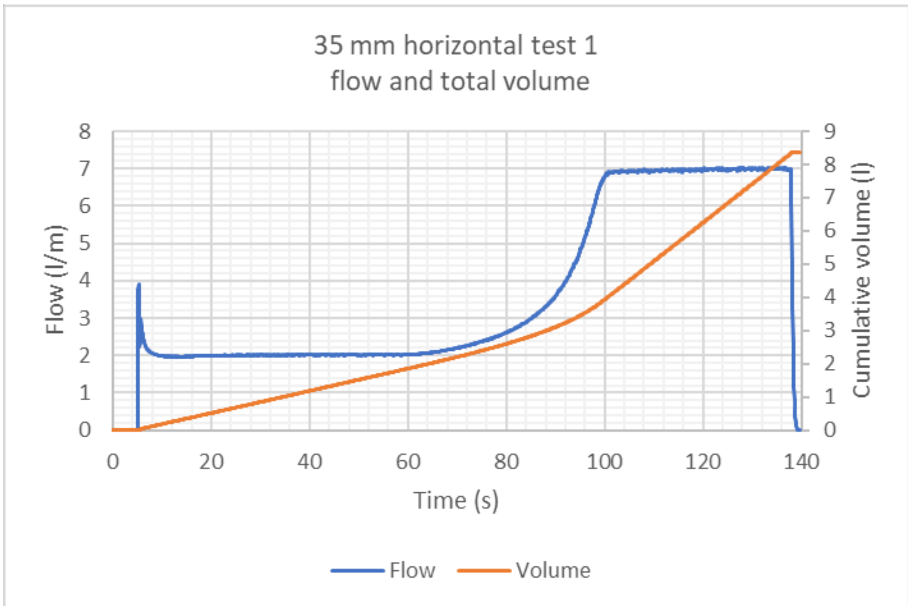


Figure 14: Result graph #1, logged flow and cumulative volume

The transition from air to hydrogen is clearly marked by the increase in flow as the test progresses. In this example, the transition for the 35 mm horizontal pipe takes about 40 seconds of time.

The second graph, Figure 15, shows the raw flow data and calculated hydrogen percentage. The calculated flammable zone is shown between the two dotted lines. This relates to the time where the gas exiting the purge point could be considered flammable, approximately lying between 4% and 75% hydrogen in air. The upper point was set to seek 80% for a conservative response due to the possibility of measurement errors.

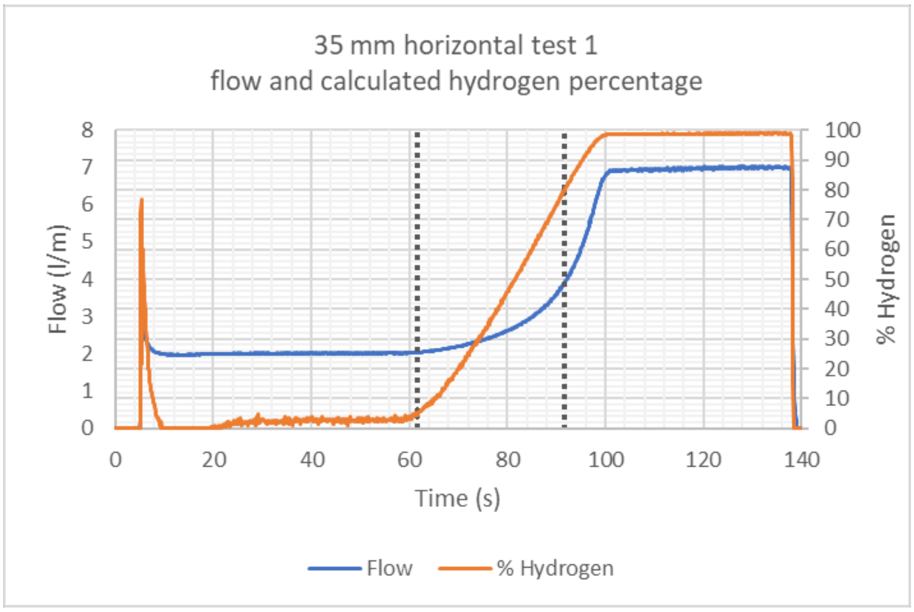


Figure 15: Result graph #2, logged flow and calculated hydrogen percentage

The third example graph is shown in Figure 16 and uses the hydrogen percentage calculation to show the flow of air displaced during the operation and the flow of hydrogen out of the purge point.

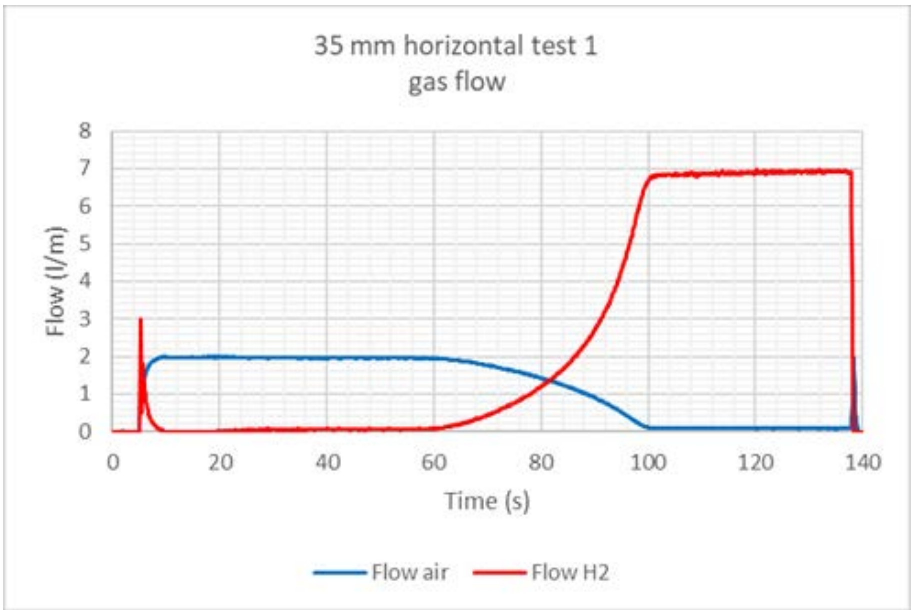


Figure 16: Result graph #3, calculated air and hydrogen flow out of the purge point

Finally, the fourth graph, Figure 17, provides cumulative gas volumes for the system as purged. This can be used to provide an estimation of the air expelled from the system. Please note these are calculated figures and so come with errors so they should be taken as qualitative data. The calculated expelled air volume can be compared to the known volume of the test system to indicate the accuracy of the tests. The calculated volume provides qualitative data, within 10% of the known volume.

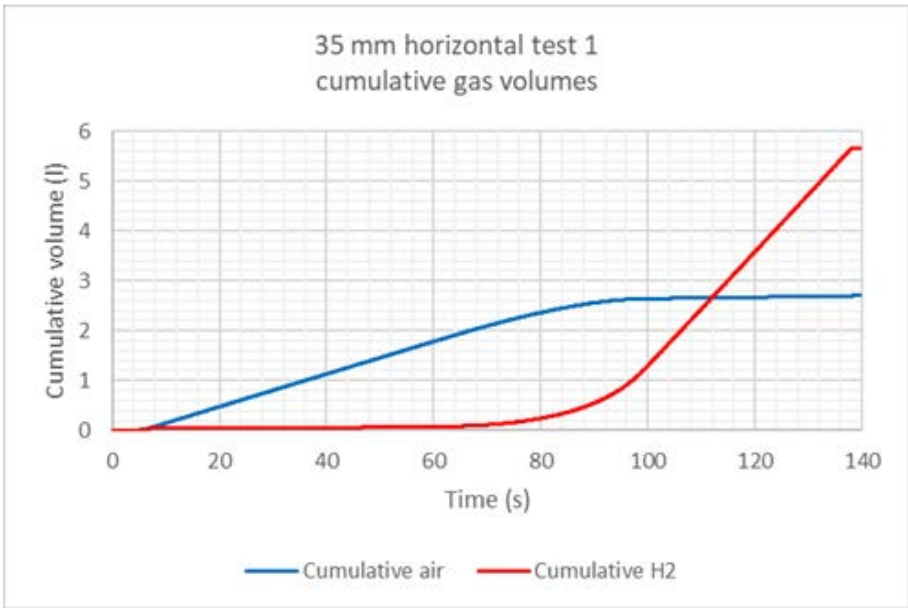


Figure 17: Result graph #4, calculated cumulative air and hydrogen released from the 1mmTP

The test result concludes with two results tables. The first provides the times and volumes read from the graphs of the transition points. The time and volume to the start of the transition period indicates the time and volume where pure air is being expelled from the system. The transition duration gives the time and volume of mixed gas being expelled from the system. Finally, the time and volume to end of transition gives the overall time and volume of gas required to completely purge the given test system of air. The end point has been set at 95% hydrogen concentration; this is done to reliably capture the end point of the main purge transition within the accuracy of the measurements.

	Time (s)	Volume (l)
To start of transition (>0% H2)	50	1.67
Duration of transition	38.3	1.84
To end of transition (>95% H2)	88.3	3.51

Figure 18: Result table #2, measured times and volumes

The final result table provides calculated results for the test purge. The installation volume is the known volume of the system and the total volume is the measured flow for the entire operation. The ratio of the purge volume to installation volume gives an indication of the efficiency of the purge process for the particular test.

Installation volume (l)	2.44
Total volume displaced to 100% hydrogen (l)	3.51
Calculated volume of air displaced (l)	2.48
Calculated volume of hydrogen displaced during purge (l)	1.03
Ratio of purge volume to installation volume	1.44

Figure 19: Result table #3, calculated results

4.4 Straight pipe sections

A domestic installation will consist of a number of elements of equipment, connected together with a variety of pipework comprising straights in different directions and branches. This gives a finite number of individual components to test. Installation sections mostly comprise, horizontal pipe runs, vertical pipe runs flowing up and down and some sloping pipe runs. A complex route will be made up with multiples of these individual components joined with elbows and bends. Key components fall into two groups, straight pipe sections and branches.

The first group of tests were carried out on 3 m straight sections of pipe. Four basic configurations were trialled as shown in Figure 20.

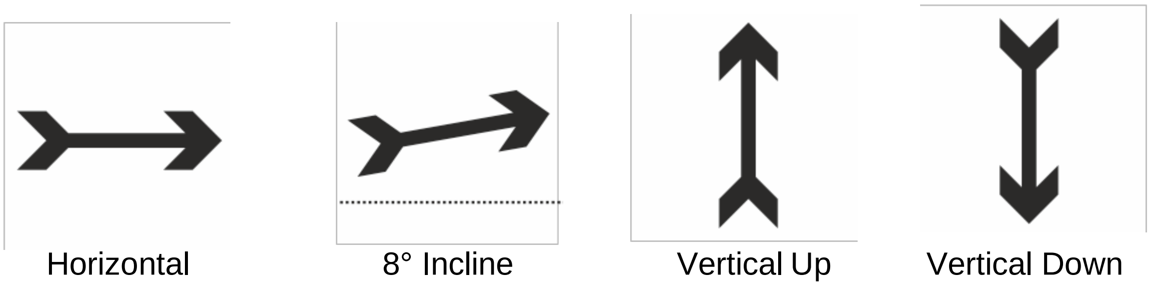


Figure 20: Test orientations

All of the tests aimed to identify the most challenging situations so whilst a full range of pipe diameters have been tested, more testing has been carried out on the largest, 35 mm, diameter pipe. The selected purge rate of 2 l/m is very slow compared with information provided by installers. This was chosen to provide a conservative result and to seek out more challenging scenarios which may pose the greatest challenge to successful purging. The majority of each purge was carried out at this slow flow rate, determined by air being displaced from the system through the purge point. Once hydrogen reaches and starts to go through the purge point, the flow increases significantly. This increase in speed also speeds up the purge process, further aiding the removal of air.

The most challenging purge scenario in relation to primary and secondary gas was expected to be the transition from air to hydrogen. This scenario was therefore selected for most of the tests. For convenience, the general discussion will refer to a purge from air to hydrogen. The results and conclusions for the installation purge are similarly valid for a purge from methane to hydrogen, and air and hydrogen mixes to pure hydrogen.

The results are tabulated in Figure 21 and Figure 22. They show that all of the systems were very easily purged, with a purge ratio in most cases less than 1.5. The tables are coloured to group similar parameters together to aid the reader pick out similar test conditions.

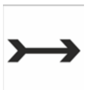
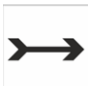
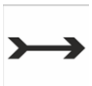
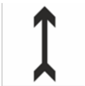
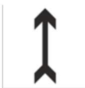
Test No.	Section	Diameter (mm)	Orientation	Flow Direction	Start Gas	End Gas	Installation volume (l)	Purge time (s)	Purge volume (l)	Vol displaced air / methane (l)	Volume of H2 displaced (l)	Purge ratio
001	Straight	35		Horizontal	Air	Hydrogen	2.44	88	3.51	2.48	1.03	1.44
002								87	3.50	2.48	1.02	1.43
003								87	3.49	2.47	1.02	1.43
004	Straight	35		Horizontal	Methane	Hydrogen	2.44	63	3.24	2.36	0.88	1.33
005								63	3.21	2.38	0.83	1.32
006								63	3.25	2.39	0.86	1.33
007	Straight	35		Horizontal	Air + Hydrogen	Hydrogen	2.44	60	2.86	1.09	1.76	1.17
008								65	2.92	1.24	1.67	1.19
009								66	2.94	1.36	1.63	1.20
010	Straight	28		Horizontal	Air	Hydrogen	1.53	66	2.36	1.83	0.53	1.54
011								55	2.15	1.73	0.42	1.40
012								56	2.14	1.70	0.44	1.39
013	Straight	15		Horizontal	Air	Hydrogen	0.40	15	0.50	0.44	0.06	1.25
014								15	0.49	0.43	0.06	1.23
015	Straight	35		8 degree incline	Air	Hydrogen	2.44	97	4.02	2.49	1.53	1.65
016								95	3.99	2.46	1.52	1.63
017								94	3.96	2.41	1.55	1.62
018	Straight	28		8 degree incline	Air	Hydrogen	1.53	58	2.27	1.69	0.58	1.48
019								57	2.28	1.72	0.56	1.49
020								58	2.29	1.73	0.56	1.50
021	Straight	35		Vertical upwards	Air	Hydrogen	2.44	94	4.02	2.39	1.63	1.65
022								90	3.91	2.35	1.56	1.60
023								91	3.93	2.36	1.57	1.61
024	Straight	35		Vertical upwards	Methane	Hydrogen	2.44	70	3.96	2.42	1.53	1.62
025								69	3.85	2.38	1.47	1.58
026								69	3.89	2.37	1.51	1.59

Figure 21: Straight section purge tests

Test No.	Section	Diameter (mm)	Orientation	Flow Direction	Start Gas	End Gas	Installation volume (l)	Purge time (s)	Purge volume (l)	Vol displaced air / methane (l)	Volume of H2 displaced (l)	Purge ratio
027	Straight	35	↑	Vertical upwards	Air + Hydrogen	Hydrogen	2.44	80	3.73	1.62	2.11	1.53
028								68	3.41	1.21	2.20	1.40
029	Straight	28	↑	Vertical upwards	Air	Hydrogen	1.53	58	2.25	1.55	0.70	1.47
030								57	2.24	1.52	0.71	1.46
031								58	2.28	1.55	0.73	1.48
032	Straight	15	↑	Vertical upwards	Air	Hydrogen	0.40	13	0.46	0.40	0.06	1.14
033								13	0.45	0.39	0.06	1.12
034								13	0.45	0.40	0.06	1.13
035	Straight	35	↓	Vertical downwards	Air	Hydrogen	2.44	82	2.75	2.52	0.24	1.13
036								82	2.76	2.52	0.24	1.13
037								83	2.77	2.51	0.25	1.13
038	Straight	35	↓	Vertical downwards	Methane	Hydrogen	2.44	59	2.63	2.35	0.28	1.08
039								59	2.66	2.39	0.27	1.09
040								59	2.63	2.33	0.30	1.08
041	Straight	35	↓	Vertical downwards	Air + Hydrogen	Hydrogen	2.44	59	2.84	1.14	1.70	1.16
042								60	2.84	1.16	1.68	1.16
043								60	2.84	1.18	1.69	1.16
044	Straight	15	↓	Vertical downwards	Air	Hydrogen	0.40	13	0.43	0.42	0.05	1.07
045								13	0.43	0.38	0.05	1.07
046								14	0.45	0.39	0.06	1.13

Figure 22: Straight section purge tests continued

The columns of the straight section results table are as follows:

- **Test No.** is the test number for reference
- **Section** identifies that it is a straight section
- **Diameter** is the nominal OD of the pipe
- **Orientation** provides an illustration of the pipe and direction of flow
- **Flow direction** shows the direction of flow
- **Start gas** is the primary gas composition which is either air, methane or air and hydrogen
- **End gas** is always hydrogen but included for clarity
- **Installation volume** is the physical measured internal volume of the pipe sections making up the installation being tested
- **Purge time** is the time in seconds taken from the start to the end of the purge, (over 95% calculated hydrogen exiting the purge point)
- **Purge volume** is the volume in litres of gas injected to the system from the start to the end of the purge

- **Volume of displaced air/methane** is the calculated volume of air or methane displaced through the purge point
- **Volume of H2 displaced** is the calculated volume of hydrogen displaced through the purge point
- **Purge ratio** is the comparison between the purge volume and the installation volume

The purge ratio gives a measure of the efficiency of the purge. A purge ratio close to 1 indicates that all the air or methane has been purged from the system with very little release of additional hydrogen. A purge ratio of 1.5 indicates that an additional 50% volume of hydrogen was required to displace all of the air in the system.

4.5 Branched pipe sections

The next installation components examined were branched sections. These systems were all of the same configuration, constructed from 22 mm diameter pipes of equal lengths for direct comparison between tests. The orientation and flow direction was changed between tests to map out how the orientation of the different branches affected the purge process.

The tests each had two flow paths - the purge flow was directed first down one leg first then down the other leg. This meant that the order of purging was important for each orientation. Two sets of tests were carried out for each orientation, with the order swapped between tests. The orientation and running order for one set are illustrated in Figure 23 to Figure 27. The second set has the installation in the same orientation but with the flow order swapped.

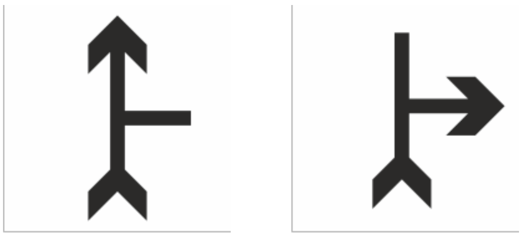


Figure 23: Orientation 1: Vertical ascending – horizontal branch

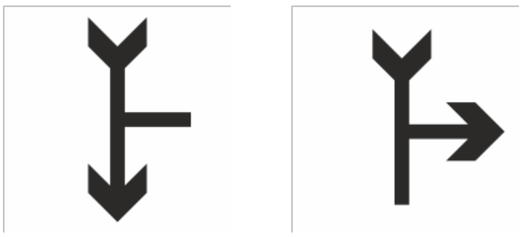


Figure 24: Orientation 2: Vertical descending – horizontal branch

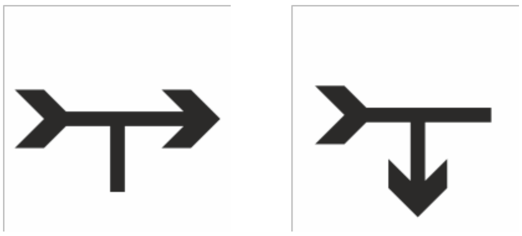


Figure 25: Orientation 3: Horizontal – Vertical descending branch

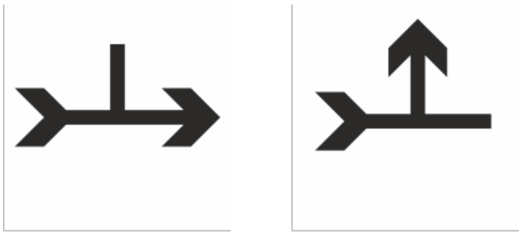


Figure 26: Orientation 4: Horizontal – Vertical ascending branch

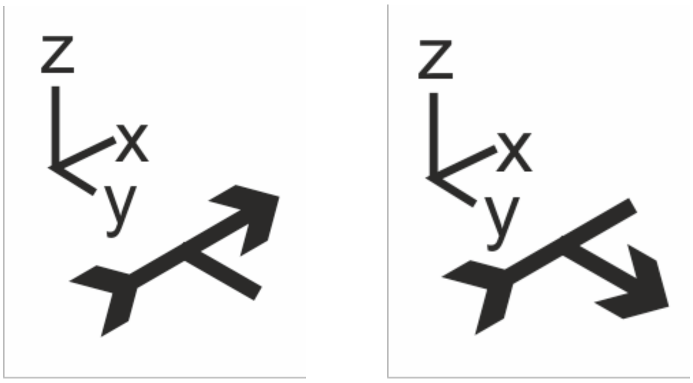


Figure 27: Orientation 5: Horizontal – horizontal branch

The results tables are similar to the straight section results, however individual information is provided for the purge operations of each leg. This enables the efficiency of each purge operation to be noted as well as the overall efficiency of purging the installation.

The first group of branch tests are with the primary section vertical and the secondary section horizontal.

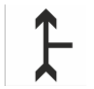
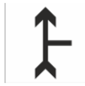
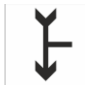
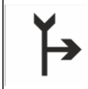
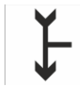
Test No.	Section	Diameter (mm)	Orientation		Flow Direction 1	Flow Direction 2	Start Gas	End Gas	Installation volume (l)	Volume 1 (l)	Volume 2 (l)	Purge time 1 (s)	Purge time 2 (s)	Purge volume 1 (l)	Purge volume 2 (l)	Volume of air displaced 1 (l)	Volume of air displaced 2 (l)	Total volume of air displaced(l)	Volume of H2 displaced 1 (l)	Volume of H2 displaced 2 (l)	Total volume of H2 displaced (l)	Purge ratio 1	Purge ratio 2	Total purge ratio
047									1.58	0.95	0.63	39	17	1.41	0.70	0.99	0.53	1.52	0.42	0.17	0.60	1.49	1.12	1.34
048	Branch	22			Vertical upwards	Horizontal	Air	Hydrogen	1.58	0.95	0.63	38	18	1.42	0.70	0.99	0.54	1.53	0.42	0.16	0.59	1.49	1.11	1.34
049									1.58	0.95	0.63	39	17	1.44	0.70	1.00	0.54	1.54	0.44	0.17	0.60	1.52	1.11	1.36
050									1.58	1.26	0.32	52	7	2.06	0.33	1.37	0.14	1.51	0.69	0.19	0.88	1.63	1.02	1.51
051	Branch	22			Horizontal	Vertical upwards	Air	Hydrogen	1.58	1.26	0.32	51	7	2.00	0.31	1.37	0.12	1.49	0.63	0.19	0.82	1.58	0.99	1.46
052									1.58	1.26	0.32	53	8	2.13	0.33	1.37	0.14	1.50	0.76	0.19	0.95	1.68	1.03	1.55
053									1.58	0.95	0.63	34	18	1.31	0.69	0.98	0.53	1.51	0.33	0.16	0.49	1.38	1.10	1.27
054	Branch	22			Vertical downwards	Horizontal	Air	Hydrogen	1.58	0.95	0.63	39	18	1.35	0.69	1.02	0.54	1.56	0.33	0.16	0.49	1.43	1.11	1.30
055									1.58	0.95	0.63	38	17	1.36	0.70	1.03	0.54	1.57	0.33	0.16	0.49	1.43	1.11	1.30
056									1.58	1.26	0.32	45	9	1.46	0.35	1.30	0.28	1.58	0.16	0.07	0.23	1.15	1.11	1.15
057	Branch	22			Horizontal	Vertical downwards	Air	Hydrogen	1.58	1.26	0.32	44	9	1.47	0.35	1.31	0.28	1.59	0.16	0.07	0.23	1.16	1.13	1.15
058									1.58	1.26	0.32	45	9	1.46	0.35	1.30	0.28	1.58	0.16	0.08	0.24	1.16	1.14	1.15

Figure 28: Branch section purge test results

The second group of branch tests have both the primary and secondary sections horizontal.

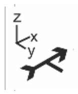
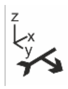
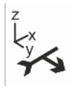
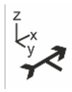
Test No.	Section	Diameter (mm)	Orientation		Flow Direction 1	Flow Direction 2	Start Gas	End Gas	Installation volume (l)	Volume 1 (l)	Volume 2 (l)	Purge time 1 (s)	Purge time 2 (s)	Purge volume 1 (l)	Purge volume 2 (l)	Volume of air displaced 1 (l)	Volume of air displaced 2 (l)	Total volume of air displaced(l)	Volume of H2 displaced 1 (l)	Volume of H2 displaced 2 (l)	Total volume of H2 displaced (l)	Purge ratio 1	Purge ratio 2	Total purge ratio
059									1.58	0.95	0.63	35	20	1.38	0.72	0.94	0.55	1.48	0.44	0.17	0.62	1.45	1.33	1.33
060									1.58	0.95	0.63	34	21	1.34	0.72	0.88	0.55	1.43	0.46	0.17	0.63	1.41	1.30	1.30
061									1.58	0.95	0.63	36	21	1.40	0.73	0.96	0.55	1.50	0.45	0.17	0.62	1.48	1.35	1.35
062	Branch	22			Horizontal	Horizontal	Air	Hydrogen	1.58	0.95	0.63	35	18	1.38	0.72	0.92	0.55	1.47	0.46	0.18	0.64	1.46	1.33	1.34
063									1.58	0.95	0.63	35	17	1.38	0.71	0.91	0.52	1.43	0.46	0.19	0.65	1.45	1.32	1.32
064									1.58	0.95	0.63	34	18	1.36	0.71	0.89	0.55	1.44	0.47	0.17	0.64	1.44	1.31	1.32
065									1.58	0.95	0.63	34	18	1.36	0.70	0.89	0.50	1.39	0.47	0.21	0.68	1.44	1.30	1.31
066									1.58	1.26	0.32	46	8	1.80	0.36	1.24	0.21	1.46	0.56	0.15	0.71	1.43	1.37	1.37
067	Branch	22			Horizontal	Horizontal	Air	Hydrogen	1.58	1.26	0.32	50	8	1.90	0.37	1.36	0.23	1.59	0.54	0.15	0.69	1.50	1.43	1.44
068									1.58	1.26	0.32	45	8	1.79	0.38	1.21	0.23	1.44	0.57	0.15	0.72	1.41	1.37	1.37

Figure 29: Branch section purge test results, continued

The third group of branch tests have the primary section horizontal and the secondary section vertical.

Test No.	Section	Diameter (mm)	Orientation		Flow Direction 1	Flow Direction 2	Start Gas	End Gas	Installation volume (l)	Volume 1 (l)	Volume 2 (l)	Purge time 1 (s)	Purge time 2 (s)	Purge volume 1 (l)	Purge volume 2 (l)	Volume of air displaced 1 (l)	Volume of air displaced 2 (l)	Total volume of air displaced(l)	Volume of H2 displaced 1 (l)	Volume of H2 displaced 2 (l)	Total volume of H2 displaced (l)	Purge ratio 1	Purge ratio 2	Total purge ratio
069									1.58	0.95	0.63	34	19	1.15	0.71	0.95	0.61	1.56	0.20	0.10	0.30	1.21	1.18	1.18
070	Branch	22			Horizontal	Vertical downwards	Air	Hydrogen	1.58	0.95	0.63	35	19	1.16	0.71	0.98	0.62	1.60	0.18	0.09	0.27	1.22	1.18	1.18
071									1.58	0.95	0.63	35	19	1.16	0.70	0.97	0.62	1.60	0.19	0.09	0.27	1.22	1.18	1.18
072									1.58	1.26	0.32	48	13	1.94	0.39	1.34	0.23	1.57	0.60	0.16	0.76	1.53	1.47	1.47
073	Branch	22			Vertical downwards	Horizontal	Air	Hydrogen	1.58	1.26	0.32	46	9	1.81	0.35	1.26	0.21	1.47	0.55	0.14	0.70	1.43	1.37	1.37
074									1.58	1.26	0.32	46	10	1.79	0.37	1.26	0.23	1.49	0.53	0.14	0.68	1.42	1.37	1.37
077									1.58	0.95	0.63	34	17	1.55	0.73	0.79	0.50	1.29	0.76	0.22	0.99	1.64	1.44	1.44
078	Branch	22			Horizontal	Vertical upwards	Air	Hydrogen	1.58	0.95	0.63	40	16	1.58	0.70	1.02	0.46	1.48	0.56	0.24	0.80	1.67	1.44	1.44
079									1.58	0.95	0.63	38	14	1.45	0.63	1.02	0.36	1.38	0.44	0.27	0.70	1.53	1.32	1.32
081									1.58	1.26	0.32	48	9	1.81	0.37	1.32	0.22	1.54	0.49	0.15	0.64	1.43	1.38	1.38
082	Branch	22			Vertical upwards	Horizontal	Air	Hydrogen	1.58	1.26	0.32	49	9	1.83	0.37	1.34	0.23	1.56	0.49	0.14	0.64	1.45	1.39	1.39
083									1.58	1.26	0.32	49	9	1.85	0.36	1.33	0.18	1.51	0.52	0.17	0.69	1.46	1.40	1.40

Figure 30: Branch section purge test results

The columns of the branch section results tables are as follows:

- **Test No**. is the test number for reference
- **Section** identifies that it is a straight section
- **Diameter** is the nominal OD of the pipe
- **Orientation** provides illustrations of the pipe and direction of flow, showing the order of which leg is purged first and which purged second
- **Flow direction 1** is the direction of flow for the purge of the first leg
- **Flow direction 2** is the direction of flow for the purge of the second leg
- **Start gas** is the initial gas composition
- **End gas** is always hydrogen but included for clarity
- **Installation volume** is the physical volume of the pipe sections making up the total installation being tested, including the feed leg and both branch legs
- **Volume 1** is the volume of the route down the first leg to be purged, this includes the volume from the crossover valve to the purge point on the first leg.
- **Volume 2** is the remaining volume which is the volume from the branch to the purge point on the second leg, volume 1 and volume 2 combine to make the installation volume
- **Purge time 1** is the time in seconds taken from the start to the end of the purge of the first leg, (over 95% calculated hydrogen exiting the purge point)
- **Purge time 2** is the time in seconds taken from the start to the end of the purge of the second leg, (over 95% calculated hydrogen exiting the purge point)
- **Purge volume 1** is the volume in litres of gas injected to the system from the start to the end of the purge of the first leg
- **Purge volume 2** is the volume in litres of gas injected to the system from the start to the end of the purge of the first leg
- **Volume of air displaced 1** is the calculated volume of air displaced through the purge point during the purge of the first leg
- **Volume of air displaced 2** is the calculated volume of air displaced through the purge point during the purge of the second leg
- **Total volume of air displaced** is the calculated sum of the volume of air displaced during both purges, this is a calculation of air removed from the system
- **Volume of H2 displaced 1** is the calculated volume of hydrogen displaced through the purge point during the purge of the first leg
- **Volume of H2 displaced 2** is the calculated volume of hydrogen displaced through the purge point during the purge of the second leg
- **Total volume of H2 displaced** is the calculated sum of the volume of hydrogen displaced during both purges
- **Purge ratio 1** is the comparison between the purge volume and the installation volume for the first purge
- **Purge ratio 2** is the comparison between the purge volume and the installation volume for the second purge
- **Purge ratio total** is the comparison of total purge volume and the full installation volume

Examination of the total volume of air displaced compares well with the installation volume and this demonstrates the effectiveness of removing air from the test installations in all cases. The purge was deemed complete when 95% of the air has been removed. This value was chosen for clarity of the calculated value. The asymptotic behaviour leads to much longer times needing to be taken to remove the remaining 5% which was close to the sensitivity of the measurement system. This has a tendency for the calculations to slightly underestimate the actual volume of air removed.

4.6 Additional tests

Additional tests were carried out to identify the effectiveness of purging meters. An MMU6 smart meter was supplied by MeterSit. This meter was a methane meter but the gas flow paths are the same as for hydrogen meters so entirely valid for the tests. A traditional U6 diaphragm meter was also tested for comparison, although these meters are not expected to be used in hydrogen installations.

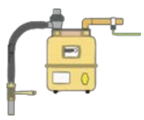
Test No.	Section	Component	Purge point	Start Gas	End Gas	Installation volume (l)	Purge time (s)	Purge volume (l)	Volume of air displaced (l)	Volume of H2 displaced (l)	Purge ratio
084	MMU6 meter and test point		Valved test port	Air	Hydrogen	1.32	59.5	3.00	1.27	1.73	2.27
085			Valved test port			1.32	56.4	2.72	1.23	1.49	2.06
086			Valved test port			1.32	59.7	2.92	1.28	1.64	2.21
087			Valved test port			1.32	58.6	2.92	1.28	1.64	2.21
088	MMU6 meter		Meter test port	Air	Hydrogen	1.00	96.7	3.12	1.29	1.84	3.12
089			Meter test port			1.00	95.5	3.07	1.29	1.77	3.07
090			Meter test port			1.00	95.6	3.07	1.29	1.78	3.07
091	Diaphragm meter and test point		Valved test port	Air	Hydrogen	8.32	325.1	17.63	5.73	11.90	2.12
092			Valved test port			8.32	327.0	18.82	5.87	12.95	2.26
093			Valved test port			8.32	317.9	17.54	5.65	11.89	2.11

Figure 31: Meter purge test results

The columns for the test results are as previously noted for other purge tests. The meter tests showed that purging the larger, more convoluted volumes of the meter takes more time than simple lengths of pipe with lower purge ratios. If we simply compare the volume of gas required for the purge, the smart meter took much less gas to complete the purge than the traditional diaphragm meter.

4.7 Stage 1 Observations

The detailed tests were all carried out at slow flows to heighten the impact of any gravitational effects. The aim was to create cases that would be challenging to purge. The expectation was that in the field, fitters will be time-pressed and will aim to purge as quickly as possible. This in turn will lead to high purge speeds and more efficient gas exchange.

In all of the tests, the purge was a routine operation. All orientations and all pipe diameters were able to be purged for the straights, branches and meters. This provides a high degree of confidence of being able to purge all systems. This was true for all the purge scenarios: air to hydrogen, methane to hydrogen and air + hydrogen to hydrogen.

The calculations also confirmed that all of the air to was able to be removed and the calculated volume was generally within 10% of the measured installation volume providing confidence in the results.

A brief discussion is provided with reference to particular tests to highlight particular trends seen during the tests.

4.7.1 Effect of straight pipe orientation

A comparison of four tests carried out on the 35 mm pipe section is given in Figure 32. This illustrates the purge process for the four different pipe orientations: horizontal, 8-degree incline, vertical upwards and vertical downwards. The graphs show the effects of gravity, most clearly this is shown in the comparison between the vertically upwards and downwards graphs. The initial average speed of the gas is 0.04 m/s, this slow speed allows gravitational effects to have an impact on the purge speed.

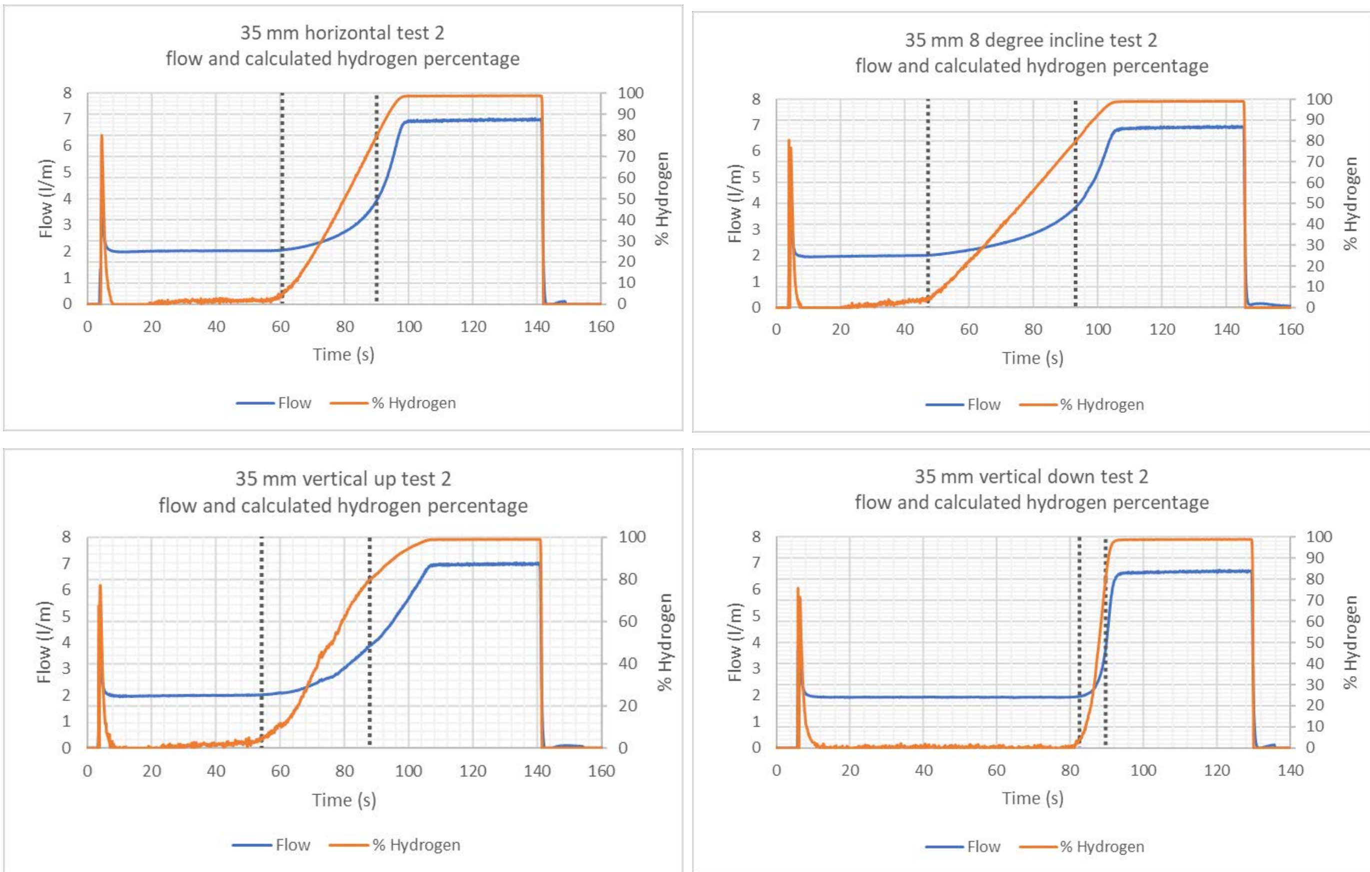


Figure 32: Comparison of pipe orientation

The vertically downward test took 74 seconds of purging air before the hydrogen reached the purge point. The transition then occurred rapidly, taking less than 9 seconds completing the purge after 84 seconds. Conversely when the purge is carried out upwards, the gas started to reach the purge point within 10 seconds and the main transition started after 44 seconds. The purge transition took 46 seconds, completing after 90 seconds. When the flow is directed up, gravitational effects cause the bulk volume of hydrogen to rise, flowing past and through the air. This promotes mixing of the gases, leading to an increase of the transition time and a slight increase in the purge time. This mixing did not, however prevent the removal of all of the air and the overall purge time was less than 10% greater. A summary of the four test results is given in Figure 33, and an overlayed graph shown in Figure 34.

	Horizontal	8° Slope	Up	Down
Installation volume	2.44	2.44	2.44	2.44
Vol displaced	3.50	3.99	3.91	2.76
Vol air displaced	2.48	2.46	2.35	2.52
Vol h2 displaced	1.02	1.52	1.56	0.24
Purge ratio	1.43	1.63	1.60	1.13

Figure 33: Comparison of pipe orientation results

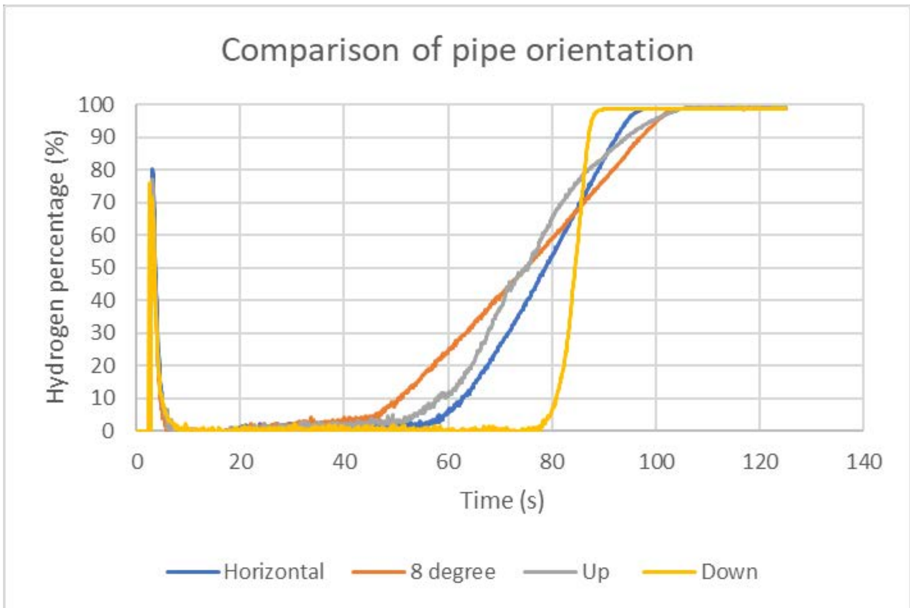


Figure 34: Overlay of hydrogen percentage for different pipe orientations

As a general observation, all of the scenarios were able to be purged. Purging with a downward flow limits the amount of mixing of the two gases resulting in a purge ratio closer to 1 than for other orientations. This in turn limits the amount of hydrogen released during the purge operation.

4.7.2 Pausing during the test

A range of experiments were carried out to investigate the effects of stopping part way through the test. The first of these involved a vertical upwards flow stopped part way through and then left overnight. On testing the following day, the gas in the pipe was found to be a uniform mix, rather than all of the hydrogen collecting at the top of the pipe. The test started with a hydrogen level of 35% which was initially uniform in consistency until the hydrogen purge gas starts to reach the purge point. This test demonstrated that, over time, hydrogen and air will diffuse together to form a homogeneous mix.

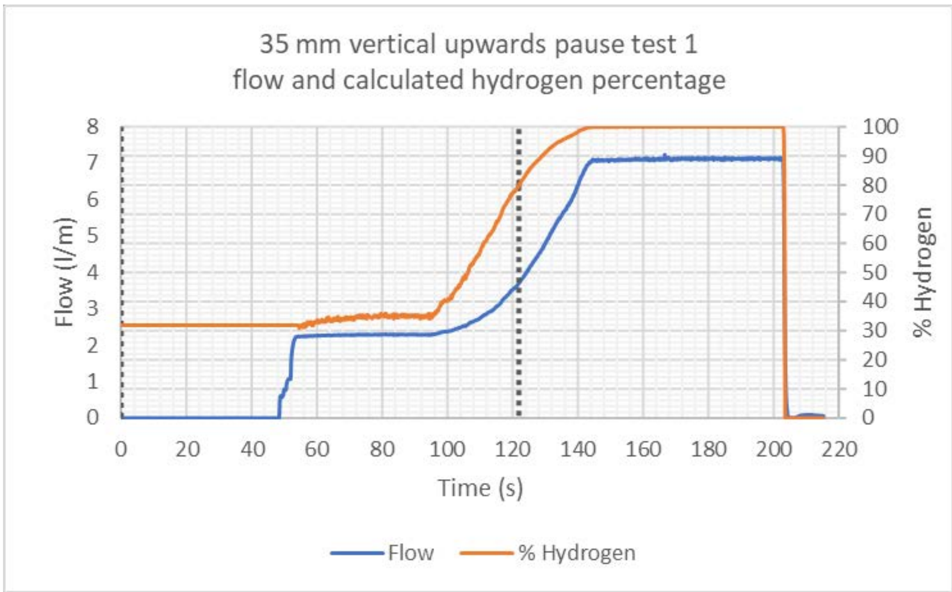


Figure 35: Test paused and left overnight

A range of tests were carried out with shorter pauses of 30 minutes, to represent the scenario of the purge operation being interrupted and re-started. These tests are shown for comparison in Figure 36 and Figure 37.

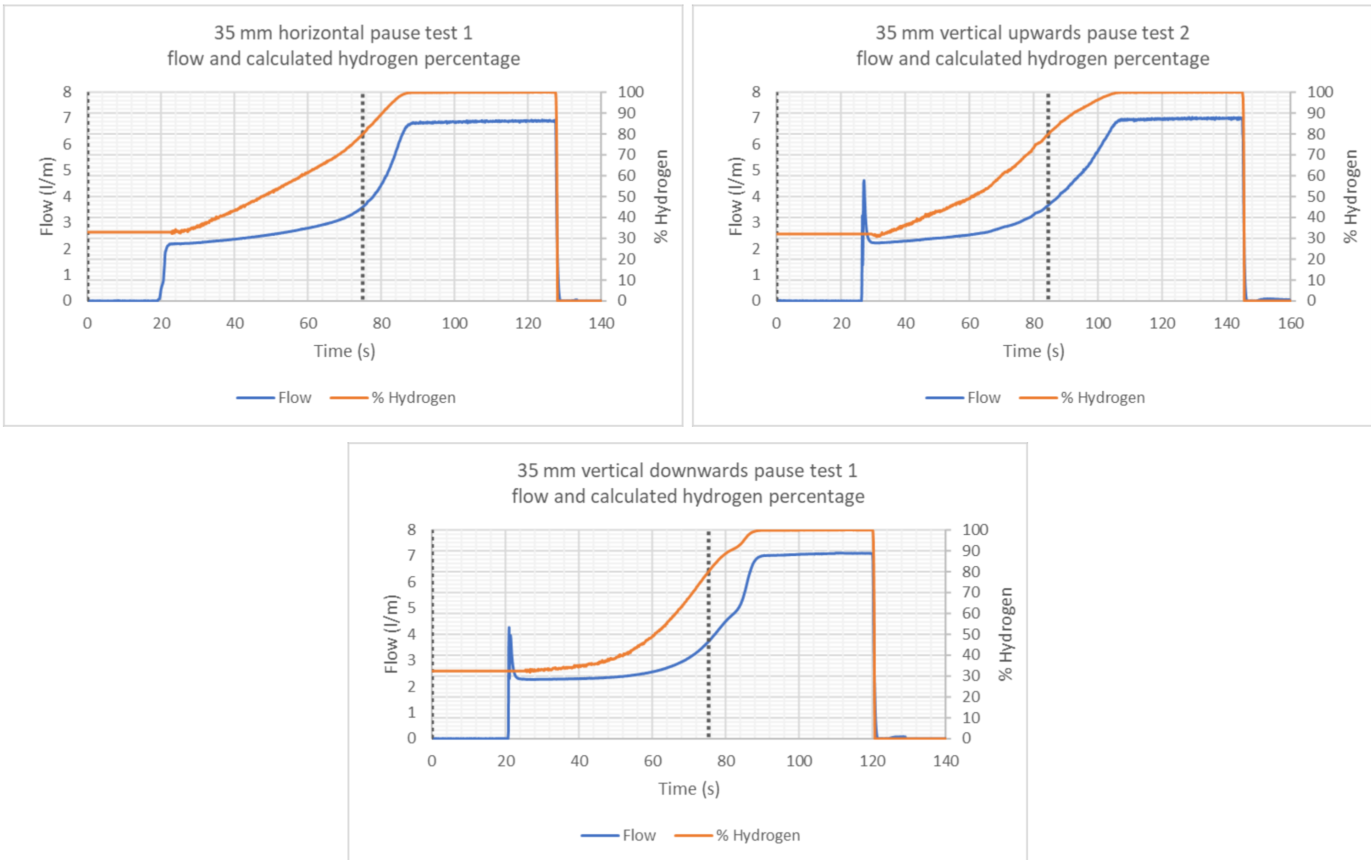


Figure 36: Comparison of purge after half hour pause

Test Orientation	007 Horizontal	028 Up	041 Down
Installation volume		2.44	
Vol displaced	2.86	3.41	2.84
Vol air displaced	1.09	1.21	1.14
Vol h2 displaced	1.76	2.20	1.70
Purge ratio	1.17	1.40	1.16

Figure 37: Test data for comparison pause tests

As a general observation, pausing during the purge operation allowed the gases to mix by diffusion. The longer the pause, the greater the degree of mixing. For the 3 m section of 35 mm pipe, the 17-hour pause resulted in a homogeneous mix, a 30 minute pause was only enough to start the mixing process.

4.7.3 Branches

The next large set of tests was carried out for branched systems. Purging a system with branches requires each branch to be purged one at a time. Dead branches provide the most likely conditions where air could be trapped in a system.

An example branch test, number 047, is given in Figure 38. The top graph shows the logged flow and cumulative sum of injected hydrogen for the duration of the test. Both legs were purged as part of the test. In this instance the feeder is vertically upwards with the branch horizontal. The first purge was the vertical straight from the feeder, past the tee to the end of the first branch section. The horizontal leg was initially dead.

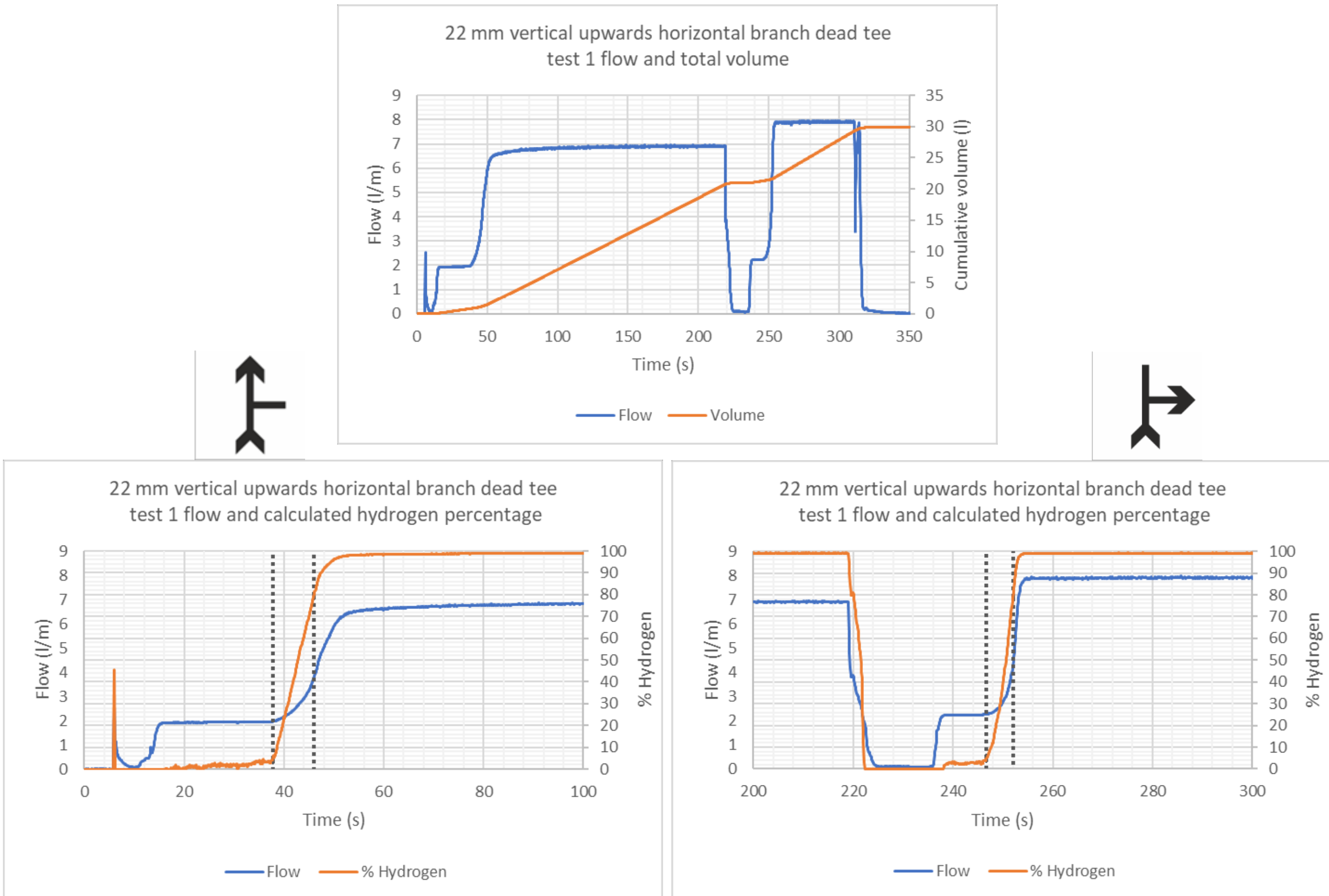


Figure 38: Example branch purge test 047

The first purge used the same 1mmTP for purging as used in the straight section tests. The second purge event used a different 1mmTP which still a nominal 1 mm hole the orifice size is slightly larger. This is reflected in the graphs by the horizontal flow sections being slightly greater for the second purge than for the first. In all of the experiments the smaller orifice valve was installed on the first leg to be purged and the larger one installed on the second leg.

Details of the logged flow and calculated hydrogen concentration from the first purge are shown on the graph on the left of Figure 38. The logged flow and calculated hydrogen for the second purge is shown on the graph on the right.

The graphs show that once all the air is expelled from the vertical straight through leg there is still air trapped in the horizontal leg.

If we reverse the purge flow order, purging the horizontal branch first and then the vertical branch then gravity effects will tend to allow the hydrogen to enter the dead vertical branch and displace the air into the purge flow in the horizontal branch. This effect is seen in Figure 39. Once again the top graph shows the two purge events, but this time the first event ends with a gently increasing flow and the second event is very rapid with little indication of a slug of air being displaced. This demonstrates the displacement of the air during the first purge exercise that helps to clear the air from the dead vertical leg.

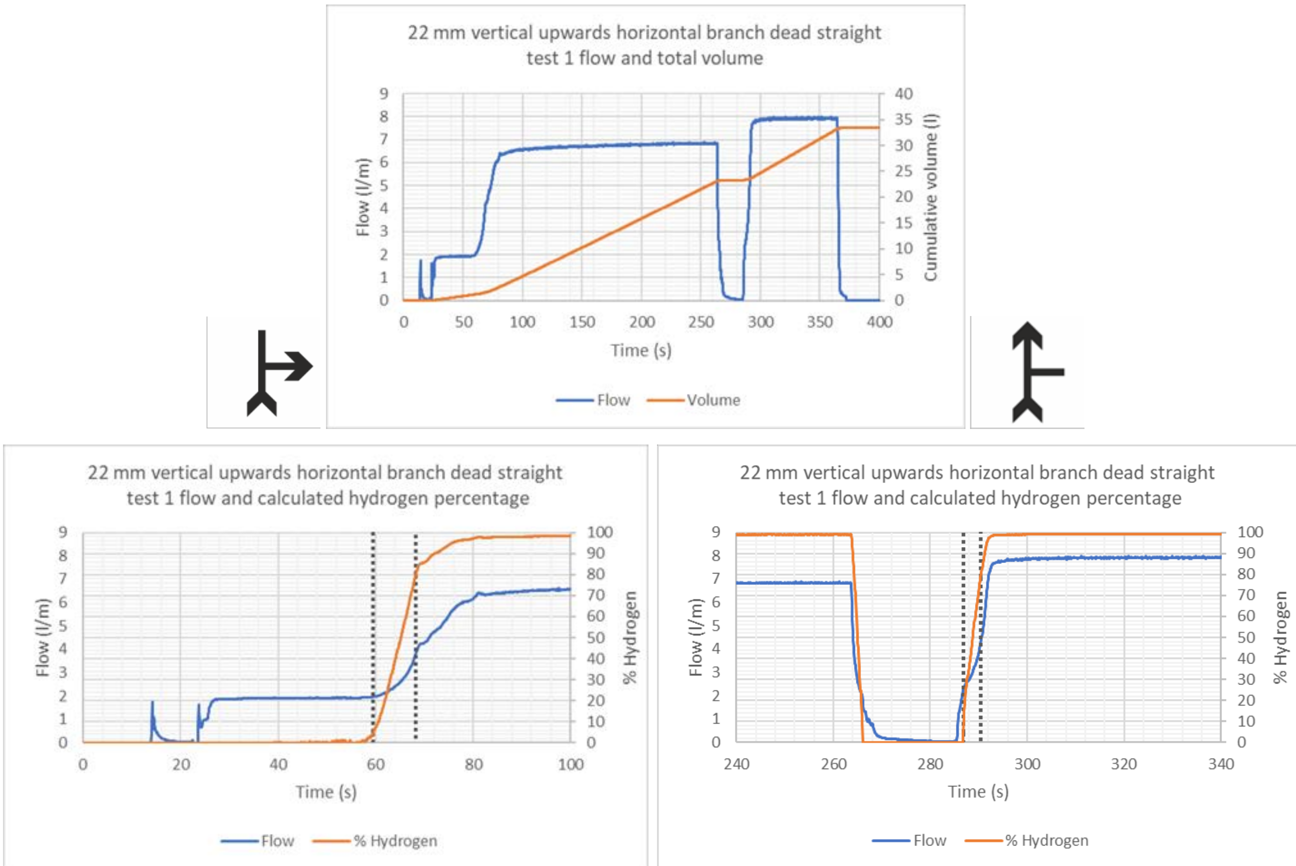


Figure 39: Example branch purge test 050

Examination of the percentage hydrogen in the first purge event on the left-hand side graph shows a longer period of air displacement than for test 047 and a more gradual completion of that purge indicating the drawing of extra air. The right-hand graph shows only a small amount of air remaining in the vertical run.

In both instances all the air was efficiently removed from the system, indicating no problems with the purge.

The configuration most likely to result in trapped air is the vertical down dead branch. Test 070 is shown in Figure 40. This test comprised a horizontal feeder with a vertical downwards branch. The top graph shows the full purge exercise and both individual purge events are clearly defined. The graph on the left shows the purge of the horizontal section with a relatively short transition period. The graph on the right shows the purge of the vertical leg. This second purge operation was also a clear purge with a very short transition time, as expected for a downwards purge. In the case of the downward facing dead branch, air would initially be trapped in the system, however like the straight downward section, access to the end of the dead branch would enable a quick and clean purge to be carried out.

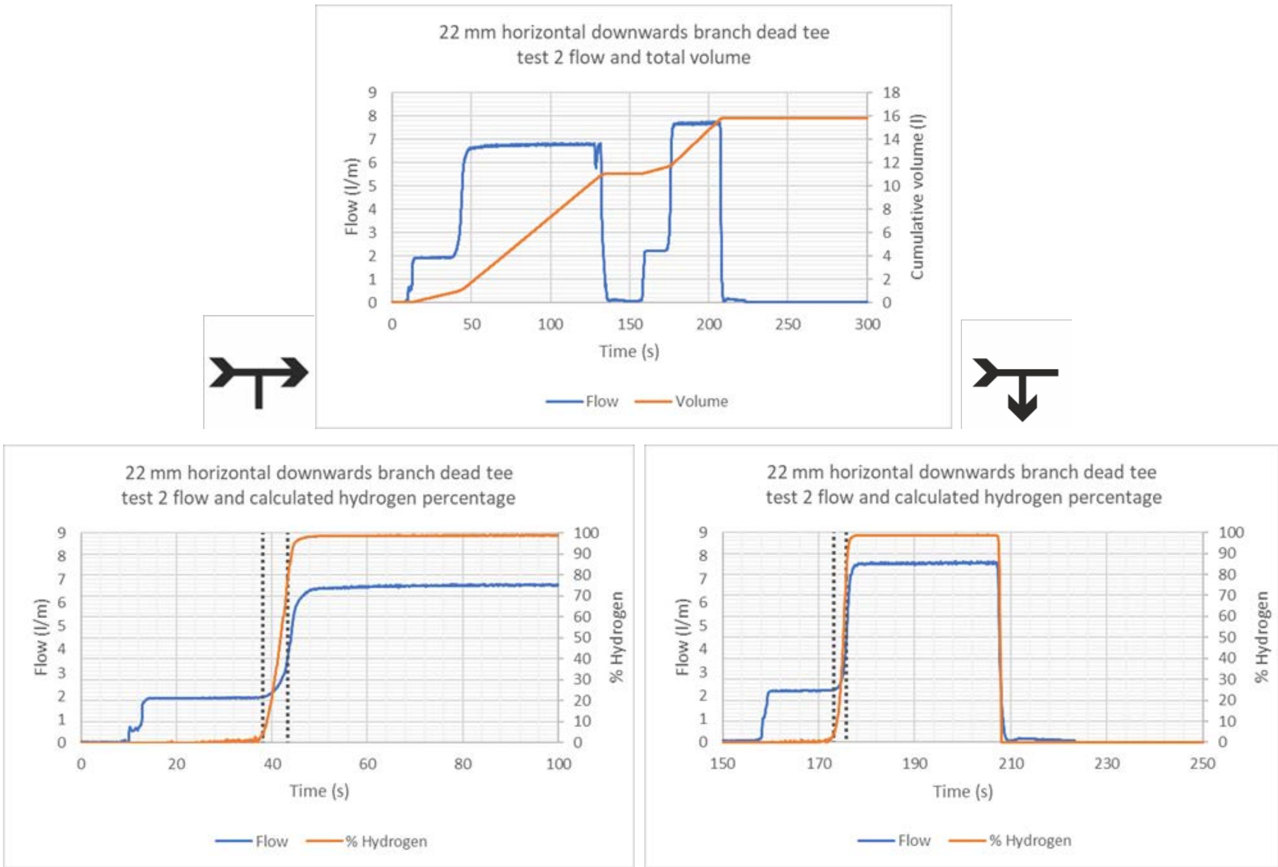


Figure 40: Test 070, dead vertical downward branch showing trapped air.

If we reverse the direction of flow in the same system, purging the vertically downward branch first then air can be displaced from the dead horizontal leg of the branch system. This is shown in the top graph of Figure 41. The first purge event shows the displacement of a clear slug of air. The second purge event shows less air remaining in the system, indicating the air has been partially displaced during the first purge event. The rounded end of the rise in hydrogen concentration at the end of the transition shown in the graph on the left indicates this drawing of air out of the dead branch. The rapid rise of the hydrogen concentration in the graph on the right indicates only a limited amount of air left in the system to be purged during the second event.

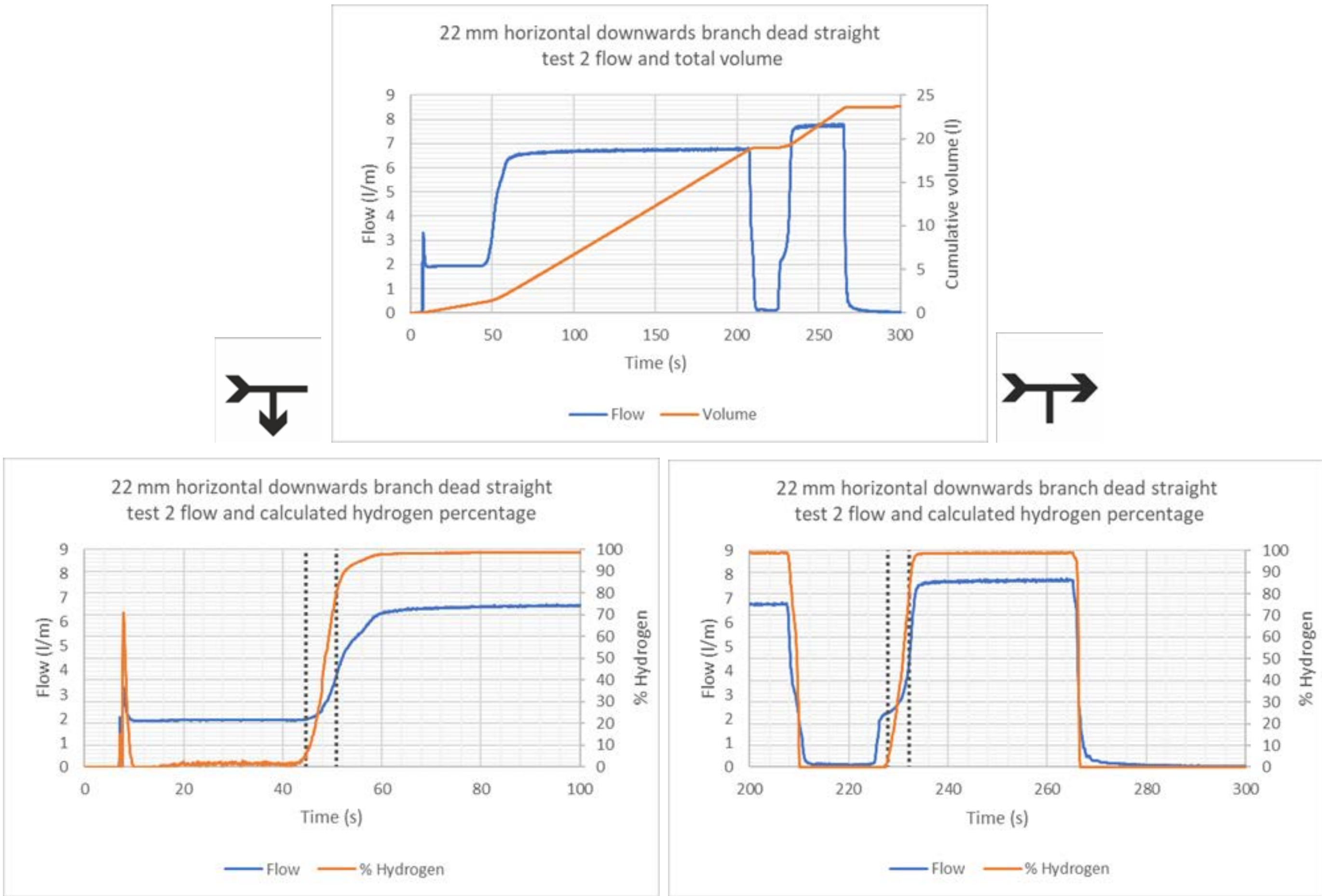


Figure 41: Test 074 horizontal feed, with initially dead straight branch

It was identified that it is possible to trap air in a dead vertically down branch, so an investigation was carried out for a scenario in which a dead branch is not identified during the installation site survey. Test 072 involved a system purge with the vertical branch kept locked in. After the initial purge, the hydrogen was left running for 1 hour to simulate a boiler or hob being operated for that time. The remaining air was then purged from the dead branch to see how much was left. The graphs of this purge are shown in Figure 42. The key graph here is on the bottom right, showing the dead branch to be a mixture of air and hydrogen. This is confirmed by the calculated volume of air displaced during the purge being 0.45 litres. Three tests of the same setup but without the 1 hour simulated operation period showed corresponding air displacement volumes of, 0.61, 0.62 and 0.62 litres. The measured volume of the dead branch was 0.63 litres.

Overall conclusions of the branch tests are that in all of the tests it was possible to purge the complete volume of air from the installations. It is possible to design systems that will trap air, but even in this case, air and hydrogen left in the installation will mix over time. The slow purge flows tested provide conservative results as larger flows will be much more likely to displace incumbent air, as gravitational effects will be reduced in comparison to the gas flow speed.

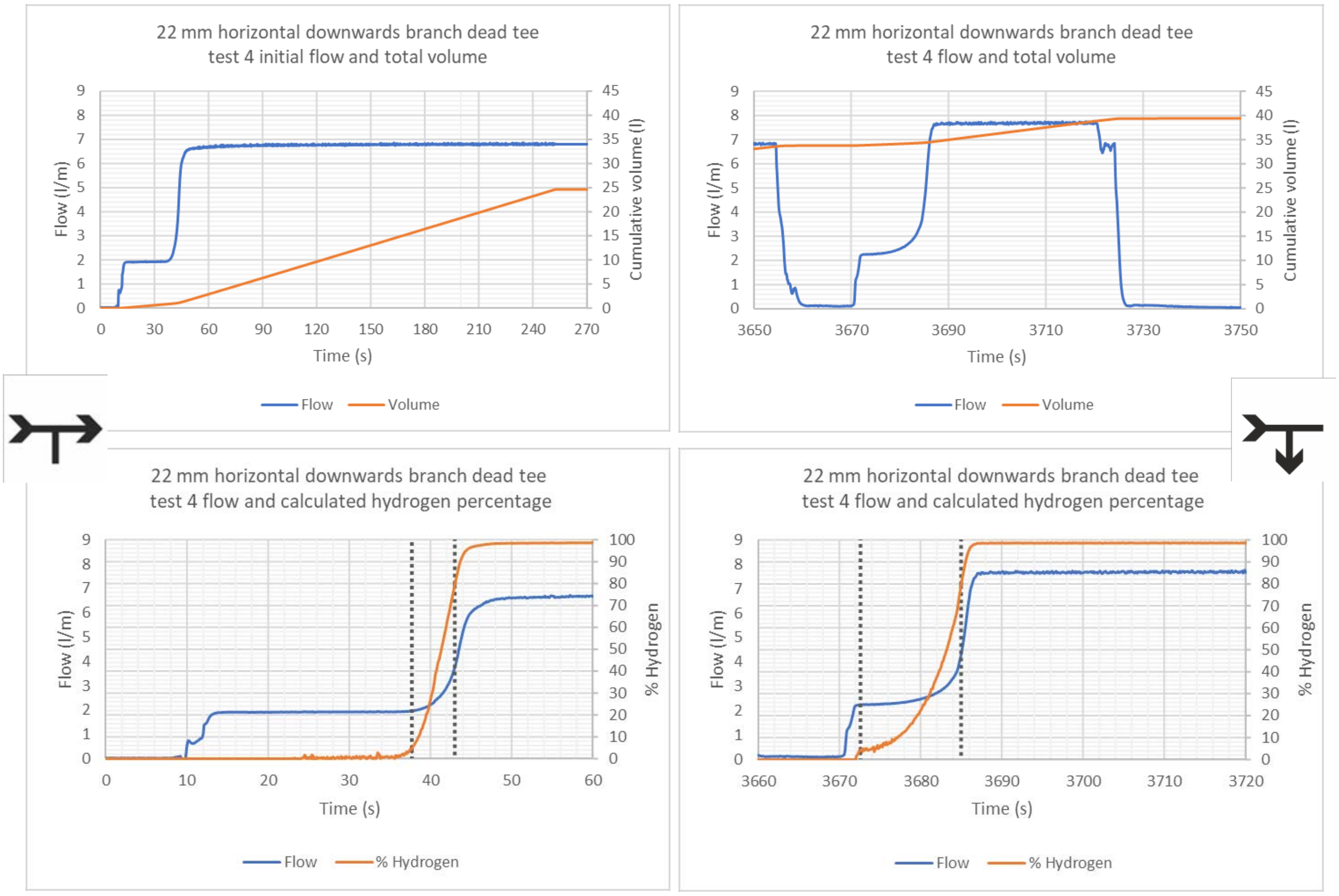


Figure 42: Test 072 horizontal branch, dead section purged after 1-hour operation

4.7.4 Meters

Two meters were tested. An MMU6 smart meter from MeteRSit and a traditional U6 diaphragm meter. The smart meter has an internal volume of 1 litre and the diaphragm meter an internal volume of 8 litres. Both meters were tested with a pipe stub, with 0.23 litres of additional volume. The graphs of the purges, shown in Figure 43 and Figure 44 show it was possible to purge both meters. The calculated figures show a similar purge ratio for both meters, 2.27 for the smart meter and 2.11 for the diaphragm. The big difference was the purge volume required. The diaphragm meter required over 17 litres of hydrogen to purge, the air being slowly drawn out of the meter over time. The smart meter is a lower volume with a simpler flow path, and this resulted in a much quicker and more complete purge.

The biggest impact on the standards is the smaller meter volume, which will result in smaller overall installation volumes.

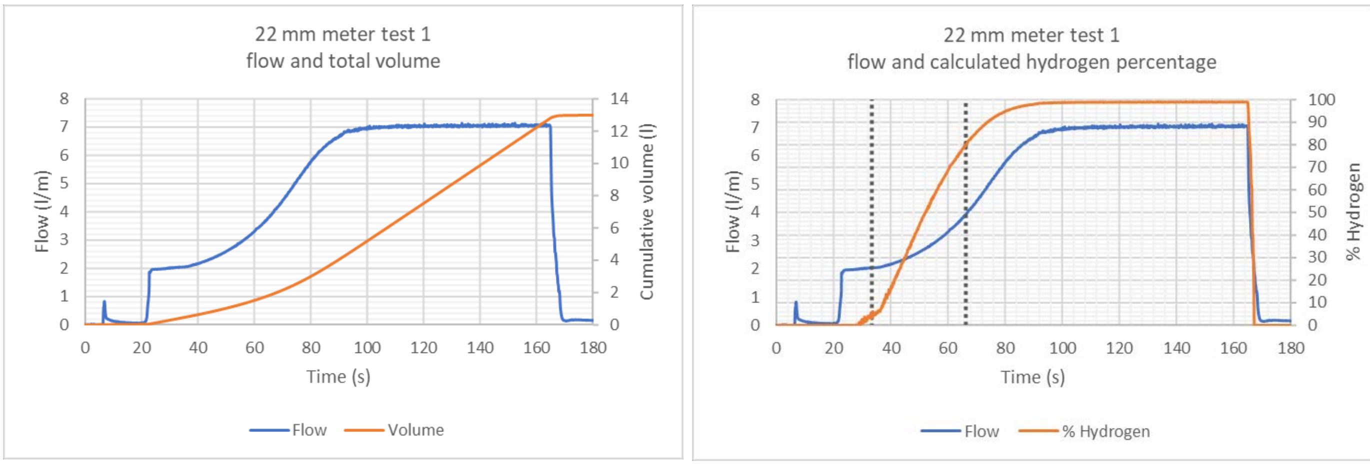


Figure 43: Test 084, smart meter with 22 mm pipe stub

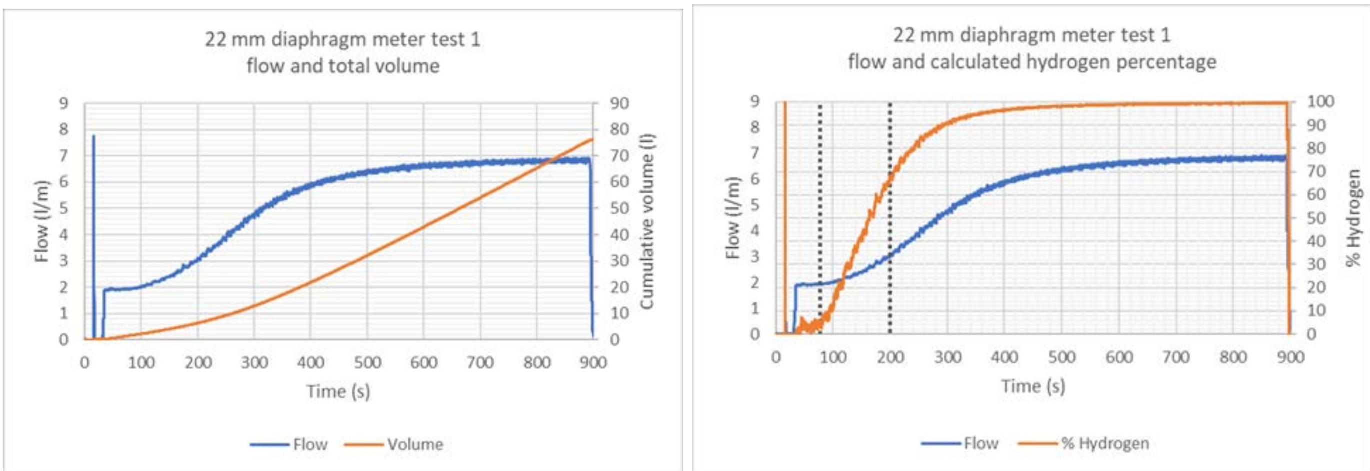


Figure 44: Test 091 Diaphragm meter with 22 mm pipe stub

4.7.5 Complete systems

The experiments sought for but did not find a system that is challenging to purge, as long as there is purging access to the end of all branches. A minimum flow for successful purging has not been found, despite early tests being carried out at 1% of the recommended minimum purge speed. The purge flow for the installation tests were carried out at between 2 and 7 l/min this corresponds to flow speeds of:

- 0.25 m/s to 0.88 m/s for 15 mm pipe
- 0.11 m/s to 0.37 m/s for 22 mm pipe
- 0.07 m/s to 0.24 m/s for 28 mm pipe
- 0.04 m/s to 0.15 m/s for 35 mm pipe

It is worthwhile noting that these speeds are significantly lower than the 0.6 m/s recommended in table 12 of the IGE/UP/1 standard. The fact that no significant challenges were found in the purge tests gives a high degree of confidence that it will be possible to purge all complete domestic installations.

The Reynolds number for hydrogen flowing at 2 l/m is 13.1 in 35 mm pipe, and 42 in 10 mm pipe.

5 WP3 Stage 2 purging into enclosure

The second element of this work was the investigation into how hydrogen gas released during the purge will behave and settle in a room-like enclosure.

This work built on the review of purging standards and reported practices carried out during WP1, with likely purge volumes and speeds indicated by the experimental results of WP3 Stage 1. The aim was to identify risks in the processes that might arise from a change in gas, particularly with a view to the relationship between dispersion and stratification of hydrogen. Situations were actively sought that might lead to pockets of hydrogen collecting and building up to a flammable mix.

5.1 The enclosure

The enclosure used for the Stage 2 tests was designed to represent a small kitchen. The worst case scenario is the smallest enclosed volume, as there is less ambient air for the flammable gas to mix with. This leads to a higher overall concentration of flammable gas.

It was not possible to represent all possibilities when looking at kitchen designs. The size selected was 2 m wide by 3 m long, with a ceiling at 2 m height. This gives a total volume of 12 m^3 (12,000 l). There were no cupboards or other furniture included, to minimise disruption to air currents produced during the tests.

The enclosure was constructed from wood, with transparent polythene sheets making the walls. A rigid polycarbonate roof was used. The corners were taped to minimise ventilation, but the bottom of the walls was not sealed to the floor. This was to ensure the air pressure of the enclosure did not increase when hydrogen is released into the room, as well as providing safety in not creating an enclosed pressure volume.

Figure 45: Stage 2 enclosure, with single central sensor post

The enclosure was placed in Steer Energy's laboratory, and external doors were closed as much as possible during tests. This minimised the movement of air around the enclosure, which may have created unwanted eddies inside the enclosure.

The IGEM/UP/1B standard stipulates that purging of an installation volume up to 0.02 m^3 can be vented freely into a well-ventilated internal space. Purging of installation volumes greater than this must be carried out through an open burner, with ignition of the gas made as soon as possible. Although it is not fully sealed, the enclosure was deliberately designed to be poorly ventilated. This will exacerbate any tendency towards stratification of the released hydrogen.

The enclosure can be ventilated easily to provide ambient clean air. The wall on the end of the enclosure was folded back for some of the tests to create a small amount of ventilation. When clearing between tests, the laboratory was also purged to prevent a possible build-up of hydrogen, and to allow the sensors to re-calibrate back to clean air.

Using the MQ-8 sensors allows a greater range of positions to be monitored simultaneously than using a detection device such as the GMI GS700H. They are also able to be logged, so can be left for extended periods of time without being monitored.

The sensors can be adhered to the walls and ceiling of the enclosure using double sided sticky tape, or clipped on to vertical sticks. The latter configuration is shown in Figure 46, with four vertical poles each holding four sensors spaced evenly apart. The sensor spacings are 50 cm apart with the upper sensor 10 cm from the ceiling. This arrangement maps the four corners of the space, at a variety of equal heights. This layout was used for the majority of tests. The posts are labelled A to D, as shown in Figure 46. The designation of sensor height is:

- Top - level 1 – 10 cm from the ceiling
- High middle - level 2 – 60 cm from the ceiling
- Low middle - level 3 – 110 cm from the ceiling
- Bottom - level 4 – 160 cm from the ceiling

The hydrogen insertion point was in the same corner as post B, and the opening used as ventilation was in the corner of post C. The sensor posts were located 60 cm from each wall.

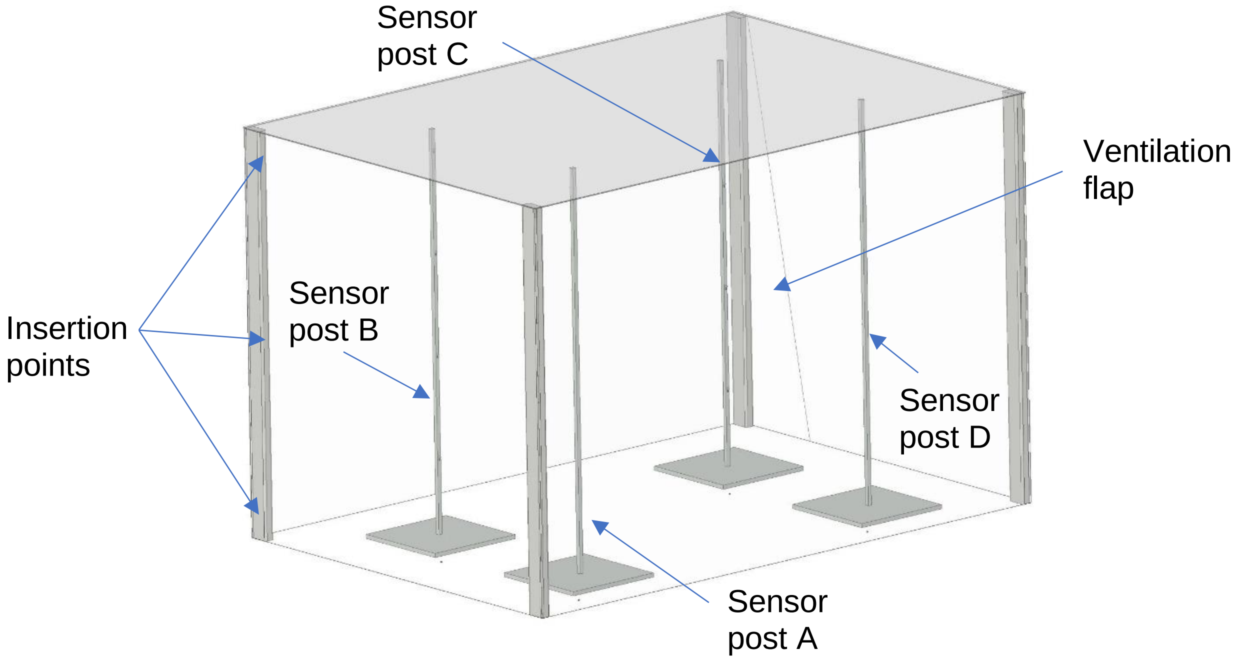


Figure 46: Sketch of enclosure with four sensor sticks

Safety was a significant factor to be considered in the design of this enclosure. Risk assessments were carried out to ensure safety of staff and the facility.

5.2 Experimental philosophy

The aim of the experiments was to determine whether hydrogen would stratify towards the top of the room, resulting in a flammable mixture, or mix into the entire volume to create a homogenous mixture. This programme of experiments was pitched towards finding possible unsafe conditions rather than providing a high number of data points for various situations to understand the fundamental behaviour of hydrogen. The critical question to be answered in all of the experiments was: do we get pockets of gas above the Lower Flammable Limit (LFL) of hydrogen?

5.3 Purge scenarios

5.3.1 Flow rates

The flow rate during purge is not determined by the current standards. The Stage 1 investigation in this report provides some analysis into required flow rates to achieve an adequate purge. 7 l/min is the most common flow rate for the Stage 2 tests, to match the nozzle from Stage 1. Other flow speeds are also briefly investigated to determine whether flow speed affects the dispersion versus stratification relationship.

5.3.2 Gas mixtures

Of the purge scenarios proposed in the discussion document, the worst case scenario for the potential of stratification in the enclosure is a release of pure hydrogen. As this is also the largest volumetric release of hydrogen, it would have the highest potential of all scenarios to reach a dangerous state. The purging of Natural Gas is an accepted procedure however, so this has not been investigated.

A purge from an unknown hydrogen/air mix to pure hydrogen represents the case where most hydrogen will be released, with an installation potentially close to full of hydrogen.

For these reasons, the purges conducted during these tests were done as an absolute volume of hydrogen released, without consideration to the installation.

5.3.3 Volumes

The current standards mandate that when purging an installation volume greater than 20 litres, there must be an attempt to ignite the released gas. This means an unknown air and Natural Gas mixture is deliberately lit.

Concerns were raised about lighting an unknown mixture of air and hydrogen, implying that it would be safer to release hydrogen from installation volumes between 20 and 35 litres than to burn it. Consideration should therefore be given to removing the stipulation to burn all purged hydrogen gas releases for installations greater than 20 litres. These experiments assume installation volumes above 20 litres are not burned off.

The current purging standards indicate a theoretical maximum purge volume up to 53 litres - 1.5x 35 litre maximum installation volume. The released volume of flammable gas should be much smaller than this however, as it will replace the air that is incumbent in the installation. Only towards the end of the purge process does Natural Gas get released.

At this point the purge will generally be stopped as one of the trigger factors is reached: smelling the gas, the open burner staying lit, or the meter indicating the purge volume has been achieved.

With the first two finishing conditions, only a small portion of flammable gas would be released. Relying on the meter alone however means the entire purge volume is used.

If the incumbent gas was expected to be air, but in actuality is flammable gas, an entire purge volume of flammable gas could be released into a room.

The test that is therefore of most interest for this investigation is a release volume of 53 litres of hydrogen. This is the worst case scenario, and is extremely unlikely to occur, due to the fail-safe procedures in place.

5.4 Theoretical findings

A number of pieces of pertinent work were identified relating to diffusion of hydrogen and the release of hydrogen into enclosed spaces.

The first of these, the *'Biennial Report on Hydrogen Safety'* [16] issued by the HySafe consortium documents the propensity of hydrogen to rapidly mix with air upon release. It also details the complexity of the mixing processes involved, being a combination of high diffusivity and turbulence effects created by the buoyancy of bulk hydrogen.

> *"Hydrogen gas exhibits a high diffusivity and a high buoyant velocity; it rapidly mixes with the ambient air upon release. The diffusion velocity is proportional to the diffusion coefficient and varies with temperature according to $T^{3/2}$. Diffusion in multi-component mixtures is usually described by the Stefan-Maxwell equation. Corresponding diffusion rates of hydrogen in air are larger by about a factor of 4 compared to those of air in air. The rising velocity under the influence of (positively) buoyant forces cannot be determined directly, since they are dependent on the density difference between hydrogen and air as well as on drag and friction forces. Also shape and size of the rising gas volume as well as atmospheric turbulence have an influence on the final velocity of the rising gas. The positive buoyancy of hydrogen is a favorable safety effect in unconfined areas, but can cause a hazardous situation in (partially) confined spaces, where the hydrogen can accumulate, e.g., underneath a roof. Both diffusion and buoyant velocities determine the rate at which the gas mixes with the ambient air. The rapid mixing of hydrogen with the air is a safety concern, since it leads very soon to flammable mixtures, which on the other hand – for the same reason – also will quickly dilute to the non-flammable range. Therefore it is estimated that in a typical unconfined hydrogen explosion, only a fraction of the gas mixture cloud is involved releasing in fact not more than a few per cent of the theoretically available energy."*

A set of small-scale tests have been reported in the paper, '*Hydrogen dispersion in a closed environment'* [17] that involved releasing hydrogen into a small chamber 0.47 m x 0.33 m by 0.20 m. The example plots given in Figure 47 show the atmosphere in the chamber rapidly becoming uniform after each release of hydrogen in a matter of minutes.

[16] Biennial Report on Hydrogen Safety - http://www.hysafe.org/BRHS
[17] International Journal of Hydrogen Energy, July 2018 - https://h2tools.org/sites/default/files/2019-09/207.pdf

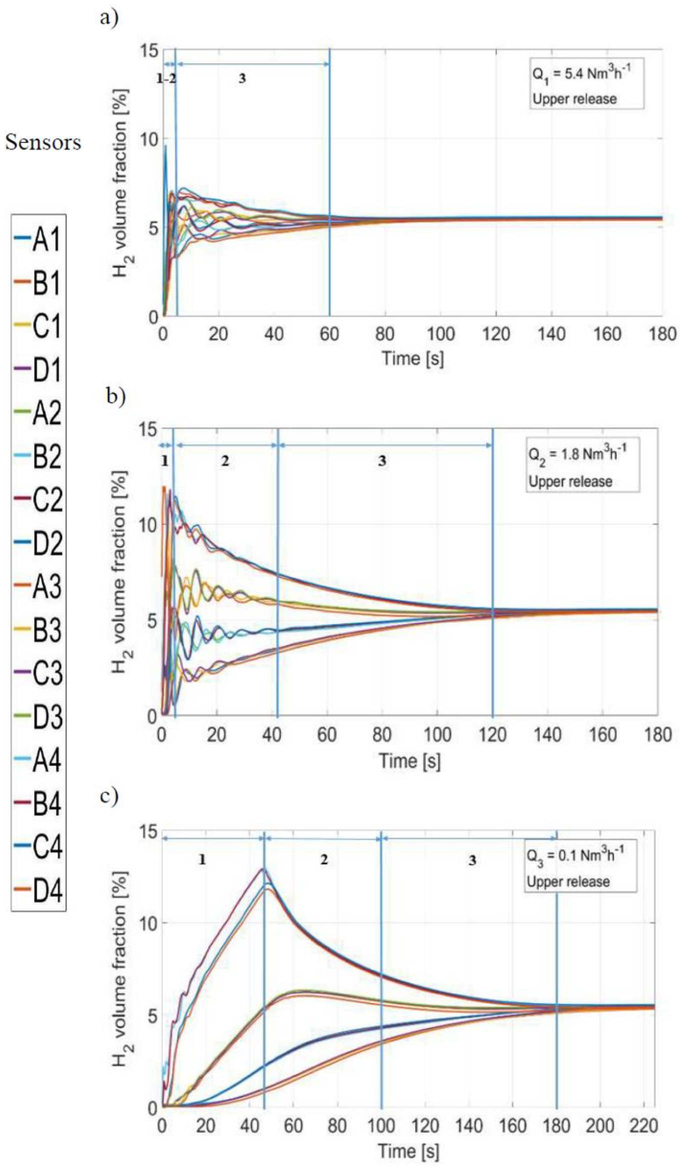


Figure 47: Hydrogen released in a closed chamber rapidly mixing

The traces in Figure 47 also show fluctuations in the concentration of gas measured with respect to time. This is most likely to be due to the effects of turbulence. The work demonstrates the speed of mixing of the hydrogen throughout the chamber in a short space of time for the small-scale tests. It also demonstrates that faster releases result in quicker mixing, this will be due to turbulence speeding up the mixing process.

A separate piece of work, *'Large-scale hydrogen release in an isothermal confined area'* [18], provides results for much larger releases of gas into a large chamber. Figure 48 shows the result of 533 litres of hydrogen being released into the chamber over 4 minutes, at a rate of 133 l/min. The sensors shown are vertically placed in a line to the right of the release point. It is worthy of note that even at this large volume release the hydrogen in the chamber did not reach LFL at the top of the chamber.

[18] International Journal of Hydrogen Energy Feb 2011

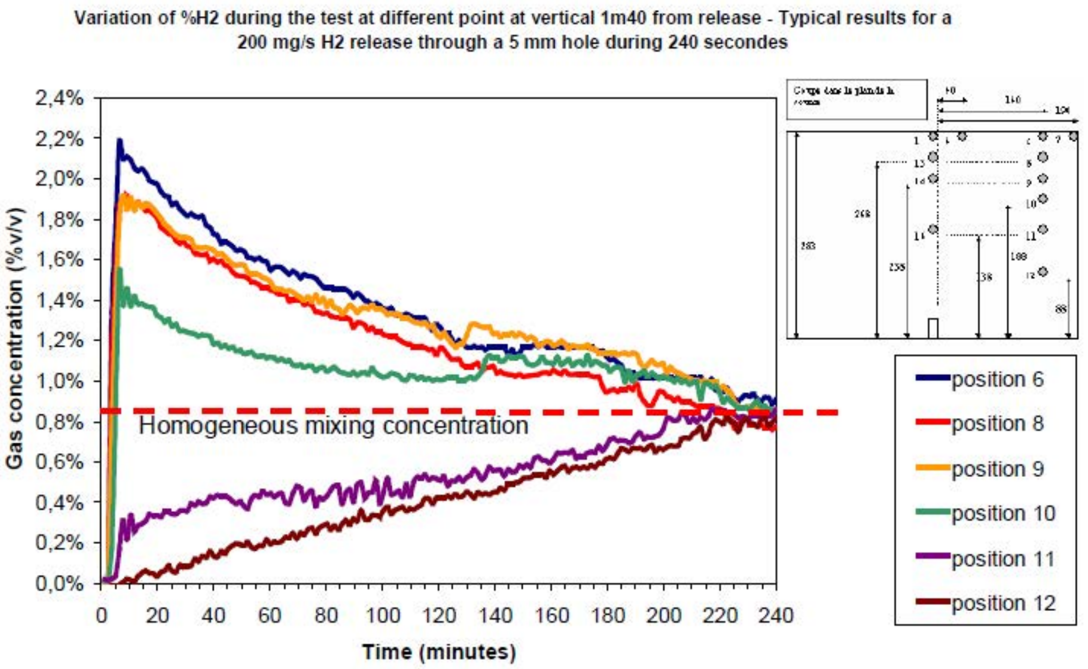


Figure 48: Example hydrogen release into 80 m³ volume

All of these publications provide good confidence in the safety of purging hydrogen into rooms as it is very unlikely that a bulk volume of gas will build up that is close to LFL in a domestic purge situation.

If 53 litres of hydrogen is released into a an enclosed volume of 12,000 litres, assuming a fully homogenous mix, the overall concentration would be 0.44% vol. This is well below the 4.4% vol. LFL, and would not be dangerous. If the same volume of hydrogen collected in a pocket of gas at the ceiling the concentration would be much higher. The level of concentration would then depend on factors such as ceiling shape, and in certain circumstances it could certainly become flammable. For example, if the ceiling sloped upwards into a cone or point.

5.5 Detecting hydrogen

A range of sensing devices were considered for this section. A Testo 316-2 was used initially. This has an integral pump and measures hydrogen from 10 ppm to 4.4% volume (LFL). The read-out is given by increasing bars, with 18 increments of increasing non-linear intensity. While this is useful for detecting hydrogen leaks, it is difficult to ascertain the exact level from this.

A GMI GS700H was also used for testing. This has multiple sensors and can measure in ppm, LEL (LFL) and up to 100% volume. Again, there is an integral pump, so the gas does not have to be flowing to get accurate readings. This device is currently a prototype still in development and was provided courtesy of GMI Teledyne and SGN. The device has been developed as part of the H100 Fife project. Information on the development of this device can be found under the NIA_SGN0156 project.

MQ-8 sensors were used for the majority of testing for Stage 2. These are catalytic sensors with a stated operating range up to 10,000 ppm (~25% of LFL). They have a high sensitivity to hydrogen compared to other hydrocarbon gases such as methane. They do not use a pump, and can be connected to a logging device, allowing an array of sensors to be used while disturbing the air in the enclosure as little as possible.

5.5.1 MQ-8 sensor calibration

These sensors are commonly used for hydrogen and town gas detectors. The sensor modules used incorporated a circuit with a load resistor of 2 kΩ which forms a potential divider with the sensor. Measuring the voltage across the load resistor enables the sensor resistance, Rs, to be calculated. As the hydrogen concentration increases the sensor resistance decreases so the voltage output of the module increases. Rs is then compared to the sensor resistance in a known gas concentration, R0. In this case 1,000 ppm hydrogen concentration was used. The ppm concentration is then read from the manufacturer's graph shown in Figure 49 for the given Rs/R0 value.

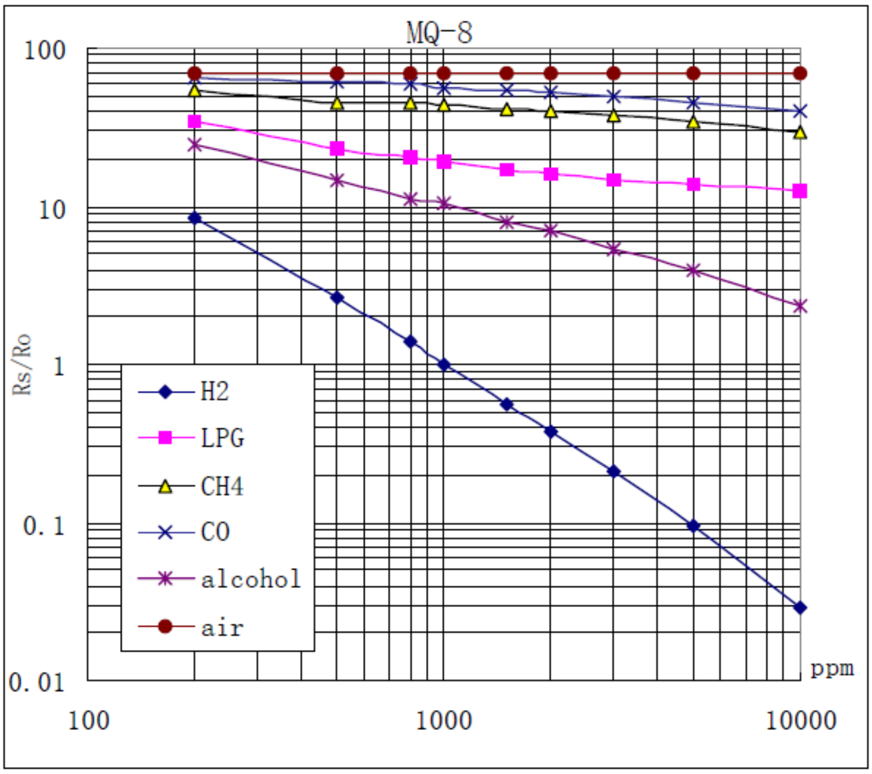


Figure 49: Published sensitivity curve for MQ-8 sensors

The sensors detect hydrogen in very low concentrations and while they do detect higher concentrations, giving details up to 10,000 ppm, they suffer from sensor fatigue, especially once they have been exposed to > 2,000 ppm for a length of time. The actual values of R0 can change significantly from sensor to sensor, so a range of calibration runs were carried out for the modules. This sensor calibration identified the R0 values and the sensitivity curves for each sensor. It was noted during testing that the R0 for each sensor drifts over time and seemingly upon repeated exposure to hydrogen.

The calibration tests involved placing four sensors at a time into a 500 ml sealed chamber, with a calibrated air and hydrogen mix flowing through the chamber at a rate of 10 litres per minute. An initial peak of hydrogen was introduced to the sensors for 1 minute followed by 5-minute steps of difference concentrations. The concentration was stepped up from 0, 500, 1,000, 1,500 and 2,000 ppm and then stepped down to 0 in 500 ppm steps. The initial 1,000 ppm mixture was flowed for 10 minutes, to increase the accuracy for the R0 value calculation for each sensor. An example calibration run is shown in Figure 50.

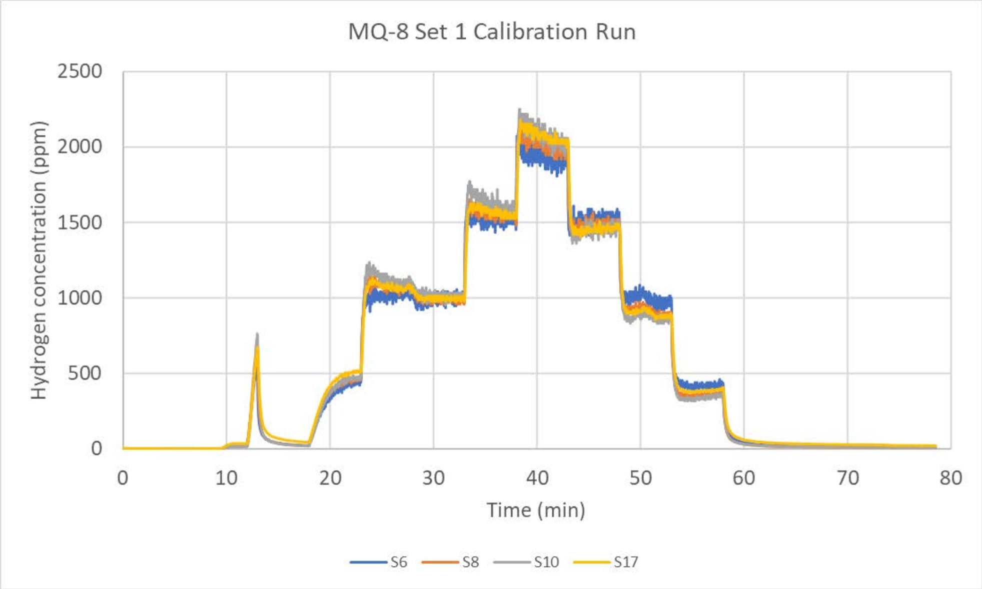


Figure 50: Example sensor calibration run

The MQ-8 sensors are prone to a reversable drift if stored for prolonged periods without power. To counter this the sensors were powered for two weeks before calibration and testing commenced, and for two months throughout the test programme.

They did provide accurate information in the ranges below 4,000 ppm, however concentrations larger than that and prolonged exposure to hydrogen resulted in a change in sensitivity. A standard way to address this issue is to sample the atmosphere by drawing a small volume of the test gas into the detector. This practice was discounted for this work due to the large number of sample points being used. This would end up creating a significant flow disturbance to the gas in the room and affect the results. The fatigue effects have been considered when examining the results of the stage 2 tests, and R0 calibration values have been adjusted accordingly.

The sensor modules were permanently wired in groups of 4 for the duration of the formal tests. One sensor post is shown in Figure 51.

Figure 51: Sensor post (not final spacings)

It is important to note that these sensors are being used for indicative measurements only and that in all of these tests we are only really concerned with the possibility of reaching LFL.

5.6 Trial investigations

In line with the risk assessment, the initial releases of hydrogen into the enclosure were small. These volumes were gradually increased, while monitoring the hydrogen concentration, particularly at high points. The MQ-8 sensors were used for some of these tests, but the GMI GS700H was the primary device for this as the calibration is known and the concentration levels reach to LFL (and beyond).

There was also a series of experiments carried out while determining the effectiveness of the various sensors available. The knowledge gained conducting these experiments did however feed into the experimental programme and development of the risk assessments, as well as calibration of sensors.

5.7 Test Programme

The test programme was developed as the tests progressed. The final test programme is shown in Figure 52. Initial tests were used to build an understanding of the process, and ensure safe limits were not surpassed. A critical factor was ensuring that LFL was not reached within the enclosure.

The highlighted rows correspond to tests referenced in section 5.8. They are colour coded to show matching tests.

	Scenario / Test Ref	Date	Room Volume (m3)	Purge Volume (litres)	H2 Flow Speed (l/min)	Hydrogen release time (min)	Release point	Ventilation	Sensor Position	Note
Setup Tests	Setup Test 1	16/11/2020	12 m3	10.5	7	1.5	Low, central	Closed		Sensors T1-T8 vertical stand high to low, 20 cm spacing
	Setup Test 2	16/11/2020	12 m3	10.5	7	1.5	Low, central	Closed		Sensors T1-T8 vertical stand high to low, 20 cm spacing
	Setup Test 3	16/11/2020	12 m3	12	12	1.0	Low, central	Open		Sensors T1-T8 vertical stand high to low, 20 cm spacing
	Setup Test 4	17/11/2020	12 m3	20	12	1.7	Low, central	Open		Sensors T1-T8 vertical stand high to low, 20 cm spacing
	Further tests done, not shown here									
** New set up of sensors: 4 posts of 4, 50 cm spacing, 10 cm from the top. Sensor position counts up from the top down on each post. Each post labelled A - D **										
Formal Tests	Test 6	30/11/2020	12 m3	2	0.2	10.0			Central	
	Test 7	30/11/2020	12 m3	2	0.2	10.0			Central	
	Test 9	01/12/2020	12 m3	10	2	5.0	High	Flap open 40cm	Central	
	Test 10	01/12/2020	12 m3	15	2	7.5	High	Flap open 40cm	Central	
	Test 11	01/12/2020	12 m3	21	7	3.0	High	Flap open 40cm	Central	
	Test 12	01/12/2020	12 m3	10	5	2.0	High	Closed	Central	Overnight test
	Test 13	02/12/2020	12 m3	21	7	3.0	High	Flap open 40cm	Central	Repeat of T11
	Test 14	02/12/2020	12 m3	21	7	3.0	High	Flap open 40cm	Central	Repeat of T11
	Test 15	02/12/2020	12 m3	28	7	4.0	High	Flap open 40cm	Central	
	Test 17	03/12/2020	12 m3	35	7	5.0	High	Flap open 40cm	Central	*Same as T21, but central posts*
	Test 18	03/12/2020	12 m3	53	7	7.6	High	Flap open 40cm	Central	
	Test 21	04/12/2020	12 m3	35	7	5.0	High	Flap open 40cm	Corners	Sensors moved to 60 cm from each wall, in the corners
	Test 22	04/12/2020	12 m3	35	7	5.0	Low	Flap open 40cm	Corners	
	Test 23	04/12/2020	12 m3	53	7	7.6	Low	Closed	Corners	Release was interupted, about 1 min gap. Overnight test
	Test 24	05/12/2020	12 m3	53	4	13.3	Middle	Closed	Corners	
	test 25	09/12/2020	12 m3	53	7	7.6	High	Closed	Corners	Overnight 17:28 start time 7 min 35 sec of 7 l/m
	Test 26	10/12/2020	12 m3	53	4	13.3	High	Closed	Corners	13 min 15 sec of 4 l/m overnight starting at 13:00
	Test 27	11/12/2020	12 m3	5	10	0.5	Middle	Closed	Corners	30 sec at 10 l/m starting at 17:15
	Test 28	15/12/2020	12 m3	53	7	7.6	High	Closed	Corners	Repeat of 25
	Test 29	15/12/2020	12 m3	53	100	0.53	Mid	Closed	Corners	Test with GMI at the top to see max level reached
	Test 30	16/12/2020	12 m3	53	7	7.6	Low	Flap open 40cm	Central	Used to check re-calibration values
	31	16/12/2020	12 m3	53	0		-	Open	Corners	Used to check re-calibration values
	32	17/12/2020	12 m3	53	5	10.6	High	Closed	Corners	Test with GMI at the top to see max level reached

Figure 52: Final test programme

5.8 Formal Tests

A Bronkhorst flow controller was used to insert hydrogen into the enclosure. This allowed precise control of the volume and flow rate. Before the test release was started, the feed tube was purged to hydrogen in a fume cabinet, to minimise accumulation of hydrogen in the ambient air. The feed tube was then quickly connected to the insertion point and the measured release of hydrogen started. When the appropriate time passed, a valve in the feed tube was closed, and the feed tube removed from the insertion point. The insertion tube was gently blown to purge it of hydrogen. This was done to prevent the remnants of hydrogen being released from the tube over time during the test, affecting the results.

Figure 53 shows a typical experiment in progress. The insertion point is at middle height, on the left of the photograph. The ventilation flap is at the far left, and the laptop shows a live trace of the raw readings from the MQ-8 sensors.

Figure 53: Formal testing

With larger releases of hydrogen, there is an initial spike seen by the top sensors, followed by a drop, then a secondary climb in the readings. This is believed to be due to overexposure of the sensors, and the levels rise again as the sensors recover. An example of this is shown in Figure 54.

The gradient of the spike and the height of the second peak can be used as indicators to the hydrogen concentration, but the absolute readings are unknown.

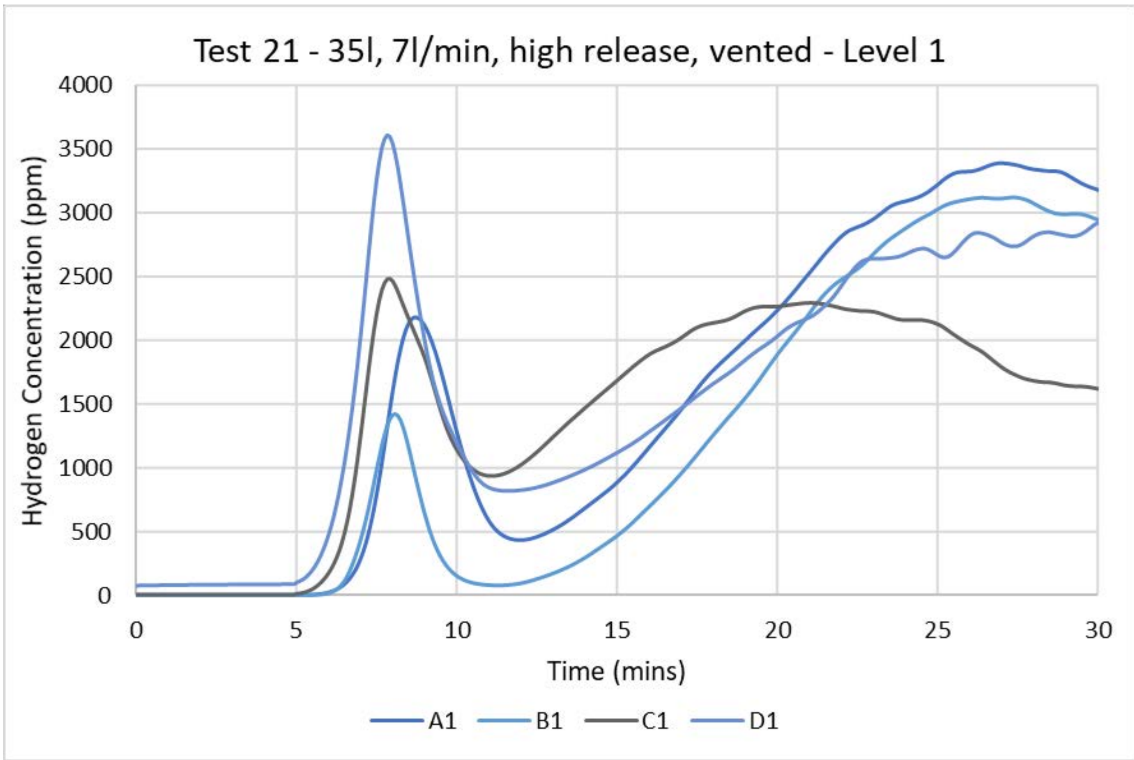


Figure 54: Spikes and unreliable readings at level 1 in Test 21

5.8.1 Reaction to hydrogen insertion

Figure 55 shows differences in detection time for Test 21. This test was a release of 35 litres, and the hydrogen is inserted at the top of the enclosure.

The y-axis has been adjusted to focus on the baseline values, with the peak off-scale. This makes it easier to see the time taken for each sensor to react to the presence of hydrogen. There is a clear trend for the higher sensors to detect hydrogen before the other sensors. There will be slight differences in reaction time between the sensors, but the trend shown here is clearly related to the presence of hydrogen at the sensor location.

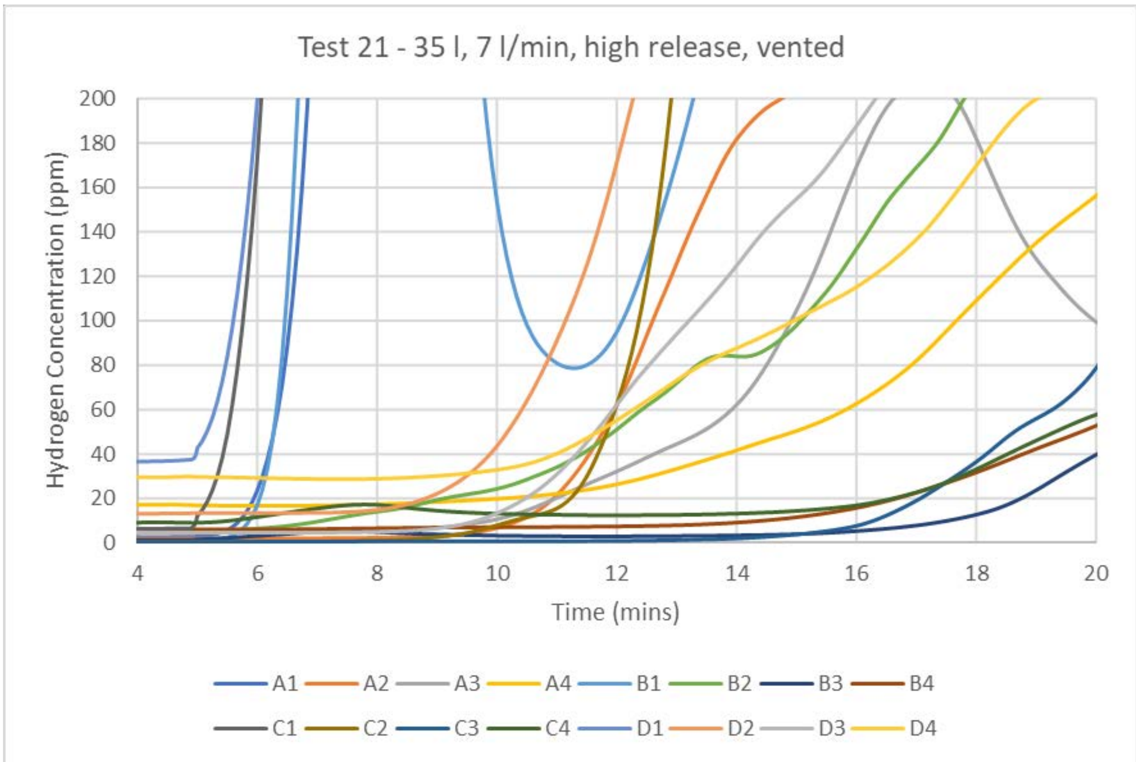


Figure 55: Test 21 – scales selected to indicate initial hydrogen detection for all sensors

There are four clear groups, which are the sensors at each level. The top four sensors indicated hydrogen 5 minutes after the start of the log. The second highest four sensors detected the presence of hydrogen at around 7 minutes and the third four at around 11 minutes. The final four sensors close to the base of the room detect hydrogen at around 17 minutes. Even though the release of hydrogen was at the top of the enclosure, all the bottom level sensors detected hydrogen within 12 minutes of the top sensors. This is a clear indicator that hydrogen mixed throughout the entire enclosure. The discrete steps show that the hydrogen is mixing downwards, and the grouping of each level shows that lateral mixing occurs first, and is thorough.

The same result was seen for other tests with high release points. For example, Figure 56 shows the initial reactions for Test 18, with the sensors averaged by height. While the lower sensors were still reducing when the test was started, the delay in reaction is clearly evident. Again, the y-axis has been adjusted to show the reaction from base level more clearly.

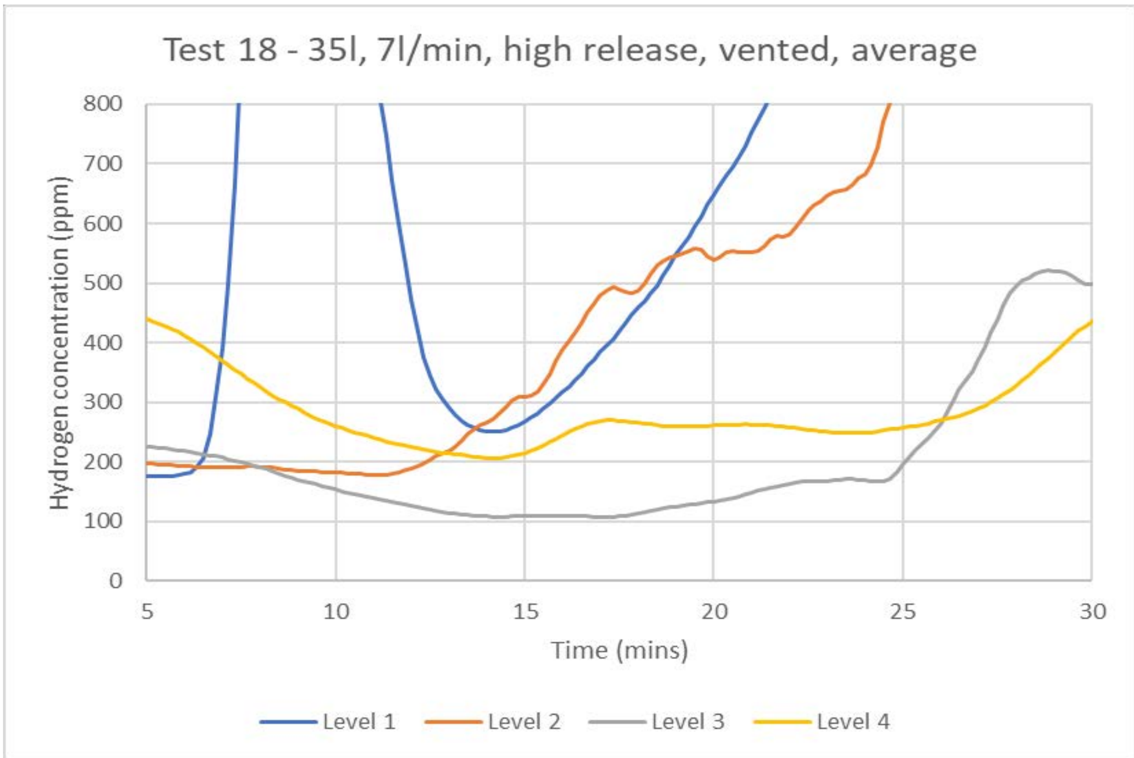


Figure 56: Test 18 scales selected to show initial sensor reactions

The conclusion from this is that the released hydrogen mixed throughout the enclosure. Lateral mixing was dominant, and vertical mixing downwards occurred over time.

5.8.2 Height of release point

Tests 21 and 22 were both done with a 35 litre release of hydrogen at a flow rate of 7 l/min. The enclosure was vented for both of these tests. Comparing tests 21 and 22 shows how the hydrogen dispersion varies when the release point is moved from high to low.

The expectation is that when the release point is moved to the bottom, the hydrogen is more likely to mix quickly with the air in the enclosure. When released it is expected to move upwards initially, and the movement of doing so will create eddies and turbulence, encouraging mixing.

The results for tests 21 and 22 are shown in Figure 57 and Figure 58. Note the differing time scales.

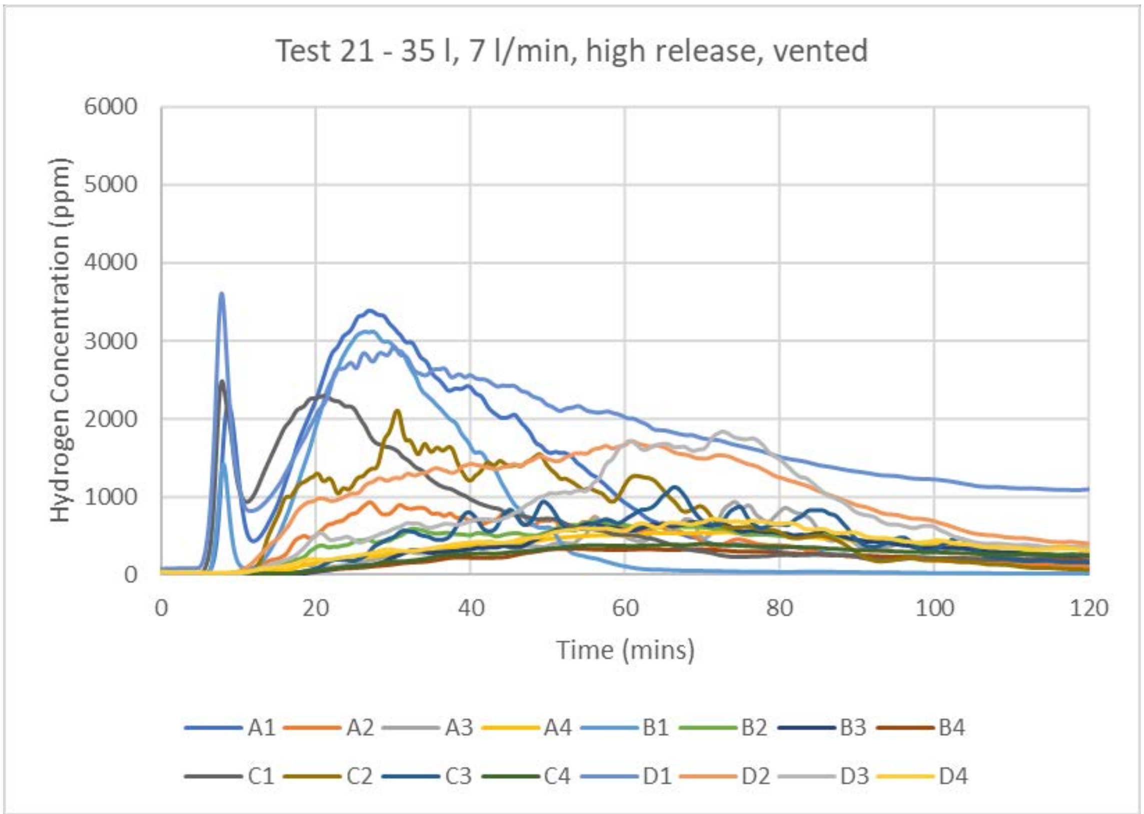


Figure 57: Test 21 - 35 litres, high release point

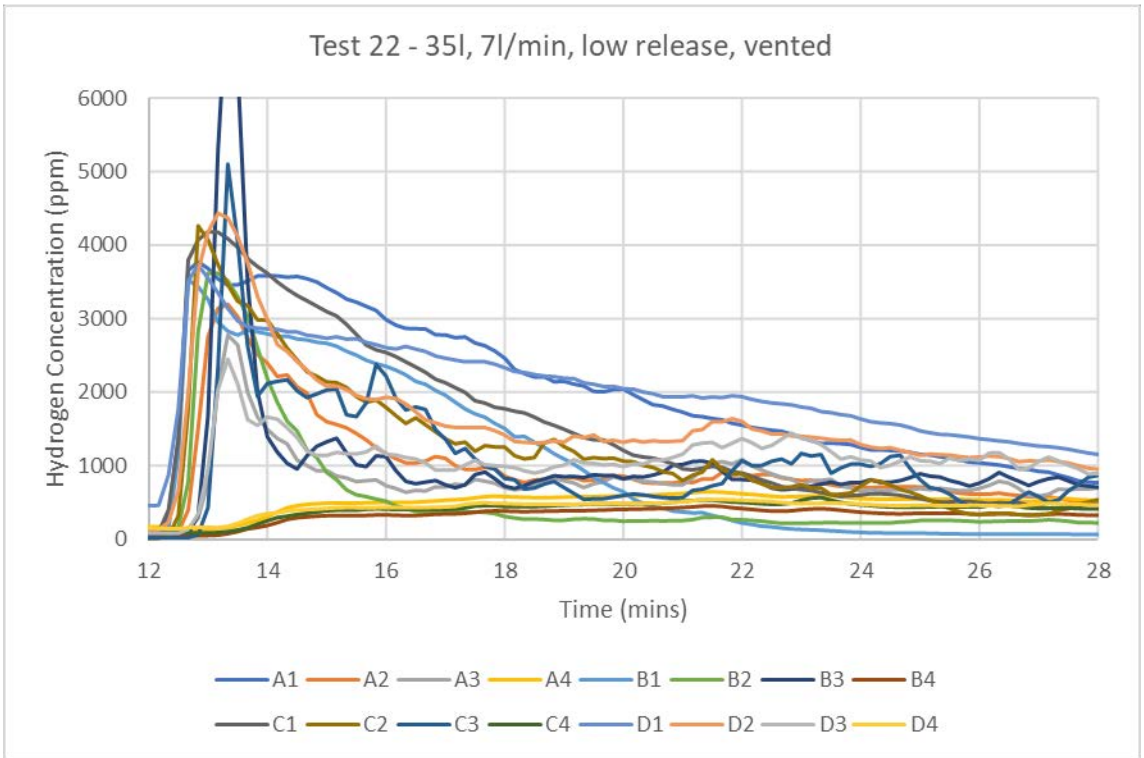


Figure 58: Test 22 - 35 litres, low release point

As anticipated, there is a significant difference in the results of tests 21 and 22. From the high release point in Test 21, the top sensors detected hydrogen significantly quicker than the lower ones. The second level of sensors then reacted, followed by the third level, and finally the bottom sensors. 50 minutes after first detection, the hydrogen levels fell at the top of the enclosure, but were still increasing throughout the rest of the space. The mixing of hydrogen downwards can be seen. The lower hydrogen concentration at the top may be due to the sensors being overexposed, and therefore becoming less responsive, or there may be some other mechanism actually reducing the hydrogen concentration at the highest level.

It is clear however that hydrogen was present throughout most of the space, with an estimated average of 500 ppm approximately 70 minutes after first detection. The dangerous scenario of a collection of hydrogen at the highest points is not seen.

As shown in Figure 58, Test 22 showed a much quicker reaction from all apart from the lowest sensors.

Figure 59 shows clearly the different reactions from the four height levels of sensors in Test 22. While the initial reaction was similar from the top three, the higher ones then reduced more slowly, while those nearer the ground reduced very quickly. The bottom level of sensors barely reacted, although they did register some hydrogen. Although they increased within a minute of the others, the level increased slowly, and then stabilised for the remaining 15 minutes.

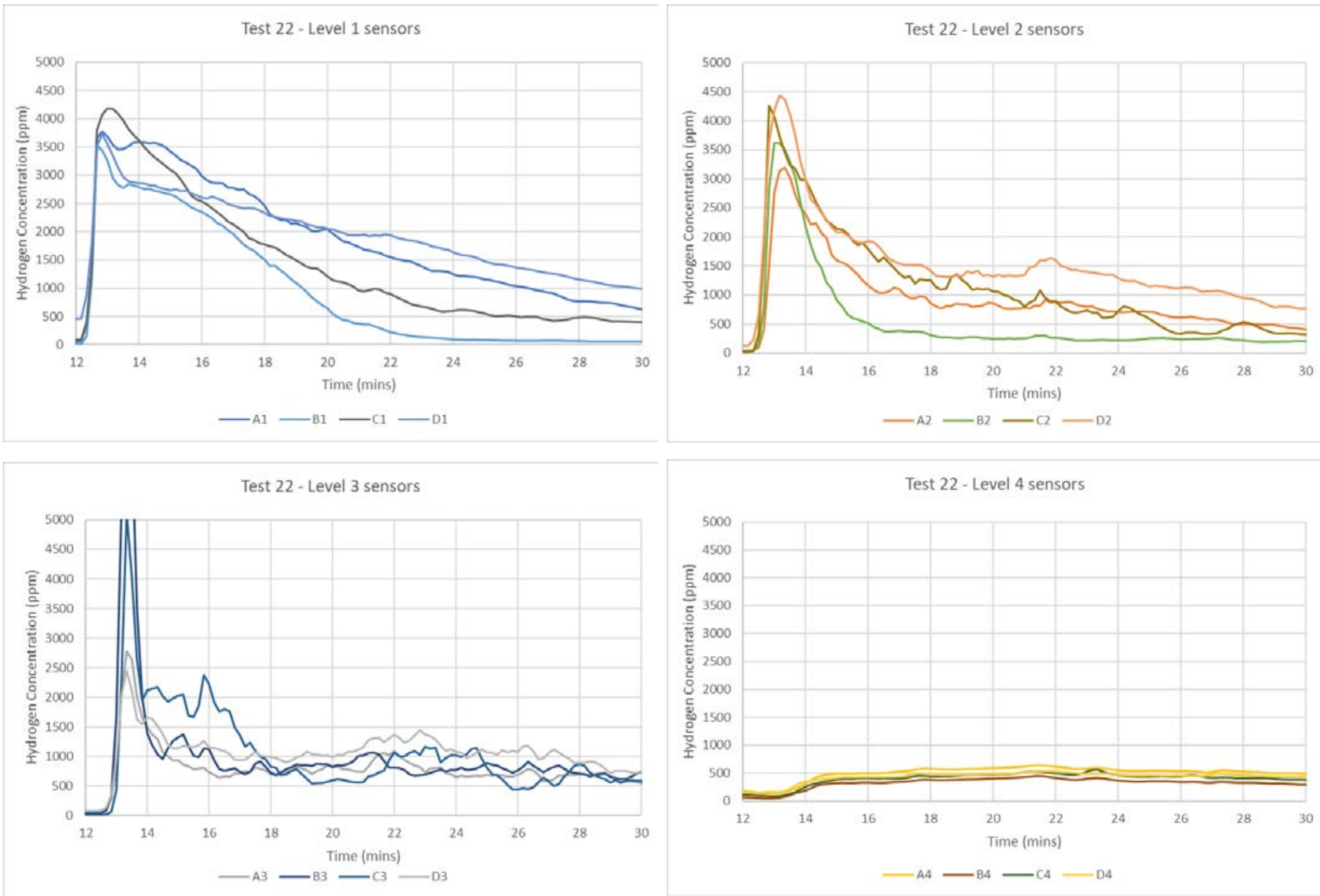


Figure 59: Test 22 - separate height sensors

The peak for most of the sensors in Test 22 was shown as higher than for Test 21, although the volume of hydrogen released was the same.

The true peak of the level 1 sensors is unknown for Test 21 due to the dip in the readings. Test 22 did not show the same dip in the top level sensors, indicating that the sensors were within their range. This saturation of the sensors indicates that the concentration at level 1 was higher for the higher release point. The rest of the sensors were significantly higher in the low release point test.

The correlation between similar heights, and distinction shown between different levels of sensors is a good indication that the data is apposite. It also indicates that the concentration of hydrogen was quite uniform across the space, at any particular height and implies that the hydrogen mixed laterally around the whole enclosure.

Test 17 was the same as Test 21, but with the sensor posts located centrally. The result is shown in Figure 60. This provides a means to check the validity of the data, as with central sensor posts we can be confident the actual concentration at each level of sensors is similar. Test 17 was only conducted for 70 minutes, but the trends and values seen up to that point are very similar.

In Test 21, Sensor 21, in position D1, showed a notably slower reduction in its reading after the peak. In Test 17 it portrayed a similar result. This confirms that it is likely to be a function of the sensor, not a true reading of residual hydrogen.

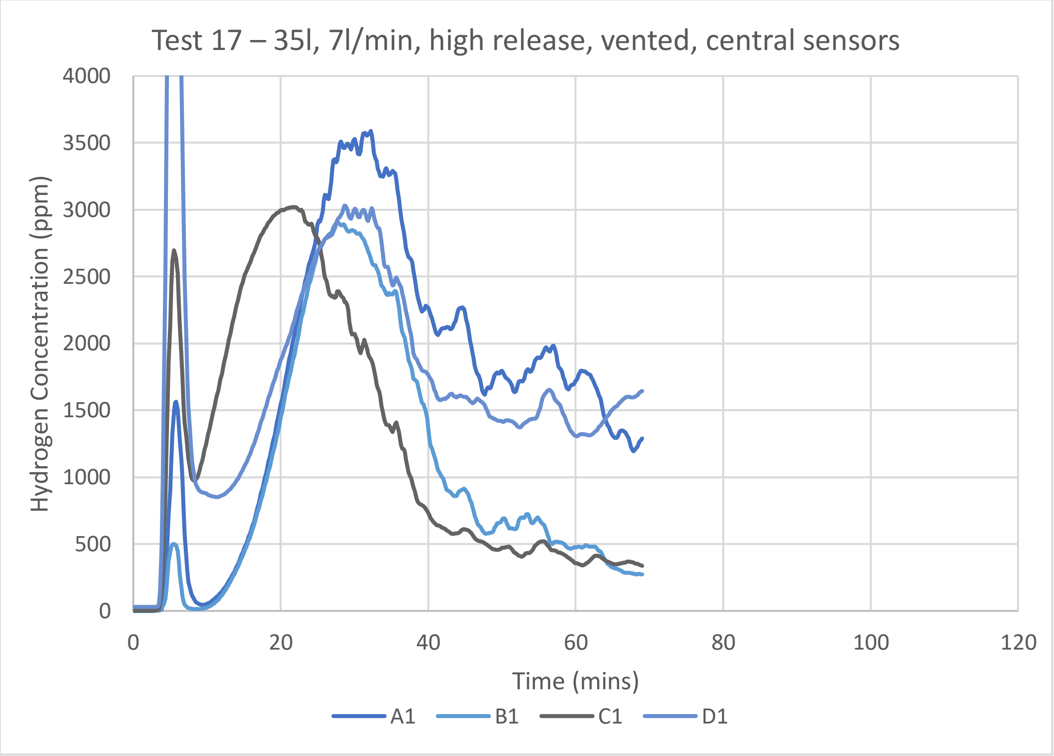


Figure 60: Test 17 - repeat of Test 21 with central sensor posts

5.8.3 Ventilation of the room

Ventilation is currently a pre-requisite of an internal purge. It is mandated by the IGEM/UP/1B standard, and every gas engineer interviewed as part of this investigation stated that they would ventilate a room before purging into it. The possibility exists however that ventilation would not be provided.

The vent for these experiments was a flap in one of the plastic walls, approximately 40 cm wide at the bottom, narrowing to a point at the top. This constituted an area of approximately 0.4 m^2. The vent was positioned at the far wall from the gas insertion point, on the adjacent corner, not centrally opposite. This corresponds to sensor post C.

Comparing the results for Tests 25 and 28 shows the difference in hydrogen dispersion and dissipation when the enclosure was vented.

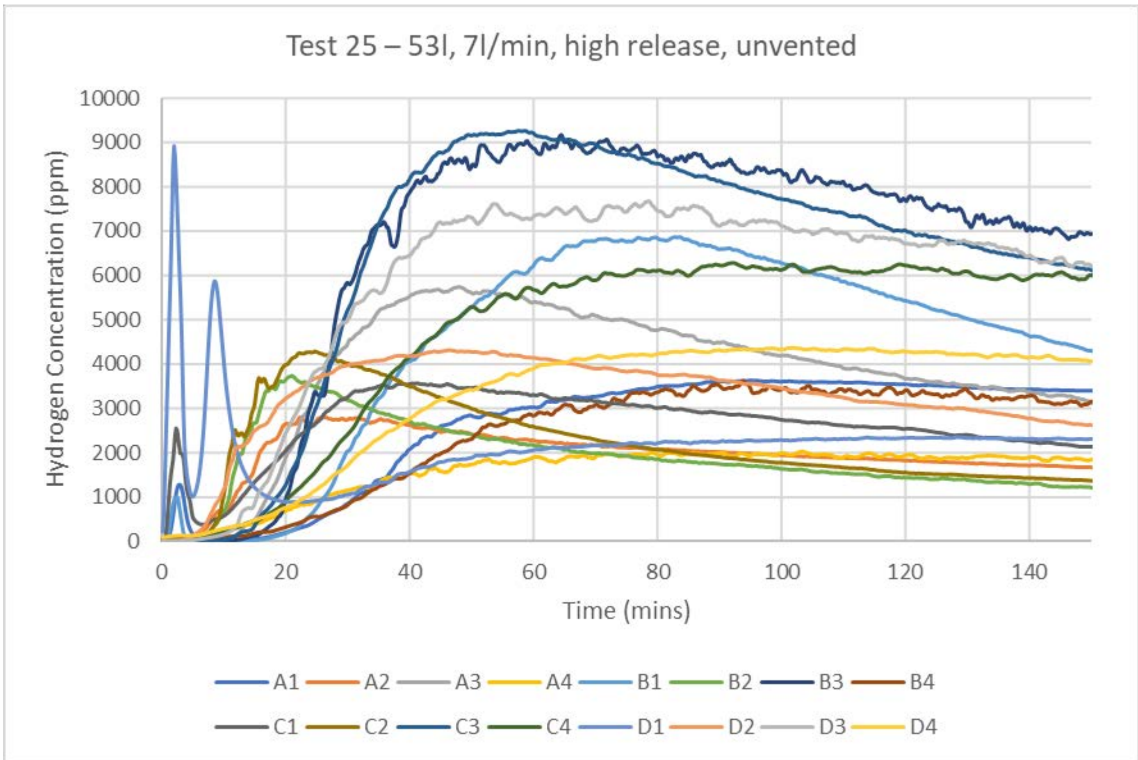


Figure 61: Test 25 - unvented enclosure

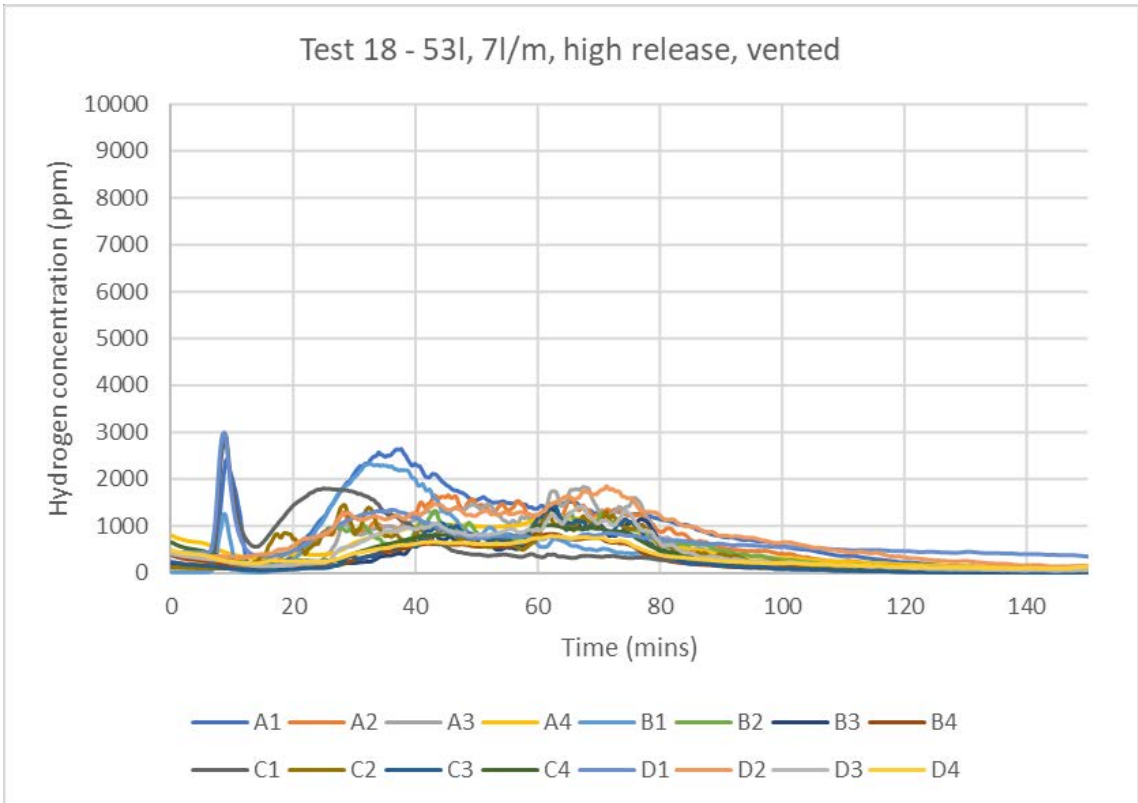
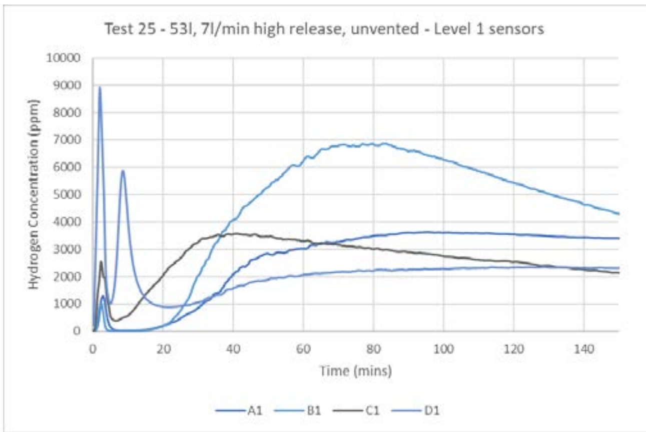
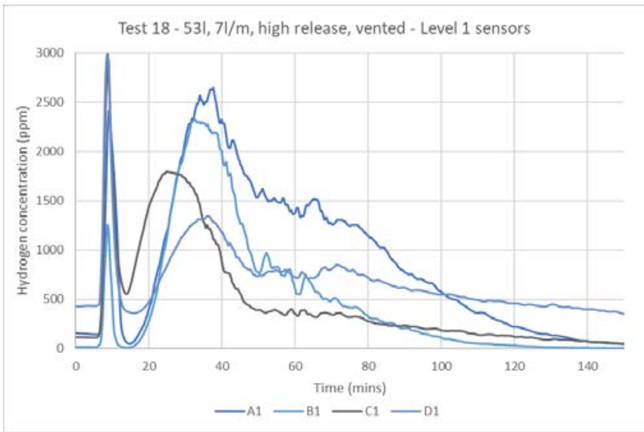


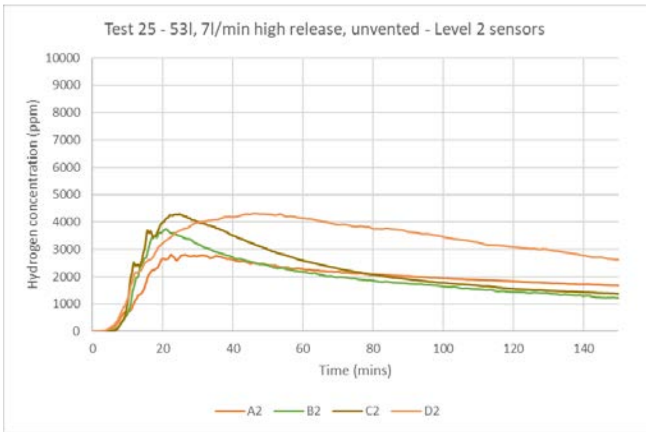
Figure 62: Test 18 - vented enclosure

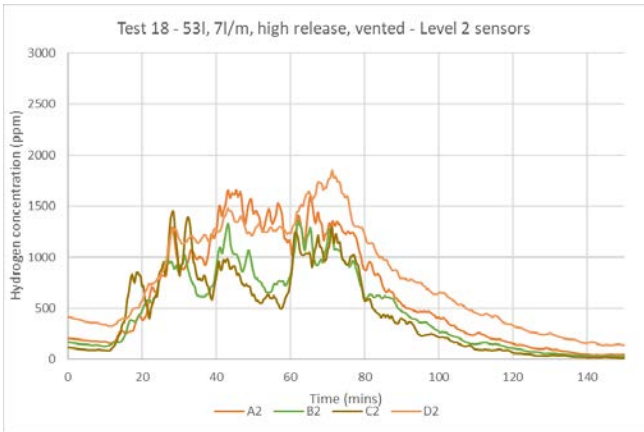
Figure 61 and Figure 62 show a direct comparison between the unvented and vented scenarios. The concentration was higher for all sensors when the enclosure is not vented.

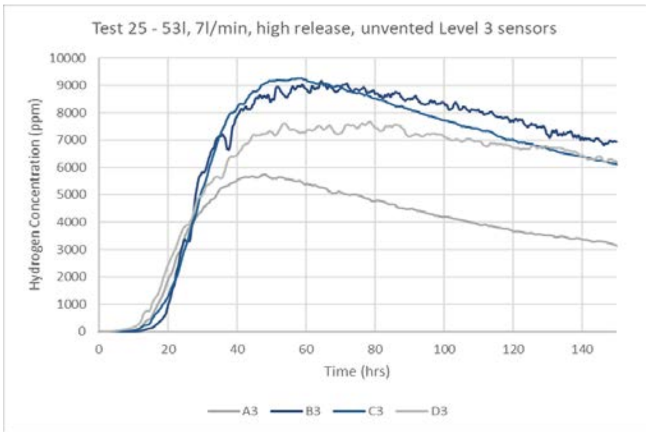
There appears to be more undulation in concentration in the vented test. This is clear from the separated level graphs in Figure 63. Note the different hydrogen concentration scales for these graphs - this is to show the pattern of diffusion more clearly. For the vented test the hydrogen at lower levels increased more gradually over time, and the change was less consistent. Due to the consistency across the sensors, this is thought to be the result of waves of hydrogen gas moving around the enclosure as the mix progressed.

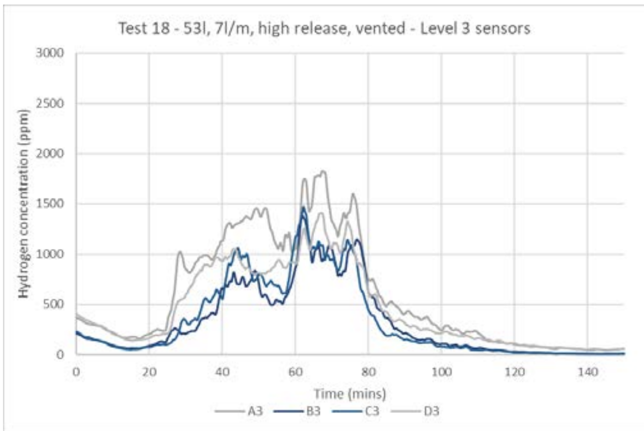












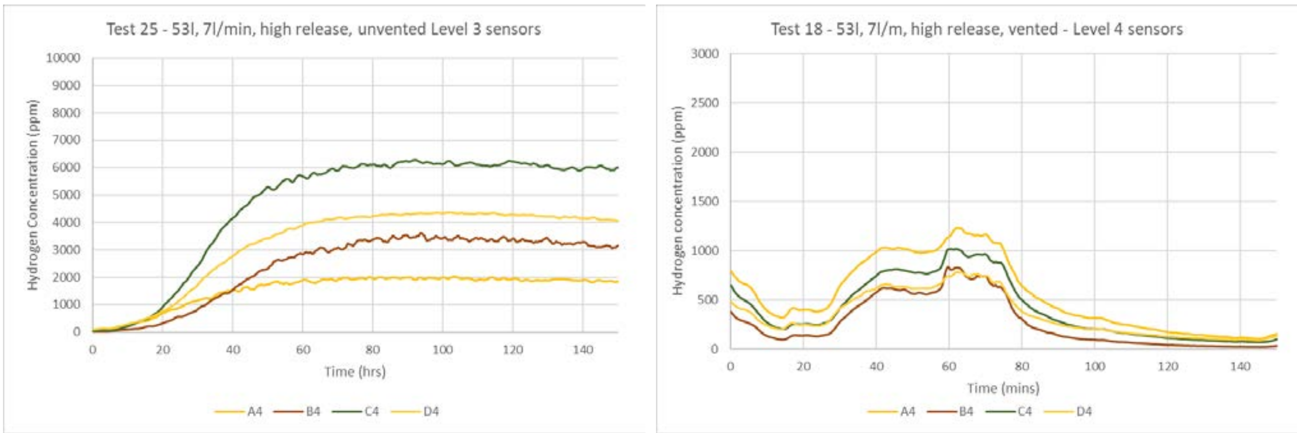


Figure 63: Test 25 and Test 18 sensor levels

The highest readings for Test 25 were from the level 3 sensors. As the hydrogen was released from the top of the room, this is an unexpected result. The same experiment was repeated as Test 28, and the results were remarkably similar, with the level 3 sensors again reading the highest.

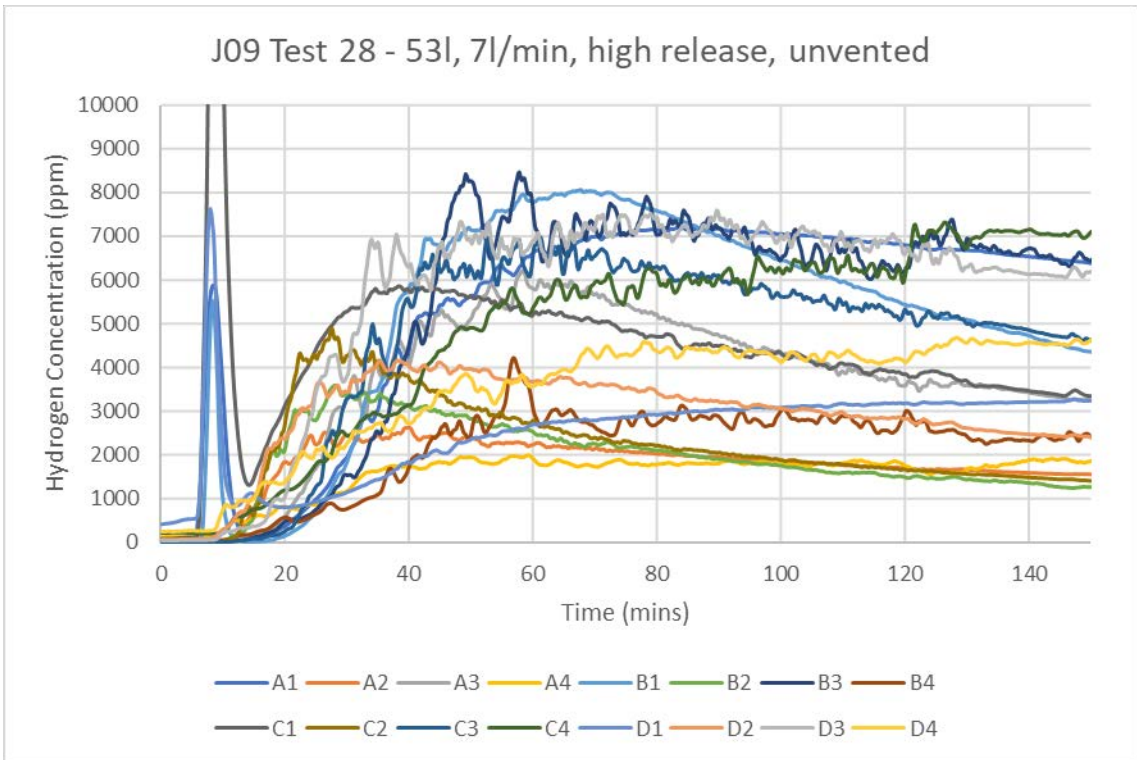


Figure 64: Test 28 - repeat of Test 25

It could be due to a circulation effect caused by the high level injection, or the result of fatigue of some of the sensors. The lowest sensors also read higher than anticipated. Further investigation would be required to determine the true cause, though it is beyond the scope of this investigation. If however it is a real phenomenon rather than a sensing error, it would constitute further evidence that hydrogen is not collecting on the ceiling.

Upon analysis of these results, a further test was done, Test 30, to re-calibrate the sensors to each other. For this the posts were moved to the centre of the enclosure, and a standard 53 litre test was carried out, with a low insertion point. The calibration R0 values used matched the sensor values to each other very well, and the lower level sensors did not give a high reading. This strongly implies that the results seen above in Test 25 and repeated in Test 28 are valid.

The hydrogen present dissipated much more quickly in the ventilated enclosure. A similar point where the hydrogen falls off more sharply, around 1000 ppm, occurs after 300 minutes in an unvented enclosure, but after only 60 minutes in the vented one. This indicates that providing good ventilation remains a key aspect to safe purging with hydrogen.

A comparison between the sensors at both level 2 and level 4 shows a different pattern emerging between the two scenarios. This is shown in Figure 65 - note the different hydrogen concentration scale. Sensor 20, in position C4, is thought to be reading erroneously high in Test 25.

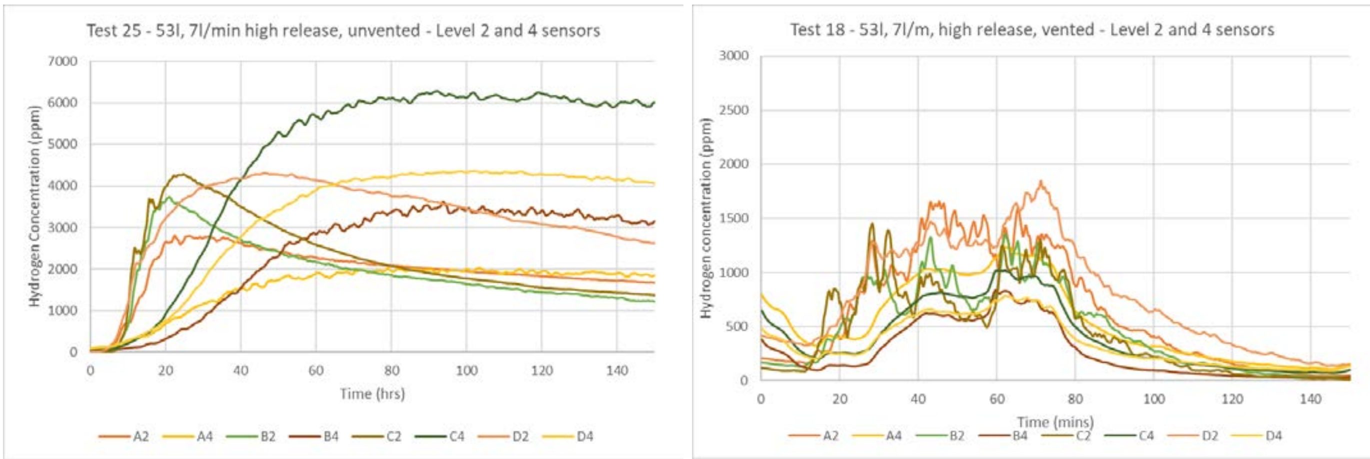


Figure 65: Unvented vs vented patterns

The correlation between the sensors on each post is very good, so the resultant indicative pattern is accurate. The lower middle sensors also follow the same pattern, just at a different scale. This is another clear indication that ventilation of the enclosure assists with dispersion and dissipation of hydrogen.

5.8.4 Release flow rate

A comparison was done with varying flow rates. The flow rate was controlled using a precise flow controller and 2 bar pressure. Most of the experiments used a 7 l/min flow rate, to represent typical flow from a single hob burner, and replicating the flow rate demonstrated in Stage 1 of this investigation. For this experiment flow rates of 4 l/min and 100 l/min were used. 4 l/min is approximately the flow rate from a small hob burner, and 100 l/min corresponds to 6 m^3/hr, which is the maximum flow from a typical Natural Gas meter.

The release point for both tests was in the middle, at 1 metre high. This is a reasonable representation of a hob height, or where gas might be released from if a fitting were loosened on the input to a boiler.

As discussed in section 5.8.3, the GMI GS700H gas detector was used in Test 29. The internal pump, and action of inserting the probe through the walls at various heights may have caused disturbances in the air, and affected the dispersion, though this is not expected to be significant.

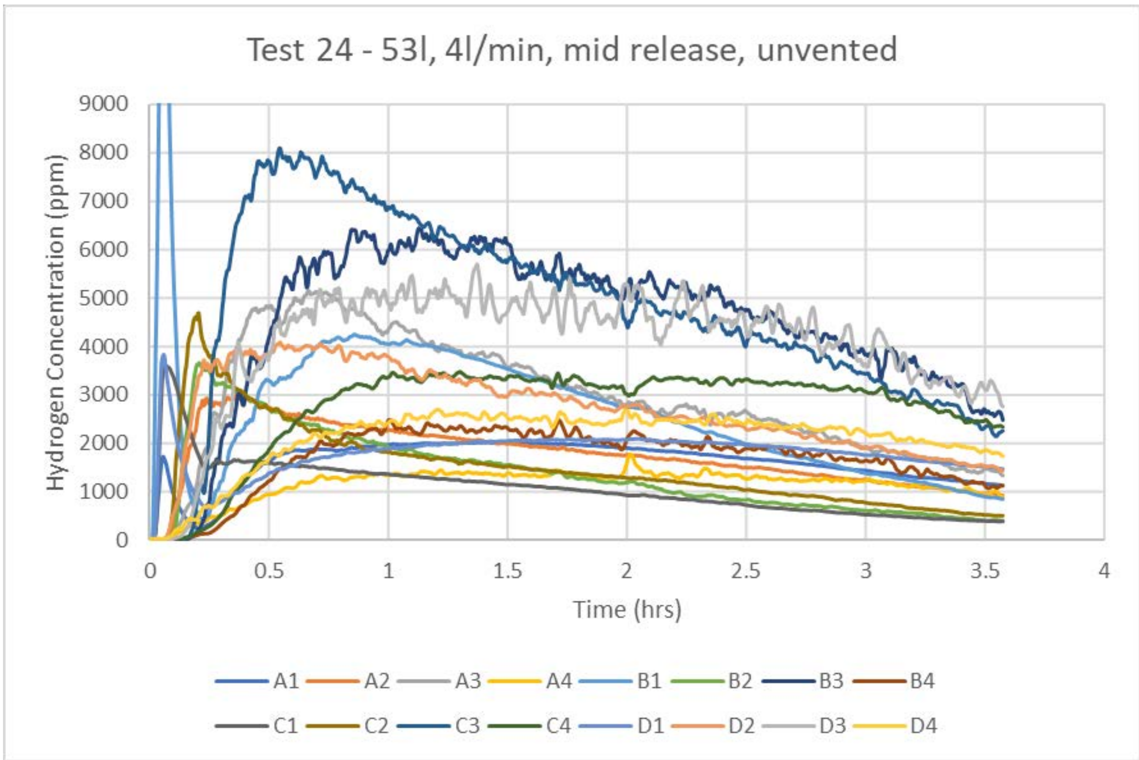


Figure 66: Test 24 - slow release of hydrogen

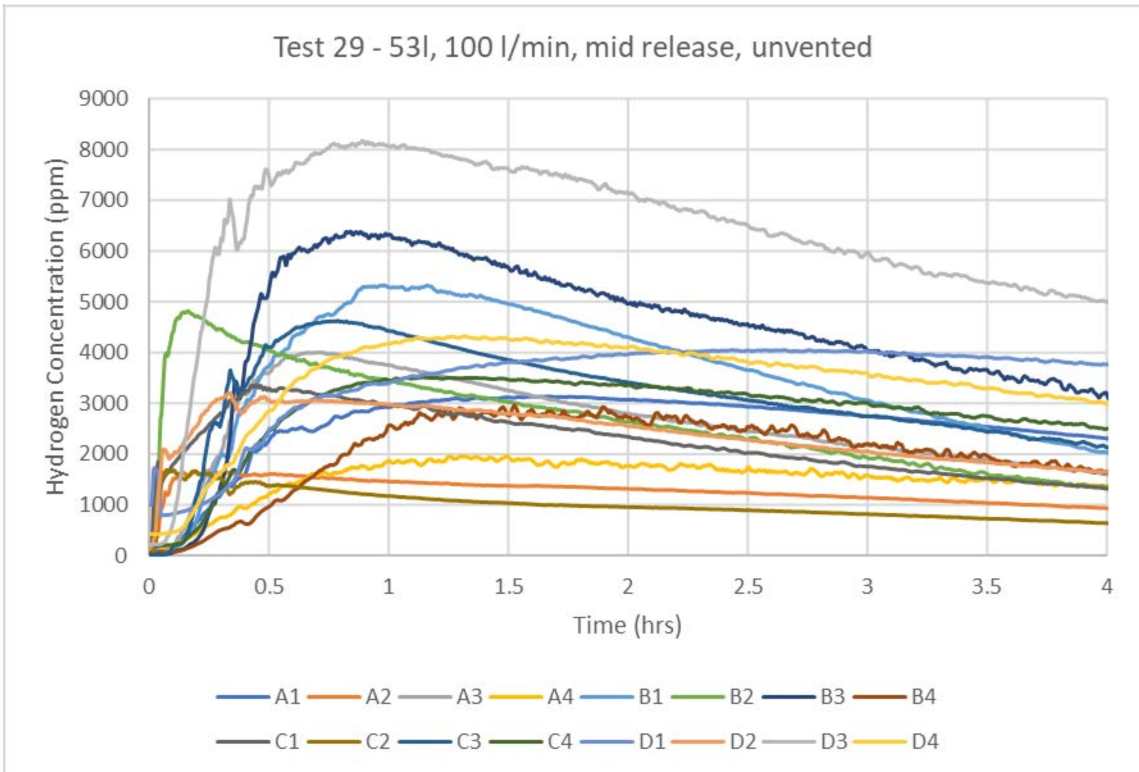


Figure 67: Test 29 - fast release of hydrogen

Figure 66 shows the pattern of dispersion when 53 litres of hydrogen was released at 1 metre height at a rate of 4 l/min, and Figure 67 at 100 l/min. Note that the zero time is not at the time of hydrogen insertion.

With the faster release in Test 29 all the sensors detected hydrogen more quickly. The slow release has more dips, indicating that more of the higher sensors were overexposed in that test, and we can infer that the hydrogen concentration was higher at those points.

The level 3 sensors were again reading higher for both experiments. The reason for this is unknown, although as discussed in section 5.8.5, Tests 28 and 30 indicate that the readings are valid. The insertion nozzle at the middle point was taped to the frame of the enclosure, in a different way to both the top and bottom insertion points, and the insertion direction was unintentionally slightly downward. This may mean the initial plume of hydrogen as it is injected was directed at the level 3 sensors, meaning there is more hydrogen present at that height. The trend for all the sensor readings to align is an indicator that although there may be a higher concentration of hydrogen at one level, it will disperse over time, and mix into the rest of the space.

The main difference when comparing the slow and fast releases of hydrogen, is the speed at which the hydrogen was detected at all the levels. This is shown more clearly in Figure 68.

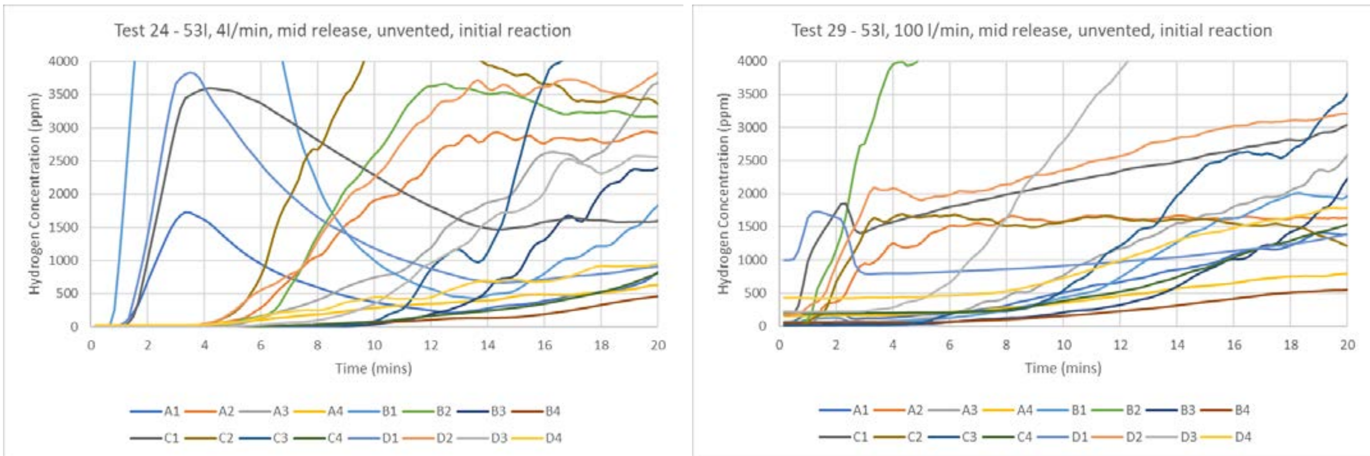


Figure 68: Slow vs fast release - initial reactions

Exploring the data for the individual levels reveals similar patterns for both releases. This is shown in Figure 69.

The hydrogen concentration at the top appears to be higher for the slower release, shown by a higher initial peak and more of a dip, indicating more overexposure of the sensors.

There was a faster and more thorough mix with the faster release. This effect was demonstrated by the higher concentrations detected in the lower areas for Test 29.

This result does not indicate a problem with release flow rates between 4 l/min and 100 l/min, when considering dispersion within an enclosed room. This result was confirmed by the readings from the GMI GS700H, discussed in section 5.8.5.

This result also agrees with the data from the paper '*Hydrogen dispersion in a closed environment'*, presented in Figure 47 in section 5.4.

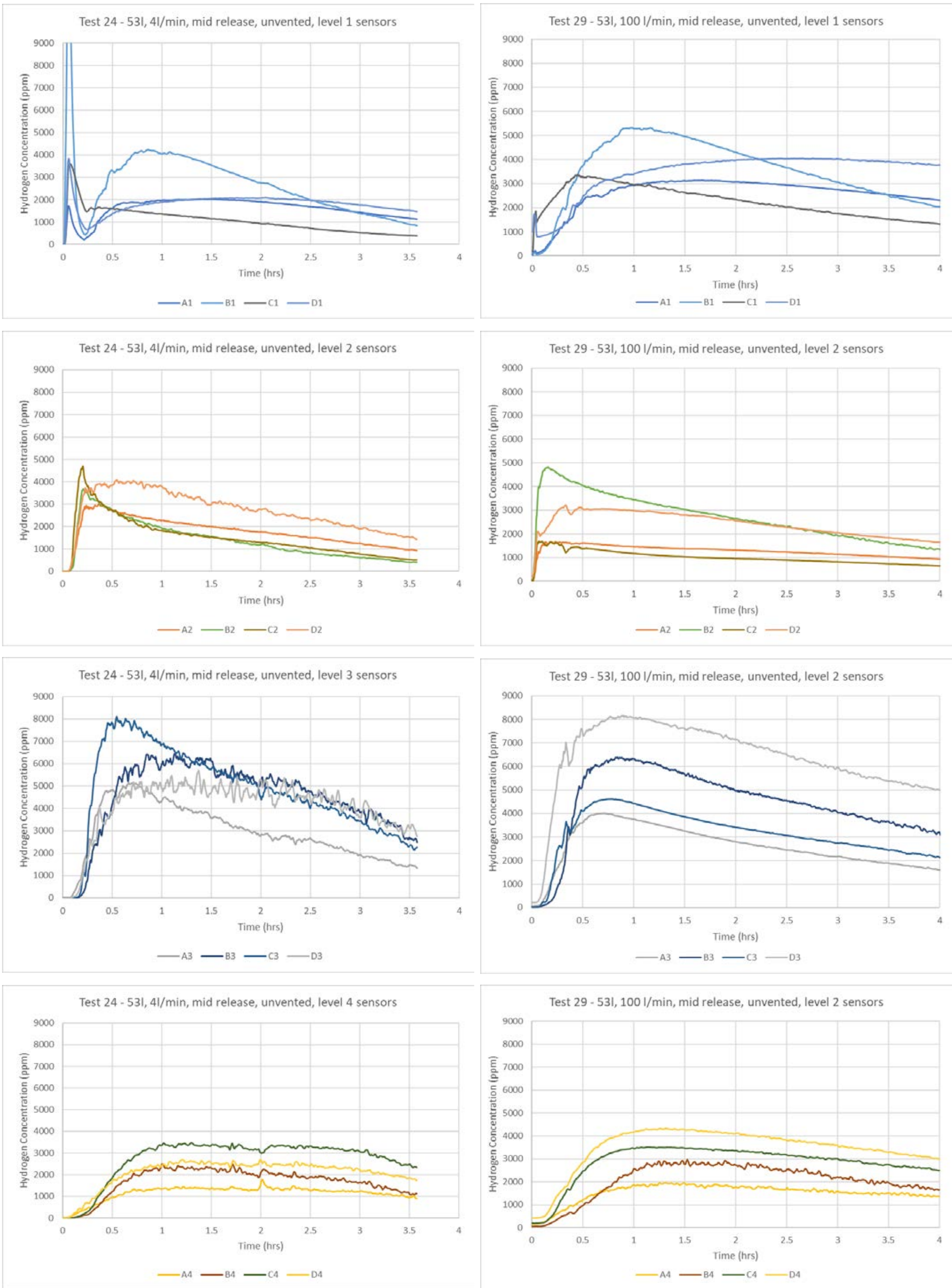


Figure 69: Dispersion patterns with varied insertion speed

5.8.5 GMI readings

The results presented above demonstrate the difference that varying things such as release speed, release volume, insertion height and ventilation make to the flammable mix created in a kitchen-sized enclosure. Using this information dictates that the most likely way to concentrate hydrogen at the top of the enclosure is with the following:

- Largest hydrogen volume
- No ventilation
- Low flow speed
- High insertion point

The GMI GS700H was used in the final tests both to corroborate the results given by the MQ-8 sensors, and give an absolute figure for the hydrogen concentration. The readings from this were expected to be more dependable, consistent and accurate. It is also able to reliably detect higher concentrations of hydrogen than the MQ-8 sensors, which are limited to 10,000 ppm and begin to be overexposed around 4,000 ppm. The GS700H does however use an internal pump, which may disturb the air-hydrogen mix in the enclosure, and create eddies of its own. The probe is inserted through the walls of the enclosure at each height level of the sensors. When it is removed, the hole is covered with tape. The readings from the GMI detector are manually noted at specific times.

Figure 70: Taking hydrogen readings from the GMI GS700H

The worst case scenario was created for Test 32, with a 53 litre release at 5 l/min, through a high release point. The enclosure was not ventilated.

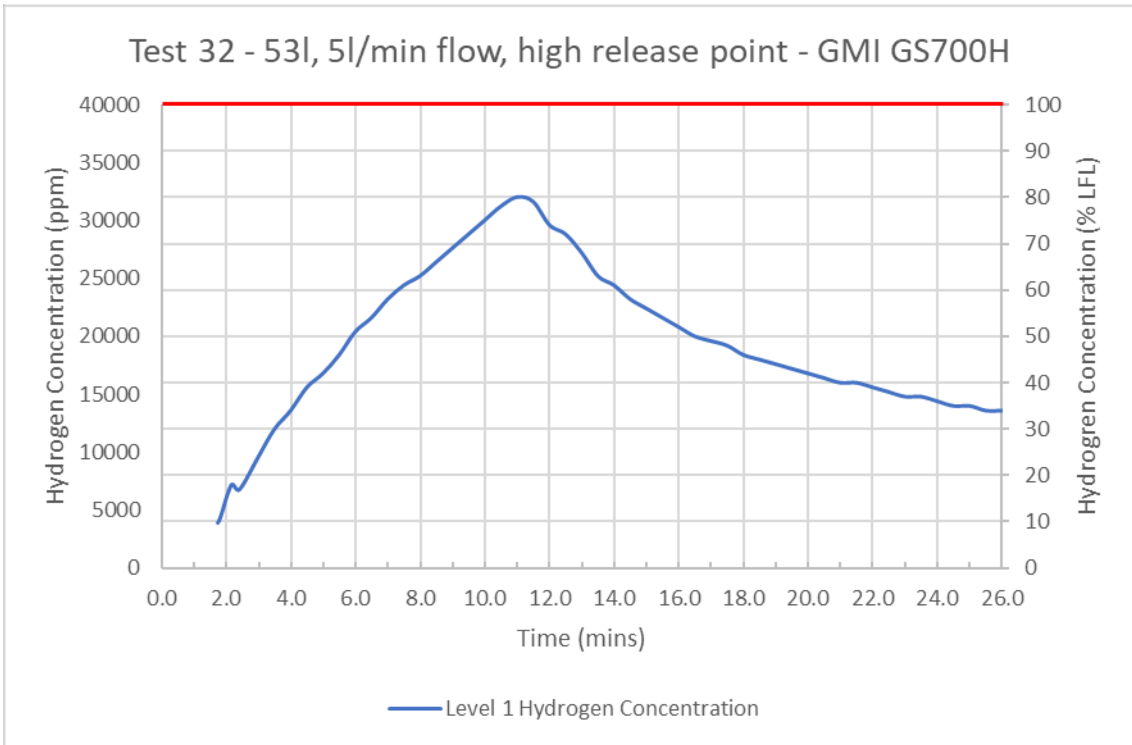


Figure 71: Test 32 - GMI GS700H readings for a worst case scenario

Figure 71 shows the results from the GMI GS700H for the worst case hydrogen release. The red line at 100% of LFL (40,000 ppm) is the point at which the gas could become ignitable. The maximum figure seen was 80% of LFL, which occurred almost exactly when the hydrogen release was finished. The timer started when the hydrogen release began, and the release ended at 10.6 minutes. As soon as the hydrogen release ended, the concentration at the top of the enclosure began to fall.

For clarity, this experiment was repeated with a very high flow, 100 l/min release speed, and the release point 1 metre above the ground. This is a more representative test, although factors such as high volume (53 litres) and no ventilation make it a situation that should never happen if the guidelines and standards are followed. In this test (Test 29), the maximum hydrogen concentration reading from the GMI GS700H was 59% of LFL, at the top of the enclosure. As with the slower flow, the concentration decreased after the flow was stopped.

While these results confirm that slower flows would produce higher concentrations at the top of the enclosure, this is short-lived, and does not reach LFL.

5.9 Stage 2 Conclusions

It has not been possible to collect a cloud of hydrogen at the top of the enclosure by minimising mixing. Even with a very slow release at the top of the enclosure, the hydrogen appears to mix into the volume.

Volumes of hydrogen up to 53 litres have been released into an unventilated room without creating a dangerous atmosphere. Ventilation is important however, greatly reducing the concentration of hydrogen and accelerating the diffusion.

Releasing the gas lower down appears to aid dispersion of the hydrogen. While it has not been tested, artificially creating turbulence using a fan or similar is likely to greatly increase dispersion of the hydrogen.

Consideration should be given to removing the stipulation to burn all purged flammable gas releases for installations greater than 20 litres.

6 WP4 Conclusions and recommendations

The programme of work has examined the process of purging domestic installations and the subsequent release of purged gas into a closed volume the size of a small kitchen. The aim was to investigate and determine changes that will be required for purging standards to be safely adapted to hydrogen.

An overview of current standards and practices was carried out in WP1. This included:

- a review of relevant gas industry standards
- a survey of gas engineers
- interviews with appliance and meter manufacturers
- an overview of pertinent practices in industry and other countries

A review of expected risks was carried out in WP2, including details of hydrogen and methane properties.

A study of purging domestic installations was carried out in WP3 Stage 1. Specific concerns that have been addressed are the possibility that hydrogen will bypass air in an installation leading to pocketing and stratification in pipes. This effect was not seen in any of the tests carried out.

A study of releasing relevant quantities of gas into an enclosure representing a small domestic kitchen has been carried out in WP3 Stage 2. Specific concerns that have been addressed are the possibility that hydrogen will stratify and collect in the enclosure, resulting in a flammable atmosphere. This effect was not seen in any of the tests carried out.

6.1 WP3 Stage 1 - installation purging conclusions

It was possible to purge all of the installation pipework using a pressure 1mmTP, in all orientations. The only instance found where the primary gas could be trapped in a tested system was in dead branches that were left unpurged, in particular downward facing dead branches.

In the case where a pocket of air is left in a dead branch after a system purge that air was seen to mix with the hydrogen remaining in the system over time. It is expected therefore that this mix would be flushed out in due course as gas is used by appliances. A situation is therefore conceivable where a large dead branch has not been fully purged, and the system is then left long enough for all the gas to mix, resulting in a system filled with a flammable mixture. While possible, we believe it is extremely unlikely for a working system that is used regularly. This same scenario of an un-purged dead branch will also remain unpurged by Natural Gas under the current guidelines.

The tests carried out in this work used very slow purge speeds compared to those recommended by table 12 of IGE/UP/1 and by industry practices. All tests resulted in acceptable installation purges and this provides a very high level of confidence in the ease of purging domestic installations. The speed of purge is likely to be driven by the engineer's time constraints rather than a requirement to achieve a certain flow.

During the purge process, hydrogen will be displaced from the system along with the air being purged. Buoyancy effects may slightly increase the transition time of air to hydrogen when compared to a purge from air to methane. If the presence of hydrogen is being detected by smell, as can be the case with methane then this is likely to happen when the hydrogen concentration of the expelled gas is significantly below the UFL of 75% by volume. The use of naked flames to detect the presence of hydrogen should therefore be avoided during this process, unless a full study has been carried out demonstrating that it is safe to do so. This also applies to hot work carried out on hydrogen-carrying installations. An alternative method of identifying not only the presence but the concentration of the gas being displaced is desirable.

Direct purging with hydrogen is fully viable and is recommended for domestic installations. The only instance found where air was retained was in a disused branch that was not purged, and this situation would not be mitigated by indirect purging. Indirect purging brings additional risks to the process, as identified in IGE/UP/1.

6.1.1 WP3 Stage 1 - installation purging recommendations:

Prior to working on an installation, a full analysis should be carried out to identify any dead branches.

As part of the tightness test carried out prior to purging, an additional operation could be carried out to measure the installation volume by monitoring the pressure rise when a known volume of gas is added to the installation. This could be achieved by a small positive displacement pump and a pressure gauge. This could be compared to the estimated system volume to identify the presence of unknown branches.

Each branch of the system should then be purged in turn without any significant pauses of more than an hour between the individual purge events.

A method of identifying the concentration of hydrogen expelled during the purge is desirable, one that works well in the 50% to 100% vol. range.

The majority of the purge tests were carried out using an isolation valve with an integral 1mmTP. Installing such a valve prior to all appliances is one option for carrying out consistent purges in hydrogen systems however a discussion should be had to decide if this is desirable. The 1mmTP only permits a flow of 2 l/min in air. This would take over 17 minutes to purge an entire 35 litre installation, which is likely to be too slow for commercial adoption. Alternative options should therefore be investigated.

6.2 WP3 Stage 2 - release into enclosure conclusions

None of the hydrogen releases into the chamber resulted in stratified layers of gas reaching LFL. It is clear that the plume of pure hydrogen released will have resulted in small transient volumes of concentrated hydrogen. This is equally true of methane. Once away from the plume itself however, the concentration of hydrogen has not ever reached the flammable limit throughout these tests. This leads to the conclusion that purging hydrogen into a room does not pose a significantly greater risk than purging Natural Gas into a room.

The tests have also confirmed findings reported in the literature that hydrogen released into enclosed spaces quickly disperses throughout the entire volume. Factors speeding up the mixing processes are turbulence caused by buoyancy effects and high flow rates, and ventilation.

These results indicate that turbulence effects cause a given volume of hydrogen released at a high flow rate to mix more quickly than one released at a low flow rate.

Hydrogen released low down in the room appears to encourage gas movement and subsequent mixing from the buoyancy effects, implying that it will pose less risk than hydrogen released at ceiling level.

Significant amounts of hydrogen collecting at the top of the enclosure have not been observed, despite these mixing effects being deliberately minimised. Even with a very slow release at ceiling height in an unventilated enclosure, the hydrogen mixed with the air in the enclosed volume by dispersion, reaching the lowest sensors in the chamber after approximately 10 minutes. The diffusion coefficient of hydrogen in air is approximately four times that of methane in air, leading to faster dispersion for unmixed hydrogen than for methane.

6.2.1 WP3 Stage 2 - release into enclosure recommendations

The requirement to burn all purged flammable gas releases for installations greater than 20 litres should be reviewed, as it may be unnecessary with hydrogen and introduces other risks. The toxic and emetic nature of the odorant may cause issues though if released in significant amounts.

While it has not been tested, artificially creating turbulence using a fan or similar is likely to greatly increase dispersion of the hydrogen. Releasing the gas lower down in the room will also aid the rapid dispersion of the hydrogen.

None of the hydrogen release tests have indicated a need to reduce the flow of hydrogen purged into the room, in fact they indicate desirable mixing caused by larger purge flows. The process of cracking a fitting may not need to be avoided on flow reasoning alone. The lower ignition energy of hydrogen may pose a risk of spark generated ignition of the plume from tools or static. It would be of use to carry out further work to investigate the ease of lighting a purge plume and therefore assess the associated risk. This could be added to work examining the likelihood of igniting a flammable mix in a partially purged network to fully understand the risks.

6.3 Further work

The programme of experimental work has led to a number of opportunities for further work. These include:

- This work has identified a gap in understanding regarding the likelihood of ignition of hydrogen during the purge process. It would be of value to identify the risks associated with ignition of partially purged installations or the use of a naked flame to detect for the presence of gas as is currently recommended for methane. This could include an investigation of the ease of lighting the purge plume and therefore assess the associated risk.
- Development of a passive indicator to identify that the gas concentration from a purge is significantly greater than 75% hydrogen thus confirming completion of purge. Use of such a system could provide a simple process for indicating an effective purge in each leg of an installation.
- Development of a burner to safely process any purged gas. This could be used for transition from methane to hydrogen as well as for pure fuel gas purges. A specific burner could be produced to achieve this transition, a safe burner that burns combinations of methane and hydrogen and air and also disables the odorant in the released gas.
- Identify a method of auto-purge for installations to make a resilient installation. Currently some boilers have an auto-purge cycle that automatically purge the boiler chambers in a safe manner, venting purged gas through the flue. This feature could be extended to auto-purge the upstream pipework in a similar safe manner. This could result in increased resilience of the installation to a loss of supply and safer easier commissioning of the installation.
- The work carried out here could be extended to cover the wider remit of the IGE/UP/1 standard to develop recommendations for purging commercial installations and networks. This could include an investigation in the purge speeds in table 12 of that standard. The majority of the tests demonstrating acceptable purges in this work were carried out at purge speeds less than 10% of the minimum recommended speeds.
- An additional piece of work should be carried out to confirm safe processes for de-commissioning hydrogen installations back to air.

- The largest challenge to complete purging of installations is posed by unidentified branches in the installation. This challenge is not mitigated by indirect purging, however a method of identifying the volume of dead branches in a system could effectively mitigate this risk.

6.4 Formal recommendations relating to the standards

The most significant recommendation from this work relates to the need to burn the gas displaced from the system during a purge. Attempting to light an appliance during the purge could result in the appliance being lit whilst being fed by a flammable hydrogen / air mix. This is not something that is tested for in the PAS4444 appliance standard and could pose a threat of burn back into the installation pipework.

6.4.1 Review of IGEM/UP/1B Purging requirements

This section provides comments on section 6 of the UP/1B standard.

6.1 All processes valid for hydrogen

6.2 Changes will have to be made in the determination of the purge volume.

The currently advised purge volume of 1.5 IV remains a reasonable guideline, but this will not guarantee a good purge. This is believed to be equally true of Natural Gas.

If an advised purge volume is to be stipulated, a purge ratio of 1.7 may be better, and would ensure a full purge to 100% hydrogen with each case tested here.

The 0.01 m^3 purge volume advised for installations with U6, G4 or E6 meters and pipework below 35 mm diameter is insufficient to fully purge either Natural Gas or hydrogen, as the volume of a U6 or G4 meter is 0.008 m^3 before any pipework is considered.

6.3 Purge procedures

6.2.1 No change

6.3.2 Natural gas

a) Valid for hydrogen

b) Valid for hydrogen

c) Valid for hydrogen

d) Changes may be required. The safety of lighting an appliance to test for gas should be investigated. A better option would be to have a separate clear indication of >75% gas concentration prior to the ignition of gas. This could be done using an audible device.

e) Valid for hydrogen

f) Changes may be required. A discussion should be held to understand if a direct indication of hydrogen present is preferred than continuing the release until a nominal purge volume has been reached. Clarity should also be provided to state if the full purge volume should be displaced from every purge point or just for the whole purge exercise as a sum of the total volumes.

g) Valid for hydrogen

h) Valid for hydrogen

6.3.3. No change

6.4 All points are valid for hydrogen, however consideration should be given to purging back to air when decommissioning pipework. Work carried out here suggests that this will not pose any significant risks.

Appendix A: Gas engineer survey

The survey was created for a Survey Monkey but ended up being issued directly to participants of Kiwa's domestic gas engineer course.

1 For roughly how many years have you been a domestic gas engineer?

2 In practice, how long (in minutes) would you generally expect a purge and light/relight to take, if there are no issues?

3 Which location would you typically start the purge from?

4 For a purge and light/relight would you calculate the purge volume and monitor the meter, or purge until gas is detected?

5 How would you normally detect the gas? (eg smell, gas detector)

6a Roughly how long (in minutes) would it take for a primary purge from a hob fed by a U6 meter?

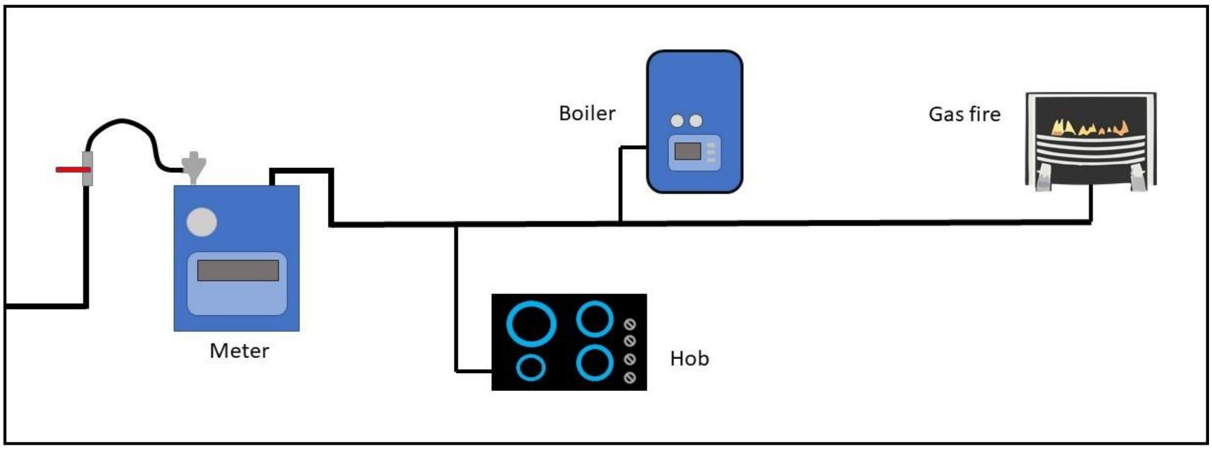
6b Roughly how long (in minutes) would it take for a primary purge from a boiler fed by a U6 meter?

6c Roughly how long (in minutes) would it take for a primary purge from a gas fire fed by a U6 meter?

6d Roughly how long (in minutes) would it take for a primary purge from a cracked nut (if applicable) fed by a U6 meter?

7 Once the system has been purged through the first appliance, do you then purge the full purge volume through all other appliances as well, or just the leg leading to that appliance?

8 On the diagram below, what would be your considerations for where to purge from? What would your procedure be/what order would you go in?



9 Assuming there have been no problems - would you revisit any appliance to repeat the purge process? Yes / No

10 If revisiting an appliance to purge, how many times might this happen?

11 Regarding question 10, how long would you expect each time to take?

12 If using a hob to purge, would you use more than one burner at a time?

13a Would you tend to purge through a hob, or would you crack open a fitting to speed up the process?

13b Would you tend to purge through a gas fire, or would you crack open a fitting to speed up the process?

13c Would you tend to purge through a boiler, or would you crack open a fitting to speed up the process?

14 In practice, would you always (try to) burn off the purged gases, or only sometimes, for example over a certain volume? Please explain:

15 If you're not burning off the purged gas or gas/air mixture, where would you normally purge to and what precautions would you take? (eg release into the room, outside, near a window etc)

16 Please explain how you would prepare the system/property for purging?

17 Please explain how you would leave the system/property after purging?

18 Are there any appliances or situations that would make your answers here change? Please include any further comments you feel may be useful.

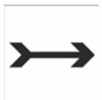
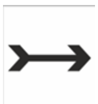
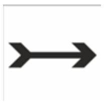
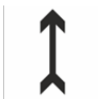
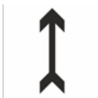
Appendix B: Test records

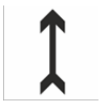
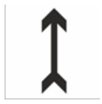
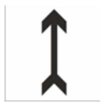
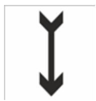
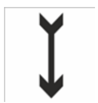
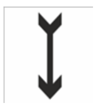
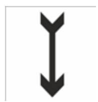
This appendix comprises all of the stage 1 test records.

Straight Tests

The naming convention of the branch tests can be broken down into the discrete categories detailed below. Examples for different tests are provided.

Test number	Main pipe size	Main flow direction	Additional test information	Which iteration of test the title details. Most tests have 3 iterations
010	28 mm	Horizontal		Test 1
028	35 mm	Vertical upwards	Pause	Test 2
040	35 mm	Vertical downwards	Methane	Test 3

Test No.	Section	Diameter (mm)	Orientation	Flow Direction	Start Gas	End Gas	Installation volume (l)	Purge time (s)	Purge volume (l)	Vol displaced air / methane (l)	Volume of H2 displaced (l)	Purge ratio
001								88	3.51	2.48	1.03	1.44
002	Straight	35		Horizontal	Air	Hydrogen	2.44	87	3.50	2.48	1.02	1.43
003								87	3.49	2.47	1.02	1.43
004								63	3.24	2.36	0.88	1.33
005	Straight	35		Horizontal	Methane	Hydrogen	2.44	63	3.21	2.38	0.83	1.32
006								63	3.25	2.39	0.86	1.33
007								60	2.86	1.09	1.76	1.17
008	Straight	35		Horizontal	Air + Hydrogen	Hydrogen	2.44	65	2.92	1.24	1.67	1.19
009								66	2.94	1.36	1.63	1.20
010								66	2.36	1.83	0.53	1.54
011	Straight	28		Horizontal	Air	Hydrogen	1.53	55	2.15	1.73	0.42	1.40
012								56	2.14	1.70	0.44	1.39
013	Straight	15		Horizontal	Air	Hydrogen	0.40	15	0.50	0.44	0.06	1.25
014								15	0.49	0.43	0.06	1.22
015								97	4.02	2.49	1.53	1.65
016	Straight	35		8 degree incline	Air	Hydrogen	2.44	95	3.99	2.46	1.52	1.63
017								94	3.96	2.41	1.55	1.62
018								58	2.27	1.69	0.58	1.48
019	Straight	28		8 degree incline	Air	Hydrogen	1.53	57	2.28	1.72	0.56	1.49
020								58	2.29	1.73	0.56	1.50
021								94	4.02	2.39	1.63	1.65
022	Straight	35		Vertical upwards	Air	Hydrogen	2.44	90	3.91	2.35	1.56	1.60
023								91	3.93	2.36	1.57	1.61
024								70	3.96	2.42	1.53	1.62
025	Straight	35		Vertical upwards	Methane	Hydrogen	2.44	69	3.85	2.38	1.47	1.58
026								69	3.89	2.37	1.51	1.59

Test No.	Section	Diameter (mm)	Orientation	Flow Direction	Start Gas	End Gas	Installation volume (l)	Purge time (s)	Purge volume (l)	Vol displaced air / methane (l)	Volume of H2 displaced (l)	Purge ratio
027	Straight	35		Vertical upwards	Air + Hydrogen	Hydrogen	2.44	80	3.73	1.62	2.11	1.53
028								68	3.41	1.21	2.20	1.40
029	Straight	28		Vertical upwards	Air	Hydrogen	1.53	58	2.25	1.55	0.70	1.47
030								57	2.24	1.52	0.71	1.46
031								58	2.28	1.55	0.73	1.48
032	Straight	15		Vertical upwards	Air	Hydrogen	0.40	13	0.46	0.40	0.06	1.14
033								13	0.45	0.39	0.06	1.12
034								13	0.45	0.40	0.06	1.13
035	Straight	35		Vertical downwards	Air	Hydrogen	2.44	82	2.75	2.52	0.24	1.13
036								82	2.76	2.52	0.24	1.13
037								83	2.77	2.51	0.25	1.13
038	Straight	35		Vertical downwards	Methane	Hydrogen	2.44	59	2.63	2.35	0.28	1.08
039								59	2.66	2.39	0.27	1.09
040								59	2.63	2.33	0.30	1.08
041	Straight	35		Vertical downwards	Air + Hydrogen	Hydrogen	2.44	59	2.84	1.14	1.70	1.16
042								60	2.84	1.16	1.68	1.16
043								60	2.84	1.18	1.69	1.16
044	Straight	15		Vertical downwards	Air	Hydrogen	0.40	13	0.43	0.42	0.05	1.07
045								13	0.43	0.38	0.05	1.07
046								14	0.45	0.39	0.06	1.13

Horizontal straight tests

001 35 mm horizontal test 1

Test #	001 35mm horizontal test 1	
Installation configuration	3 m x 35 mm Horizontal	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

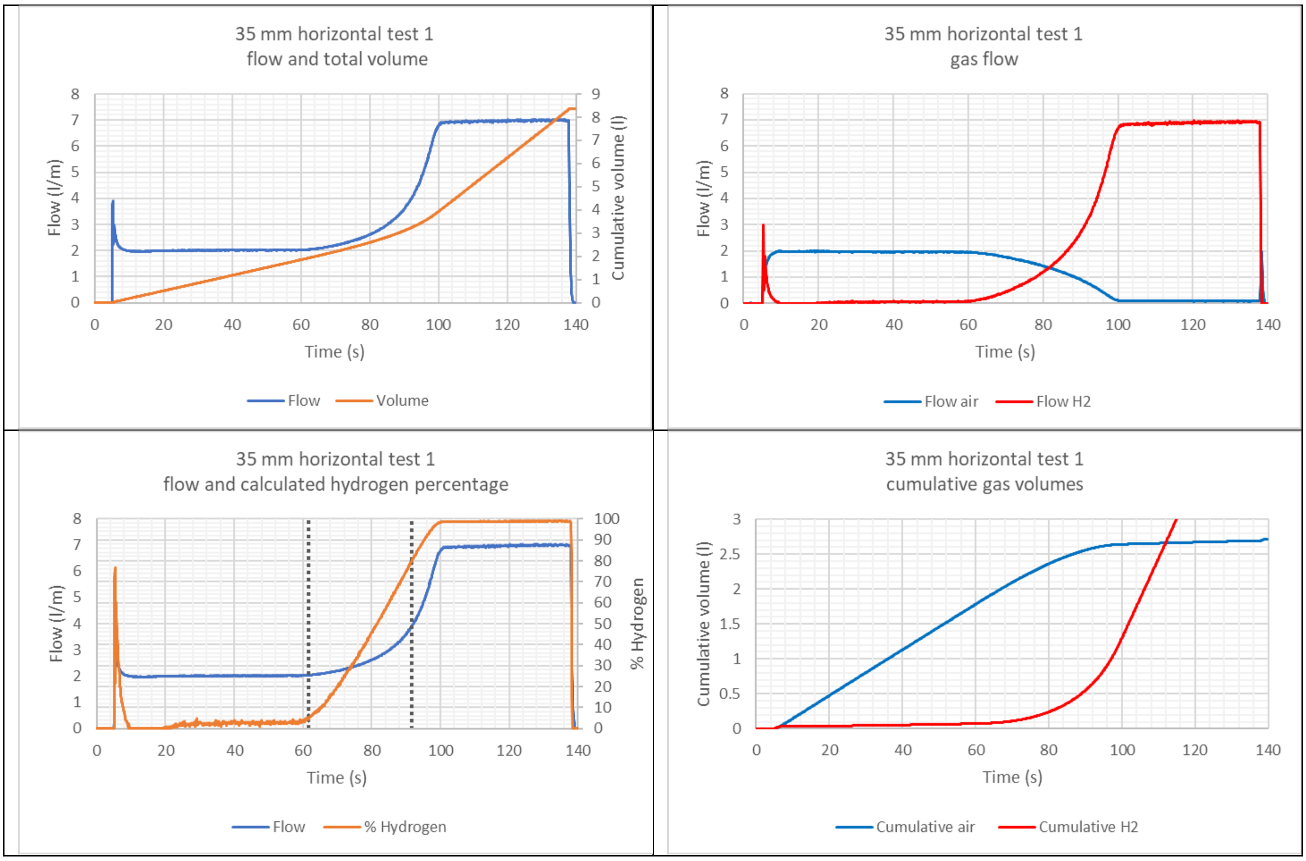


Figure 1: 35 mm horizontal test 1

	Time (s)	Volume (l)
To start of transition (>0% H2)	50	1.67
Duration of transition	38.3	1.84
To end of transition (95% H2)	88.3	3.51

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	3.51
Calculated volume of air displaced (l)	2.48
Calculated volume of hydrogen displaced during purge (l)	1.03
Ratio of purge volume to installation volume	1.44

002 35 mm horizontal test 2

Test #	002 35mm horizontal test 2	
Installation configuration	3 m x 35 mm Horizontal	→
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

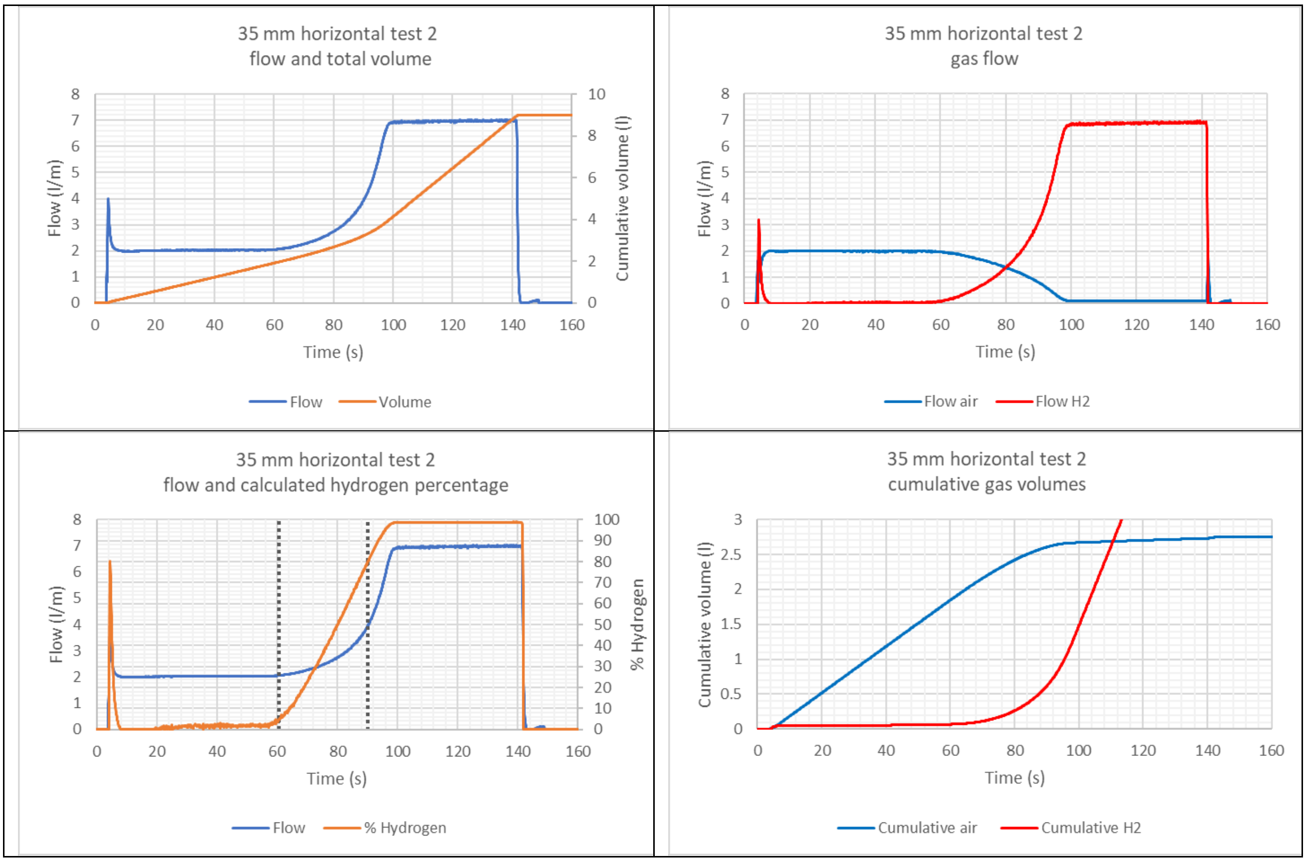


Figure 2: 35 mm horizontal test 2

	Time (s)	Volume (l)
To start of transition (>0% H2)	52.2	1.76
Duration of transition	35.1	1.74
To end of transition (95% H2)	87.3	3.50

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	3.50
Calculated volume of air displaced (l)	2.48
Calculated volume of hydrogen displaced during purge (l)	1.02
Ratio of purge volume to installation volume	1.43

003 35 mm horizontal test 3

Test #	003 35mm horizontal test 3	
Installation configuration	3 m x 35 mm Horizontal	→
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

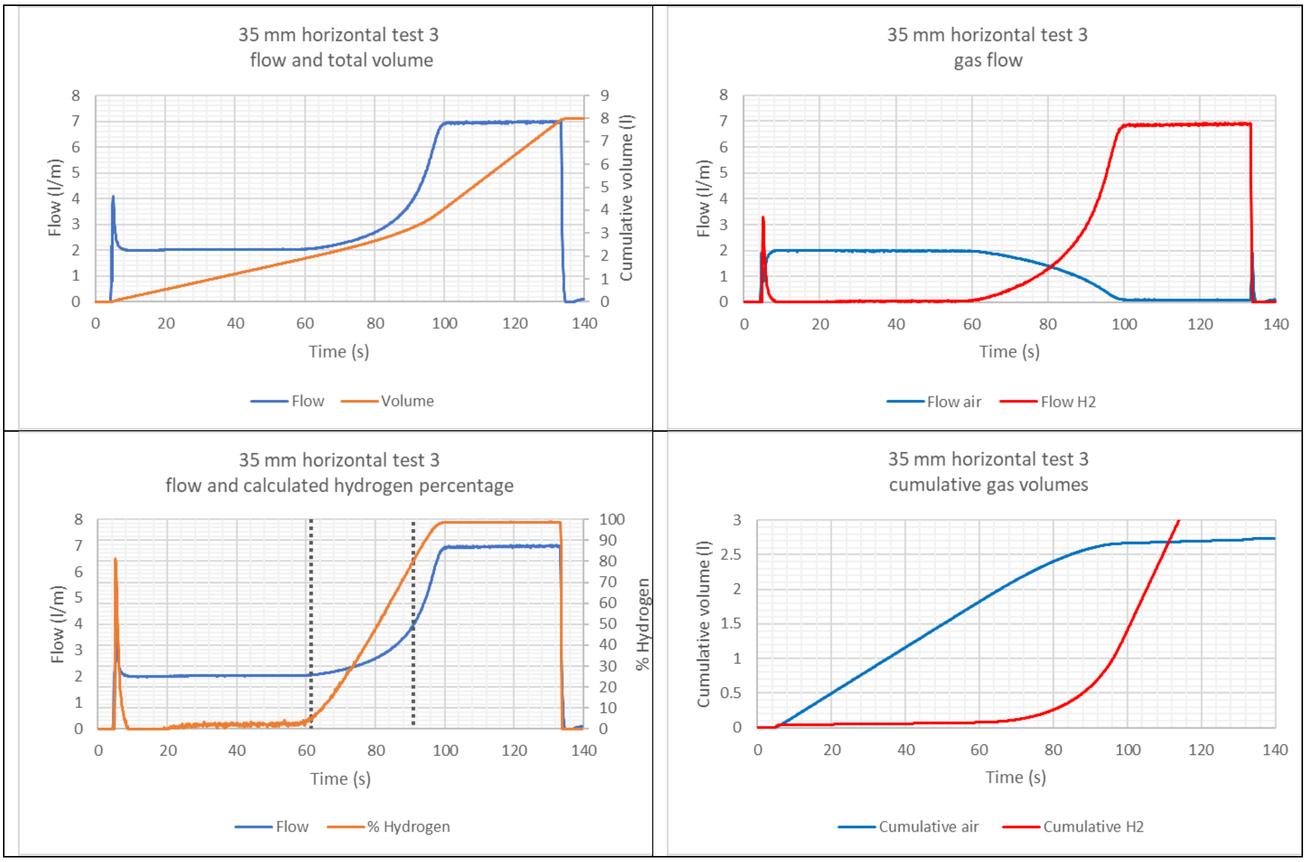


Figure 3: 35 mm horizontal test 3

	Time (s)	Volume (l)
To start of transition (>0% H2)	51.9	1.76
Duration of transition	35	1.74
To end of transition (95% H2)	86.9	3.49

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	3.49
Calculated volume of air displaced (l)	2.47
Calculated volume of hydrogen displaced during purge (l)	1.02
Ratio of purge volume to installation volume	1.43

004 35 mm horizontal methane test 1

Test #	004 35mm horizontal methane test 1	
Installation configuration	3 m x 35 mm Horizontal	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

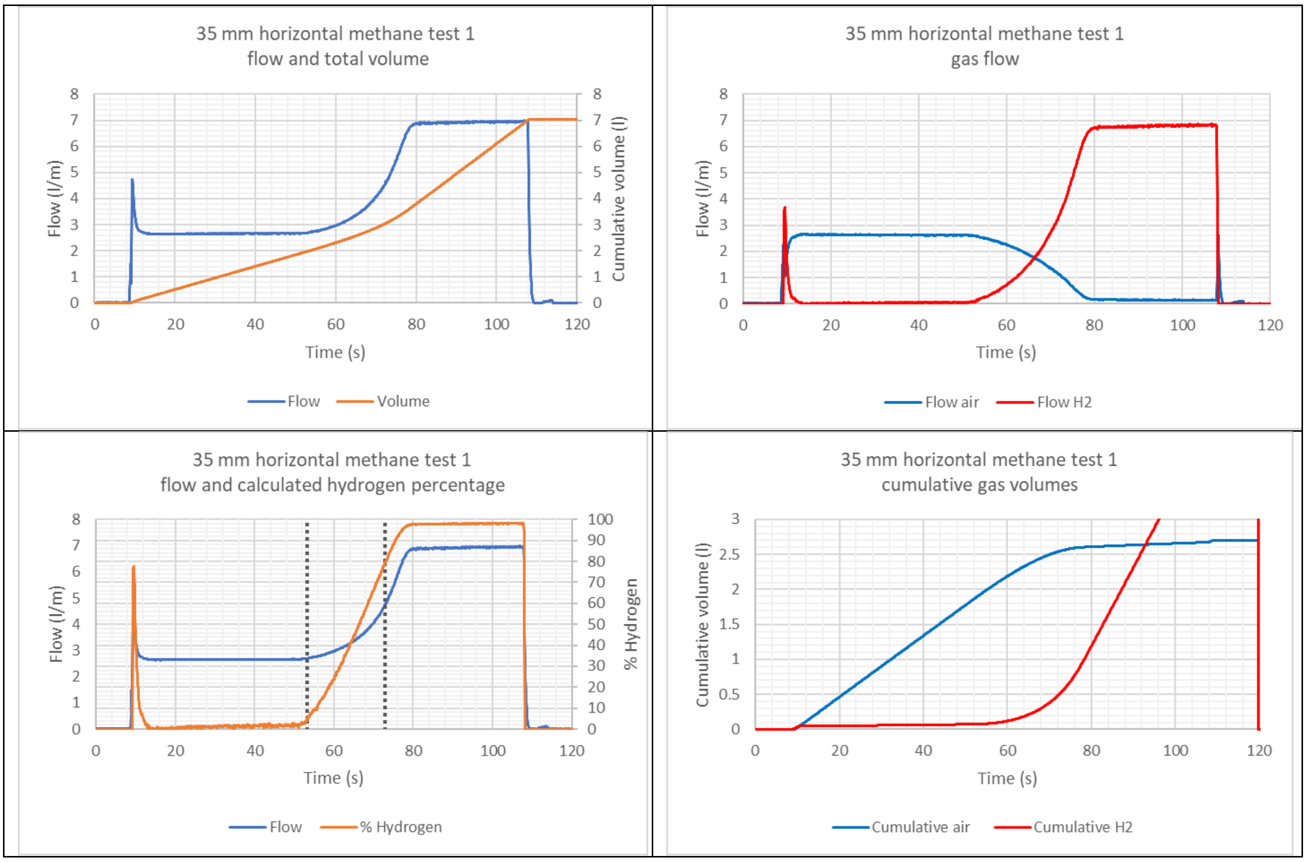


Figure 4: 35 mm methane horizontal test 1

	Time (s)	Volume (l)
To start of transition (>0% H2)	39.5	1.38
Duration of transition	23.9	1.87
To end of transition (95% H2)	63.4	3.24

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	3.24
Calculated volume of air displaced (l)	2.36
Calculated volume of hydrogen displaced during purge (l)	0.88
Ratio of purge volume to installation volume	1.33

005 35 mm horizontal methane test 2

Test #	005 35mm horizontal methane test 2	
Installation configuration	3 m x 35 mm Horizontal	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

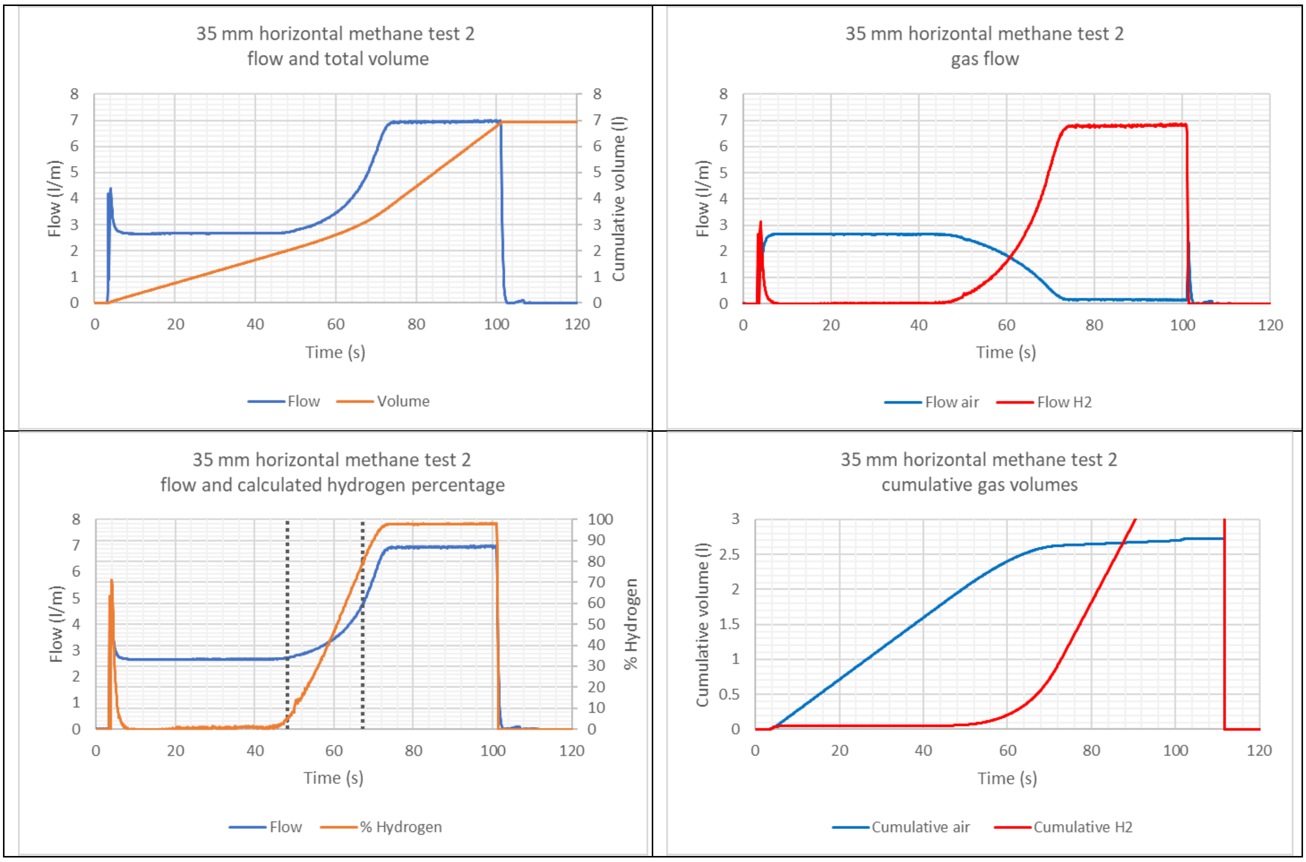


Figure 5: 35 mm methane horizontal test 2

	Time (s)	Volume (l)
To start of transition (>0% H2)	40.2	1.62
Duration of transition	22.8	1.59
To end of transition (95% H2)	63	3.21

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	3.21
Calculated volume of air displaced (l)	2.38
Calculated volume of hydrogen displaced during purge (l)	0.83
Ratio of purge volume to installation volume	1.32

006 35 mm horizontal methane test 3

Test #	006 35mm horizontal methane test 3	
Installation configuration	3 m x 35 mm Horizontal	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

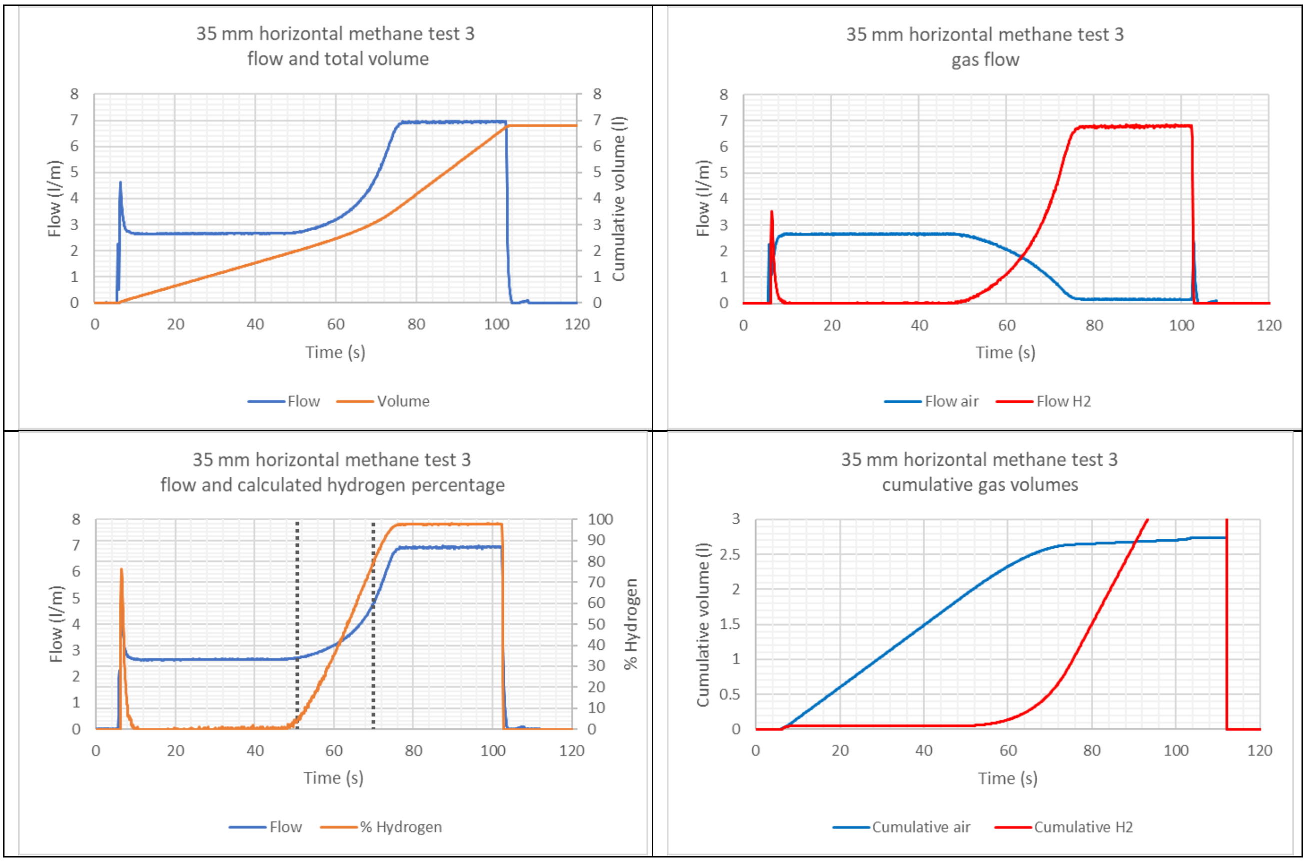


Figure 6: 35 mm methane horizontal test 3

	Time (s)	Volume (l)
To start of transition (>0% H2)	40.4	1.50
Duration of transition	22.9	1.75
To end of transition (95% H2)	63.3	3.25

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	3.25
Calculated volume of air displaced (l)	2.39
Calculated volume of hydrogen displaced during purge (l)	0.86
Ratio of purge volume to installation volume	1.33

007 35 mm horizontal pause test 1

Test #	007 35 mm horizontal pause test 1	
Installation configuration	3 m x 35 mm Horizontal	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

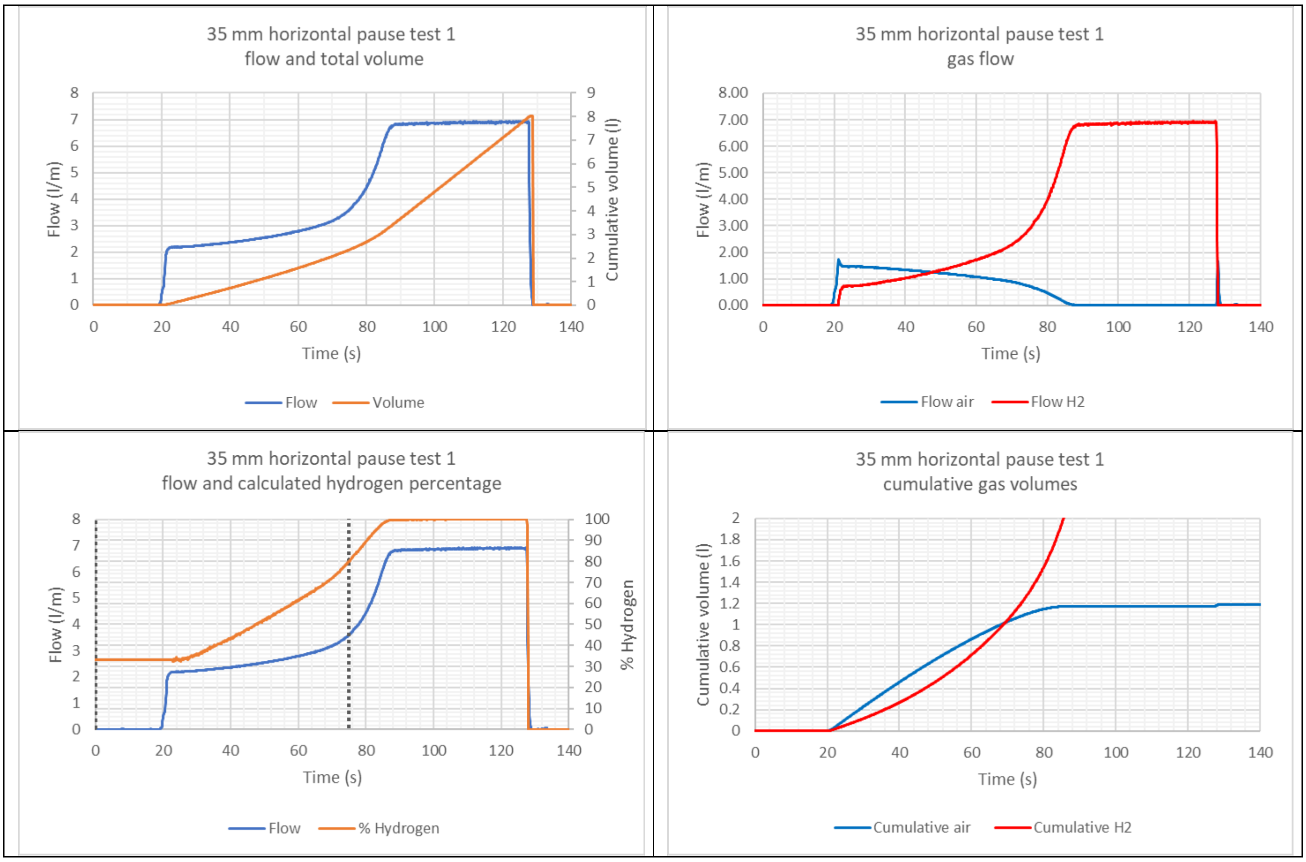


Figure 7: 35mm horizontal pause test 1

	Time (s)	Volume (l)
To start of transition (>0% H2)	8.6	0.32
Duration of transition	51.7	2.54
To end of transition (95% H2)	60.3	2.86

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	2.86
Calculated volume of air displaced (l)	1.09
Calculated volume of hydrogen displaced during purge (l)	1.76
Ratio of purge volume to installation volume	1.17

008 35 mm horizontal pause test 2

Test #	008 35 mm horizontal pause test 2	
Installation configuration	3 m x 35 mm Horizontal	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

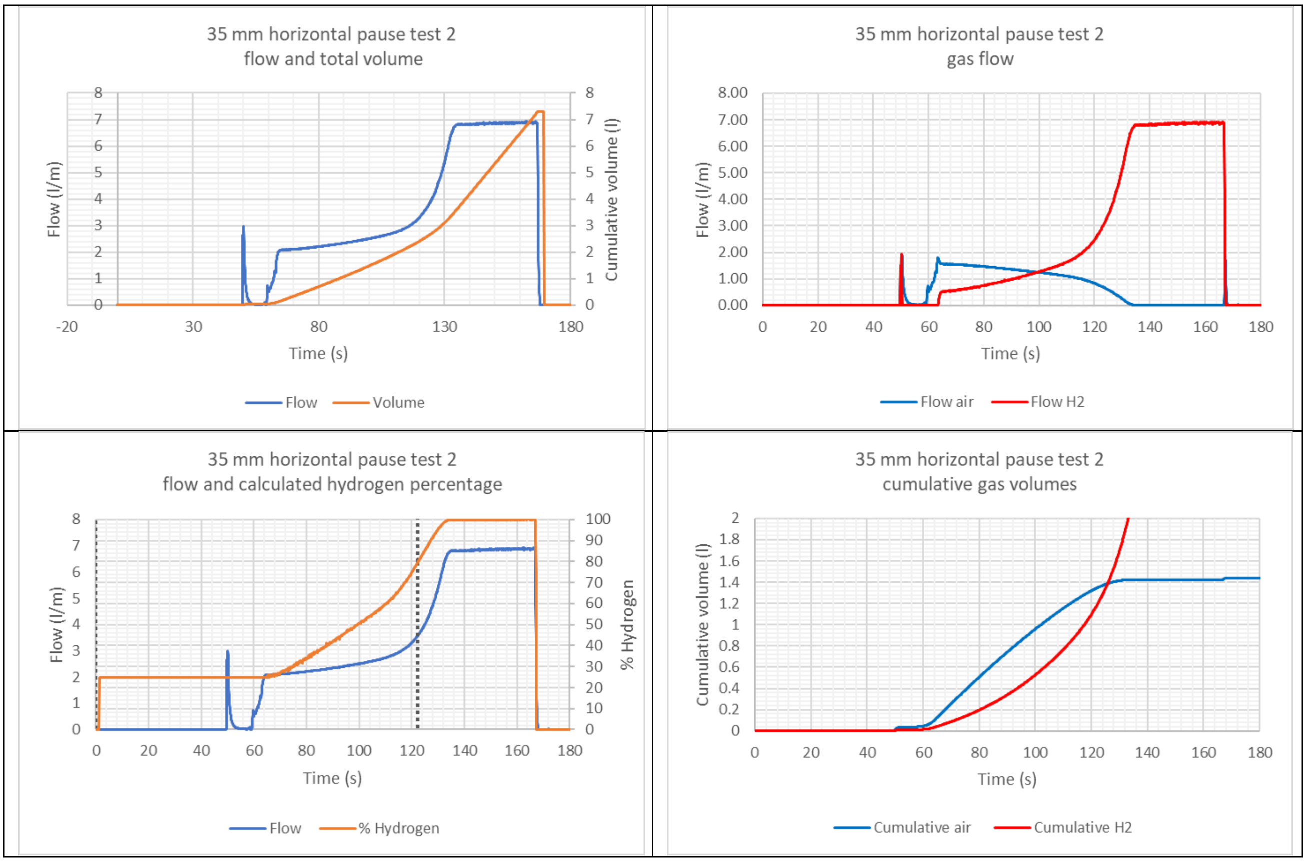


Figure 8: 35mm horizontal pause test 2

	Time (s)	Volume (l)
To start of transition (>0% H2)	3.9	0.14
Duration of transition	60.8	2.78
To end of transition (95% H2)	64.7	2.92

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	2.92
Calculated volume of air displaced (l)	1.24
Calculated volume of hydrogen displaced during purge (l)	1.67
Ratio of purge volume to installation volume	1.19

009 35 mm horizontal pause test 3

Test #	009 35 mm horizontal pause test 3	
Installation configuration	3 m x 35 mm Horizontal	→
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

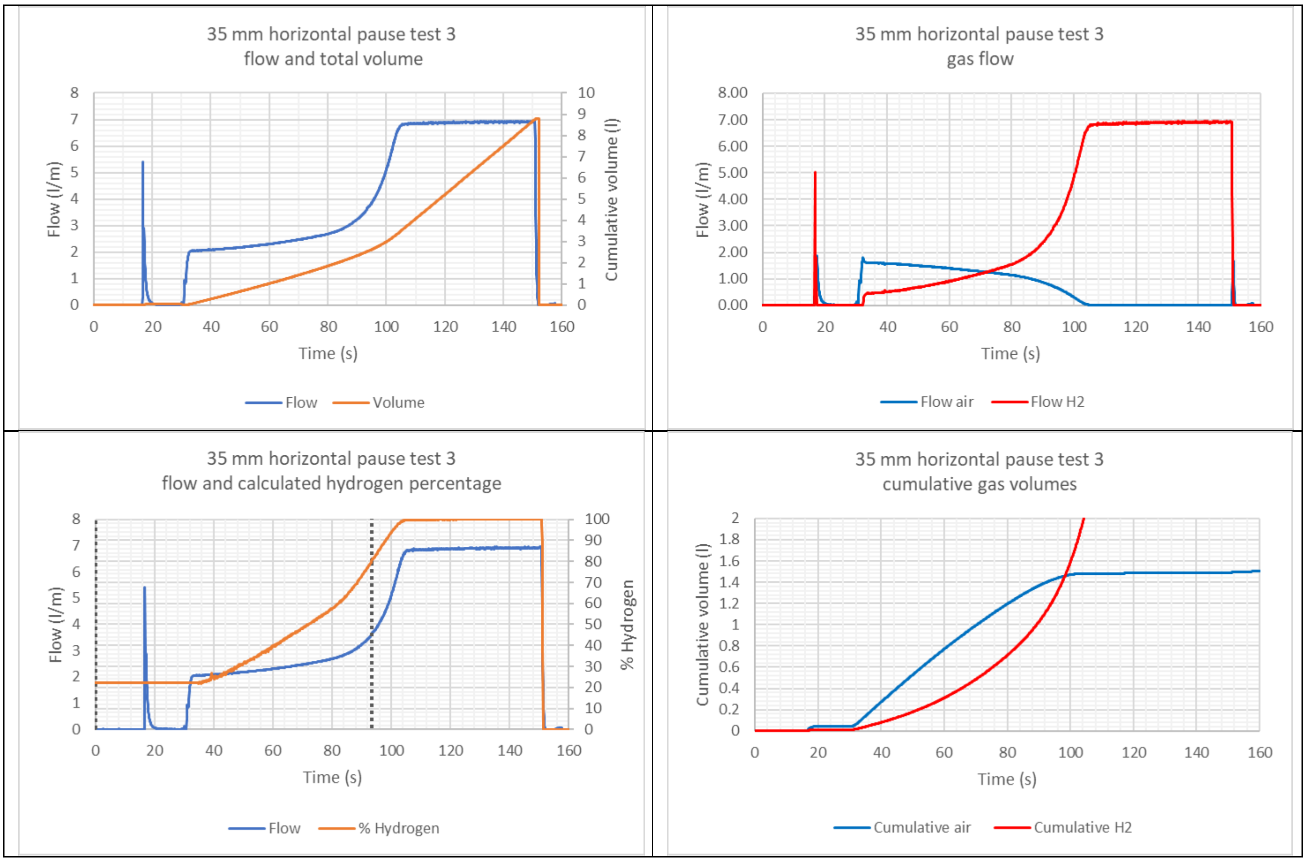


Figure 9: 35mm horizontal pause test 3

	Time (s)	Volume (l)
To start of transition (>0% H2)	3.7	0.13
Duration of transition	62.1	2.81
To end of transition (95% H2)	65.8	2.94

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	2.94
Calculated volume of air displaced (l)	1.36
Calculated volume of hydrogen displaced during purge (l)	1.63
Ratio of purge volume to installation volume	1.20

010 28 mm horizontal test 1

Test #	010 28 mm horizontal test 1	
Installation configuration	3 m x 28 mm Horizontal	
Installation volume	1.53 l	
Flow and speed with pure air	2 l/m	0.07 m/s
Flow and speed with pure hydrogen	7 l/m	0.24 m/s

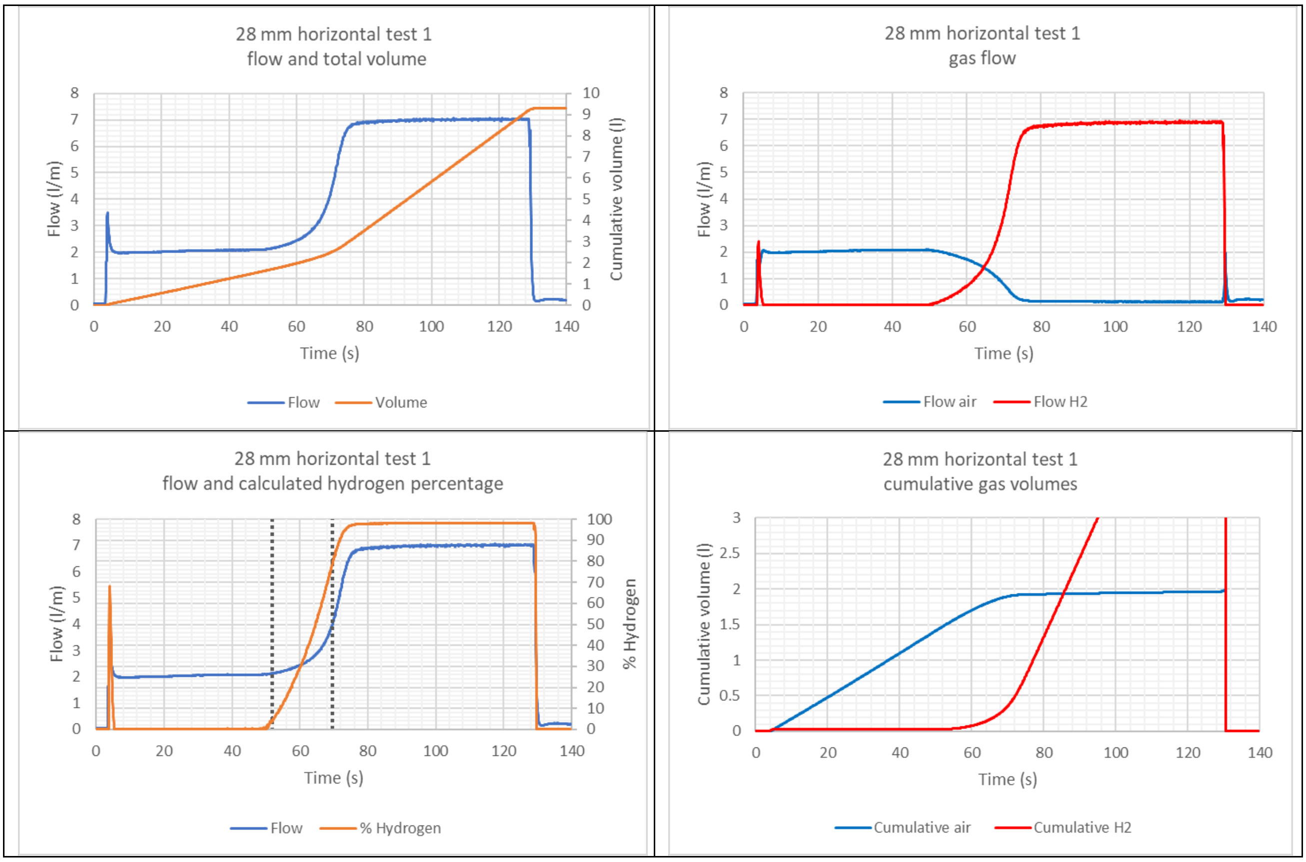


Figure 10: 28 mm horizontal test 1

	Time (s)	Volume (l)
To start of transition (>0% H2)	45.6	1.19
Duration of transition	20.7	1.17
To end of transition (95% H2)	66.3	2.36

Installation volume (l)	1.53
Total volume displaced to 95% hydrogen (l)	2.36
Calculated volume of air displaced (l)	1.83
Calculated volume of hydrogen displaced during purge (l)	0.53
Ratio of purge volume to installation volume	1.54

011 28 mm horizontal test 2

Test #	011 28 mm horizontal test 2	
Installation configuration	3 m x 28 mm Horizontal	
Installation volume	1.53 l	
Flow and speed with pure air	2 l/m	0.07 m/s
Flow and speed with pure hydrogen	7 l/m	0.24 m/s

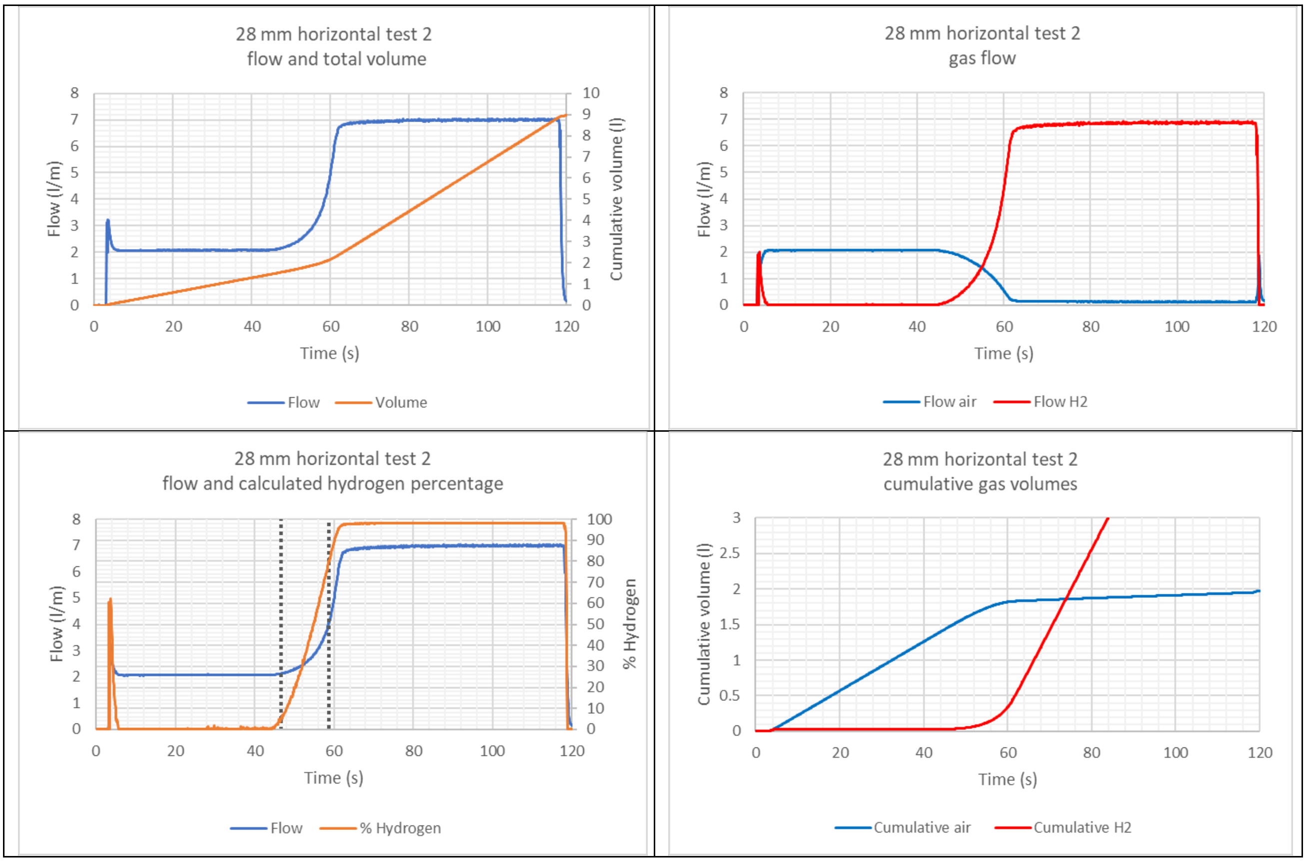


Figure 11: 28 mm horizontal test 2

	Time (s)	Volume (l)
To start of transition (>0% H2)	41	1.36
Duration of transition	14.4	0.79
To end of transition (95% H2)	55.4	2.15

Installation volume (l)	1.53
Total volume displaced to 95% hydrogen (l)	2.15
Calculated volume of air displaced (l)	1.73
Calculated volume of hydrogen displaced during purge (l)	0.42
Ratio of purge volume to installation volume	1.40

012 28 mm horizontal test 3

Test #	012 28 mm horizontal test 3	
Installation configuration	3 m x 28 mm Horizontal	
Installation volume	1.53 l	
Flow and speed with pure air	2 l/m	0.07 m/s
Flow and speed with pure hydrogen	7 l/m	0.24 m/s

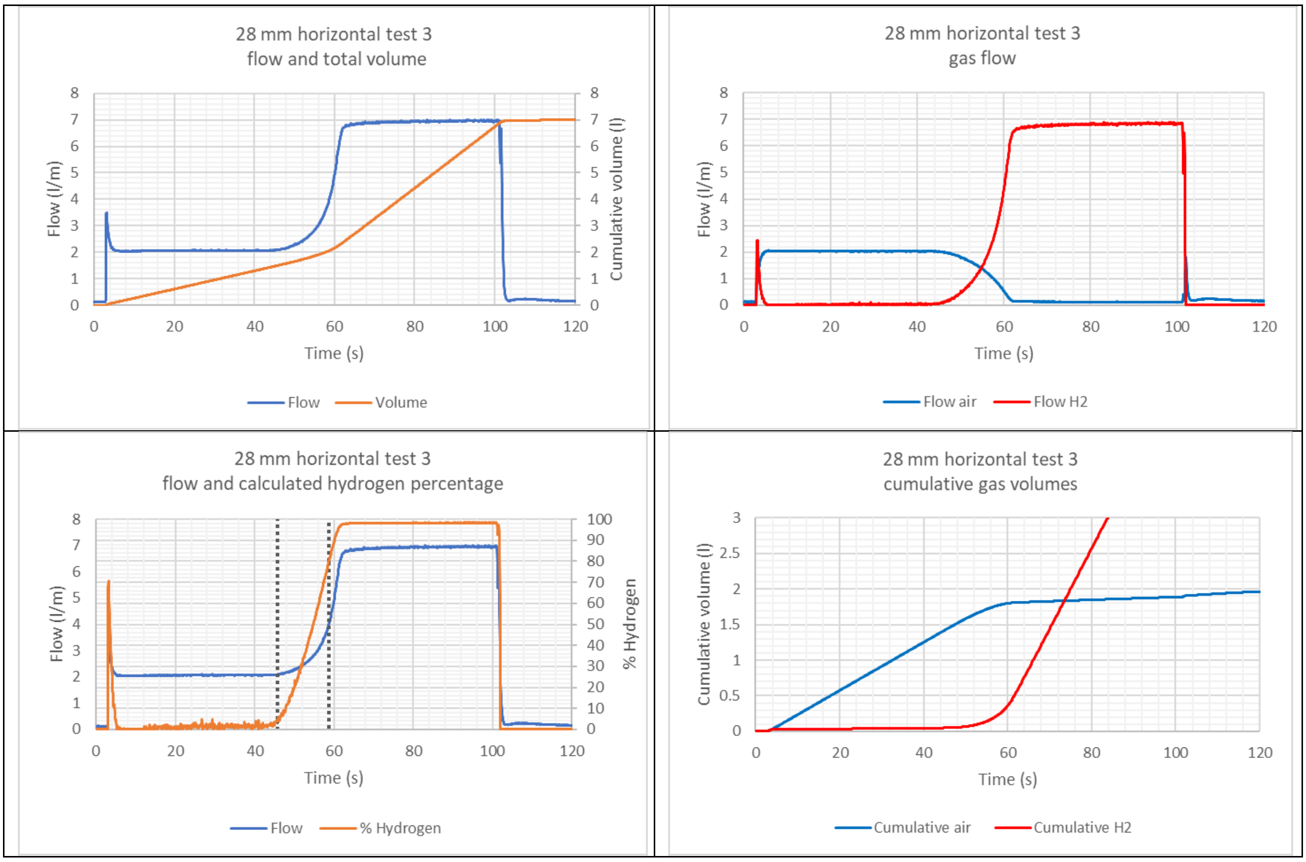


Figure 12: 28 mm horizontal test 3

	Time (s)	Volume (l)
To start of transition (>0% H2)	40.4	1.35
Duration of transition	15.1	0.79
To end of transition (95% H2)	55.5	2.14

Installation volume (l)	1.53
Total volume displaced to 95% hydrogen (l)	2.14
Calculated volume of air displaced (l)	1.70
Calculated volume of hydrogen displaced during purge (l)	0.44
Ratio of purge volume to installation volume	1.39

013 15 mm horizontal test 5

Test #	013 15 mm horizontal test 5	
Installation configuration	3 m x 15 mm Horizontal	→
Installation volume	0.4 l	
Flow and speed with pure air	2 l/m	0.25 m/s
Flow and speed with pure hydrogen	7 l/m	0.88 m/s

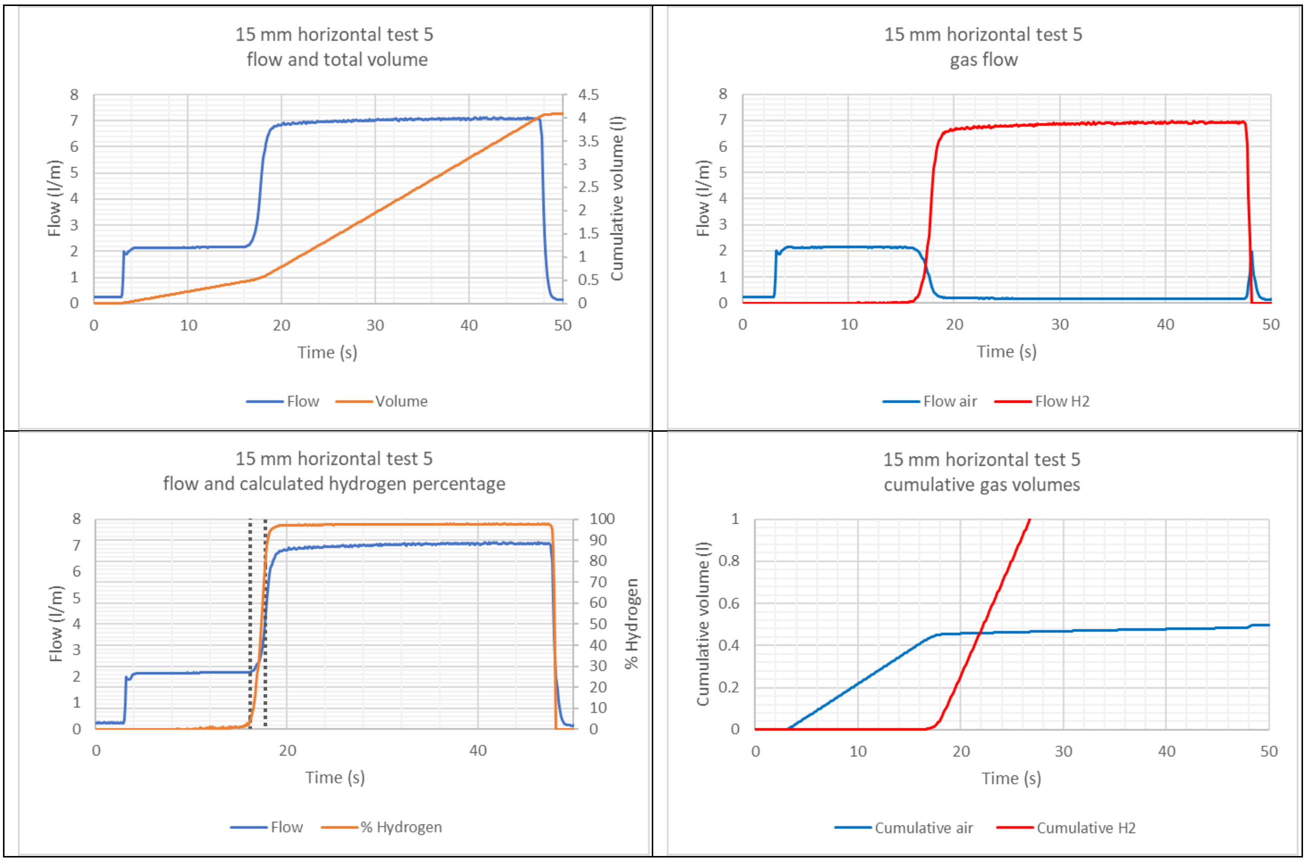


Figure 13: 15 mm horizontal test 5

	Time (s)	Volume (l)
To start of transition (>0% H2)	12.9	0.40
Duration of transition	2	0.10
To end of transition (95% H2)	14.9	0.50

Installation volume (l)	0.40
Total volume displaced to 95% hydrogen (l)	0.50
Calculated volume of air displaced (l)	0.44
Calculated volume of hydrogen displaced during purge (l)	0.06
Ratio of purge volume to installation volume	1.25

014 15 mm horizontal test 6

Test #	014 15 mm horizontal test 6	
Installation configuration	3 m x 15 mm Horizontal	→
Installation volume	0.4 l	
Flow and speed with pure air	2 l/m	0.25 m/s
Flow and speed with pure hydrogen	7 l/m	0.88 m/s

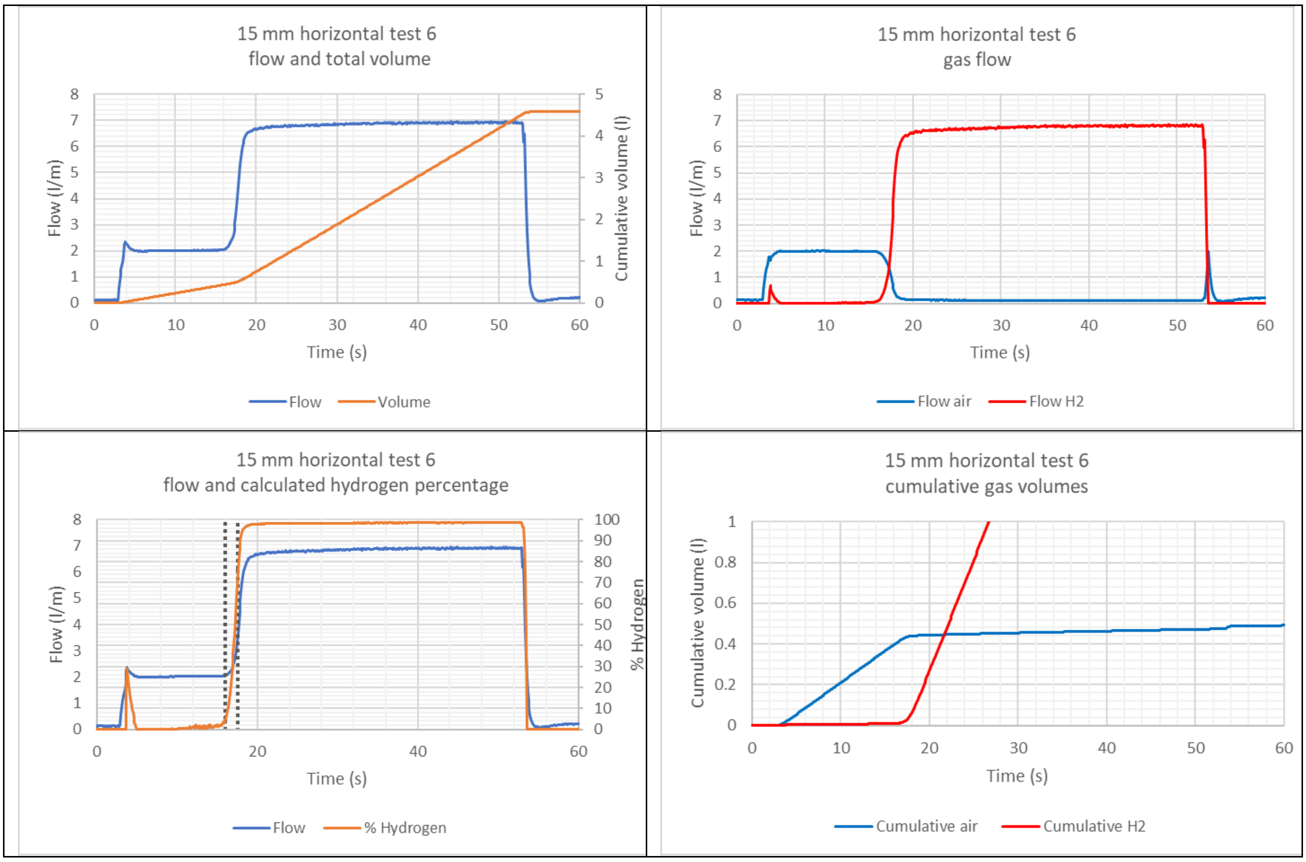


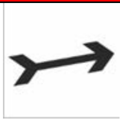
Figure 14: 15 mm horizontal test 6

	Time (s)	Volume (l)
To start of transition (>0% H2)	12.3	0.38
Duration of transition	2.4	0.11
To end of transition (95% H2)	14.7	0.49

Installation volume (l)	0.40
Total volume displaced to 95% hydrogen (l)	0.49
Calculated volume of air displaced (l)	0.43
Calculated volume of hydrogen displaced during purge (l)	0.06
Ratio of purge volume to installation volume	1.22

8 degree incline straight tests

015 35 mm 8 degree incline test 1

Test #	015 35 mm 8 degree incline test 1	
Installation configuration	3 m x 35 mm at an 8° angle to the horizontal	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

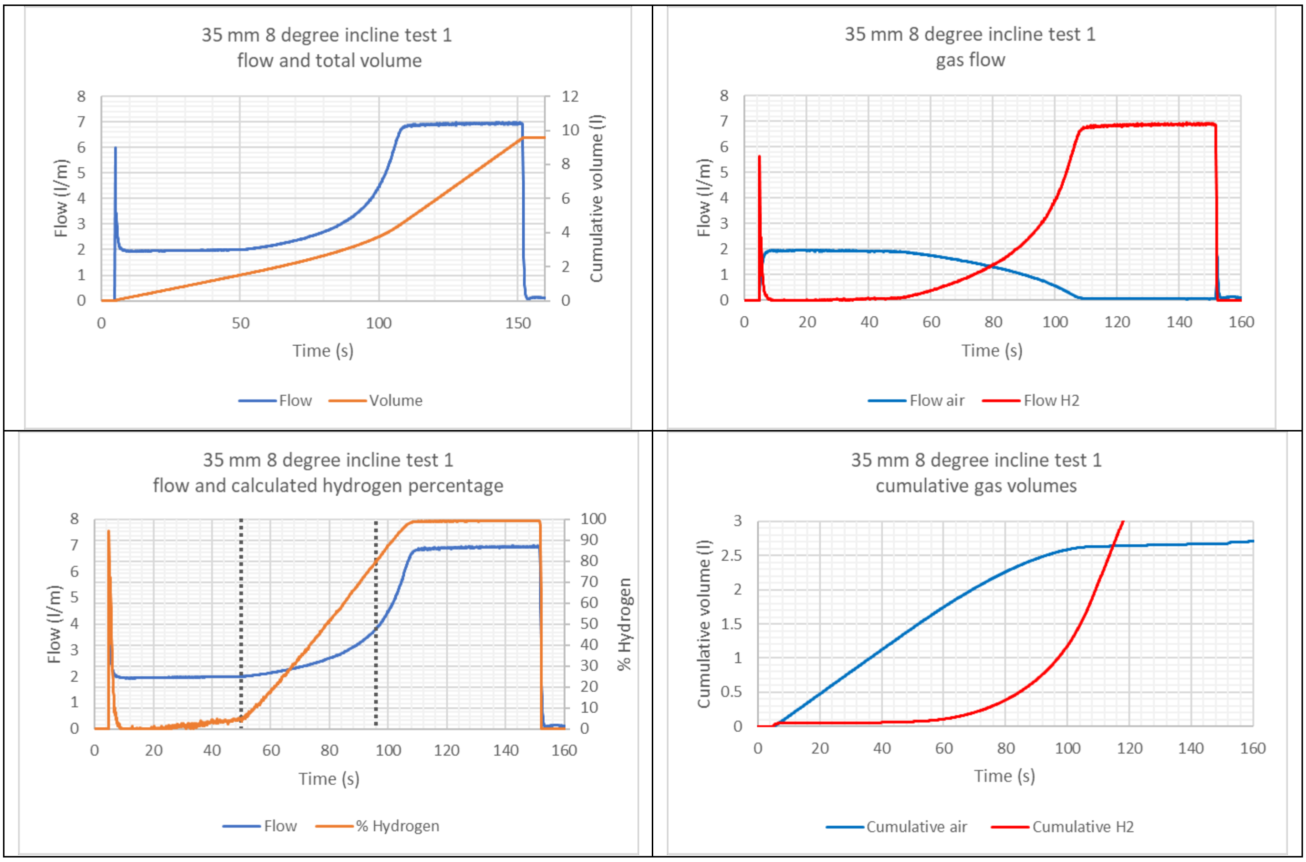
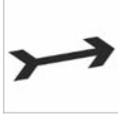


Figure 15: 35 mm 8 degree incline test 1

	Time (s)	Volume (l)
To start of transition (>0% H2)	42.3	1.38
Duration of transition	54.5	2.64
To end of transition (95% H2)	96.8	4.02

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	4.02
Calculated volume of air displaced (l)	2.49
Calculated volume of hydrogen displaced during purge (l)	1.53
Ratio of purge volume to installation volume	1.65

016 35 mm 8 degree incline test 2

Test #	016 35 mm 8 degree incline test 2	
Installation configuration	3 m x 35 mm at an 8° angle to the horizontal	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

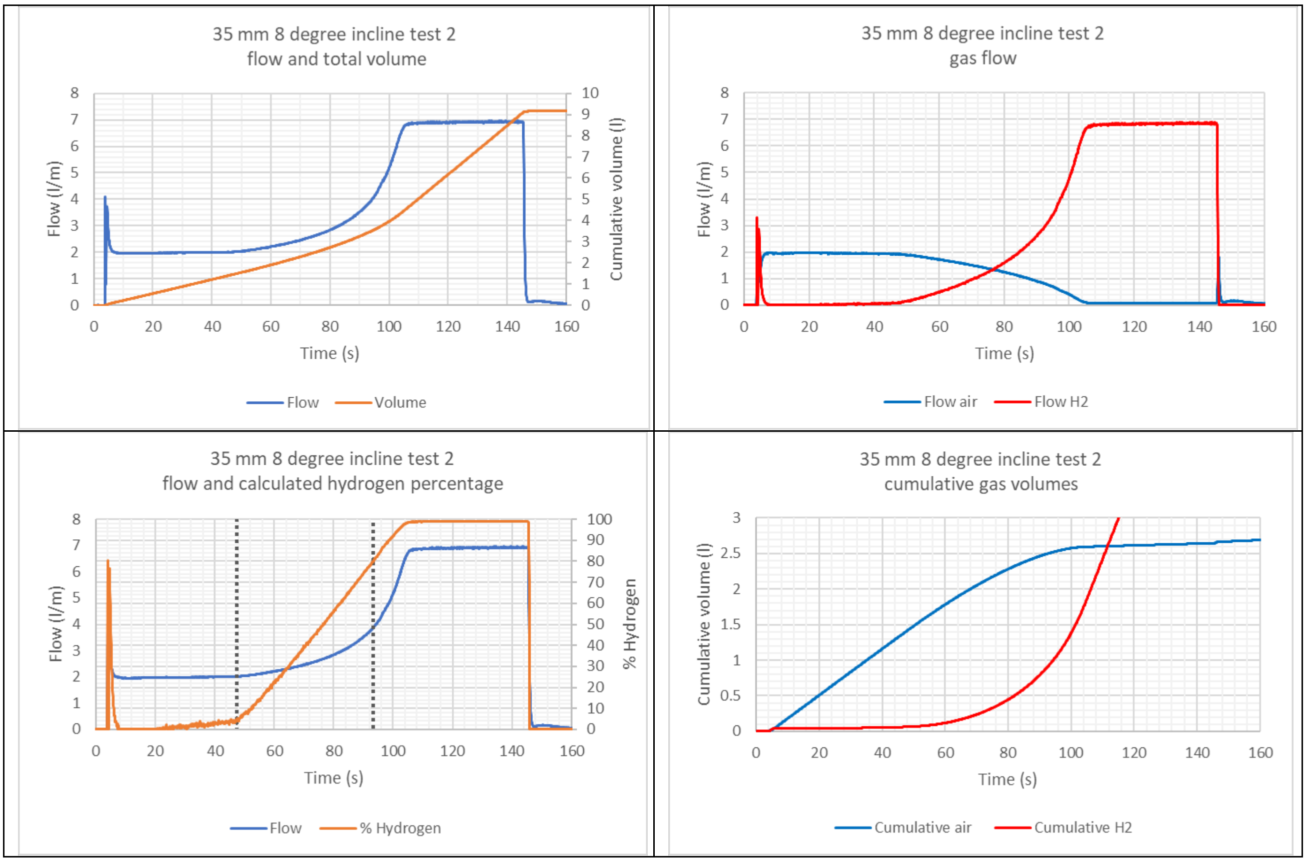
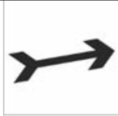


Figure 16: 35 mm 8 degree incline test 2

	Time (s)	Volume (l)
To start of transition (>0% H2)	40.4	1.34
Duration of transition	54.4	2.65
To end of transition (95% H2)	94.8	3.99

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	3.99
Calculated volume of air displaced (l)	2.46
Calculated volume of hydrogen displaced during purge (l)	1.52
Ratio of purge volume to installation volume	1.63

017 35 mm 8 degree incline test 3

Test #	017 35 mm 8 degree incline test 3	
Installation configuration	3 m x 35 mm at an 8° angle to the horizontal	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

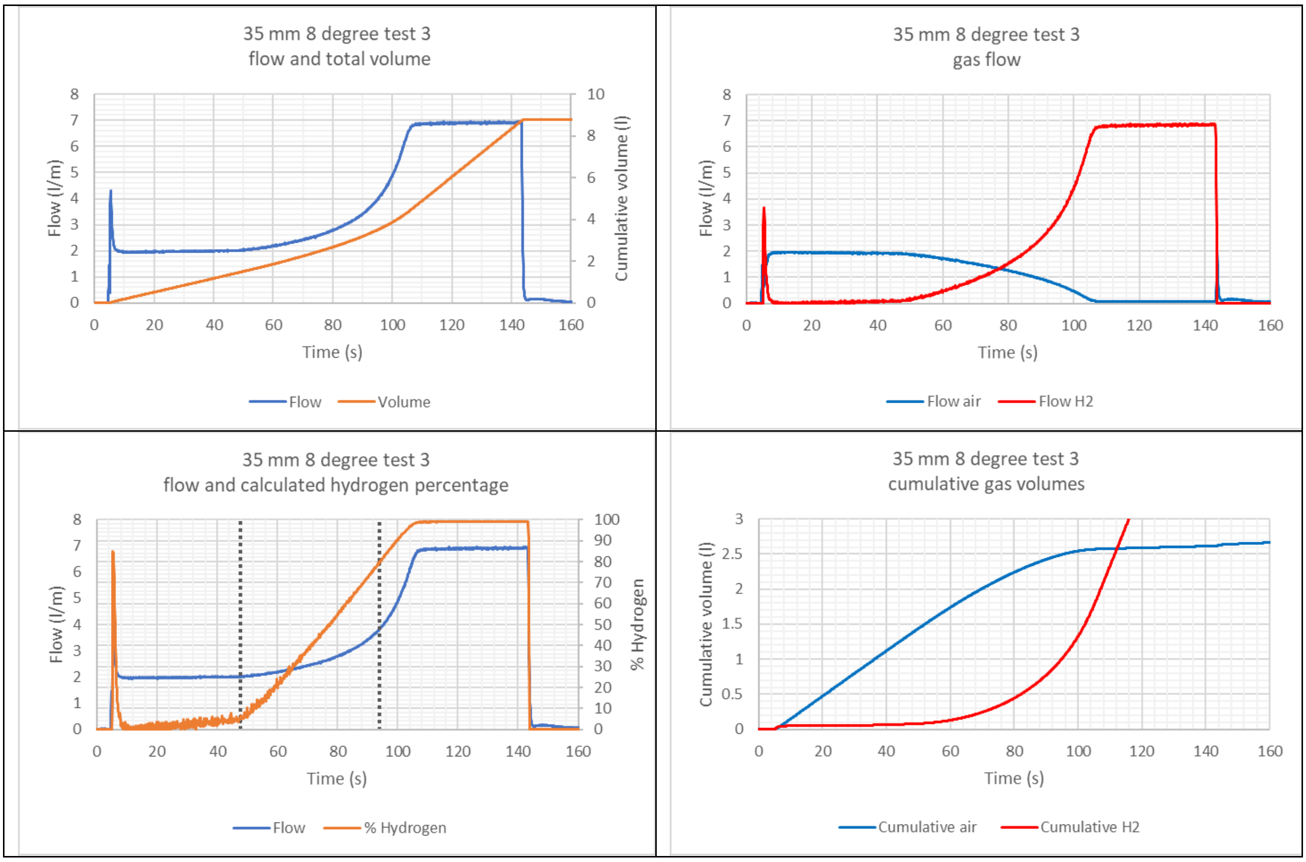


Figure 17: 35 mm degree incline test 3

	Time (s)	Volume (l)
To start of transition (>0% H2)	39.1	1.29
Duration of transition	55.1	2.67
To end of transition (95% H2)	94.2	3.96

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	3.96
Calculated volume of air displaced (l)	2.41
Calculated volume of hydrogen displaced during purge (l)	1.55
Ratio of purge volume to installation volume	1.62

018 28 mm 8 degree incline test 1

Test #	018 28 mm 8 degree incline test 1	
Installation configuration	3 m x 28 mm 8 degree incline	
Installation volume	1.53 l	
Flow and speed with pure air	2 l/m	0.07 m/s
Flow and speed with pure hydrogen	7 l/m	0.24 m/s

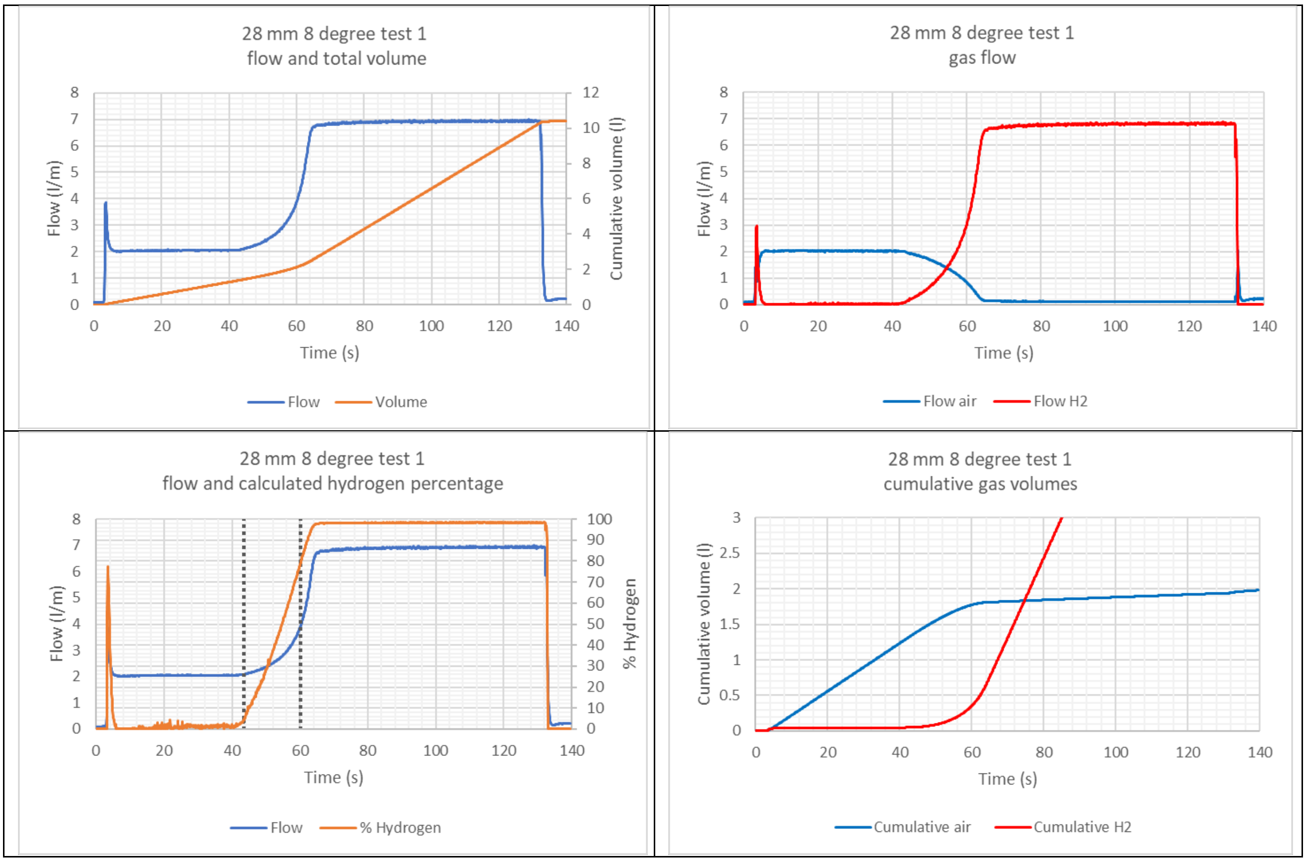


Figure 18: 28 mm 8 degree incline test 1

	Time (s)	Volume (l)
To start of transition (>0% H2)	37.8	1.29
Duration of transition	19.7	0.98
To end of transition (95% H2)	57.5	2.27

Installation volume (l)	1.53
Total volume displaced to 95% hydrogen (l)	2.27
Calculated volume of air displaced (l)	1.69
Calculated volume of hydrogen displaced during purge (l)	0.58
Ratio of purge volume to installation volume	1.48

019 28 mm 8 degree incline test 2

Test #	019 28 mm 8 degree incline test 2	
Installation configuration	3 m x 28 mm 8 degree incline	
Installation volume	1.53 l	
Flow and speed with pure air	2 l/m	0.07 m/s
Flow and speed with pure hydrogen	7 l/m	0.24 m/s

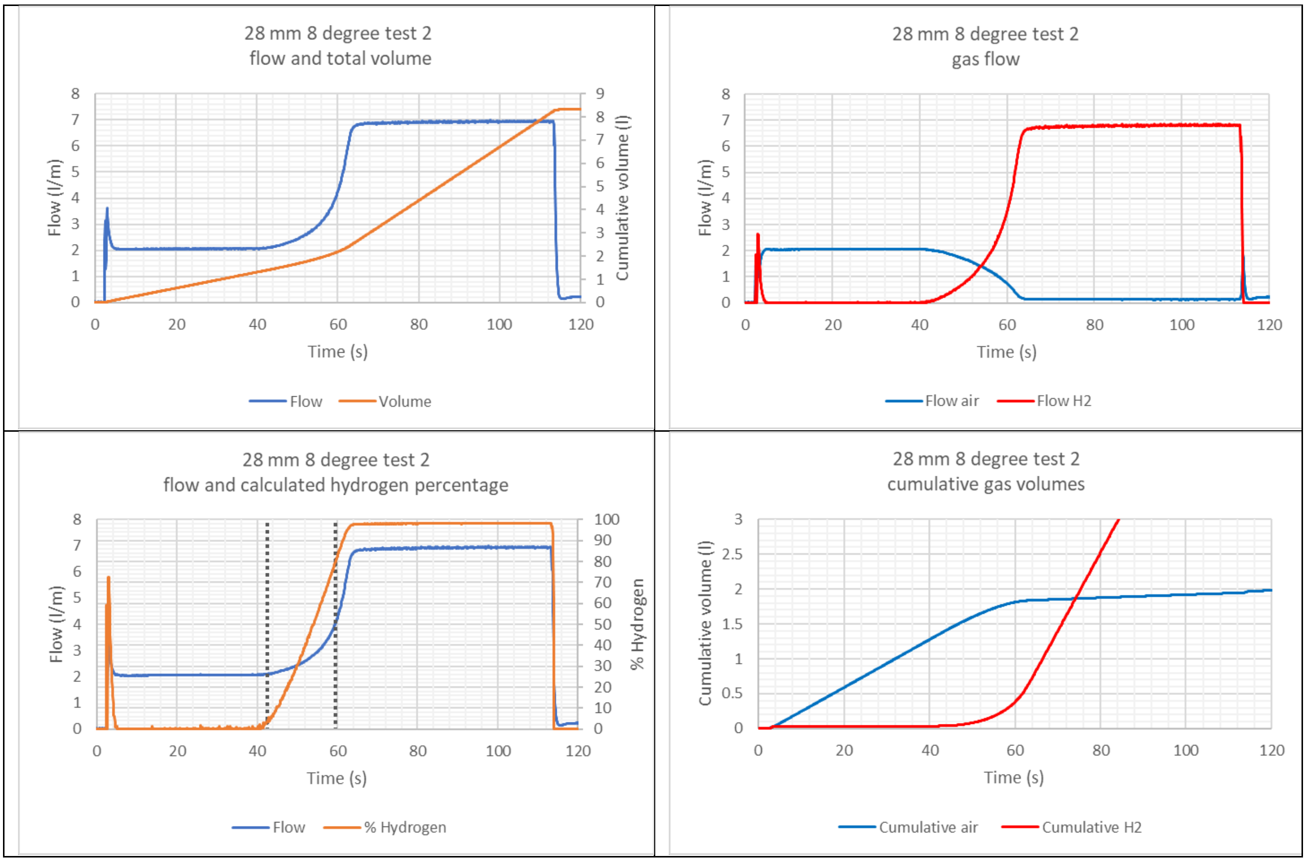


Figure 19: 28 mm 8 degree incline test 2

	Time (s)	Volume (l)
To start of transition (>0% H2)	37.9	1.29
Duration of transition	19.4	0.99
To end of transition (95% H2)	57.3	2.28

Installation volume (l)	1.53
Total volume displaced to 95% hydrogen (l)	2.28
Calculated volume of air displaced (l)	1.72
Calculated volume of hydrogen displaced during purge (l)	0.56
Ratio of purge volume to installation volume	1.49

020 28 mm 8 degree incline test 3

Test #	020 28 mm 8 degree incline test 3	
Installation configuration	3 m x 28 mm 8 degree incline	
Installation volume	1.53 l	
Flow and speed with pure air	2 l/m	0.07 m/s
Flow and speed with pure hydrogen	7 l/m	0.24 m/s

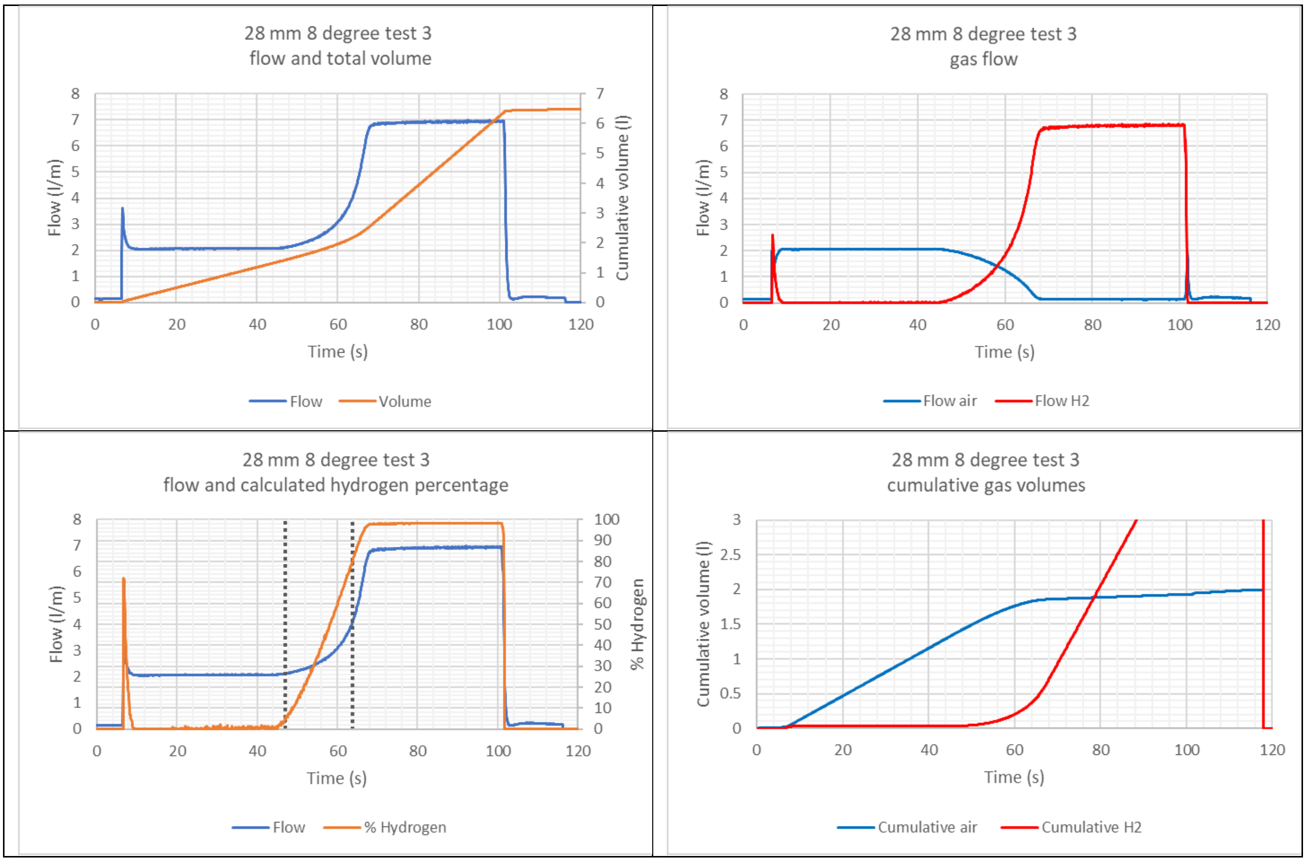


Figure 20: 28 mm 8 degree incline test 3

	Time (s)	Volume (l)
To start of transition (>0% H2)	38	1.23
Duration of transition	19.5	1.06
To end of transition (95% H2)	57.5	2.29

Installation volume (l)	1.53
Total volume displaced to 95% hydrogen (l)	2.29
Calculated volume of air displaced (l)	1.73
Calculated volume of hydrogen displaced during purge (l)	0.56
Ratio of purge volume to installation volume	1.50

Vertical upwards straight tests

021 35 mm vertical upwards test 1

Test #	021 35 mm vertical upwards test 1	
Installation configuration	3 m x 35 mm Vertical upwards	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

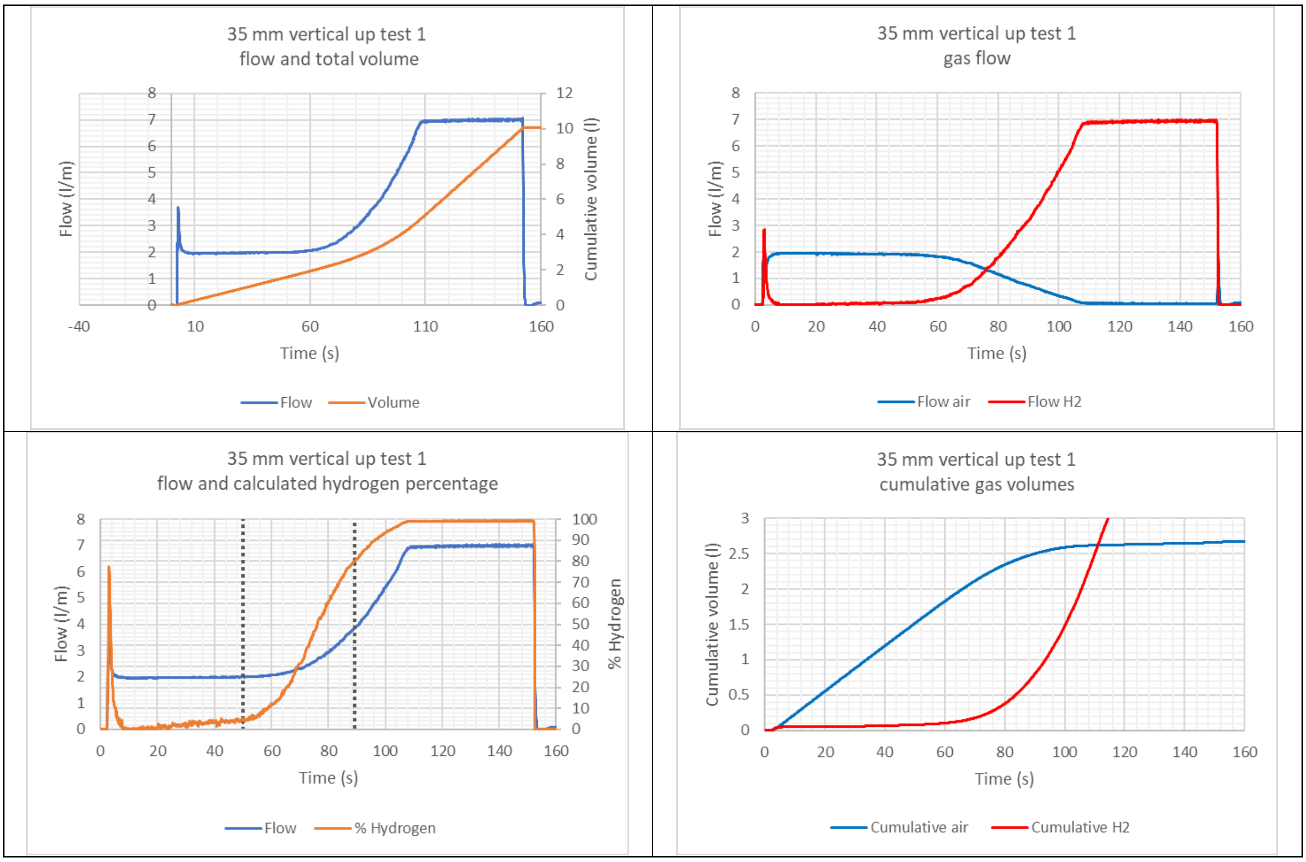


Figure 21: 35 mm vertical upwards test 1

	Time (s)	Volume (l)
To start of transition (>0% H2)	45.3	1.49
Duration of transition	48.5	2.53
To end of transition (95% H2)	93.8	4.02

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	4.02
Calculated volume of air displaced (l)	2.39
Calculated volume of hydrogen displaced during purge (l)	1.63
Ratio of purge volume to installation volume	1.65

022 35 mm vertical upwards test 2

Test #	022 35 mm vertical upwards test 2	
Installation configuration	3 m x 35 mm Vertical upwards	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

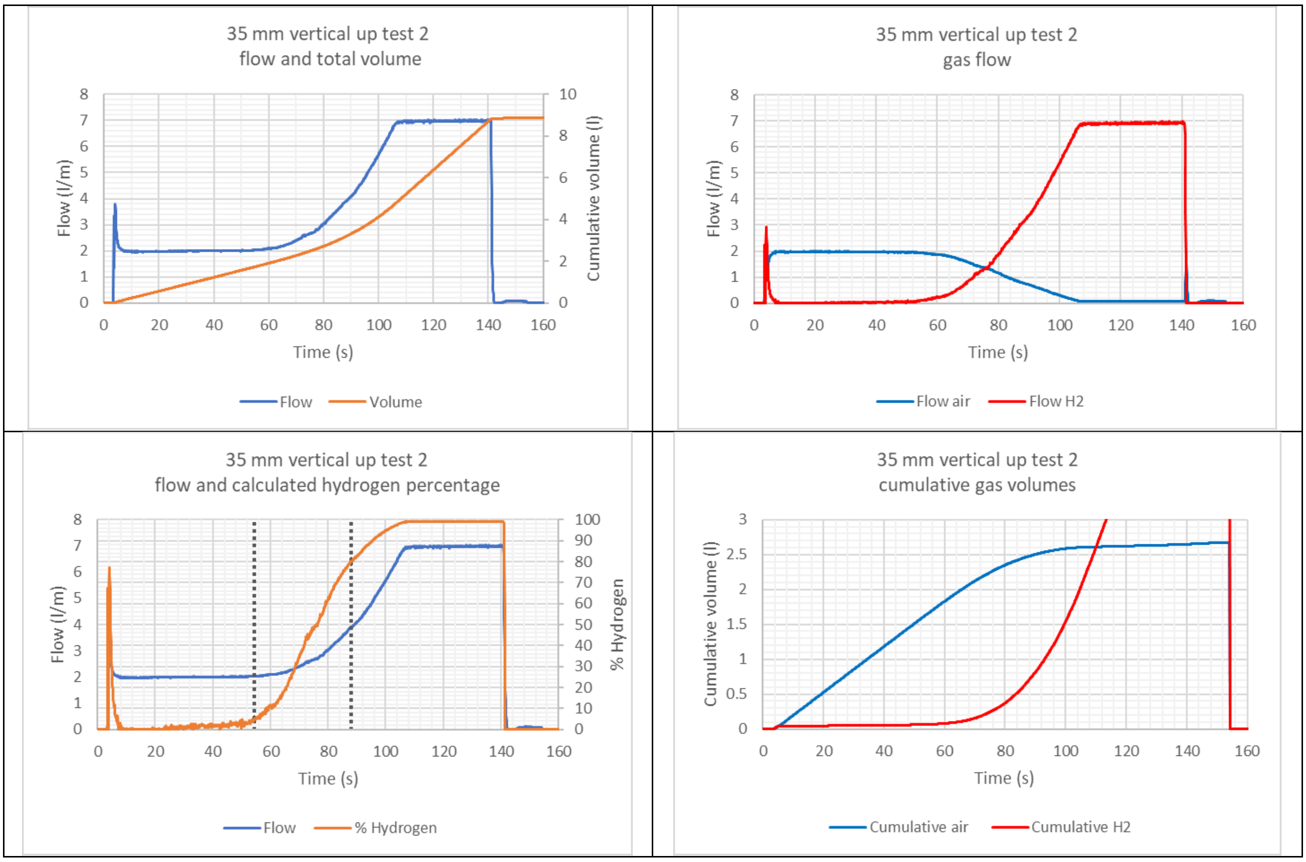
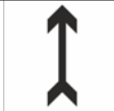


Figure 22: 35 mm vertical upwards test 2

	Time (s)	Volume (l)
To start of transition (>0% H2)	44.2	1.47
Duration of transition	46	2.44
To end of transition (95% H2)	90.2	3.91

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	3.91
Calculated volume of air displaced (l)	2.35
Calculated volume of hydrogen displaced during purge (l)	1.56
Ratio of purge volume to installation volume	1.60

023 35 mm vertical upwards test 3

Test #	023 35 mm vertical upwards test 3	
Installation configuration	3 m x 35 mm Vertical upwards	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

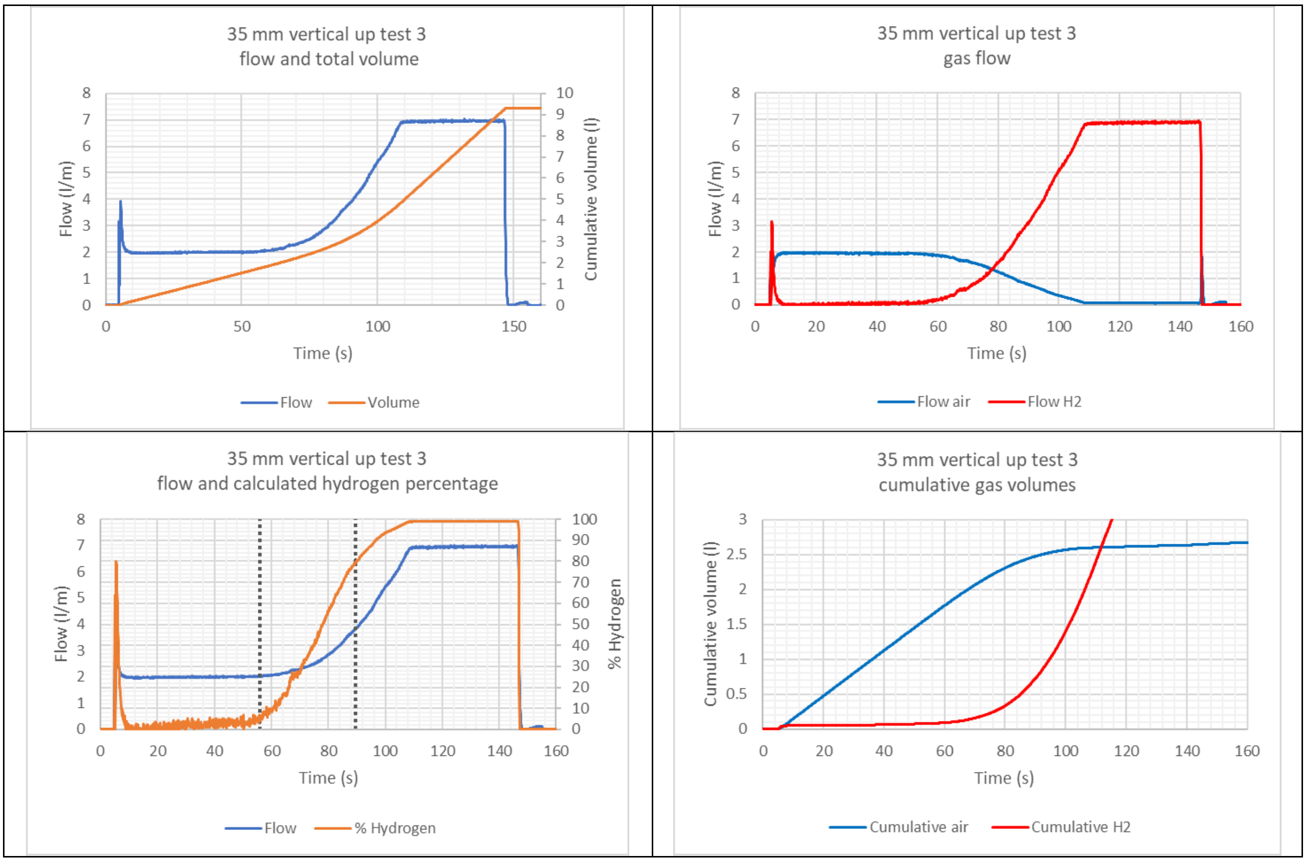
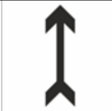


Figure 23: 35 mm vertical upwards test 3

	Time (s)	Volume (l)
To start of transition (>0% H2)	45.3	1.51
Duration of transition	45.9	2.43
To end of transition (95% H2)	91.2	3.93

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	3.93
Calculated volume of air displaced (l)	2.36
Calculated volume of hydrogen displaced during purge (l)	1.57
Ratio of purge volume to installation volume	1.61

024 35 mm vertical upwards methane test 1

Test #	024 35 mm vertical upwards methane test 1	
Installation configuration	3 m x 35 mm Vertical	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

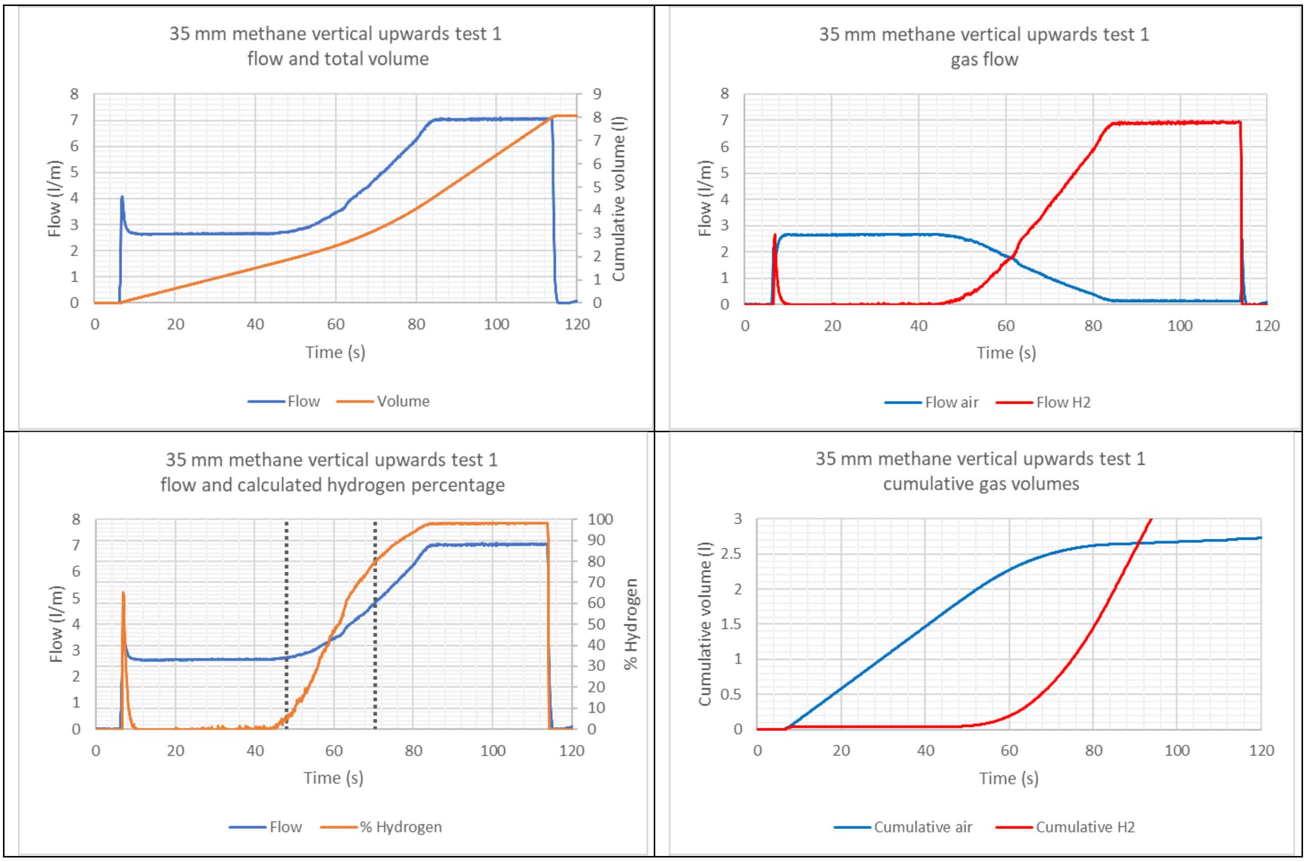
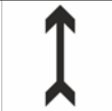


Figure 24: 35 mm methane vertical upwards test 1

	Time (s)	Volume (l)
To start of transition (>0% H2)	37.9	1.52
Duration of transition	32.5	2.44
To end of transition (95% H2)	70.4	3.96

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	3.96
Calculated volume of air displaced (l)	2.42
Calculated volume of hydrogen displaced during purge (l)	1.53
Ratio of purge volume to installation volume	1.62

025 35 mm vertical upwards methane test 2

Test #	025 35 mm vertical upwards methane test 2	
Installation configuration	3 m x 35 mm Vertical	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

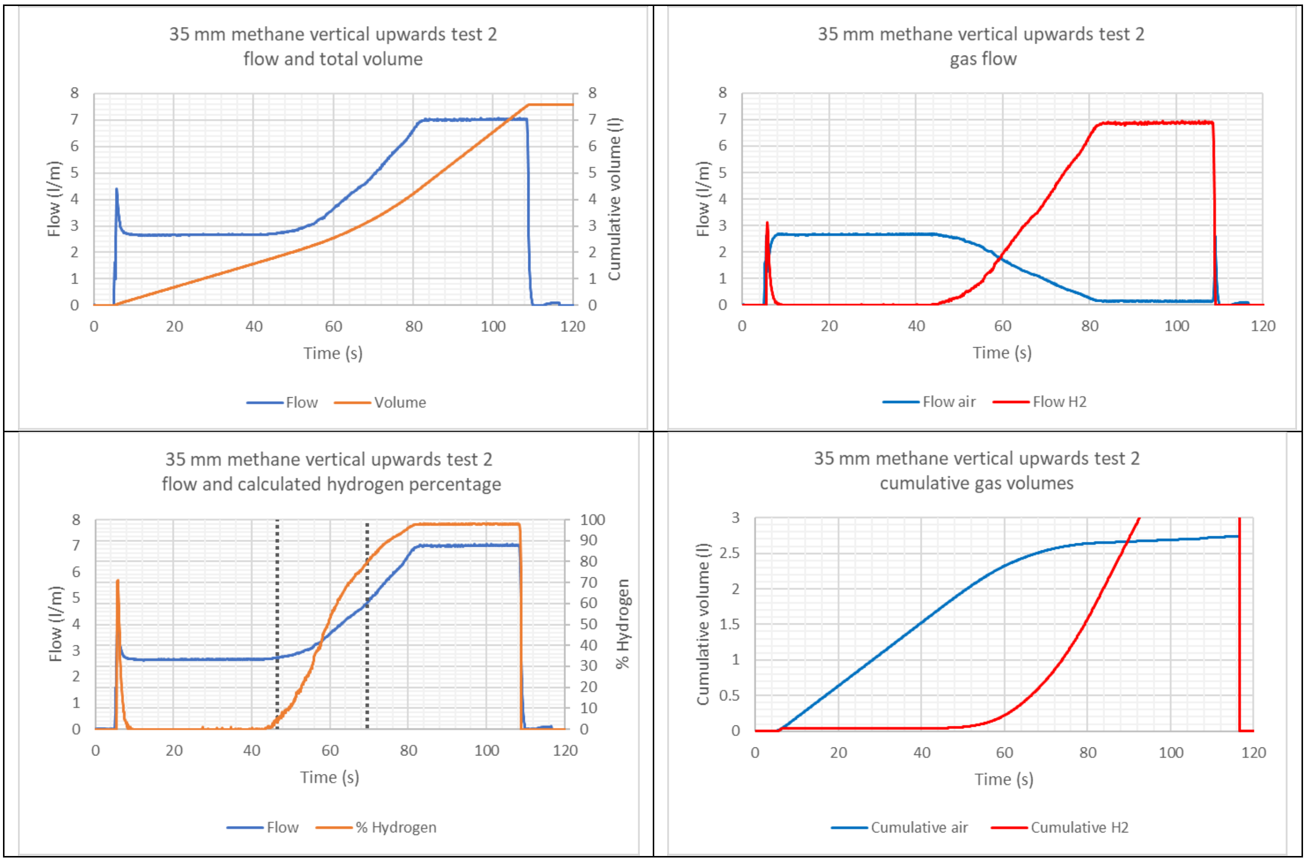
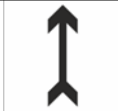


Figure 25: 35 mm methane vertical upwards test 2

	Time (s)	Volume (l)
To start of transition (>0% H2)	35.9	1.53
Duration of transition	32.7	2.32
To end of transition (95% H2)	68.6	3.85

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	3.85
Calculated volume of air displaced (l)	2.38
Calculated volume of hydrogen displaced during purge (l)	1.47
Ratio of purge volume to installation volume	1.58

026 35 mm vertical upwards methane test 3

Test #	026 35 mm vertical upwards methane test 3	
Installation configuration	3 m x 35 mm Vertical	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

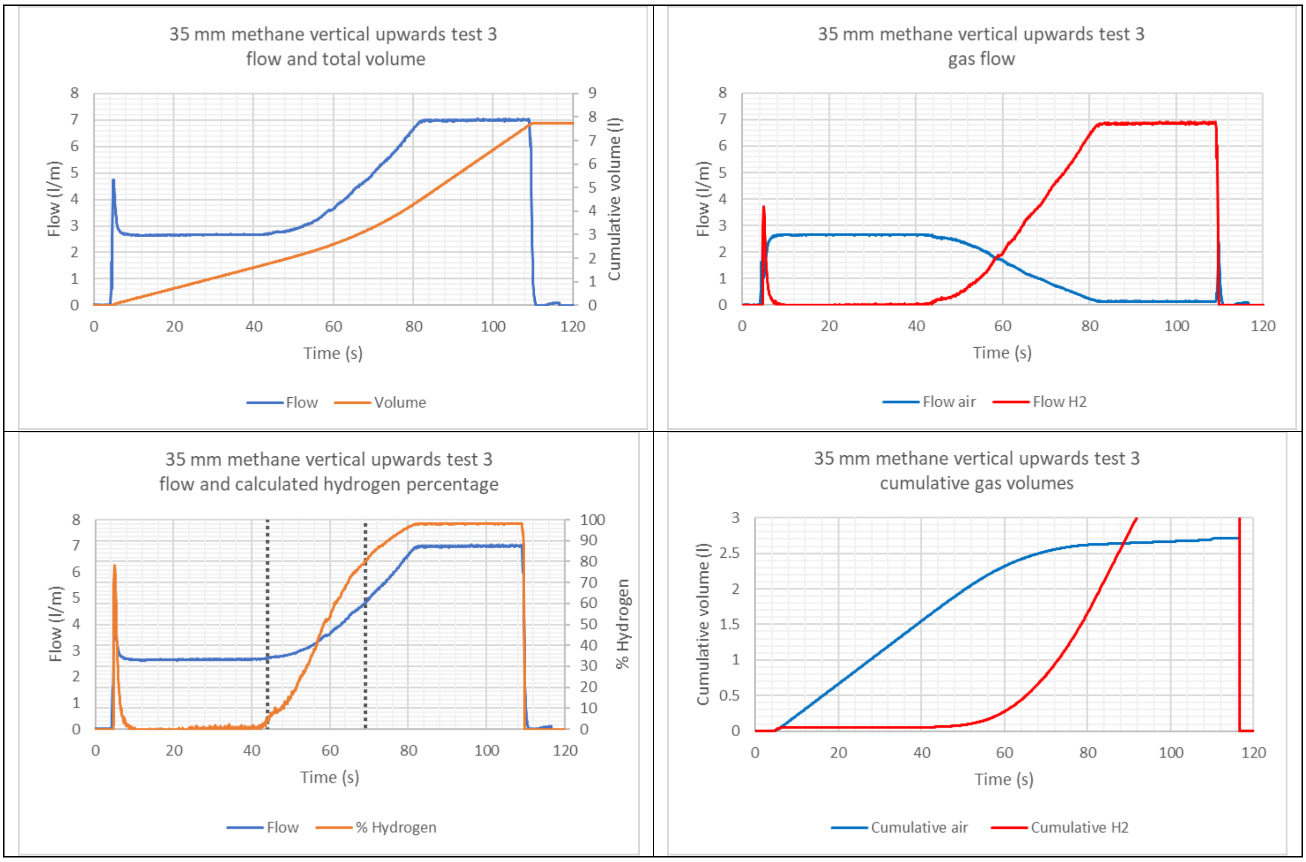
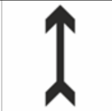


Figure 26: 35 mm methane vertical upwards test 3

	Time (s)	Volume (l)
To start of transition (>0% H2)	35.3	1.52
Duration of transition	34.1	2.36
To end of transition (95% H2)	69.4	3.89

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	3.89
Calculated volume of air displaced (l)	2.37
Calculated volume of hydrogen displaced during purge (l)	1.51
Ratio of purge volume to installation volume	1.59

027 35mm vertical upwards pause test 1

Test #	027 35mm vertical upwards pause test 1	
Installation configuration	3 m x 35 mm Vertical upwards	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

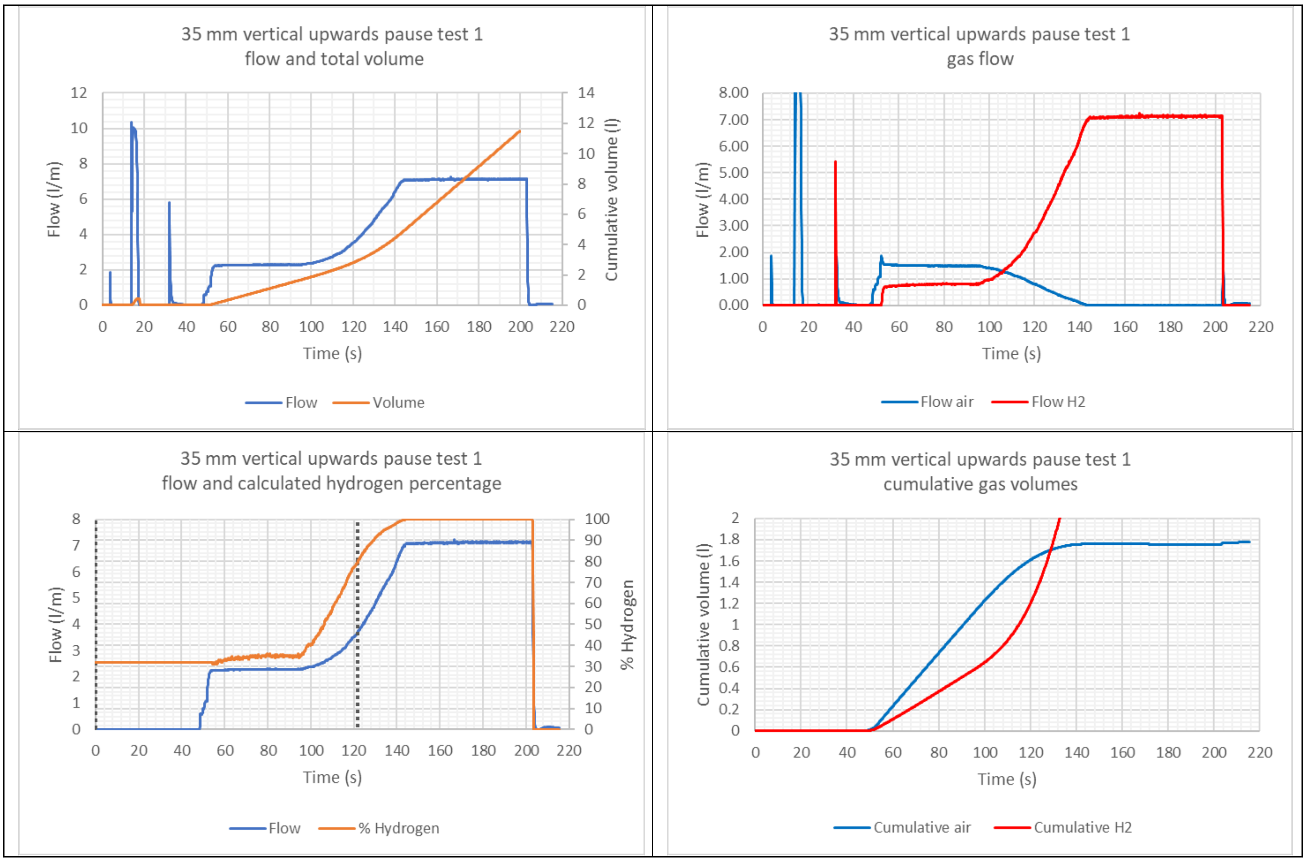


Figure 27: 35mm vertical upwards pause test 1

	Time (s)	Volume (l)
To start of transition (>0% H2)	42.5	1.61
Duration of transition	37.6	2.12
To end of transition (95% H2)	80.1	3.73

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	3.73
Calculated volume of air displaced (l)	1.62
Calculated volume of hydrogen displaced during purge (l)	2.11
Ratio of purge volume to installation volume	1.53

028 35mm vertical upwards pause test 2

Test #	028 35mm vertical upwards pause test 2	
Installation configuration	3 m x 35 mm Vertical upwards	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

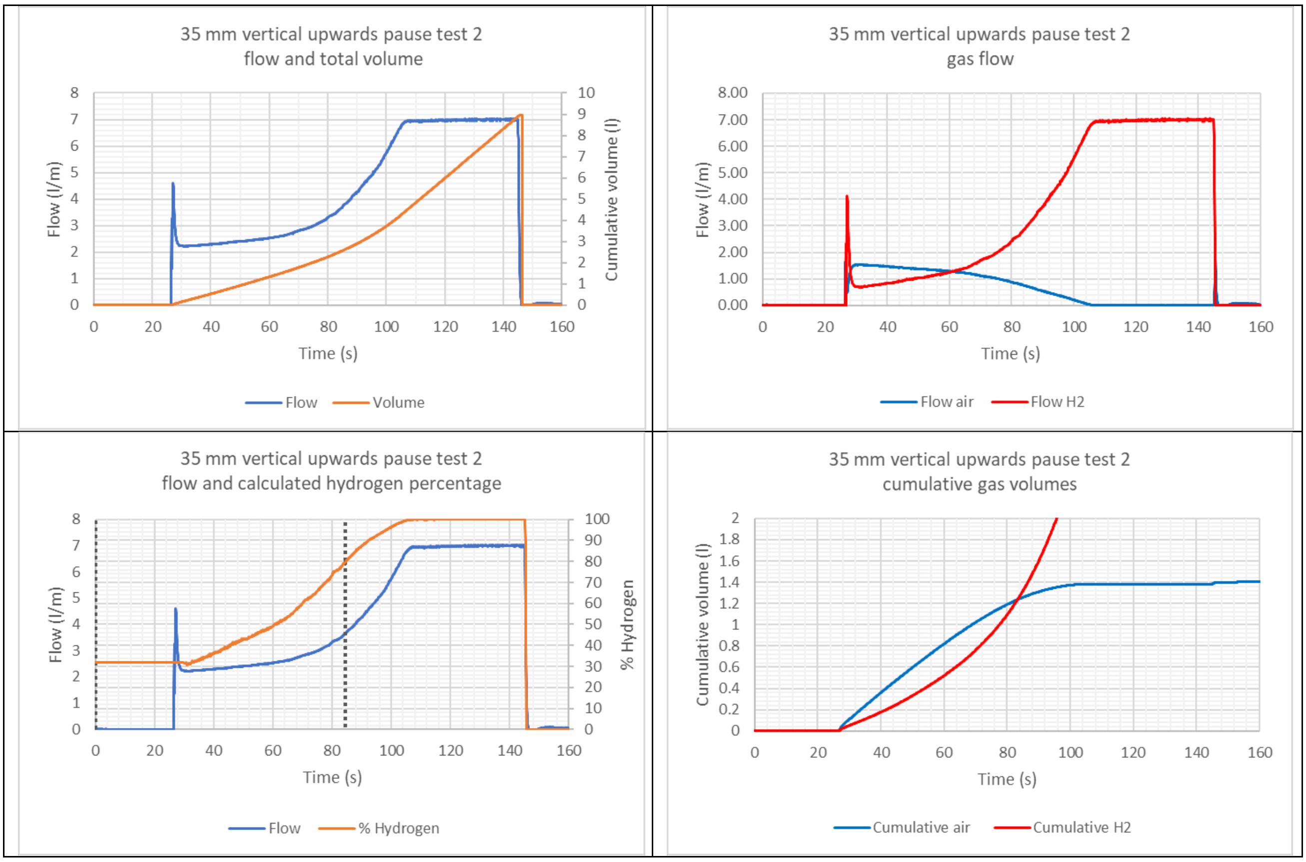
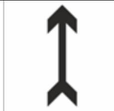


Figure 28: 35mm vertical upwards pause test 2

	Time (s)	Volume (l)
To start of transition (>0% H2)	2.7	0.10
Duration of transition	65.8	3.31
To end of transition (95% H2)	68.5	3.41

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	3.41
Calculated volume of air displaced (l)	1.21
Calculated volume of hydrogen displaced during purge (l)	2.20
Ratio of purge volume to installation volume	1.40

029 28 mm vertical upwards test 1

Test #	029 28 mm vertical upwards test 1	
Installation configuration	3 m x 28 mm Vertical upwards	
Installation volume	1.53 l	
Flow and speed with pure air	2 l/m	0.07 m/s
Flow and speed with pure hydrogen	7 l/m	0.24 m/s

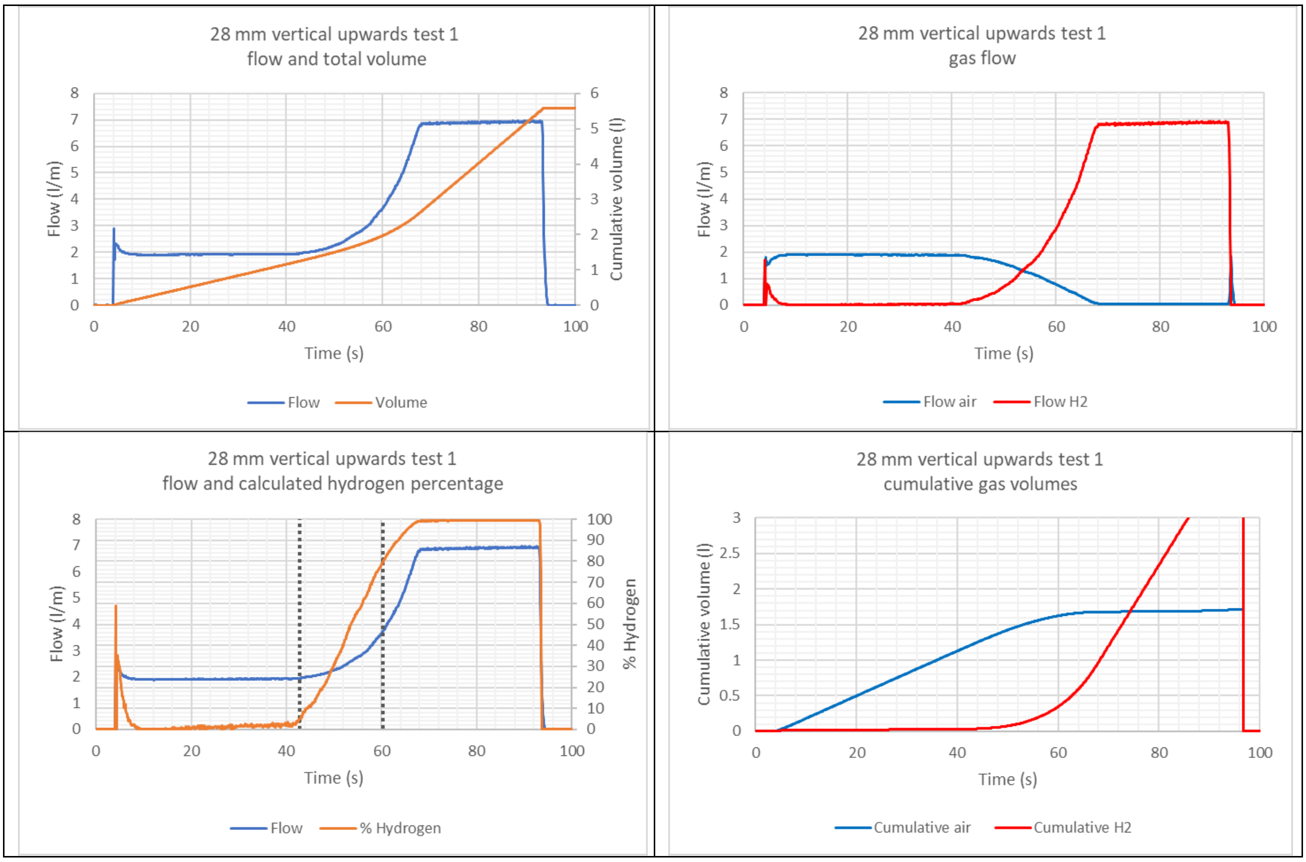


Figure 29: 28 mm vertical upwards test 1

	Time (s)	Volume (l)
To start of transition (>0% H2)	35.5	1.13
Duration of transition	22.5	1.12
To end of transition (95% H2)	58	2.25

Installation volume (l)	1.53
Total volume displaced to 95% hydrogen (l)	2.25
Calculated volume of air displaced (l)	1.55
Calculated volume of hydrogen displaced during purge (l)	0.70
Ratio of purge volume to installation volume	1.47

030 28 mm vertical upwards test 2

Test #	030 28 mm vertical upwards test 2	
Installation configuration	3 m x 28 mm Vertical upwards	
Installation volume	1.53 l	
Flow and speed with pure air	2 l/m	0.07 m/s
Flow and speed with pure hydrogen	7 l/m	0.24 m/s

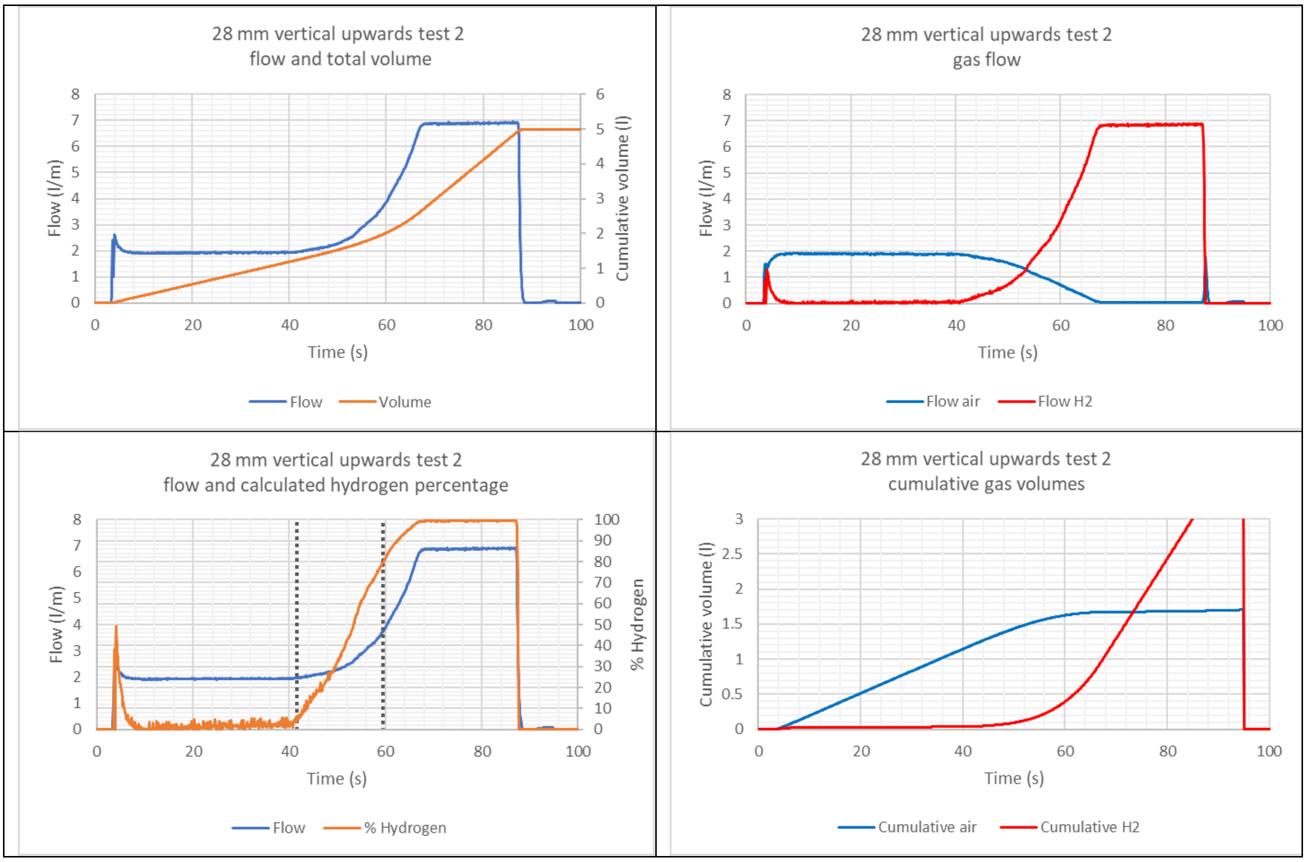
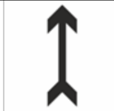


Figure 30: 28 mm vertical upwards test 2

	Time (s)	Volume (l)
To start of transition (>0% H2)	33.3	1.09
Duration of transition	23.8	1.15
To end of transition (95% H2)	57.1	2.24

Installation volume (l)	1.53
Total volume displaced to 95% hydrogen (l)	2.24
Calculated volume of air displaced (l)	1.52
Calculated volume of hydrogen displaced during purge (l)	0.71
Ratio of purge volume to installation volume	1.46

031 28 mm vertical upwards test 3

Test #	031 28 mm vertical upwards test 3	
Installation configuration	3 m x 28 mm Vertical upwards	
Installation volume	1.53 l	
Flow and speed with pure air	2 l/m	0.07 m/s
Flow and speed with pure hydrogen	7 l/m	0.24 m/s

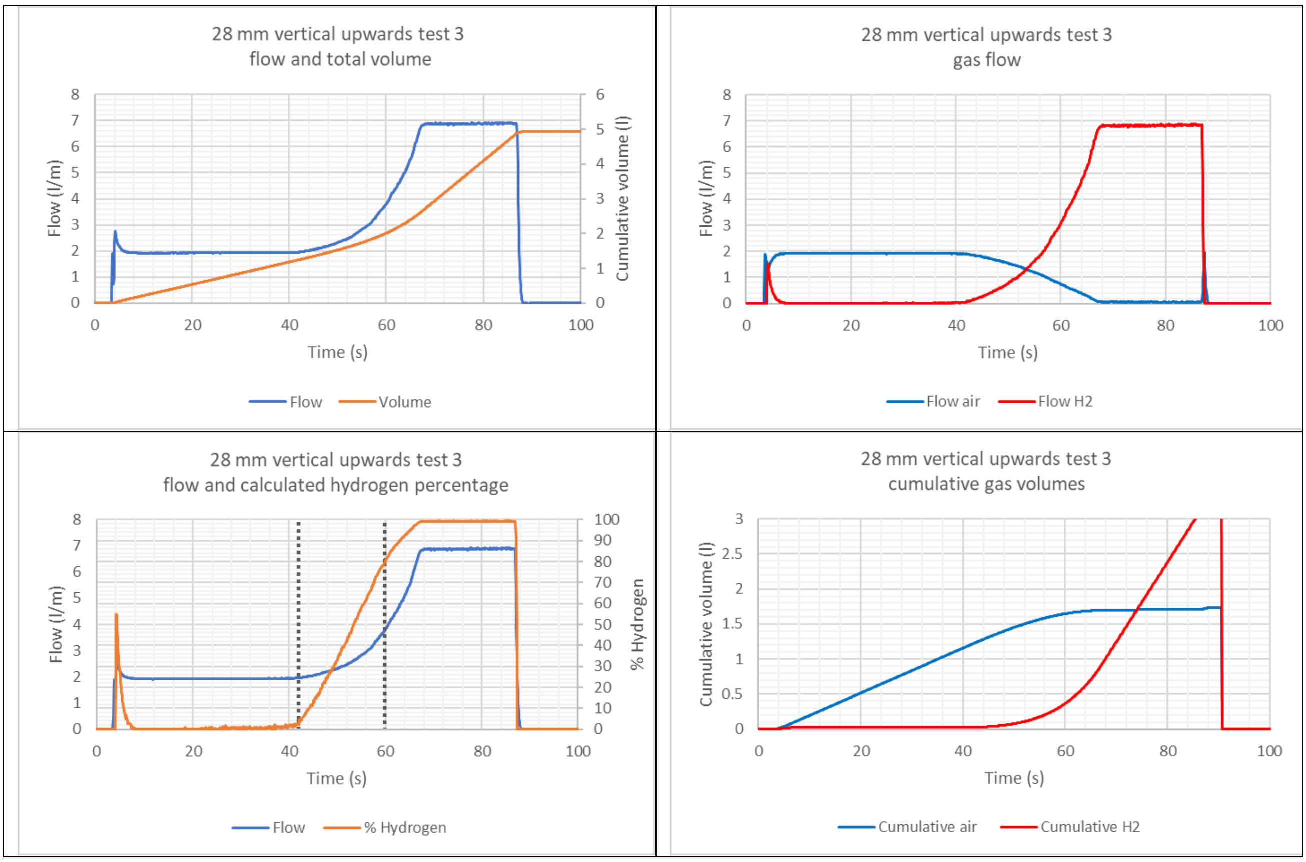
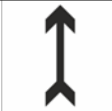


Figure 31: 28 mm vertical upwards test 3

	Time (s)	Volume (l)
To start of transition (>0% H2)	34.6	1.12
Duration of transition	22.9	1.16
To end of transition (95% H2)	57.5	2.28

Installation volume (l)	1.53
Total volume displaced to 95% hydrogen (l)	2.28
Calculated volume of air displaced (l)	1.55
Calculated volume of hydrogen displaced during purge (l)	0.73
Ratio of purge volume to installation volume	1.48

032 15 mm vertical upwards test 1

Test #	032 15 mm vertical upwards test 1	
Installation configuration	3 m x 15 mm Vertical upwards	
Installation volume	0.4 l	
Flow and speed with pure air	2 l/m	0.25 m/s
Flow and speed with pure hydrogen	7 l/m	0.88 m/s

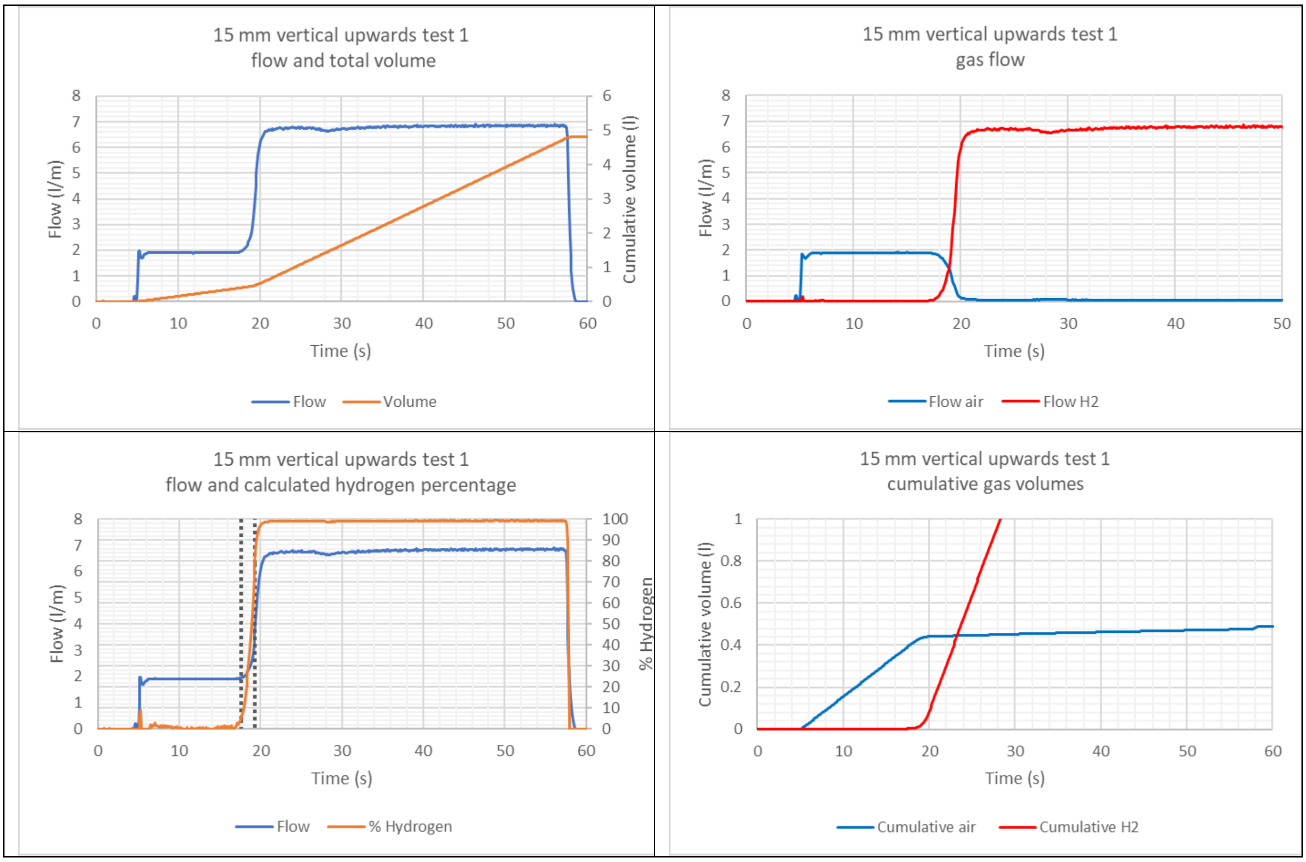
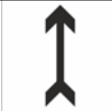


Figure 32: 15 mm vertical upwards test 1

	Time (s)	Volume (l)
To start of transition (>0% H2)	11.2	0.35
Duration of transition	2.2	0.10
To end of transition (95% H2)	13.4	0.46

Installation volume (l)	0.40
Total volume displaced to 95% hydrogen (l)	0.46
Calculated volume of air displaced (l)	0.40
Calculated volume of hydrogen displaced during purge (l)	0.06
Ratio of purge volume to installation volume	1.14

033 15 mm vertical upwards test 2

Test #	033 15 mm vertical upwards test 2	
Installation configuration	3 m x 15 mm Vertical upwards	
Installation volume	0.4 l	
Flow and speed with pure air	2 l/m	0.25 m/s
Flow and speed with pure hydrogen	7 l/m	0.88 m/s

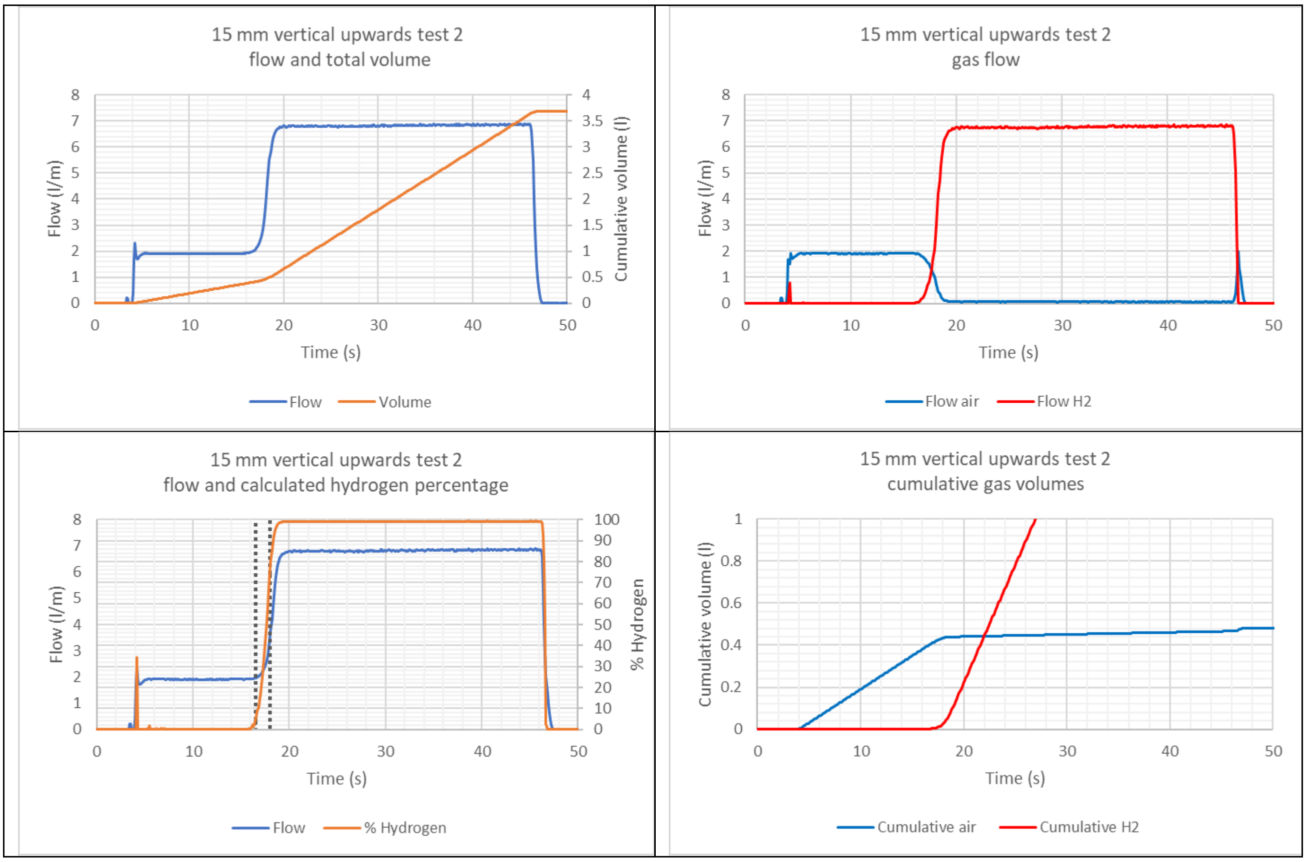


Figure 33: 15 mm vertical upwards test 2

	Time (s)	Volume (l)
To start of transition (>0% H2)	11	0.35
Duration of transition	2.1	0.10
To end of transition (95% H2)	13.1	0.45

Installation volume (l)	0.40
Total volume displaced to 95% hydrogen (l)	0.45
Calculated volume of air displaced (l)	0.39
Calculated volume of hydrogen displaced during purge (l)	0.06
Ratio of purge volume to installation volume	1.12

034 15 mm vertical upwards test 3

Test #	034 15 mm vertical upwards test 3	
Installation configuration	3 m x 15 mm Vertical upwards	
Installation volume	0.4 l	
Flow and speed with pure air	2 l/m	0.25 m/s
Flow and speed with pure hydrogen	7 l/m	0.88 m/s

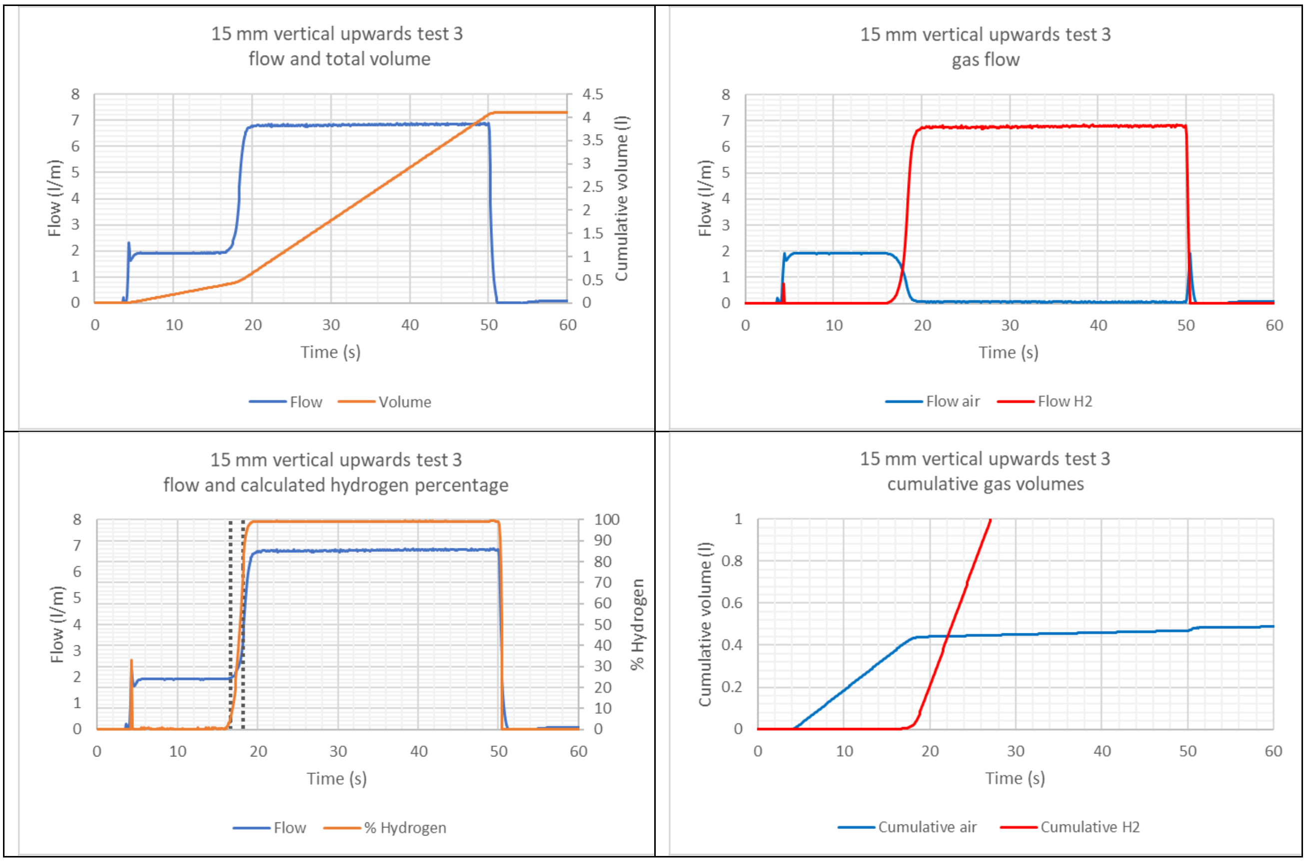


Figure 34: 15 mm vertical upwards test 3

	Time (s)	Volume (l)
To start of transition (>0% H2)	11.1	0.35
Duration of transition	2.1	0.10
To end of transition (95% H2)	13.2	0.45

Installation volume (l)	0.40
Total volume displaced to 95% hydrogen (l)	0.45
Calculated volume of air displaced (l)	0.40
Calculated volume of hydrogen displaced during purge (l)	0.06
Ratio of purge volume to installation volume	1.13

Vertical downward straight tests

035 35 mm vertical downwards test 1

Test #	035 35 mm vertical downwards test 1	
Installation configuration	3 m x 35 mm Vertical downwards	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

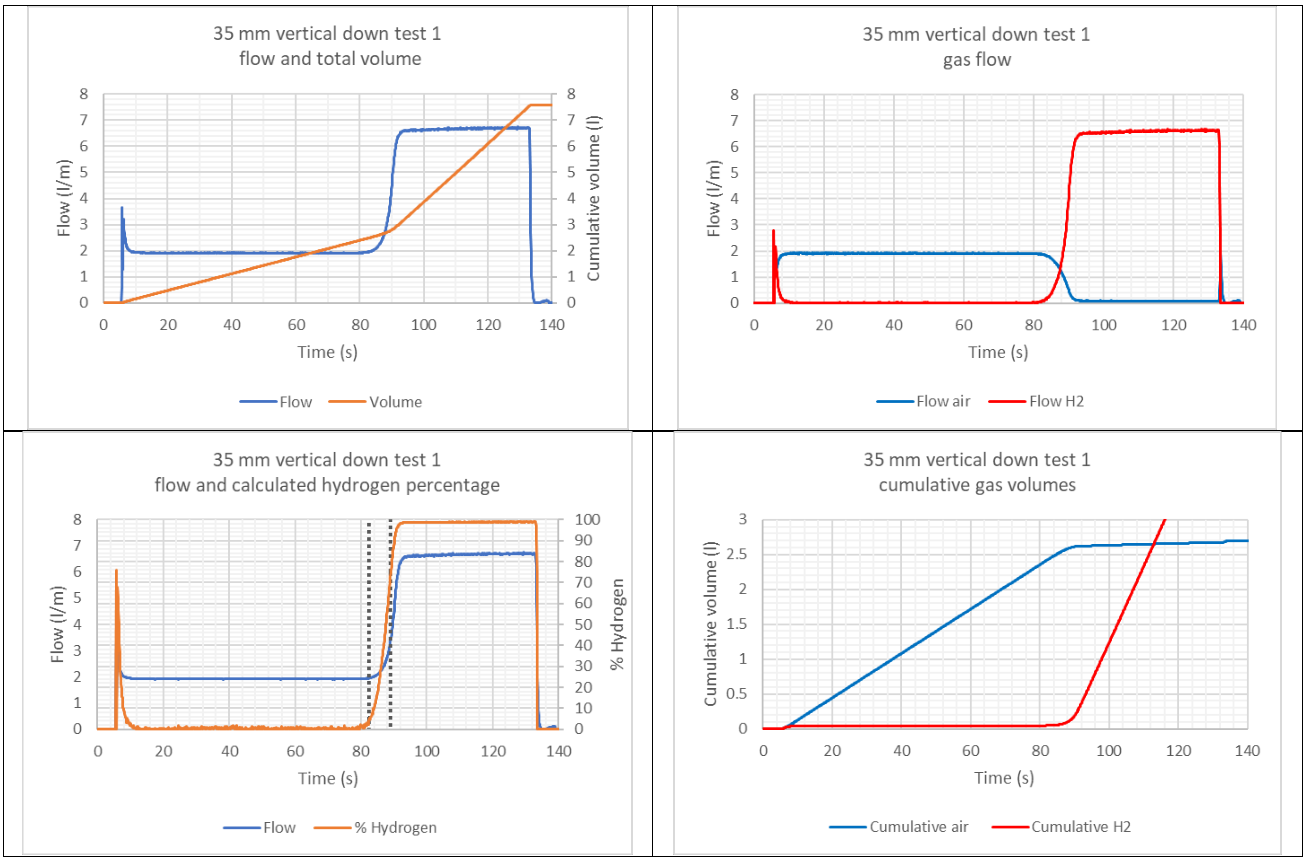


Figure 35: 35 mm vertical downwards test 1

	Time (s)	Volume (l)
To start of transition (>0% H2)	74.4	2.38
Duration of transition	8.1	0.37
To end of transition (95% H2)	82.5	2.75

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	2.75
Calculated volume of air displaced (l)	2.52
Calculated volume of hydrogen displaced during purge (l)	0.24
Ratio of purge volume to installation volume	1.13

036 35 mm vertical downwards test 2

Test #	036 35 mm vertical downwards test 2	
Installation configuration	3 m x 35 mm Vertical downwards	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

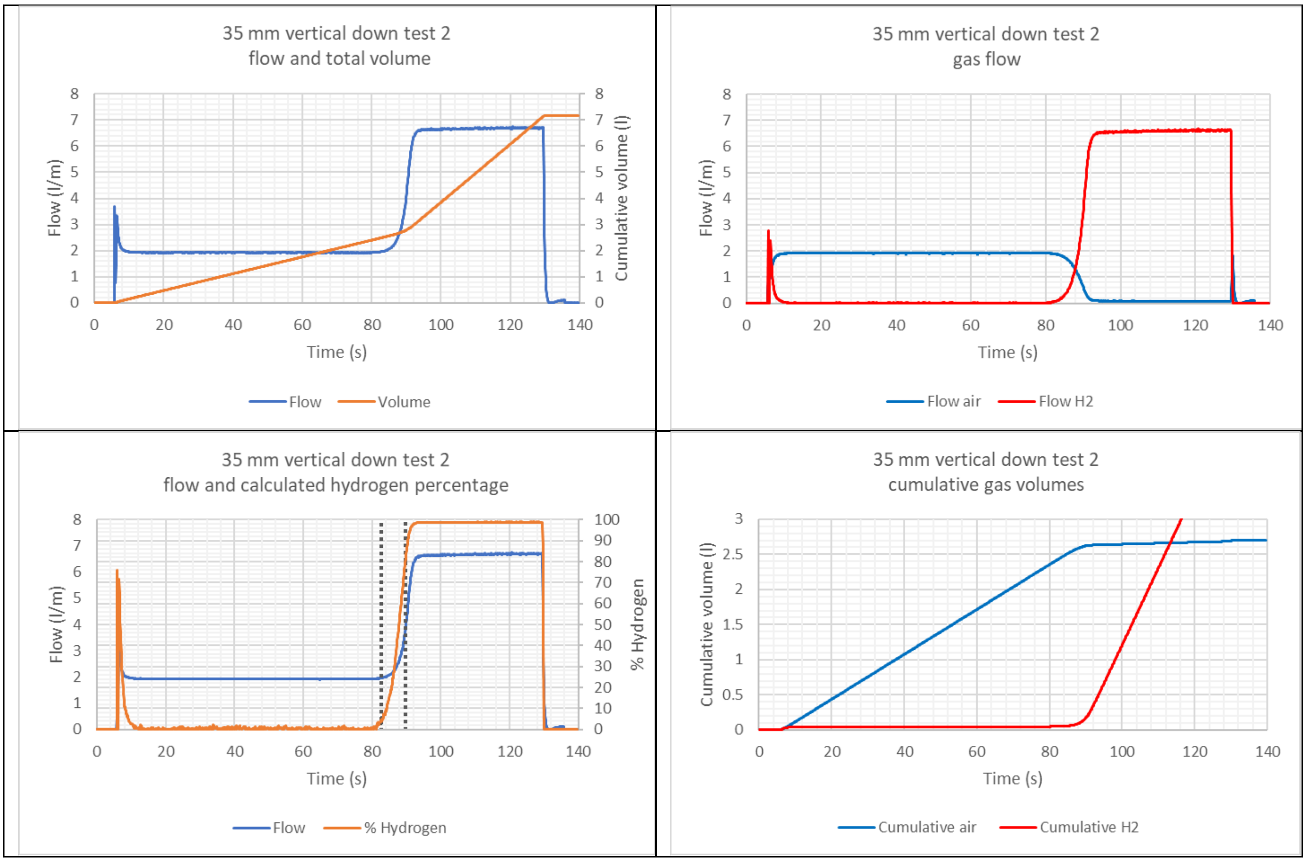
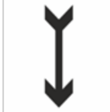


Figure 36: 35 mm vertical downwards test 2

	Time (s)	Volume (l)
To start of transition (>0% H2)	74	2.38
Duration of transition	8.4	0.38
To end of transition (95% H2)	82.4	2.76

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	2.76
Calculated volume of air displaced (l)	2.52
Calculated volume of hydrogen displaced during purge (l)	0.24
Ratio of purge volume to installation volume	1.13

037 35 mm vertical downwards test 3

Test #	037 35 mm vertical downwards test 3	
Installation configuration	3 m x 35 mm Vertical downwards	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

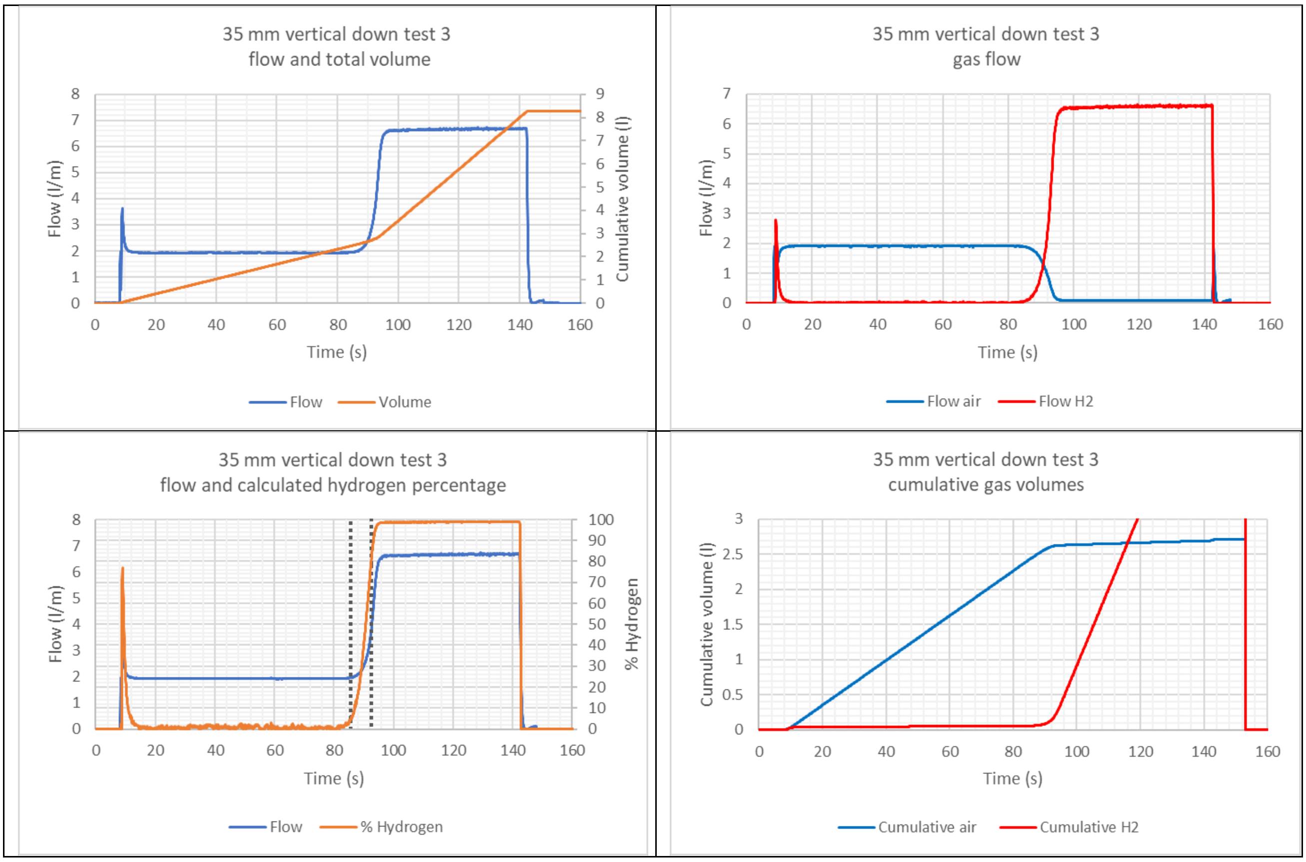
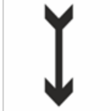


Figure 37: 35 mm vertical downwards test 3

	Time (s)	Volume (l)
To start of transition (>0% H2)	74.4	2.39
Duration of transition	8.2	0.38
To end of transition (95% H2)	82.6	2.77

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	2.77
Calculated volume of air displaced (l)	2.51
Calculated volume of hydrogen displaced during purge (l)	0.25
Ratio of purge volume to installation volume	1.13

038 35 mm vertical downwards methane test 1

Test #	038 35 mm vertical downwards methane test 1	
Installation configuration	3 m x 35 mm Vertical downwards	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

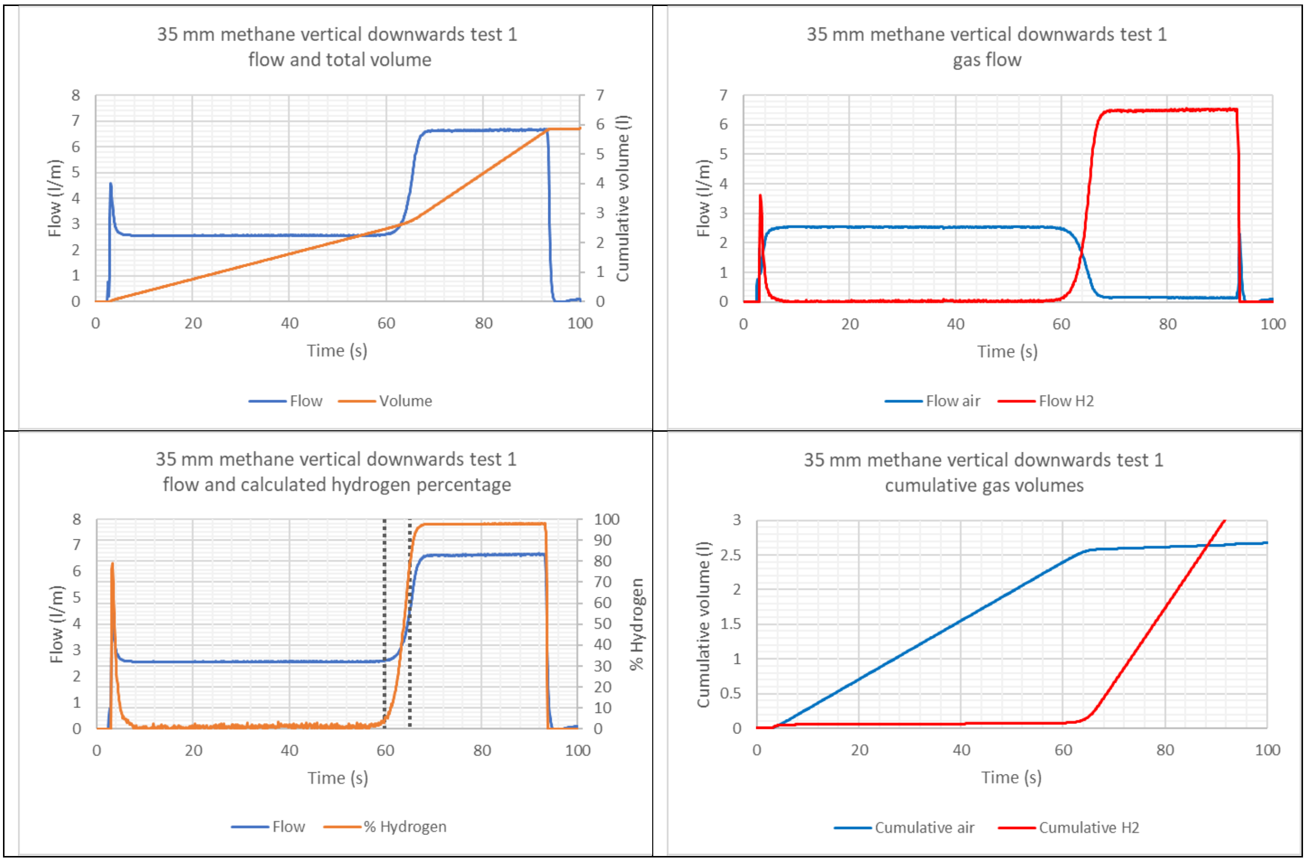
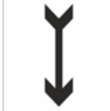


Figure 38: 35 mm methane vertical downwards test 1

	Time (s)	Volume (l)
To start of transition (>0% H2)	52.4	1.59
Duration of transition	6.6	1.04
To end of transition (95% H2)	59	2.63

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	2.63
Calculated volume of air displaced (l)	2.35
Calculated volume of hydrogen displaced during purge (l)	0.28
Ratio of purge volume to installation volume	1.08

039 35 mm vertical downwards methane test 2

Test #	039 35 mm vertical downwards methane test 2	
Installation configuration	3 m x 35 mm Vertical downwards	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

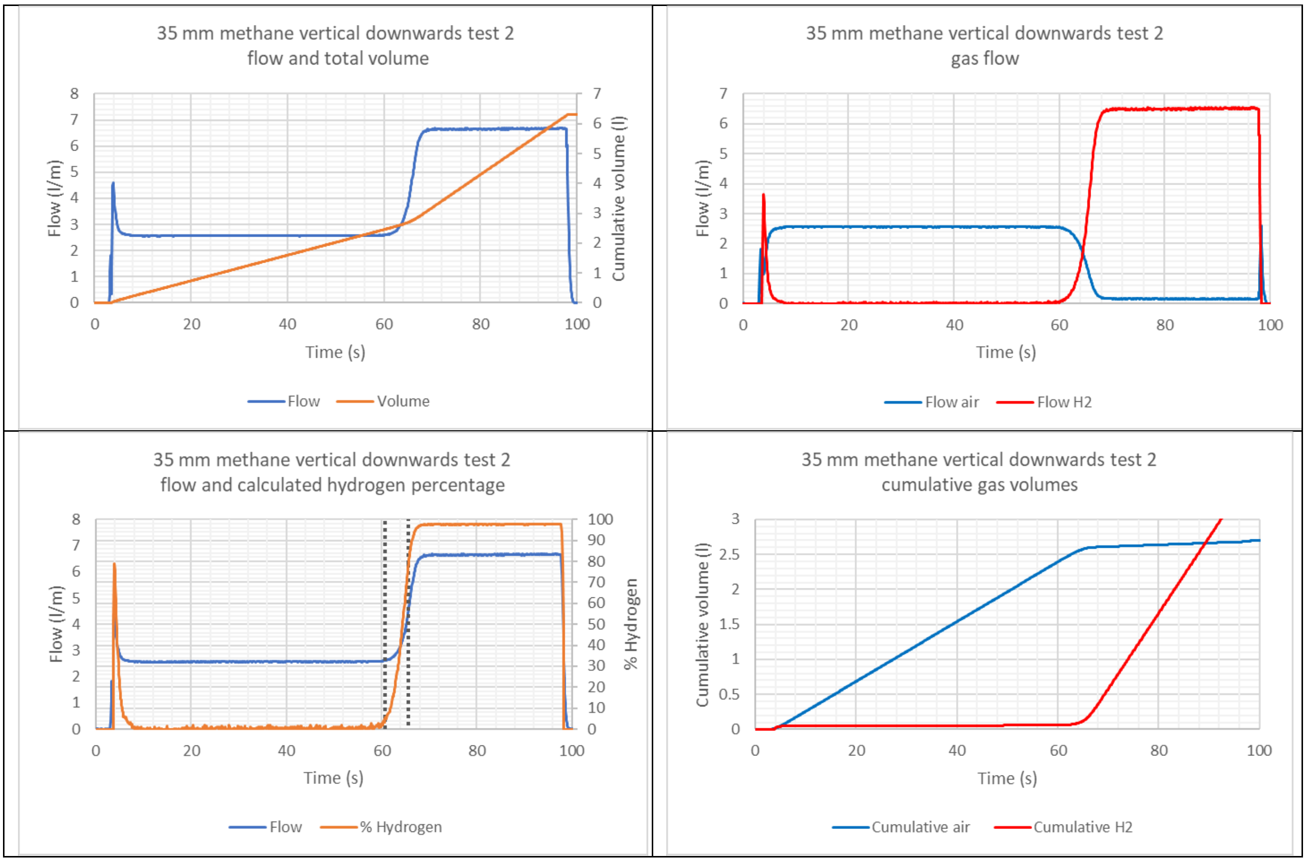
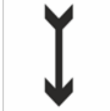


Figure 39: 35 mm methane vertical downwards test 2

	Time (s)	Volume (l)
To start of transition (>0% H2)	53.3	1.59
Duration of transition	6.1	1.07
To end of transition (95% H2)	59.4	2.66

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	2.66
Calculated volume of air displaced (l)	2.39
Calculated volume of hydrogen displaced during purge (l)	0.27
Ratio of purge volume to installation volume	1.09

040 35 mm vertical downwards methane test 3

Test #	040 35 mm vertical downwards methane test 3	
Installation configuration	3 m x 35 mm Vertical downwards	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

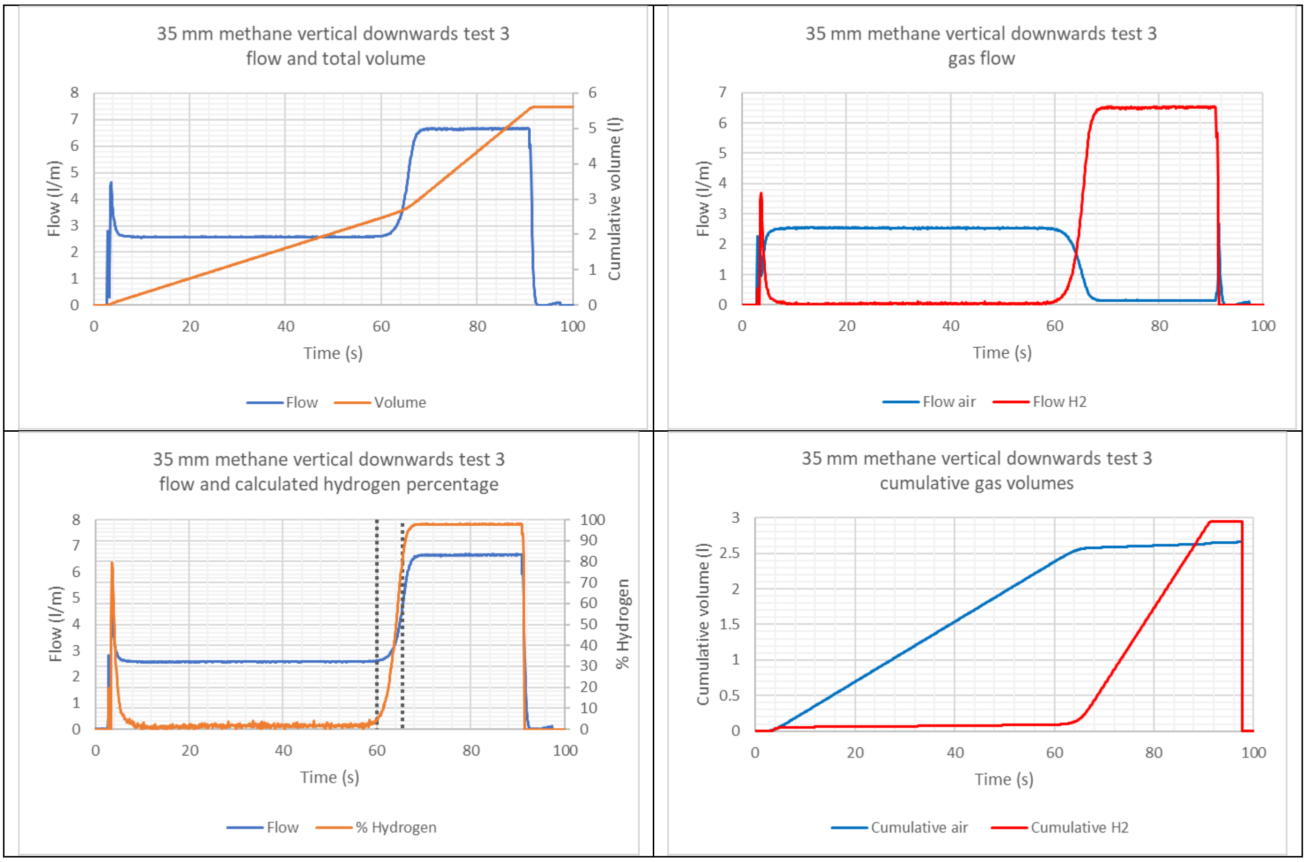


Figure 40: 35 mm methane vertical downwards test 3

	Time (s)	Volume (l)
To start of transition (>0% H2)	51.8	1.58
Duration of transition	7	1.05
To end of transition (95% H2)	58.8	2.63

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	2.63
Calculated volume of air displaced (l)	2.33
Calculated volume of hydrogen displaced during purge (l)	0.30
Ratio of purge volume to installation volume	1.08

041 35mm vertical downwards pause test 1

Test #	041 35mm vertical downwards pause test 1	
Installation configuration	3 m x 35 mm Vertical downwards	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

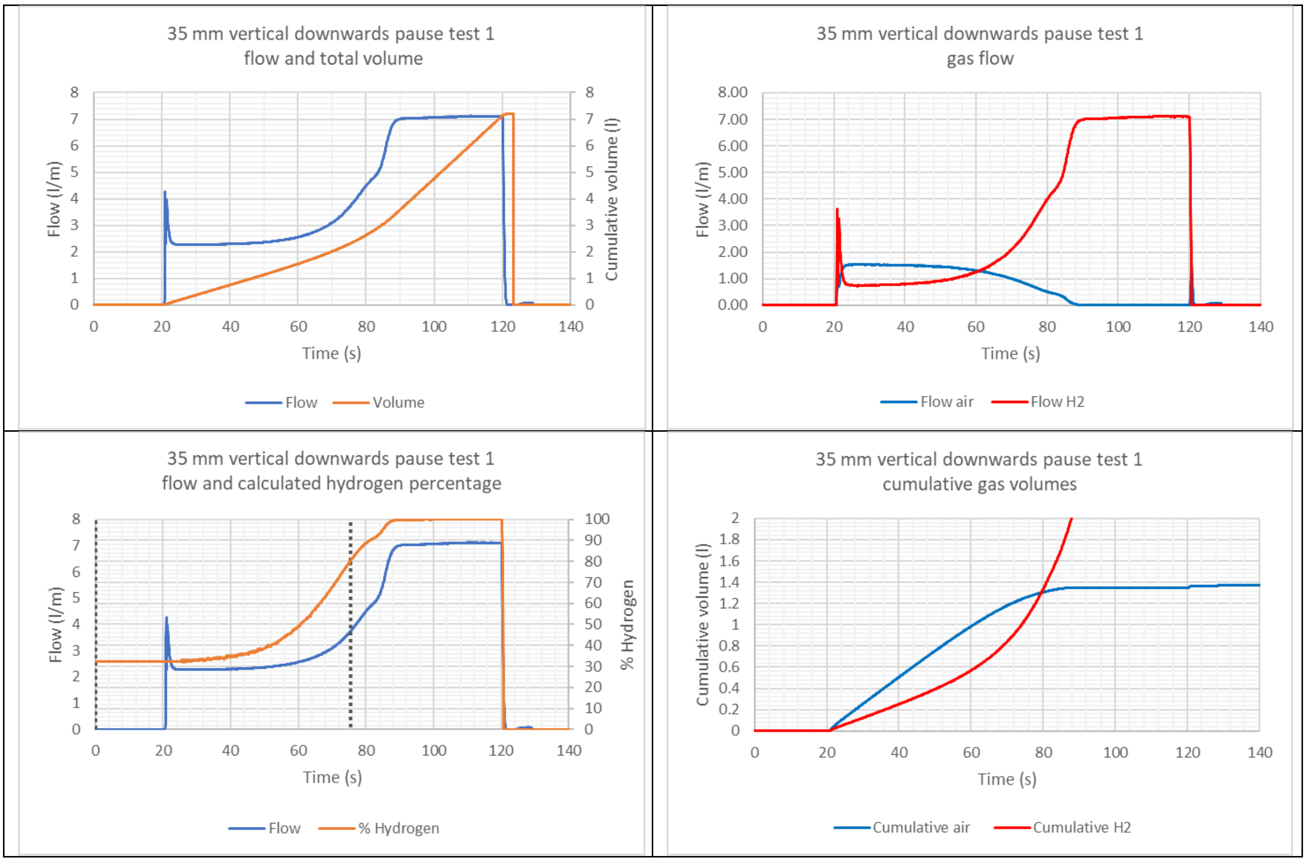
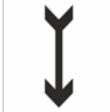


Figure 41: 35mm vertical downwards pause test 1

	Time (s)	Volume (l)
To start of transition (>0% H2)	7.5	0.29
Duration of transition	52	2.55
To end of transition (95% H2)	59.5	2.84

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	2.84
Calculated volume of air displaced (l)	1.14
Calculated volume of hydrogen displaced during purge (l)	1.70
Ratio of purge volume to installation volume	1.16

042 35mm vertical downwards pause test 2

Test #	042 35mm vertical downwards pause test 2	
Installation configuration	3 m x 35 mm Vertical downwards	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

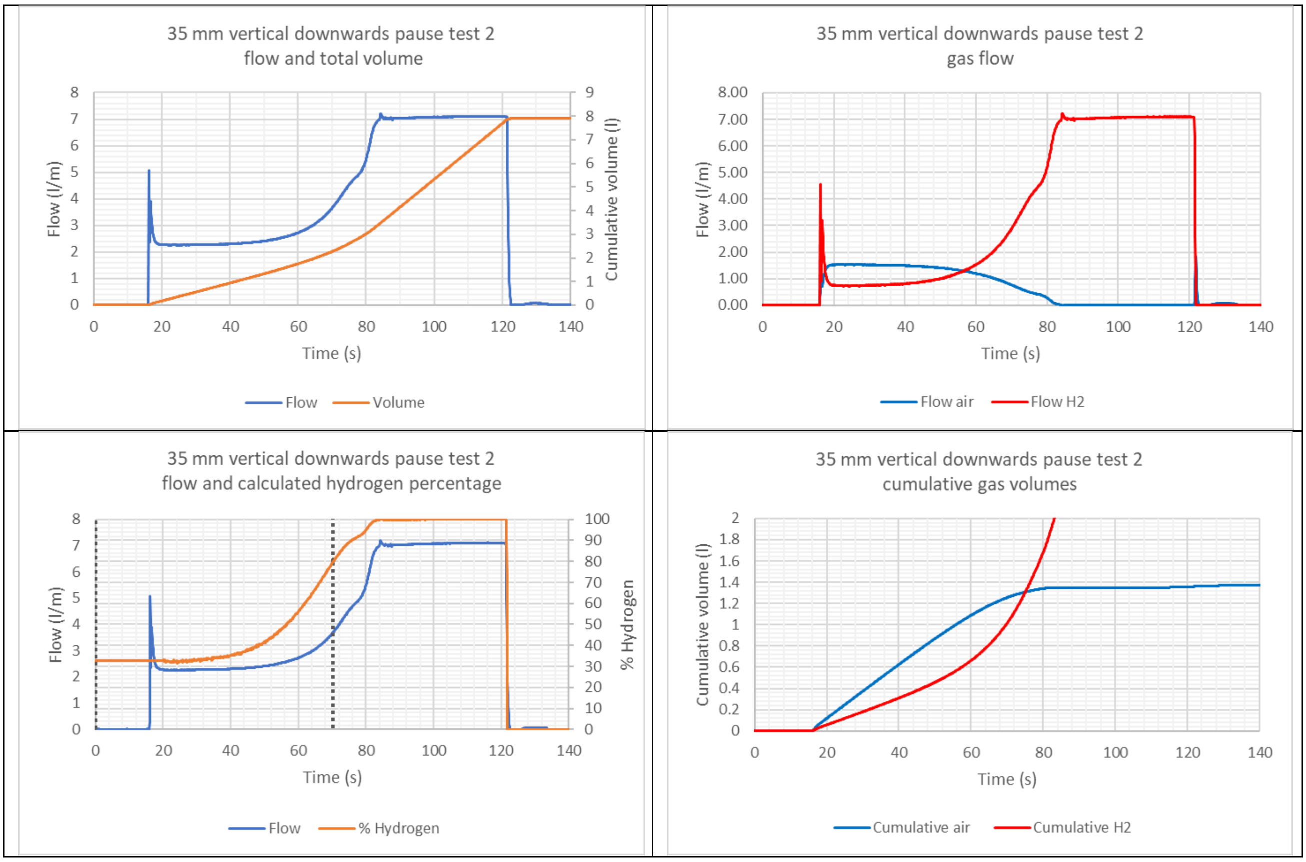
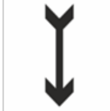


Figure 42: 35mm vertical downwards pause test 2

	Time (s)	Volume (l)
To start of transition (>0% H2)	11.1	0.42
Duration of transition	48.8	2.42
To end of transition (95% H2)	59.9	2.84

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	2.84
Calculated volume of air displaced (l)	1.16
Calculated volume of hydrogen displaced during purge (l)	1.68
Ratio of purge volume to installation volume	1.16

043 35mm vertical downwards pause test 3

Test #	043 35mm vertical downwards pause test 3	
Installation configuration	3 m x 35 mm Vertical downwards	
Installation volume	2.44 l	
Flow and speed with pure air	2 l/m	0.04 m/s
Flow and speed with pure hydrogen	7 l/m	0.15 m/s

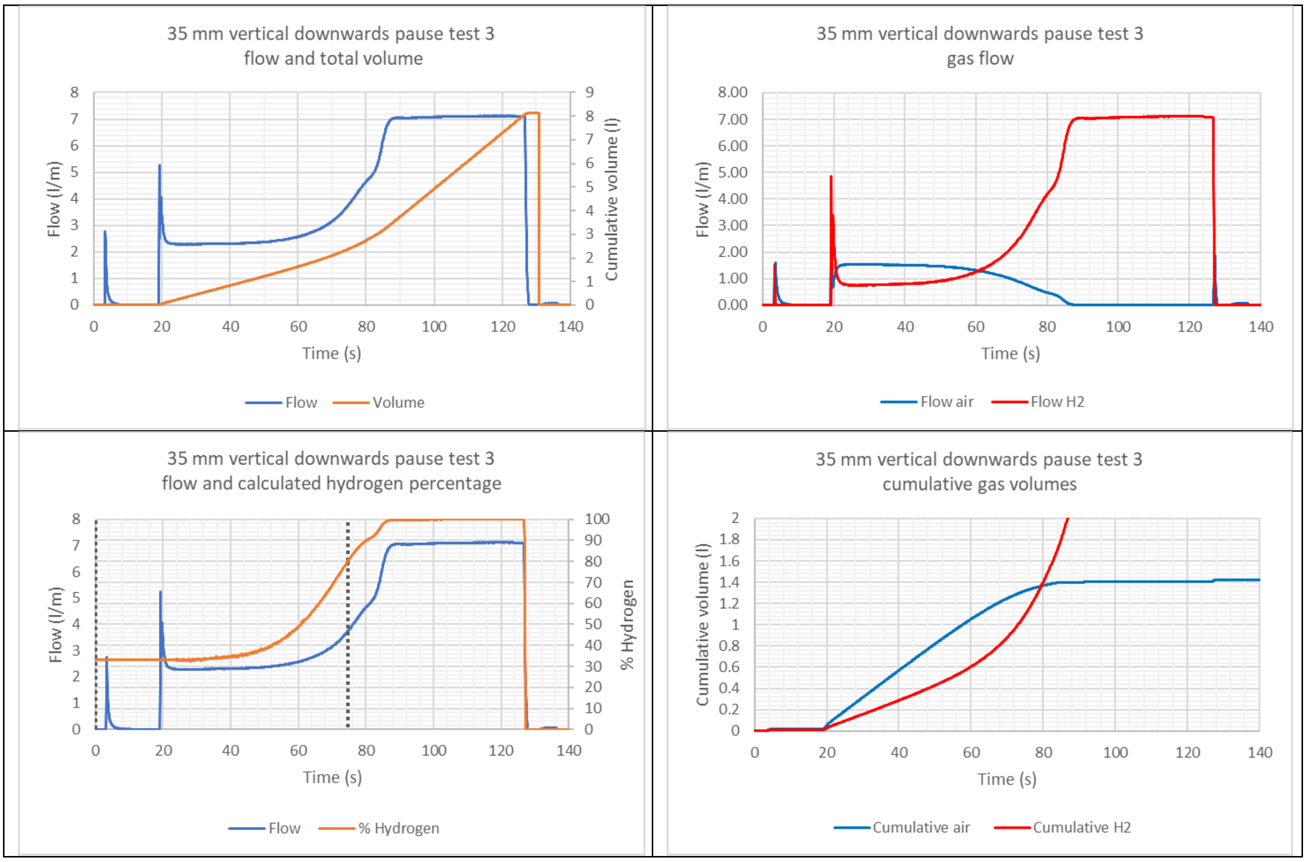


Figure 43: 35mm vertical downwards pause test 3

	Time (s)	Volume (l)
To start of transition (>0% H2)	11.5	0.44
Duration of transition	48.4	2.40
To end of transition (95% H2)	59.9	2.84

Installation volume (l)	2.44
Total volume displaced to 95% hydrogen (l)	2.84
Calculated volume of air displaced (l)	1.18
Calculated volume of hydrogen displaced during purge (l)	1.69
Ratio of purge volume to installation volume	1.16

044 15mm vertical downwards test 1

Test #	044 15mm vertical downwards test 1	
Installation configuration	3 m x 15 mm Vertical downwards	
Installation volume	0.4 l	
Flow and speed with pure air	2 l/m	0.25 m/s
Flow and speed with pure hydrogen	7 l/m	0.88 m/s

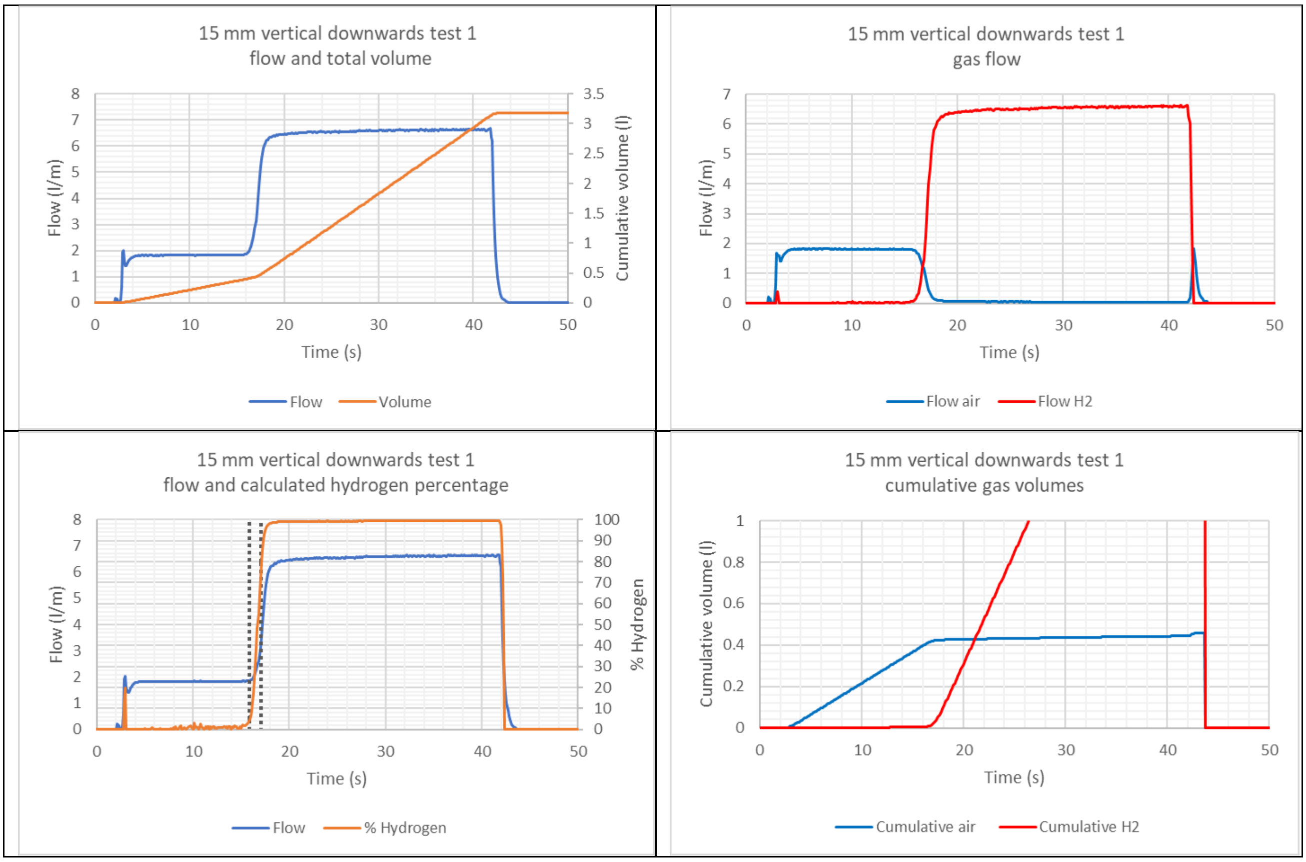
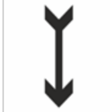


Figure 44: 15mm vertical downwards test 1

	Time (s)	Volume (l)
To start of transition (>0% H2)	11.2	0.34
Duration of transition	1.7	0.08
To end of transition (95% H2)	12.9	0.43

Installation volume (l)	0.40
Total volume displaced to 95% hydrogen (l)	0.43
Calculated volume of air displaced (l)	0.42
Calculated volume of hydrogen displaced during purge (l)	0.05
Ratio of purge volume to installation volume	1.07

045 15mm vertical downwards test 2

Test #	045 15mm vertical downwards test 2	
Installation configuration	3 m x 15 mm Vertical downwards	
Installation volume	0.4 l	
Flow and speed with pure air	2 l/m	0.25 m/s
Flow and speed with pure hydrogen	7 l/m	0.88 m/s

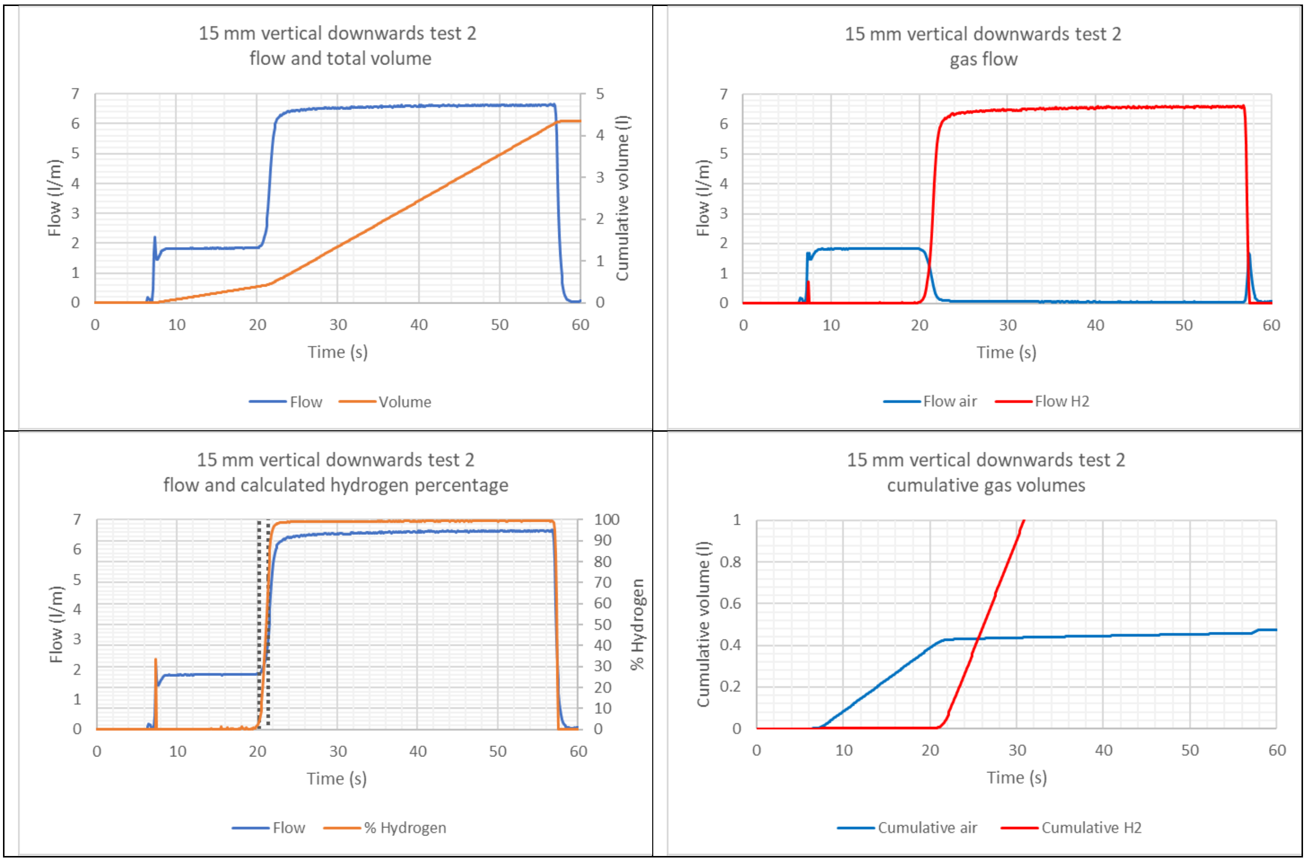


Figure 45: 15mm vertical downwards test 2

	Time (s)	Volume (l)
To start of transition (>0% H2)	11.2	0.35
Duration of transition	1.7	0.08
To end of transition (95% H2)	12.9	0.43

Installation volume (l)	0.40
Total volume displaced to 95% hydrogen (l)	0.43
Calculated volume of air displaced (l)	0.38
Calculated volume of hydrogen displaced during purge (l)	0.05
Ratio of purge volume to installation volume	1.07

046 15mm vertical downwards test 3

Test #	046 15mm vertical downwards test 3	
Installation configuration	3 m x 15 mm Vertical downwards	
Installation volume	0.4 l	
Flow and speed with pure air	2 l/m	0.25 m/s
Flow and speed with pure hydrogen	7 l/m	0.88 m/s

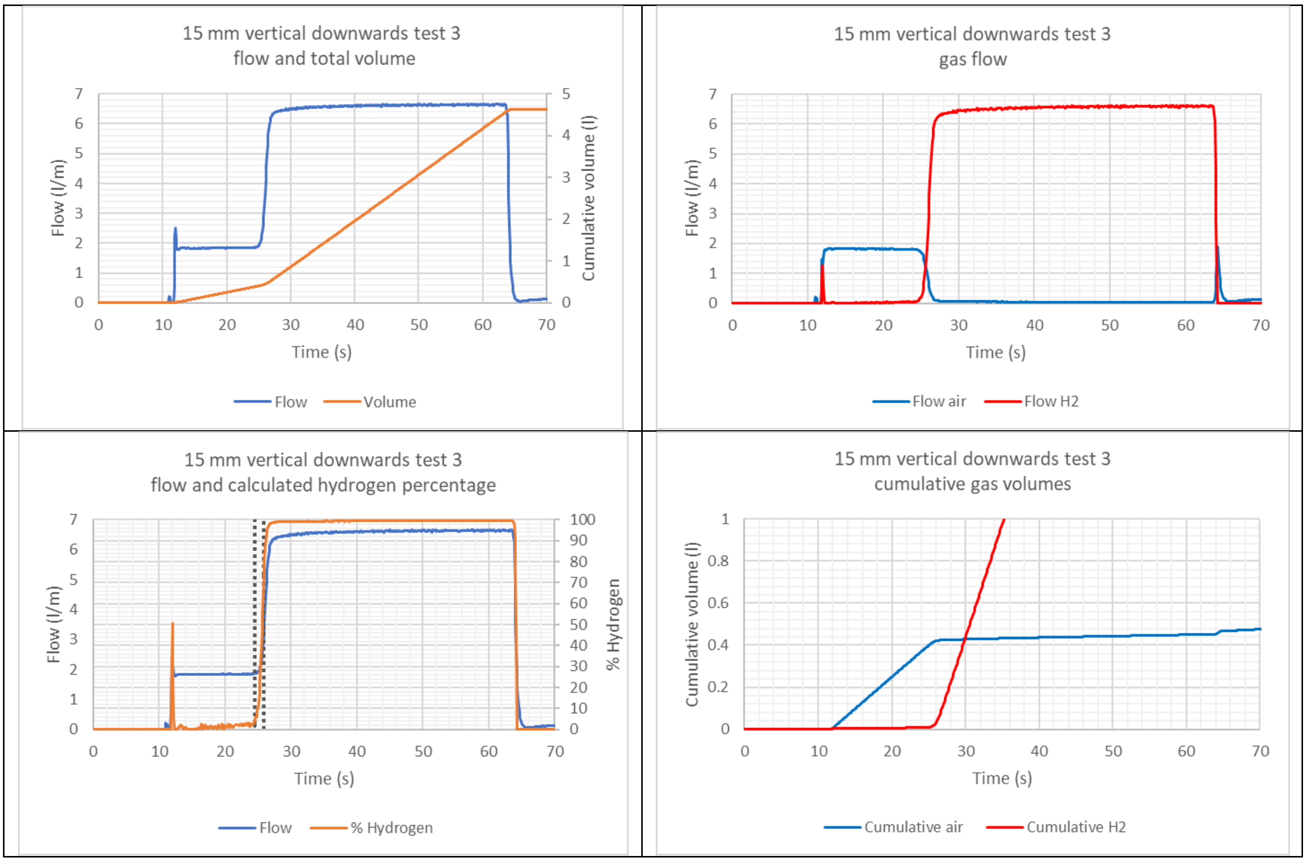


Figure 46: 15 mm vertical downwards test 3

	Time (s)	Volume (l)
To start of transition (>0% H2)	11.7	0.36
Duration of transition	1.9	0.09
To end of transition (95% H2)	13.6	0.45

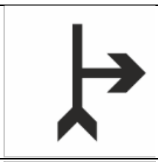
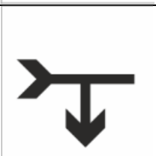
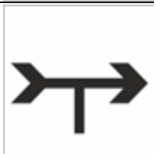
Installation volume (l)	0.40
Total volume displaced to 95% hydrogen (l)	0.45
Calculated volume of air displaced (l)	0.39
Calculated volume of hydrogen displaced during purge (l)	0.06
Ratio of purge volume to installation volume	1.13

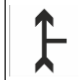
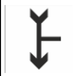
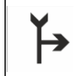
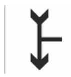
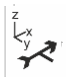
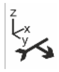
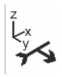
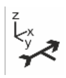
Branch tests

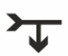
The naming convention of the branch tests can be broken down into discrete categories detailed below. Examples for different tests are provided.

Test number	Main pipe size	Main flow direction	The branch direction.	Which section of pipework is NOT getting purged in the first instance	Which iteration of test the title details. Most tests have 3 iterations
047	22 mm	Vertical upwards	Horizontal branch	Dead tee	Test 1
075	22 mm	Horizontal	Vertical downwards	Dead straight	Test 3

To provide clarity on the directions of flow, the following table is attached. The arrow heads denote the direction of flow.

Test number	Image of primary flow	Image of Secondary flow
047		
075		

Test No.	Section	Diameter (mm)	Orientation		Flow Direction 1	Flow Direction 2	Pause	Start Gas	ID	Installation volume (l)	Volume 1 (l)	Volume 2 (l)	Purge time 1 (s)	Purge time 2 (s)	Purge volume 1 (l)	Purge volume 2 (l)	Volume of air displaced 1 (l)	Volume of air displaced 2 (l)	Total volume of air displaced(l)	Volume of H2 displaced 1 (l)	Volume of H2 displaced 2 (l)	Total volume of H2 displaced (l)	Purge ratio 1	Purge ratio 2	Total purge ratio
047									047	1.58	0.95	0.63	39	17	1.41	0.70	0.99	0.53	1.52	0.42	0.17	0.60	1.49	1.11	1.34
048	Branch	22			Vertical upwards	Horizontal	N/A	Air	048	1.58	0.95	0.63	38	18	1.42	0.70	0.99	0.54	1.53	0.42	0.16	0.59	1.49	1.11	1.34
049									049	1.58	0.95	0.63	39	17	1.44	0.70	1.00	0.54	1.54	0.44	0.17	0.60	1.52	1.10	1.35
050									050	1.58	1.26	0.32	52	7	2.06	0.33	1.37	0.14	1.51	0.69	0.19	0.88	1.63	1.04	1.51
051	Branch	22			Horizontal	Vertical upwards	N/A	Air	051	1.58	1.26	0.32	51	7	2.00	0.31	1.37	0.12	1.49	0.63	0.19	0.82	1.58	0.99	1.46
052									052	1.58	1.26	0.32	53	8	2.13	0.33	1.37	0.14	1.50	0.76	0.19	0.95	1.68	1.03	1.55
053									053	1.58	0.95	0.63	34	18	1.31	0.69	0.98	0.53	1.51	0.33	0.16	0.49	1.38	1.10	1.27
054	Branch	22			Vertical downwards	Horizontal	N/A	Air	054	1.58	0.95	0.63	39	18	1.35	0.69	1.02	0.54	1.56	0.33	0.16	0.49	1.43	1.10	1.30
055									055	1.58	0.95	0.63	38	17	1.36	0.70	1.03	0.54	1.57	0.33	0.16	0.49	1.43	1.10	1.30
056									056	1.58	1.26	0.32	45	9	1.46	0.35	1.30	0.28	1.58	0.16	0.07	0.23	1.15	1.11	1.15
057	Branch	22			Horizontal	Vertical downwards	N/A	Air	057	1.58	1.26	0.32	44	9	1.47	0.35	1.31	0.28	1.59	0.16	0.07	0.23	1.16	1.11	1.15
058									058	1.58	1.26	0.32	45	9	1.46	0.35	1.30	0.28	1.58	0.16	0.08	0.24	1.16	1.12	1.15
059									059	1.58	0.95	0.63	35	20	1.38	0.72	0.94	0.55	1.48	0.44	0.17	0.62	1.45	1.14	1.33
060									060	1.58	0.95	0.63	34	21	1.34	0.72	0.88	0.55	1.43	0.46	0.17	0.63	1.41	1.14	1.30
061									061	1.58	0.95	0.63	36	21	1.40	0.73	0.96	0.55	1.50	0.45	0.17	0.62	1.48	1.15	1.35
062	Branch	22			Horizontal	Horizontal	N/A	Air	062	1.58	0.95	0.63	35	18	1.38	0.72	0.92	0.55	1.47	0.46	0.18	0.64	1.46	1.14	1.33
063									063	1.58	0.95	0.63	35	17	1.38	0.71	0.91	0.52	1.43	0.46	0.19	0.65	1.45	1.12	1.32
064									064	1.58	0.95	0.63	34	18	1.36	0.71	0.89	0.55	1.44	0.47	0.17	0.64	1.44	1.13	1.31
065									065	1.58	0.95	0.63	34	18	1.36	0.70	0.89	0.50	1.39	0.47	0.21	0.68	1.44	1.10	1.30
066									066	1.58	1.26	0.32	46	8	1.80	0.36	1.24	0.21	1.46	0.56	0.15	0.71	1.43	1.14	1.37
067	Branch	22			Horizontal	Horizontal	N/A	Air	067	1.58	1.26	0.32	50	8	1.90	0.37	1.36	0.23	1.59	0.54	0.15	0.69	1.50	1.17	1.43
068									068	1.58	1.26	0.32	45	8	1.79	0.38	1.21	0.23	1.44	0.57	0.15	0.72	1.41	1.20	1.37

Test No.	Section	Diameter (mm)	Orientation		Flow Direction 1	Flow Direction 2	Pause	Start Gas	ID	Installation volume (l)	Volume 1 (l)	Volume 2 (l)	Purge time 1 (s)	Purge time 2 (s)	Purge volume 1 (l)	Purge volume 2 (l)	Volume of air displaced 1 (l)	Volume of air displaced 2 (l)	Total volume of air displaced(l)	Volume of H2 displaced 1 (l)	Volume of H2 displaced 2 (l)	Total volume of H2 displaced (l)	Purge ratio 1	Purge ratio 2	Total purge ratio
069									069	1.58	0.95	0.63	34	19	1.15	0.71	0.95	0.61	1.56	0.20	0.10	0.30	1.21	1.12	1.18
070	Branch	22			Horizontal	Vertical downwards	N/A	Air	070	1.58	0.95	0.63	35	19	1.16	0.71	0.98	0.62	1.60	0.18	0.09	0.27	1.22	1.12	1.18
071									071	1.58	0.95	0.63	35	19	1.16	0.70	0.97	0.62	1.60	0.19	0.09	0.27	1.22	1.11	1.18
073									073	1.58	1.26	0.32	48	13	1.94	0.39	1.34	0.23	1.57	0.60	0.16	0.76	1.53	1.22	1.47
074	Branch	22			Vertical downwards	Horizontal	N/A	Air	074	1.58	1.26	0.32	46	9	1.81	0.35	1.26	0.21	1.47	0.55	0.14	0.70	1.43	1.11	1.37
075									075	1.58	1.26	0.32	46	10	1.79	0.37	1.26	0.23	1.49	0.53	0.14	0.68	1.42	1.18	1.37
077									077	1.58	0.95	0.63	34	17	1.55	0.73	0.79	0.50	1.29	0.76	0.22	0.99	1.64	1.15	1.44
078	Branch	22			Horizontal	Vertical upwards	N/A	Air	078	1.58	0.95	0.63	40	16	1.58	0.70	1.02	0.46	1.48	0.56	0.24	0.80	1.67	1.11	1.44
079									079	1.58	0.95	0.63	38	14	1.45	0.63	1.02	0.36	1.38	0.44	0.27	0.70	1.53	0.99	1.32
081									081	1.58	1.26	0.32	48	9	1.81	0.37	1.32	0.22	1.54	0.49	0.15	0.64	1.43	1.17	1.38
082	Branch	22			Vertical upwards	Horizontal	N/A	Air	082	1.58	1.26	0.32	49	9	1.83	0.37	1.34	0.23	1.56	0.49	0.14	0.64	1.45	1.18	1.39
083									083	1.58	1.26	0.32	49	9	1.85	0.36	1.33	0.18	1.51	0.52	0.17	0.69	1.46	1.13	1.40

Branch pause tests

Test No.	Section	Diameter (mm)	Orientation		Flow Direction 1	Flow Direction 2	Pause	Start Gas	ID	Installation volume (l)	Volume 1 (l)	Volume 2 (l)	Inserted volume 1 (l)	Calculated % Hydrogen	Purge volume 2 (l)	Purge volume 3 (l)	Volume of air displaced 1 (l)	Volume of air displaced 2 (l)	Volume of air displaced 3 (l)	Volume of H2 displaced 1 (l)	Volume of H2 displaced 2 (l)	Volume of H2 displaced 3 (l)	Purge ratio 2	Purge ratio 3	Purge ratio total
072	Branch	22			Horizontal	Vertical downwards	Yes	Air + Hydrogen	072	1.58	0.95	0.63	N/A	N/A	1.16	0.67	N/A	0.98	0.45	N/A	0.19	0.22	1.22	1.07	1.14
076					Vertical downwards	Horizontal	Yes	Air + Hydrogen	076	1.58	1.26	0.32	2.53	100	0.79	0.70	1.01	0.21	0.46	1.53	0.58	0.24	0.62	2.21	2.54
080	Branch	22			Horizontal	Vertical upwards	Yes	Air + Hydrogen	080	1.58	0.95	0.63	0.79	50.2	0.74	0.69	0.78	0.27	0.43	0.01	0.48	0.28	0.78	1.10	1.41

Branch vertical upwards feed

047 22 mm vertical upwards horizontal branch dead tee test 1

Test #	047 22 mm vertical upwards horizontal branch dead tee test 1	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	 
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

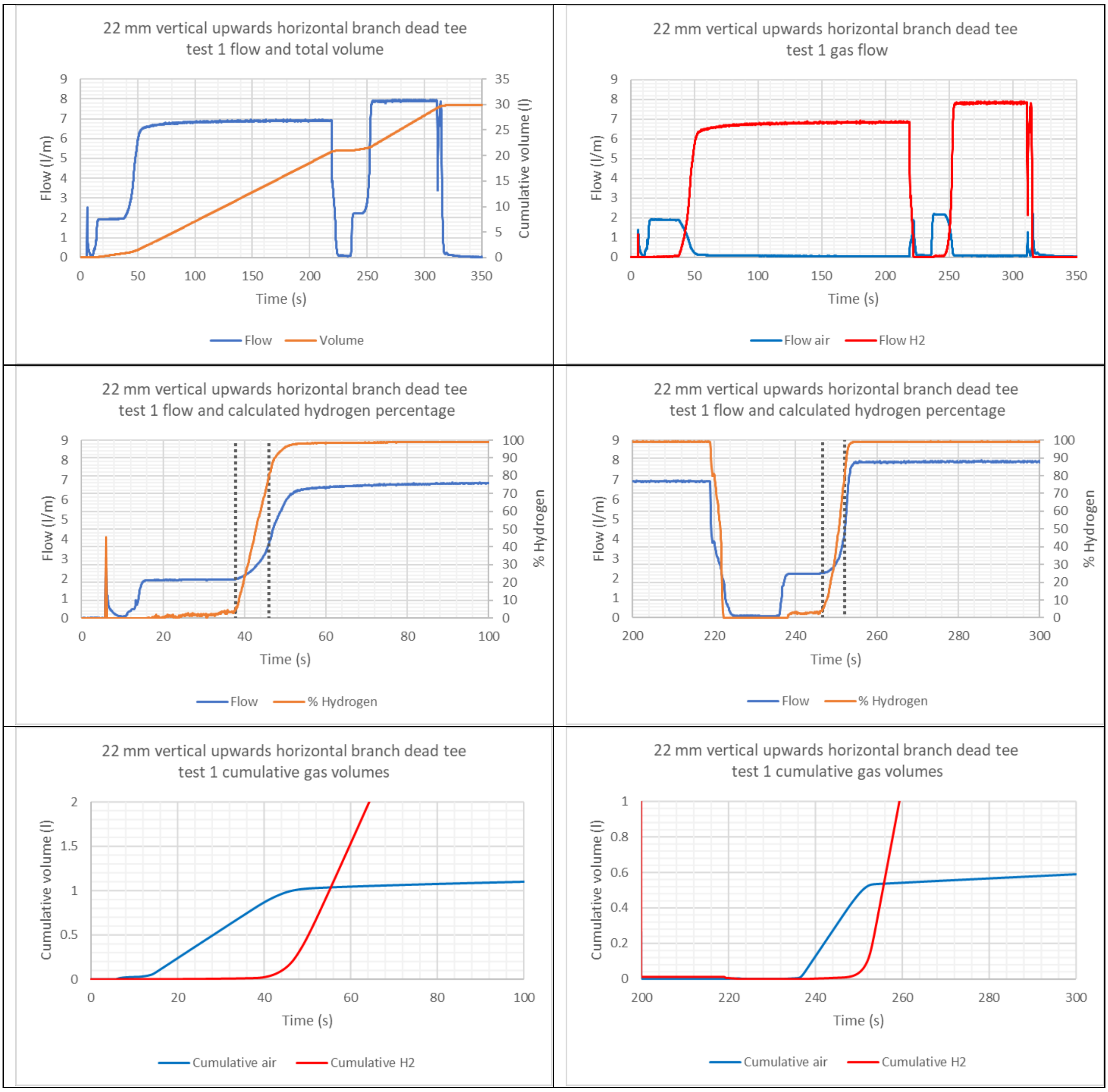


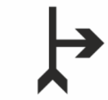
Figure 47: 22 mm vertical upwards horizontal branch dead tee test 1

1	Time (s)	Volume (l)
To start of transition (>0% H2)	27.7	0.79
Duration of transition	11.6	0.63
To end of transition (95% H2)	39.3	1.41

2	Time (s)	Volume (l)
To start of transition (>0% H2)	10.5	0.36
Duration of transition	6.5	0.34
To end of transition (95% H2)	17	0.70

	1	2	Total
Installation volume (l)	0.95	0.63	1.58
Total volume displaced to 95% hydrogen (l)	1.41	0.70	2.11
Calculated volume of air displaced (l)	0.99	0.53	1.52
Calculated volume of hydrogen displaced during purge (l)	0.42	0.17	0.60
Ratio of purge volume to installation volume	1.49	1.11	1.34

048 22 mm vertical upwards horizontal branch dead tee test 2

Test #	048 22 mm vertical upwards horizontal branch dead tee test 2	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	 
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

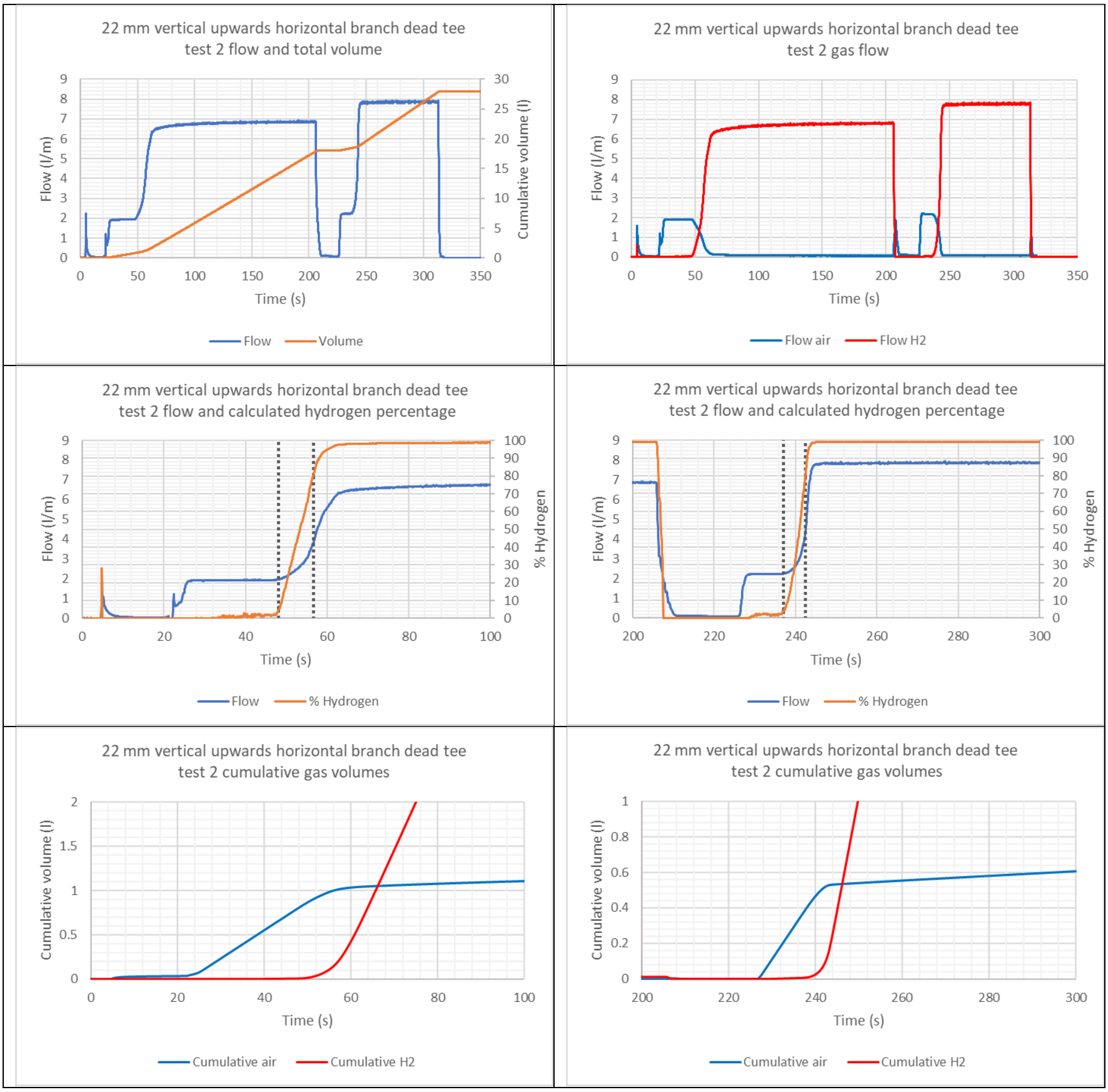


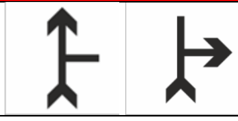
Figure 48: 22 mm vertical upwards horizontal branch dead tee test 2

1	Time (s)	Volume (l)
To start of transition (>0% H2)	26	0.78
Duration of transition	11.8	0.64
To end of transition (95% H2)	37.8	1.42

2	Time (s)	Volume (l)
To start of transition (>0% H2)	11.6	0.38
Duration of transition	6.2	0.32
To end of transition (95% H2)	17.8	0.70

	1	2	Total
Installation volume (l)	0.95	0.63	1.58
Total volume displaced to 95% hydrogen (l)	1.42	0.70	2.12
Calculated volume of air displaced (l)	0.99	0.54	1.53
Calculated volume of hydrogen displaced during purge (l)	0.42	0.16	0.59
Ratio of purge volume to installation volume	1.49	1.11	1.34

049 22 mm vertical upwards horizontal branch dead tee test 3

Test #	049 22 mm vertical upwards horizontal branch dead tee test 3	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

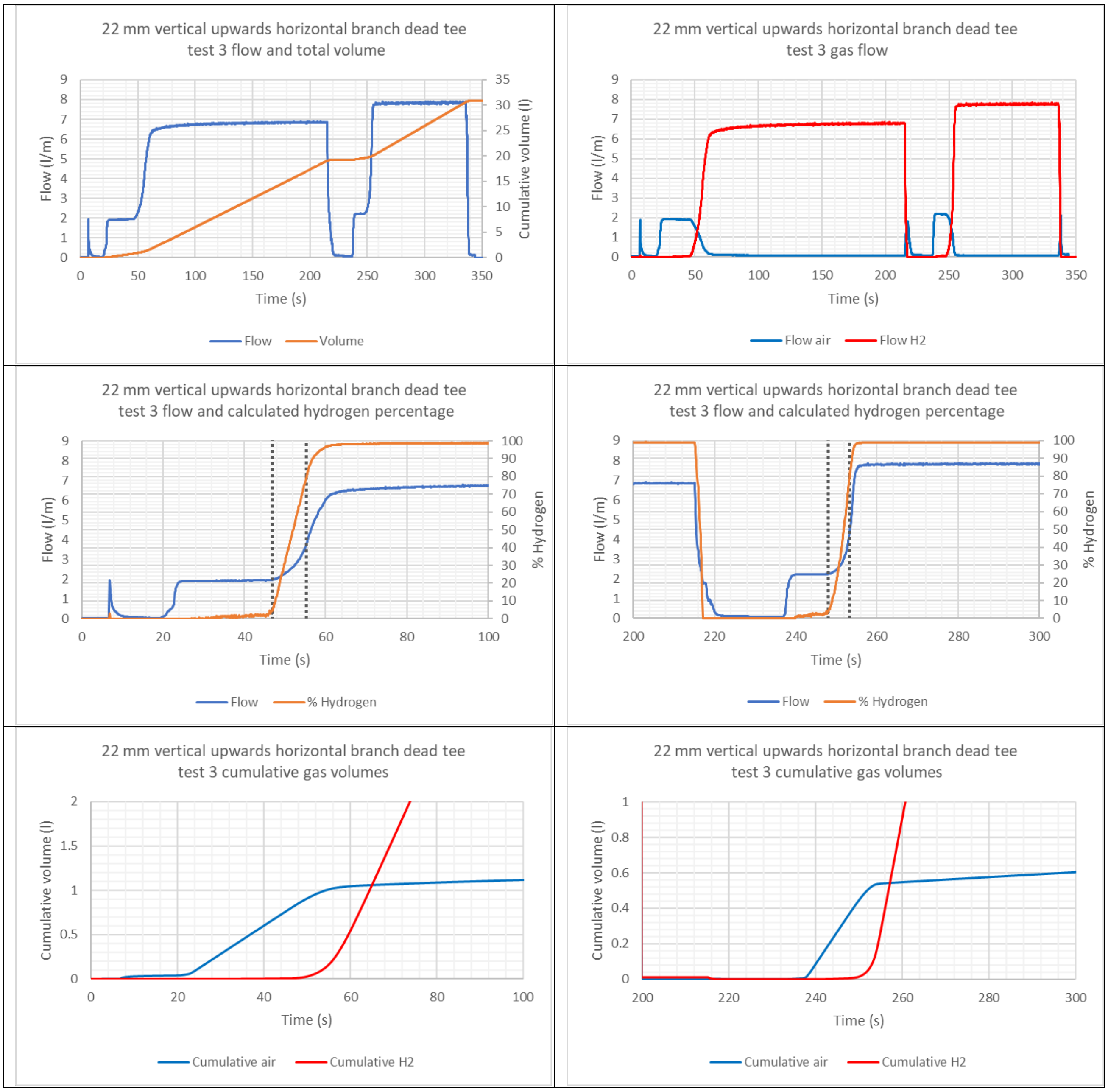


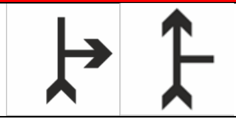
Figure 49: 22 mm vertical upwards horizontal branch dead tee test 3

1	Time (s)	Volume (l)
To start of transition (>0% H2)	27.3	0.79
Duration of transition	12	0.65
To end of transition (95% H2)	39.3	1.44

2	Time (s)	Volume (l)
To start of transition (>0% H2)	11.2	0.38
Duration of transition	6.1	0.32
To end of transition (95% H2)	17.3	0.70

	1	2	Total
Installation volume (l)	0.95	0.63	1.58
Total volume displaced to 95% hydrogen (l)	1.44	0.70	2.14
Calculated volume of air displaced (l)	1.00	0.54	1.54
Calculated volume of hydrogen displaced during purge (l)	0.44	0.17	0.60
Ratio of purge volume to installation volume	1.52	1.10	1.35

050 22 mm vertical upwards horizontal branch dead straight test 1

Test #	050 22 mm vertical upwards horizontal branch dead straight test 1	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

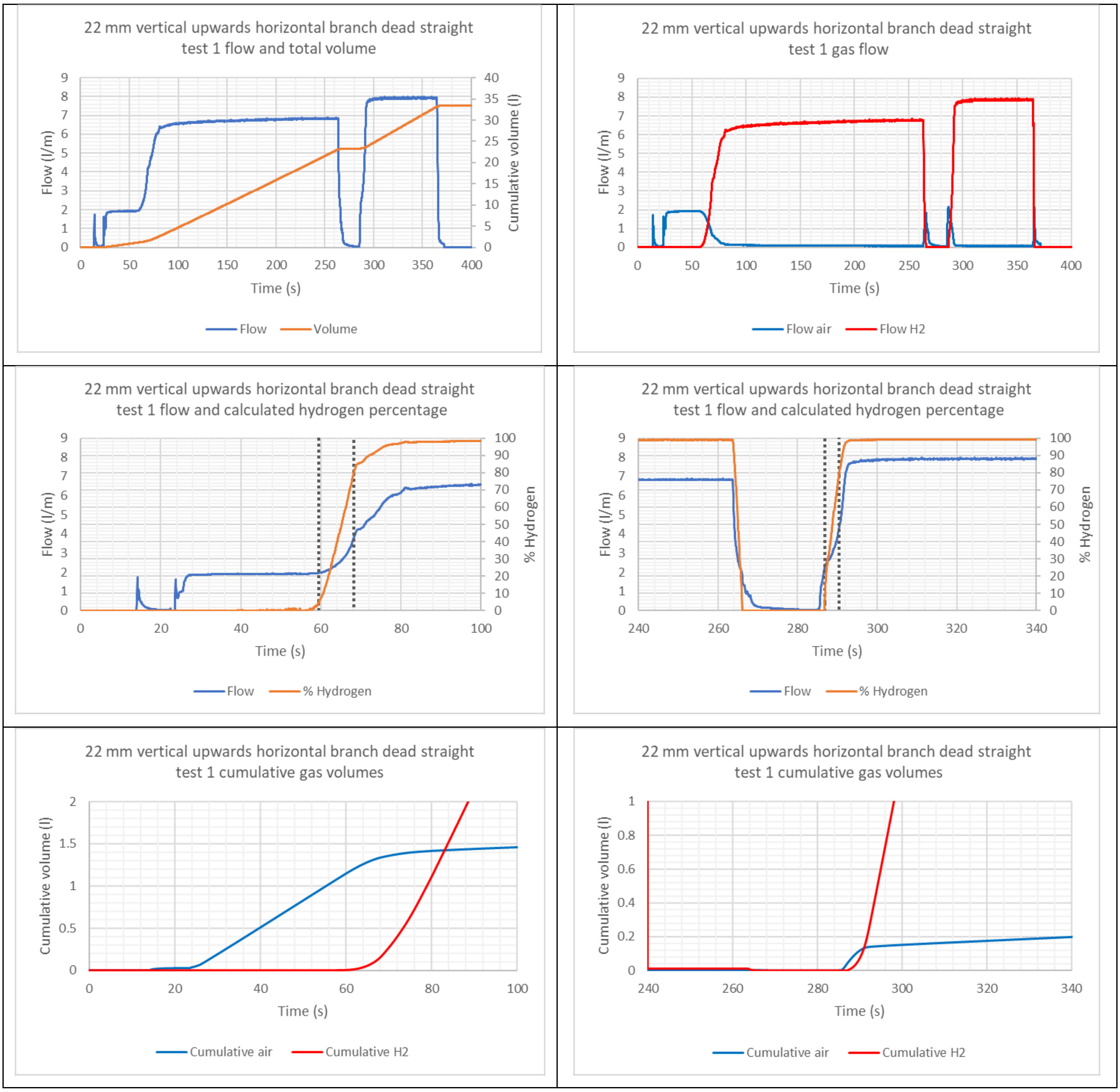


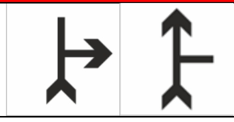
Figure 50: 22 mm vertical upwards horizontal branch dead straight test 1

1	Time (s)	Volume (l)
To start of transition (>0% H2)	36	1.10
Duration of transition	16.2	0.96
To end of transition (95% H2)	52.2	2.06

2	Time (s)	Volume (l)
To start of transition (>0% H2)	1.9	0.04
Duration of transition	4.8	0.29
To end of transition (95% H2)	6.7	0.33

	1	2	Total
Installation volume (l)	1.26	0.32	1.58
Total volume displaced to 95% hydrogen (l)	2.06	0.33	2.39
Calculated volume of air displaced (l)	1.37	0.14	1.51
Calculated volume of hydrogen displaced during purge (l)	0.69	0.19	0.88
Ratio of purge volume to installation volume	1.63	1.04	1.51

051 22 mm vertical upwards horizontal branch dead straight test 2

Test #	**051 22 mm vertical upwards horizontal branch dead straight test 2**	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

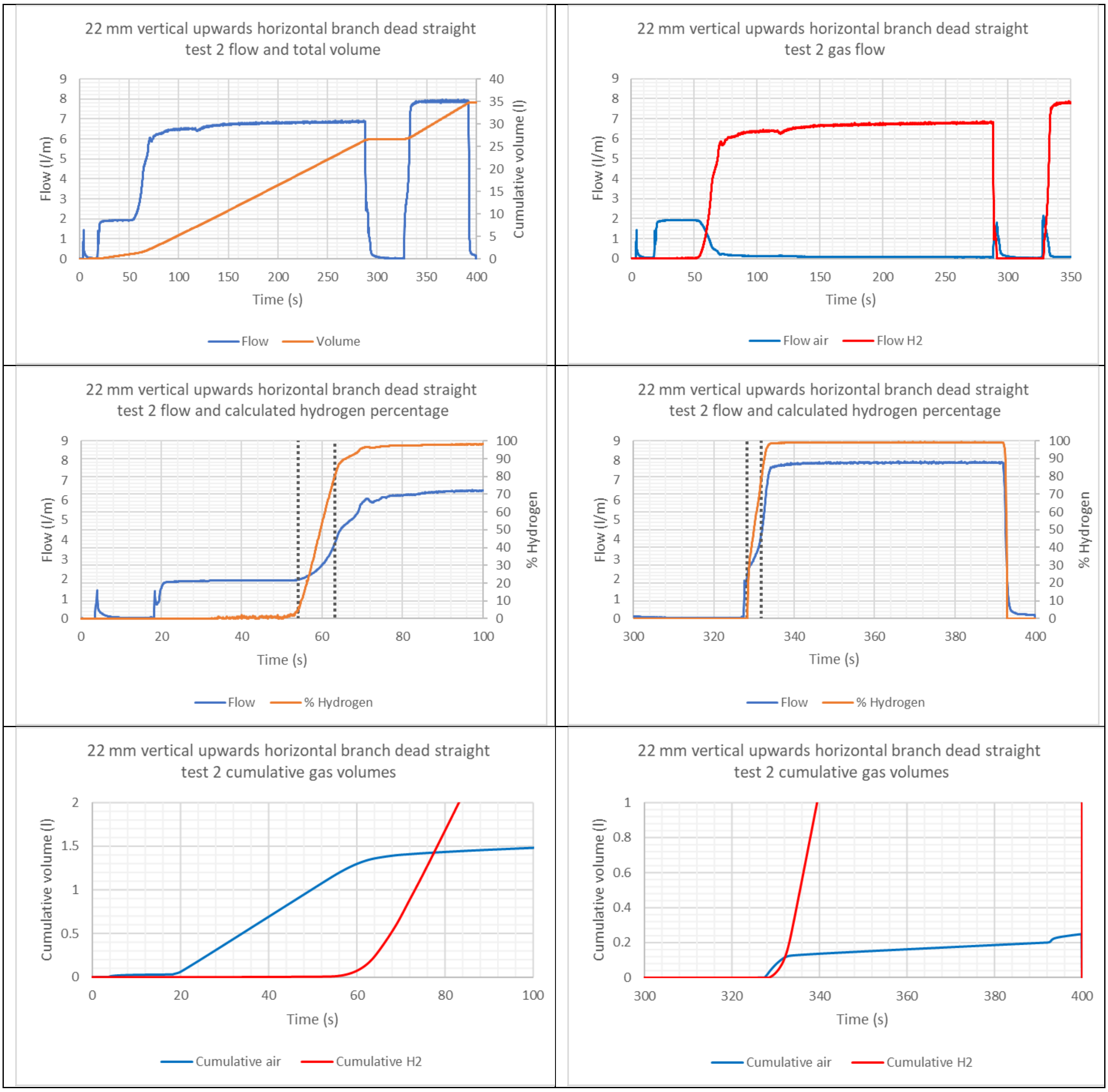


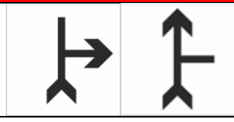
Figure 51: 22 mm vertical upwards horizontal branch dead straight test 2

1	Time (s)	Volume (l)
To start of transition (>0% H2)	35.8	0.82
Duration of transition	15.3	1.18
To end of transition (95% H2)	51.1	2.00

2	Time (s)	Volume (l)
To start of transition (>0% H2)	1.9	0.03
Duration of transition	4.6	0.28
To end of transition (95% H2)	6.5	0.31

	1	2	Total
Installation volume (l)	1.26	0.32	1.58
Total volume displaced to 95% hydrogen (l)	2.00	0.31	2.31
Calculated volume of air displaced (l)	1.37	0.12	1.49
Calculated volume of hydrogen displaced during purge (l)	0.63	0.19	0.82
Ratio of purge volume to installation volume	1.58	0.99	1.46

052 22 mm vertical upwards horizontal branch dead straight test 3

Test #	052 22 mm vertical upwards horizontal branch dead straight test 3	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

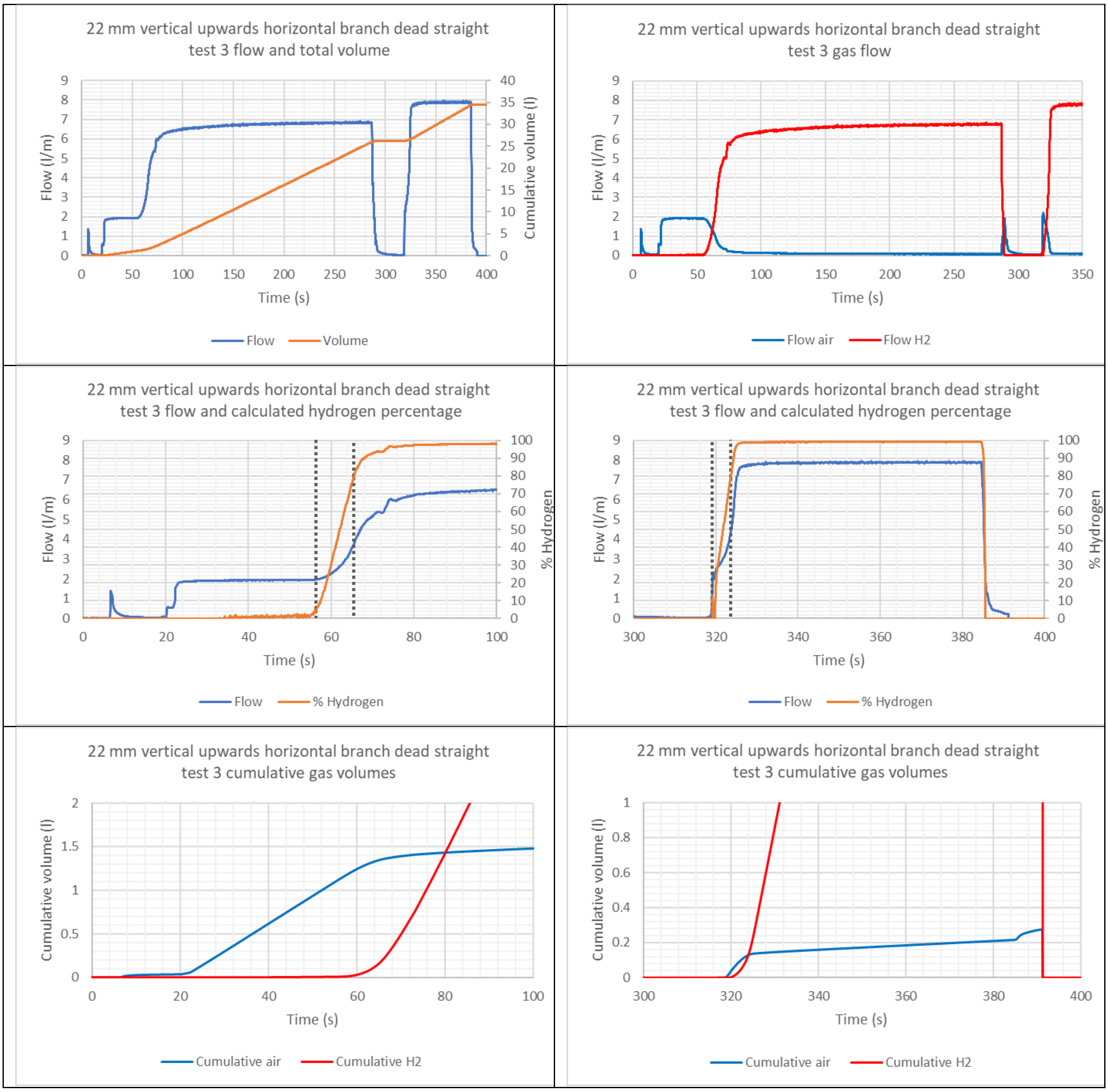


Figure 52: 22 mm vertical upwards horizontal branch dead straight test 3

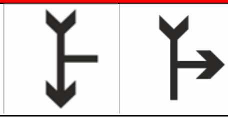
1	Time (s)	Volume (l)
To start of transition (>0% H2)	36.4	0.73
Duration of transition	16.8	1.40
To end of transition (95% H2)	53.2	2.13

2	Time (s)	Volume (l)
To start of transition (>0% H2)	2.6	0.03
Duration of transition	4.9	0.30
To end of transition (95% H2)	7.5	0.33

	1	2	Total
Installation volume (l)	1.26	0.32	1.58
Total volume displaced to 95% hydrogen (l)	2.13	0.33	2.45
Calculated volume of air displaced (l)	1.37	0.14	1.50
Calculated volume of hydrogen displaced during purge (l)	0.76	0.19	0.95
Ratio of purge volume to installation volume	1.68	1.03	1.55

Branch vertical downwards feed

053 22 mm vertical downwards horizontal branch dead tee test 1

Test #	053 22 mm vertical downwards horizontal branch dead tee test 1	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

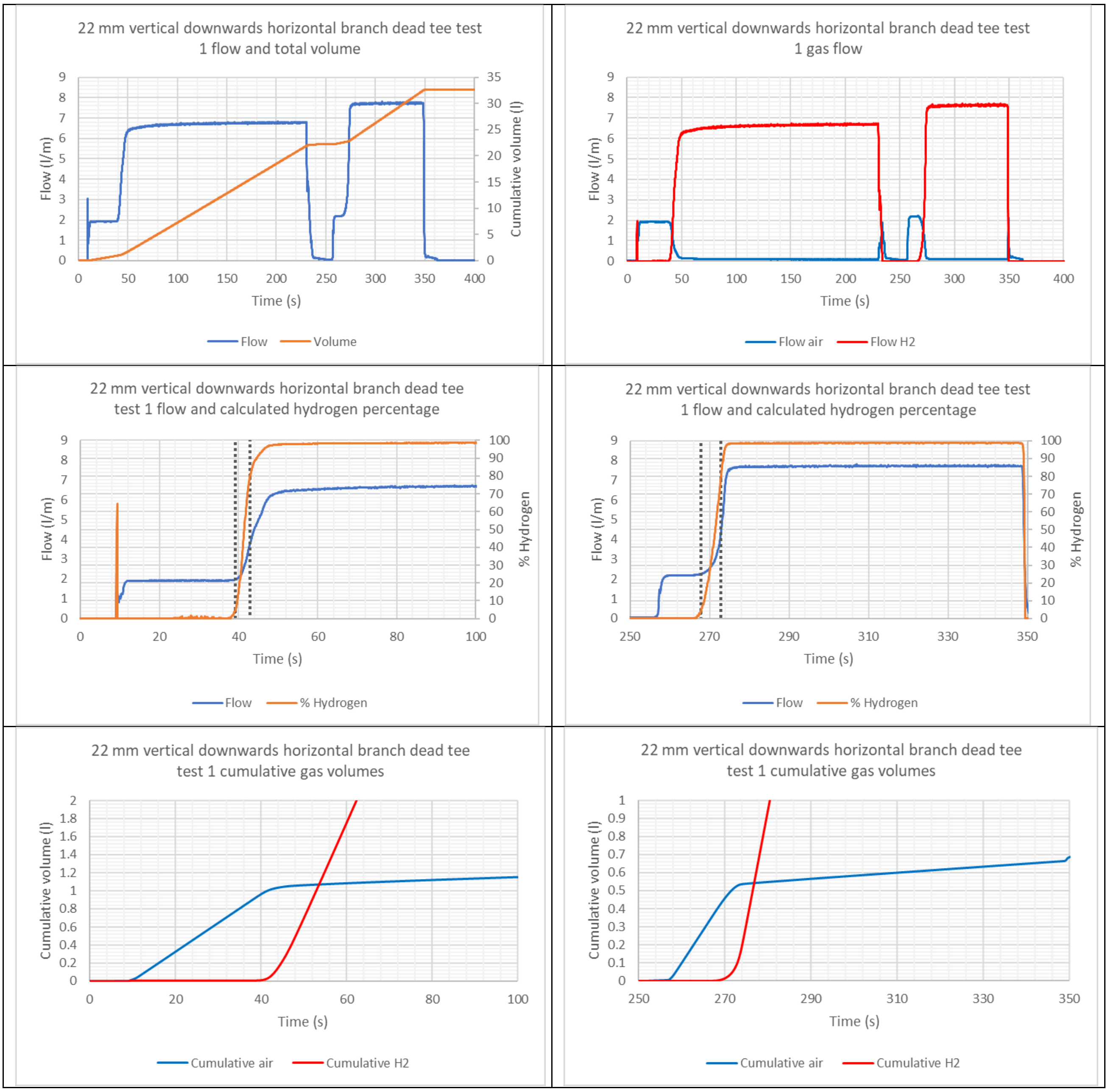


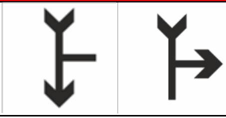
Figure 53: 22 mm vertical downwards horizontal branch dead tee test 1

1	Time (s)	Volume (l)
To start of transition (>0% H2)	27.3	0.87
Duration of transition	7.1	0.43
To end of transition (95% H2)	34.4	1.31

2	Time (s)	Volume (l)
To start of transition (>0% H2)	11.7	0.38
Duration of transition	5.9	0.31
To end of transition (95% H2)	17.6	0.69

	1	2	Total
Installation volume (l)	0.95	0.63	1.58
Total volume displaced to 95% hydrogen (l)	1.31	0.69	2.00
Calculated volume of air displaced (l)	0.98	0.53	1.51
Calculated volume of hydrogen displaced during purge (l)	0.33	0.16	0.49
Ratio of purge volume to installation volume	1.38	1.10	1.27

054 22 mm vertical downwards horizontal branch dead tee test 2

Test #	054 22 mm vertical downwards horizontal branch dead tee test 2	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

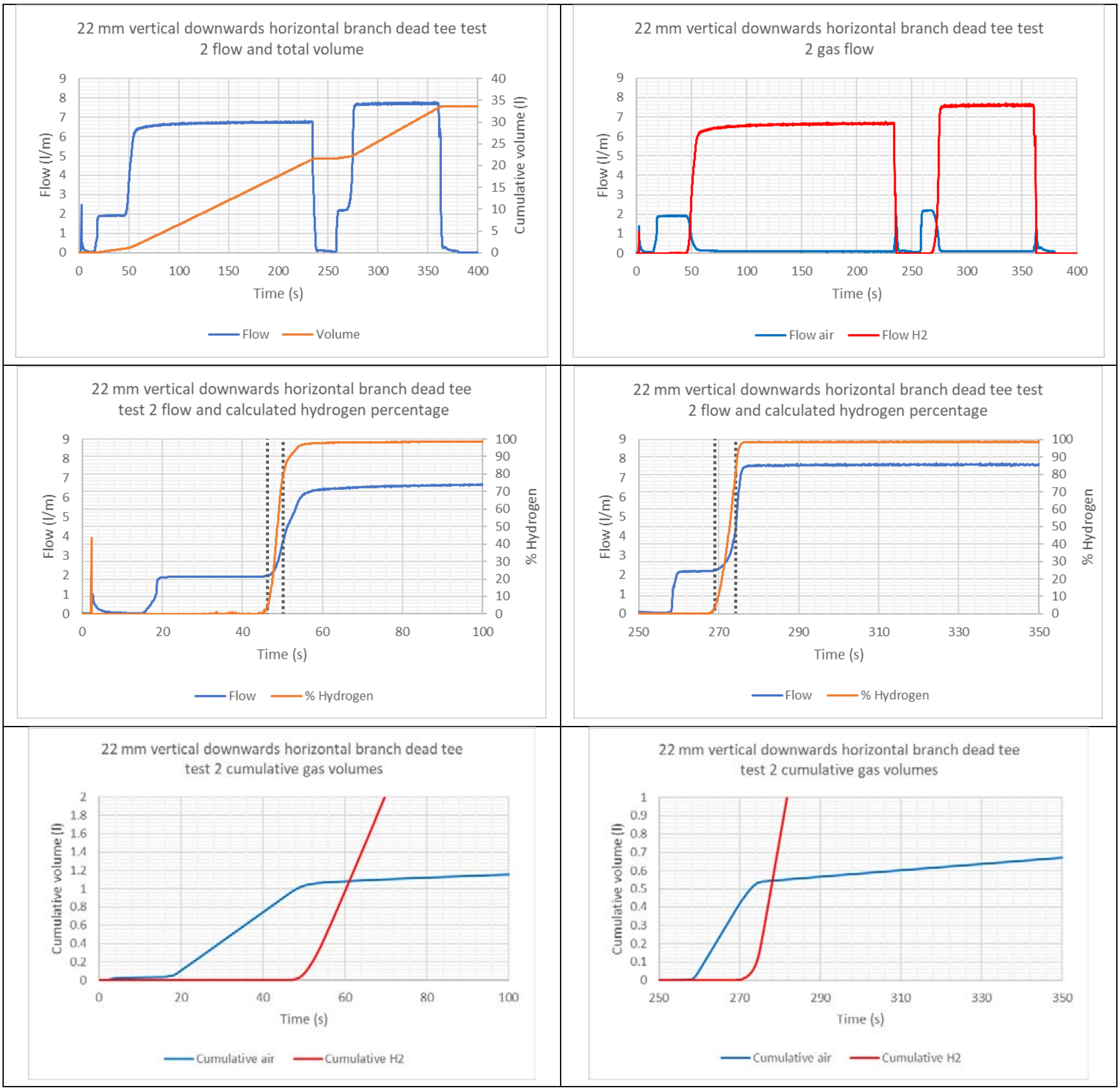


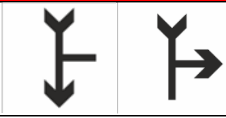
Figure 54: 22 mm vertical downwards horizontal branch dead tee test 2

1	Time (s)	Volume (l)
To start of transition (>0% H2)	31.3	0.86
Duration of transition	7.5	0.50
To end of transition (95% H2)	38.8	1.35

2	Time (s)	Volume (l)
To start of transition (>0% H2)	11.6	0.38
Duration of transition	5.9	0.31
To end of transition (95% H2)	17.5	0.69

	1	2	Total
Installation volume (l)	0.95	0.63	1.58
Total volume displaced to 95% hydrogen (l)	1.35	0.69	2.05
Calculated volume of air displaced (l)	1.02	0.54	1.56
Calculated volume of hydrogen displaced during purge (l)	0.33	0.16	0.49
Ratio of purge volume to installation volume	1.43	1.10	1.30

055 22 mm vertical downwards horizontal branch dead tee test 3

Test #	**055 22 mm vertical downwards horizontal branch dead tee test 3**	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

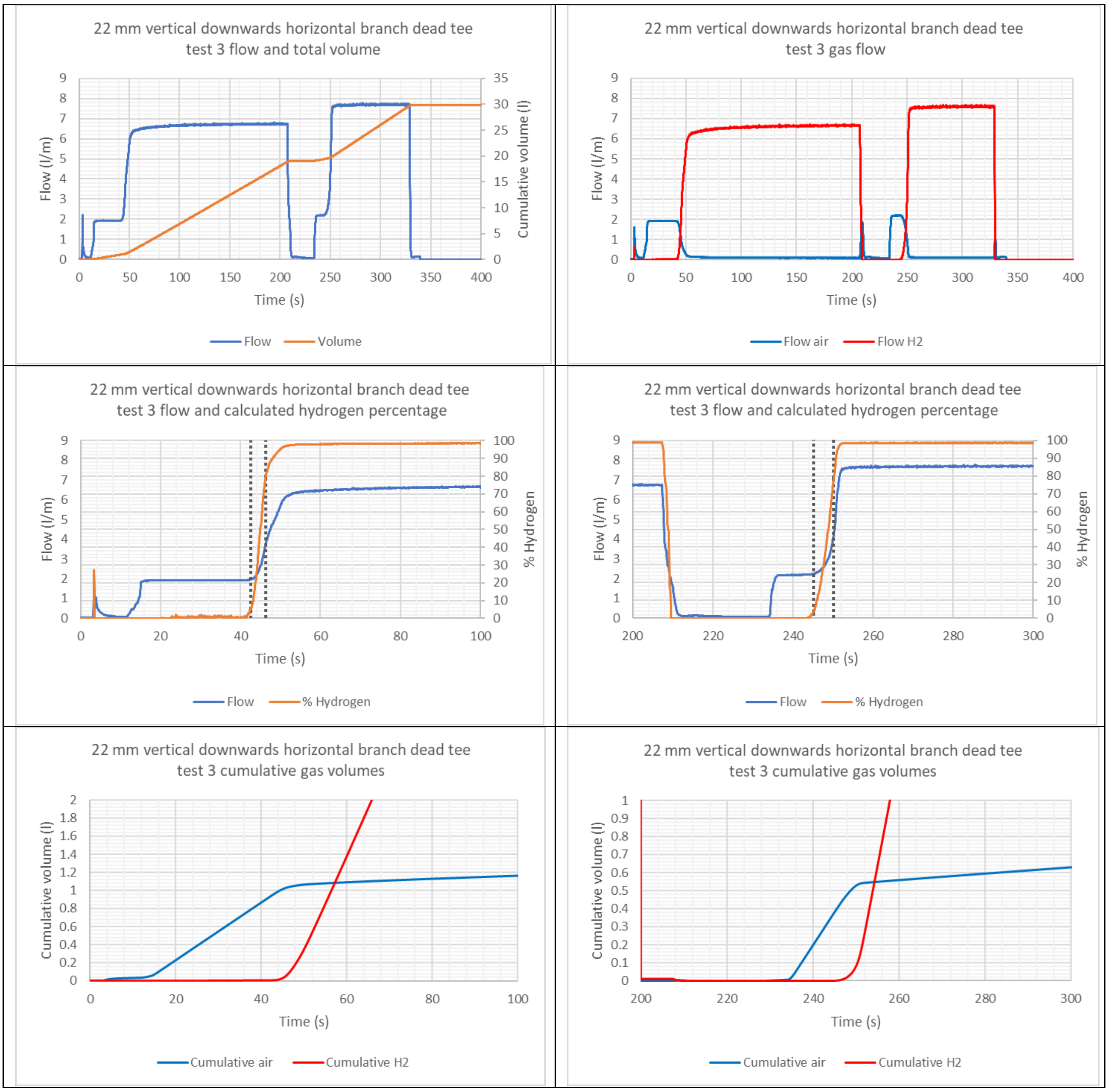


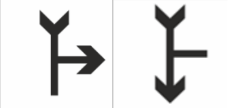
Figure 55: 22 mm vertical downwards horizontal branch dead tee test 3

1	Time (s)	Volume (l)
To start of transition (>0% H2)	31.1	0.92
Duration of transition	7.3	0.44
To end of transition (95% H2)	38.4	1.36

2	Time (s)	Volume (l)
To start of transition (>0% H2)	11.1	0.38
Duration of transition	6	0.32
To end of transition (95% H2)	17.1	0.70

	1	2	Total
Installation volume (l)	0.95	0.63	1.58
Total volume displaced to 95% hydrogen (l)	1.36	0.70	2.05
Calculated volume of air displaced (l)	1.03	0.54	1.57
Calculated volume of hydrogen displaced during purge (l)	0.33	0.16	0.49
Ratio of purge volume to installation volume	1.43	1.10	1.30

056 22 mm vertical downwards horizontal branch dead straight test 1

Test #	056 22 mm vertical downwards horizontal branch dead straight test 1	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

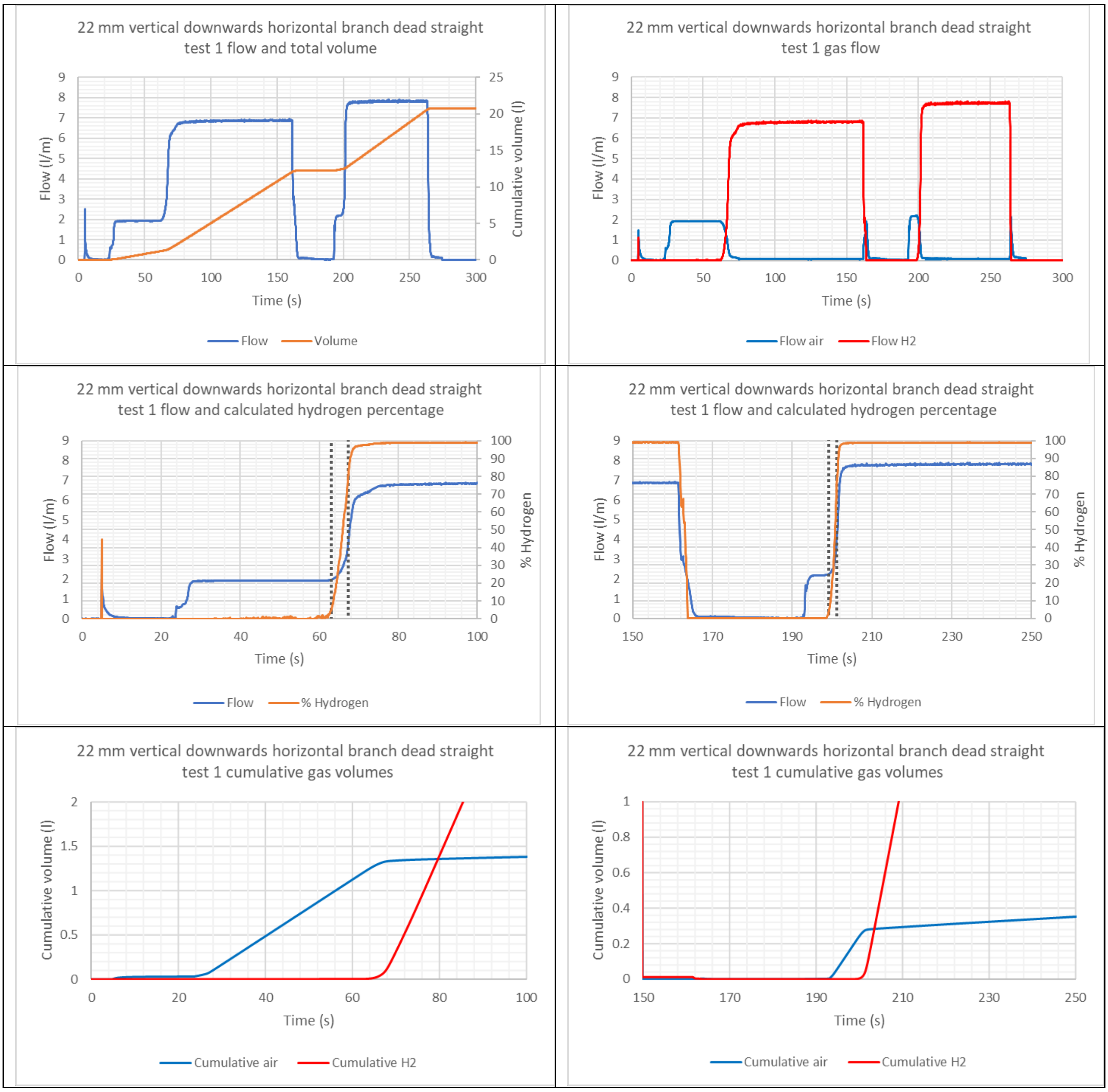


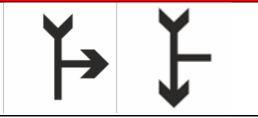
Figure 56: 22 mm vertical downwards horizontal branch dead straight test 1

1	Time (s)	Volume (l)
To start of transition (>0% H2)	39.3	0.61
Duration of transition	5.4	0.85
To end of transition (95% H2)	44.7	1.46

2	Time (s)	Volume (l)
To start of transition (>0% H2)	6.5	0.21
Duration of transition	2.6	0.14
To end of transition (95% H2)	9.1	0.35

	1	2	Total
Installation volume (l)	1.26	0.32	1.58
Total volume displaced to 95% hydrogen (l)	1.46	0.35	1.81
Calculated volume of air displaced (l)	1.30	0.28	1.58
Calculated volume of hydrogen displaced during purge (l)	0.16	0.07	0.23
Ratio of purge volume to installation volume	1.15	1.11	1.15

057 22 mm vertical downwards horizontal branch dead straight test 2

Test #	057 22 mm vertical downwards horizontal branch dead straight test 2	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

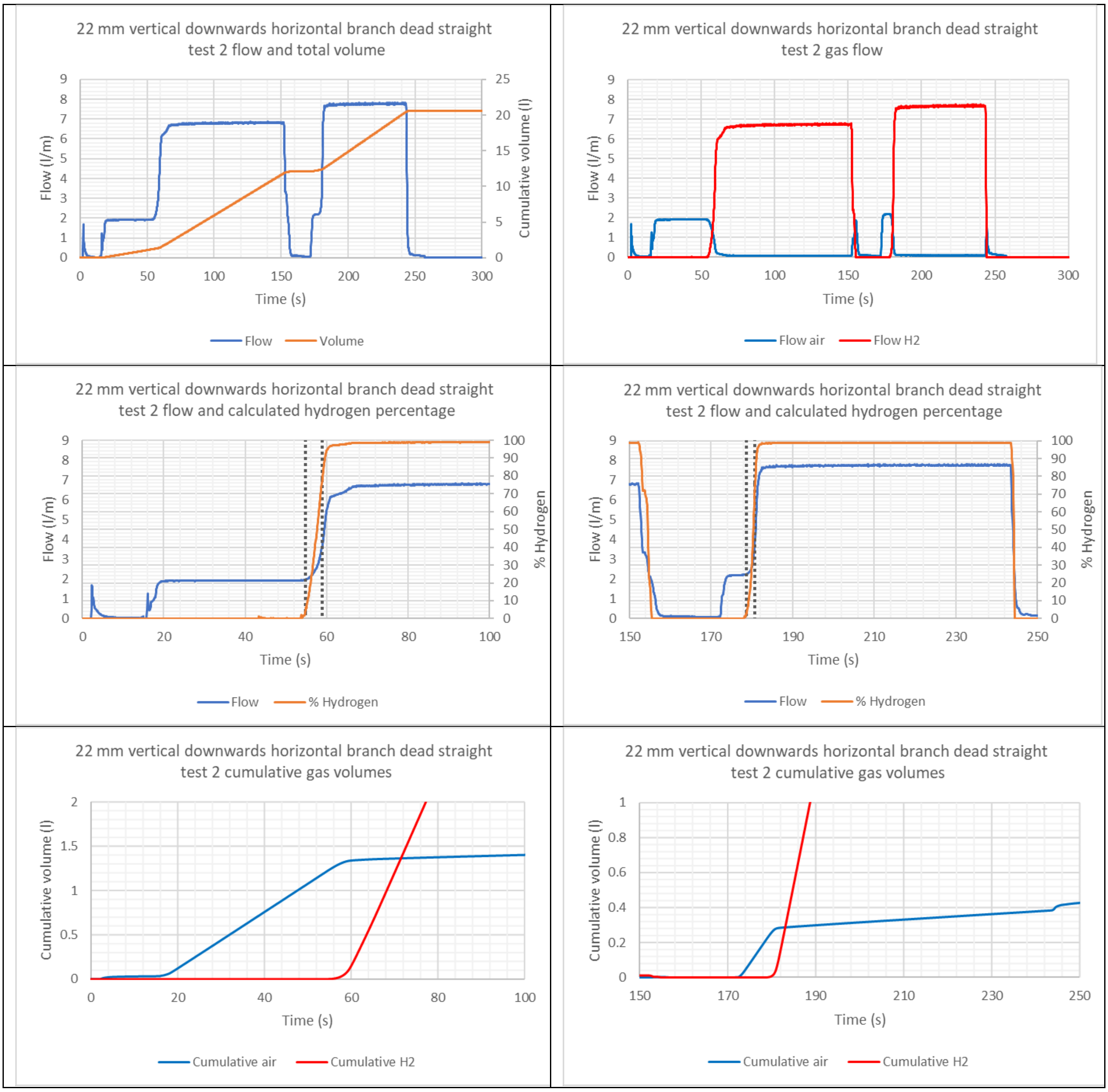


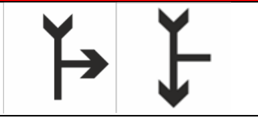
Figure 57: 22 mm vertical downwards horizontal branch dead straight test 2

1	Time (s)	Volume (l)
To start of transition (>0% H2)	38.8	0.88
Duration of transition	5.4	0.58
To end of transition (95% H2)	44.2	1.47

2	Time (s)	Volume (l)
To start of transition (>0% H2)	6.5	0.21
Duration of transition	2.6	0.14
To end of transition (95% H2)	9.1	0.35

	1	2	Total
Installation volume (l)	1.26	0.32	1.58
Total volume displaced to 95% hydrogen (l)	1.47	0.35	1.82
Calculated volume of air displaced (l)	1.31	0.28	1.59
Calculated volume of hydrogen displaced during purge (l)	0.16	0.07	0.23
Ratio of purge volume to installation volume	1.16	1.11	1.15

058 22 mm vertical downwards horizontal branch dead straight test 3

Test #	058 22 mm vertical downwards horizontal branch dead straight test 3	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

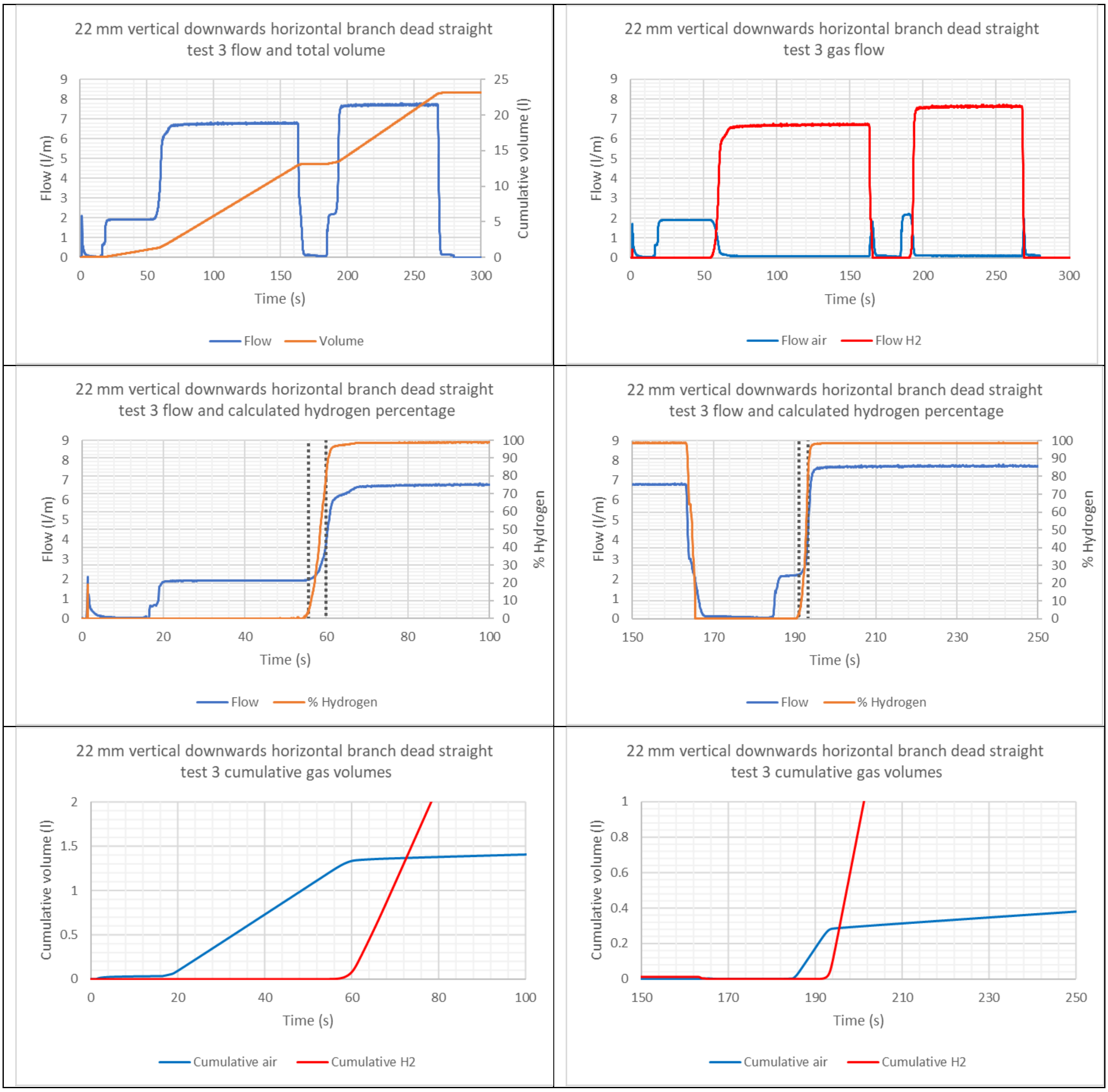


Figure 58: 22 mm vertical downwards horizontal branch dead straight test 3

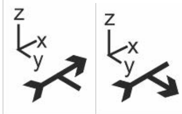
1	Time (s)	Volume (l)
To start of transition (>0% H2)	39	0.84
Duration of transition	5.6	0.62
To end of transition (95% H2)	44.6	1.46

2	Time (s)	Volume (l)
To start of transition (>0% H2)	5.9	0.20
Duration of transition	2.9	0.15
To end of transition (95% H2)	8.8	0.35

	1	2	Total
Installation volume (l)	1.26	0.32	1.58
Total volume displaced to 95% hydrogen (l)	1.46	0.35	1.81
Calculated volume of air displaced (l)	1.30	0.28	1.58
Calculated volume of hydrogen displaced during purge (l)	0.16	0.08	0.24
Ratio of purge volume to installation volume	1.16	1.12	1.15

Branch horizontal feed

059 22 mm horizontal horizontal branch dead tee test 1

Test #	059 22 mm horizontal horizontal branch dead tee test 1	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

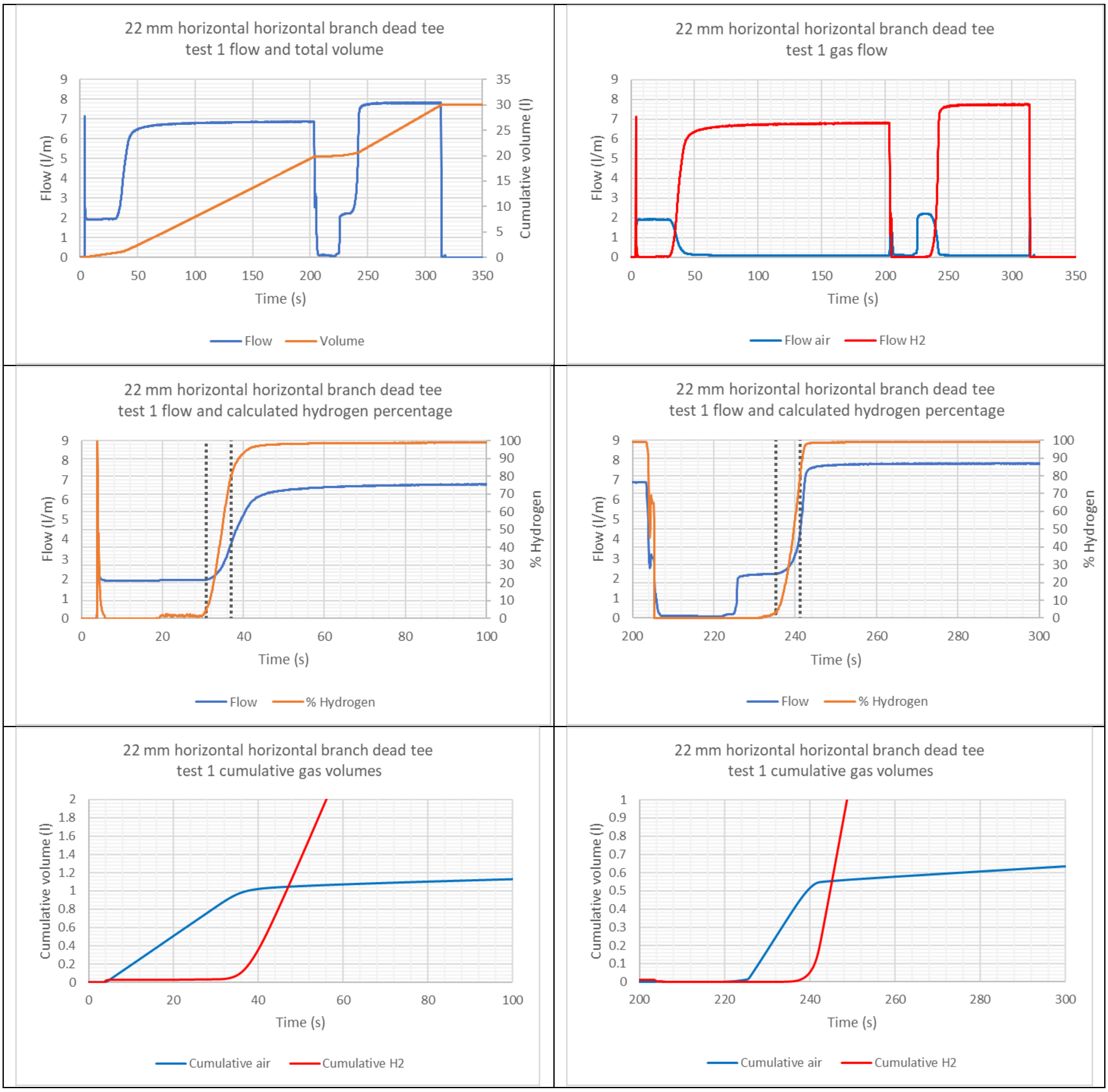


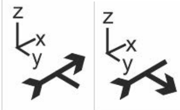
Figure 59: 22 mm horizontal horizontal branch dead tee test 1

1	Time (s)	Volume (l)
To start of transition (>0% H2)	24.9	0.80
Duration of transition	10.1	0.58
To end of transition (95% H2)	35	1.38

2	Time (s)	Volume (l)
To start of transition (>0% H2)	11.8	0.31
Duration of transition	8.4	0.41
To end of transition (95% H2)	20.2	0.72

	1	2	Total
Installation volume (l)	0.95	0.63	1.58
Total volume displaced to 95% hydrogen (l)	1.38	0.72	2.10
Calculated volume of air displaced (l)	0.94	0.55	1.48
Calculated volume of hydrogen displaced during purge (l)	0.44	0.17	0.62
Ratio of purge volume to installation volume	1.45	1.14	1.33

060 22 mm horizontal horizontal branch dead tee test 2

Test #	060 22 mm horizontal horizontal branch dead tee test 2	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

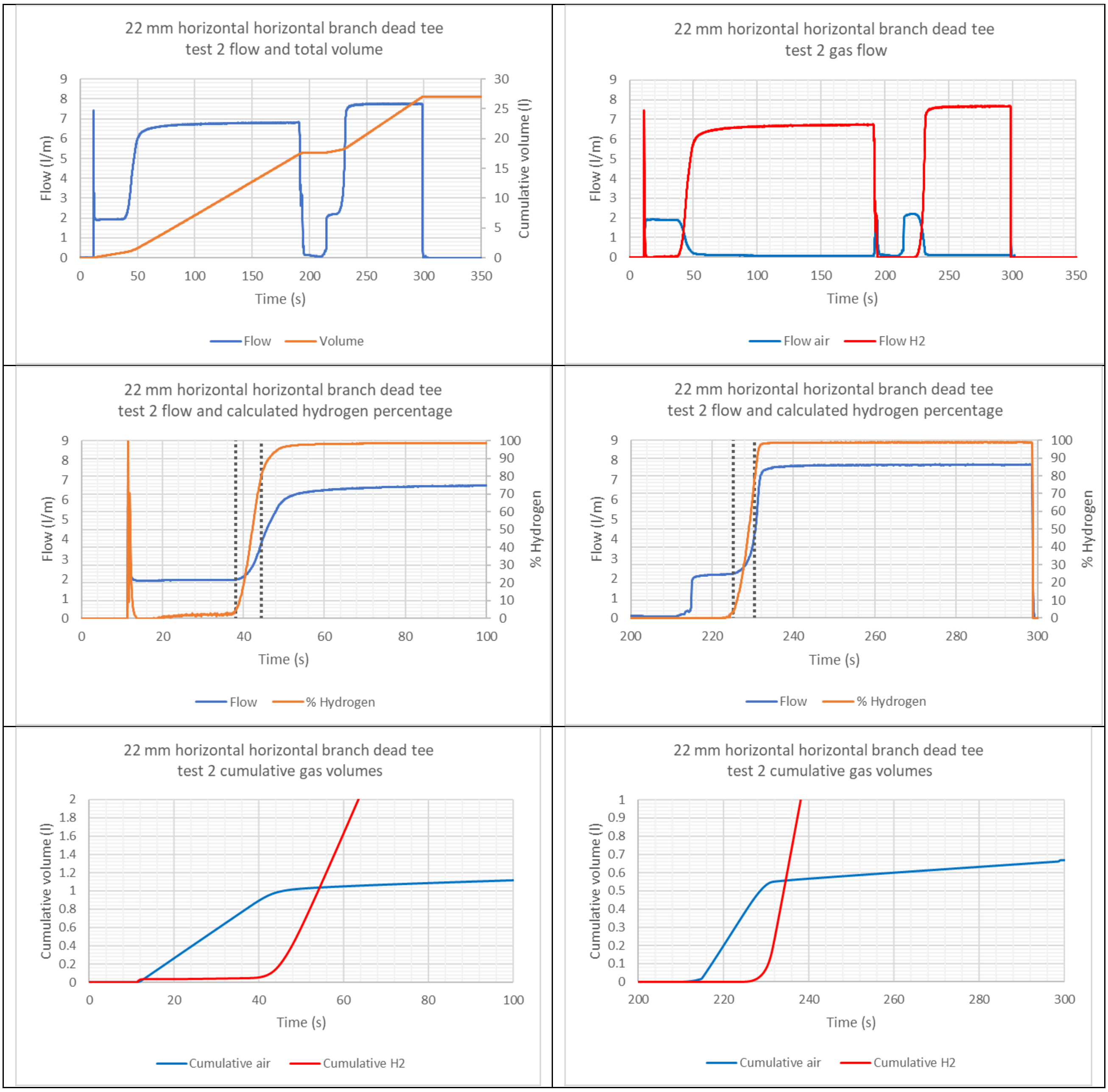


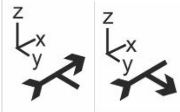
Figure 60: 22 mm horizontal horizontal branch dead tee test 2

1	Time (s)	Volume (l)
To start of transition (>0% H2)	23.1	0.74
Duration of transition	10.4	0.60
To end of transition (95% H2)	33.5	1.34

2	Time (s)	Volume (l)
To start of transition (>0% H2)	13.3	0.35
Duration of transition	7.5	0.38
To end of transition (95% H2)	20.8	0.72

	1	2	Total
Installation volume (l)	0.95	0.63	1.58
Total volume displaced to 95% hydrogen (l)	1.34	0.72	2.06
Calculated volume of air displaced (l)	0.88	0.55	1.43
Calculated volume of hydrogen displaced during purge (l)	0.46	0.17	0.63
Ratio of purge volume to installation volume	1.41	1.14	1.30

061 22 mm horizontal horizontal branch dead tee test 3

Test #	061 22 mm horizontal horizontal branch dead tee test 2	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

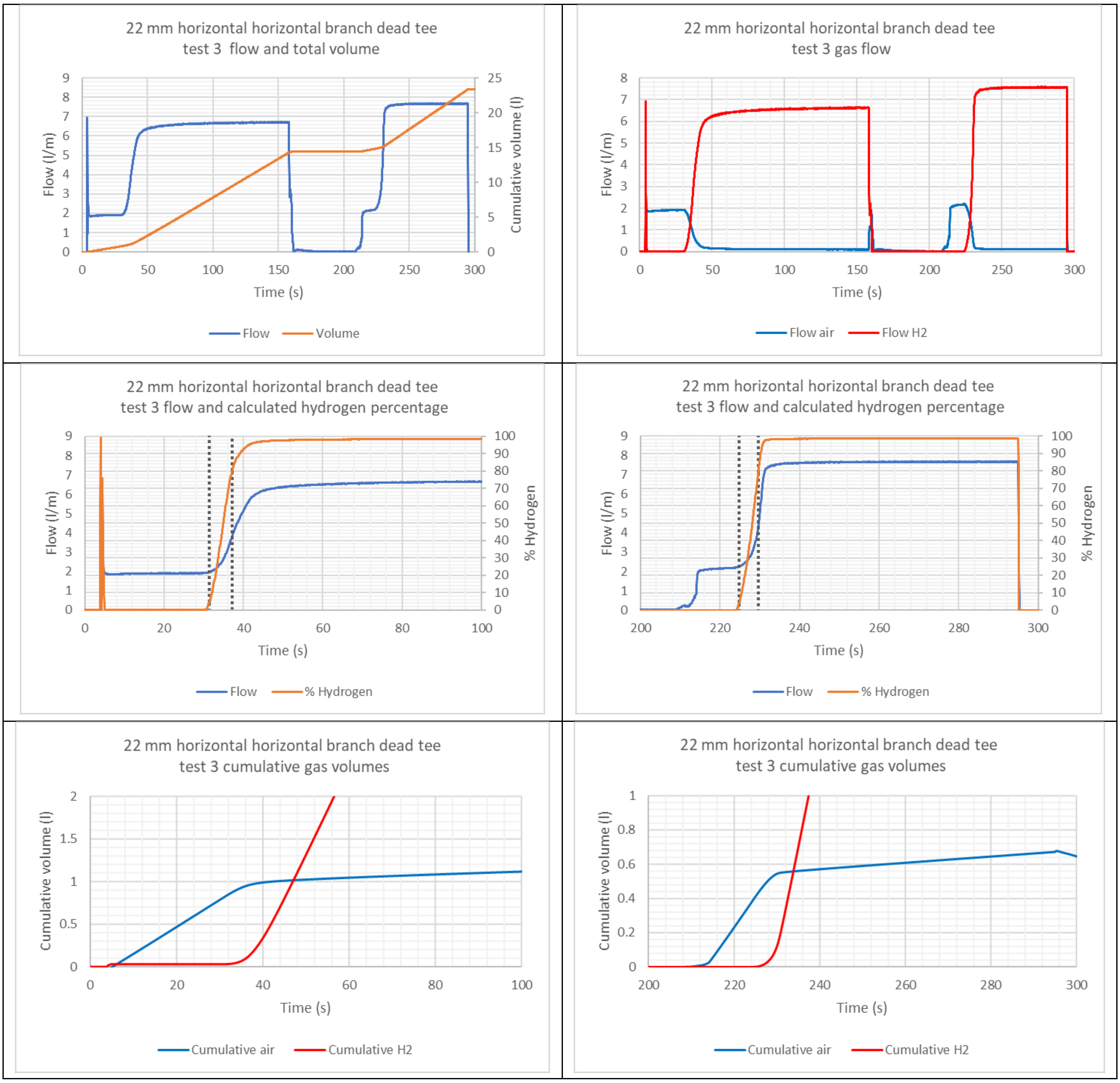


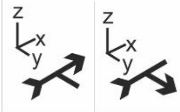
Figure 61: 22 mm horizontal horizontal branch dead tee test 3

1	Time (s)	Volume (l)
To start of transition (>0% H2)	25.9	0.82
Duration of transition	9.9	0.58
To end of transition (95% H2)	35.8	1.40

2	Time (s)	Volume (l)
To start of transition (>0% H2)	15.3	0.40
Duration of transition	6.1	0.33
To end of transition (95% H2)	21.4	0.73

	1	2	Total
Installation volume (l)	0.95	0.63	1.58
Total volume displaced to 95% hydrogen (l)	1.40	0.73	2.13
Calculated volume of air displaced (l)	0.96	0.55	1.50
Calculated volume of hydrogen displaced during purge (l)	0.45	0.17	0.62
Ratio of purge volume to installation volume	1.48	1.15	1.35

062 22 mm horizontal horizontal branch dead tee test 4

Test #	062 22 mm horizontal horizontal branch dead tee test 4	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

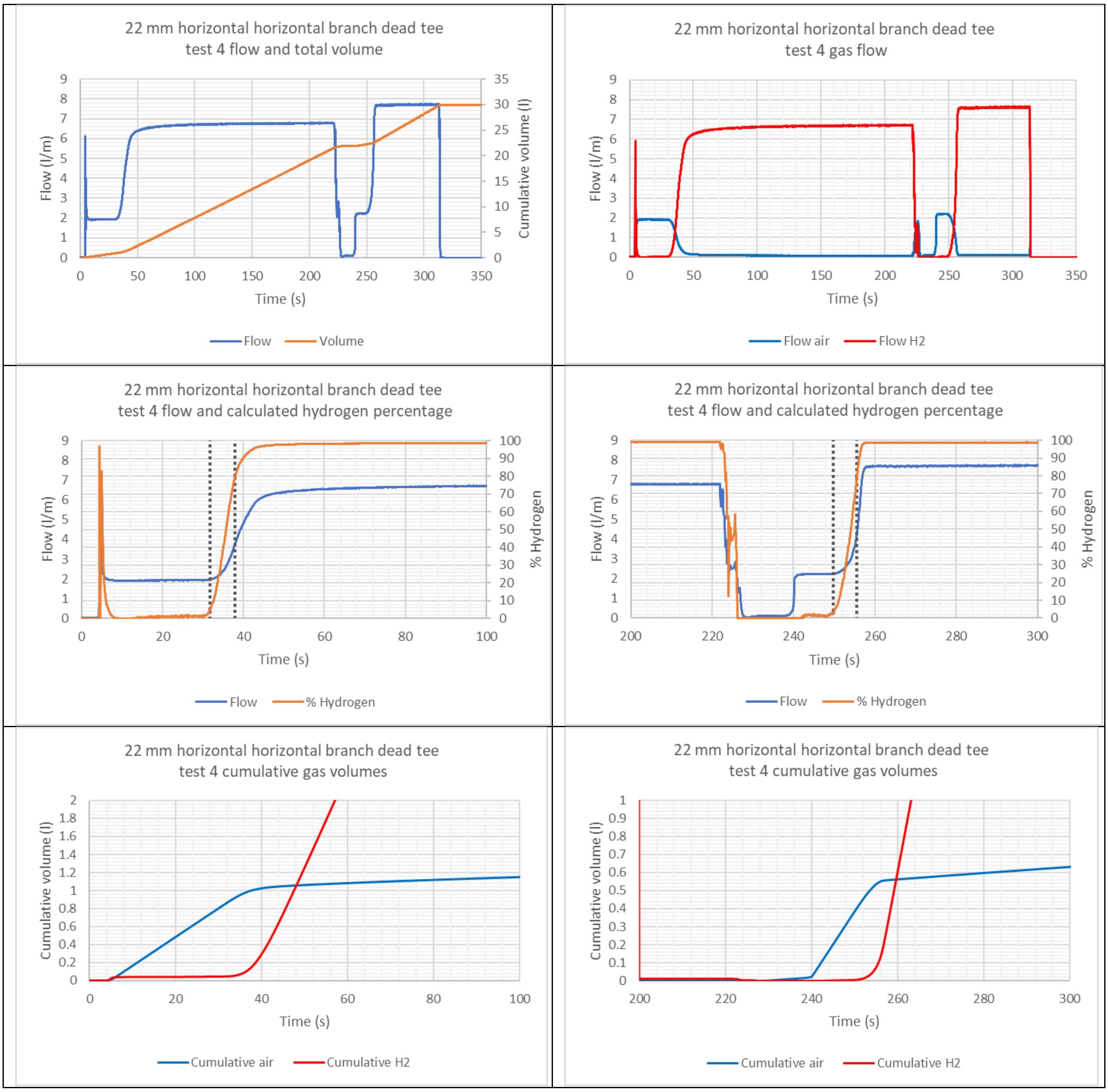


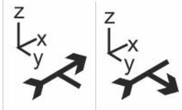
Figure 62: 22 mm horizontal horizontal branch dead tee test 4

1	Time (s)	Volume (l)
To start of transition (>0% H2)	24.6	0.79
Duration of transition	10.3	0.60
To end of transition (95% H2)	34.9	1.38

2	Time (s)	Volume (l)
To start of transition (>0% H2)	10.6	0.34
Duration of transition	7.6	0.38
To end of transition (95% H2)	18.2	0.72

	1	2	Total
Installation volume (l)	0.95	0.63	1.58
Total volume displaced to 95% hydrogen (l)	1.38	0.72	2.10
Calculated volume of air displaced (l)	0.92	0.55	1.47
Calculated volume of hydrogen displaced during purge (l)	0.46	0.18	0.64
Ratio of purge volume to installation volume	1.46	1.14	1.33

063 22 mm horizontal horizontal branch dead tee test 5

Test #	063 22 mm horizontal horizontal branch dead tee test 5	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

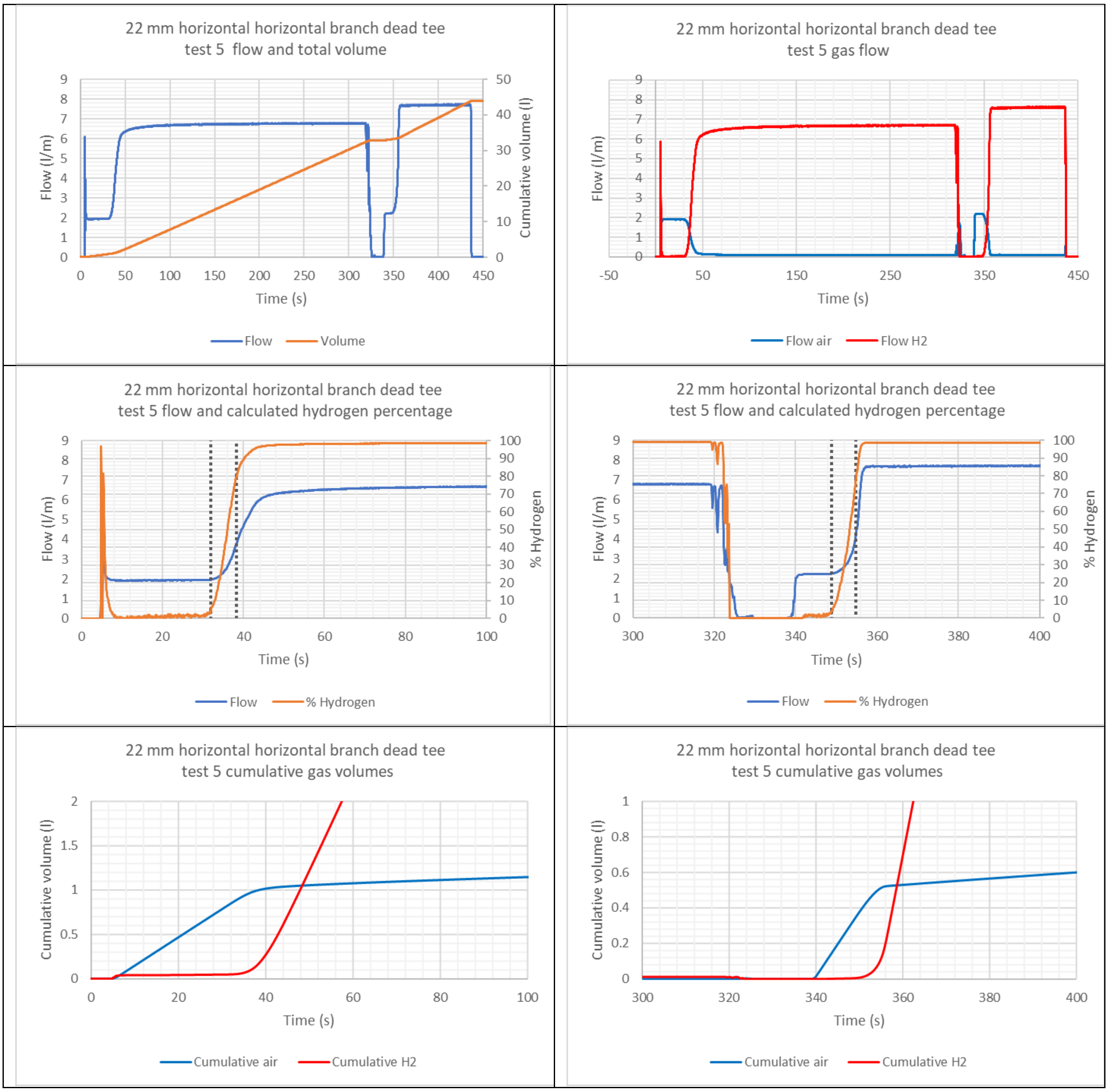


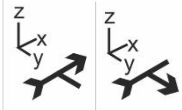
Figure 63: 22 mm horizontal horizontal branch dead tee test 5

1	Time (s)	Volume (l)
To start of transition (>0% H2)	24.1	0.78
Duration of transition	10.4	0.60
To end of transition (95% H2)	34.5	1.38

2	Time (s)	Volume (l)
To start of transition (>0% H2)	9.2	0.32
Duration of transition	7.7	0.39
To end of transition (95% H2)	16.9	0.71

	1	2	Total
Installation volume (l)	0.95	0.63	1.58
Total volume displaced to 95% hydrogen (l)	1.38	0.71	2.08
Calculated volume of air displaced (l)	0.91	0.52	1.43
Calculated volume of hydrogen displaced during purge (l)	0.46	0.19	0.65
Ratio of purge volume to installation volume	1.45	1.12	1.32

064 22 mm horizontal horizontal branch dead tee test 6

Test #	**064 22 mm horizontal horizontal branch dead tee test 6**	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

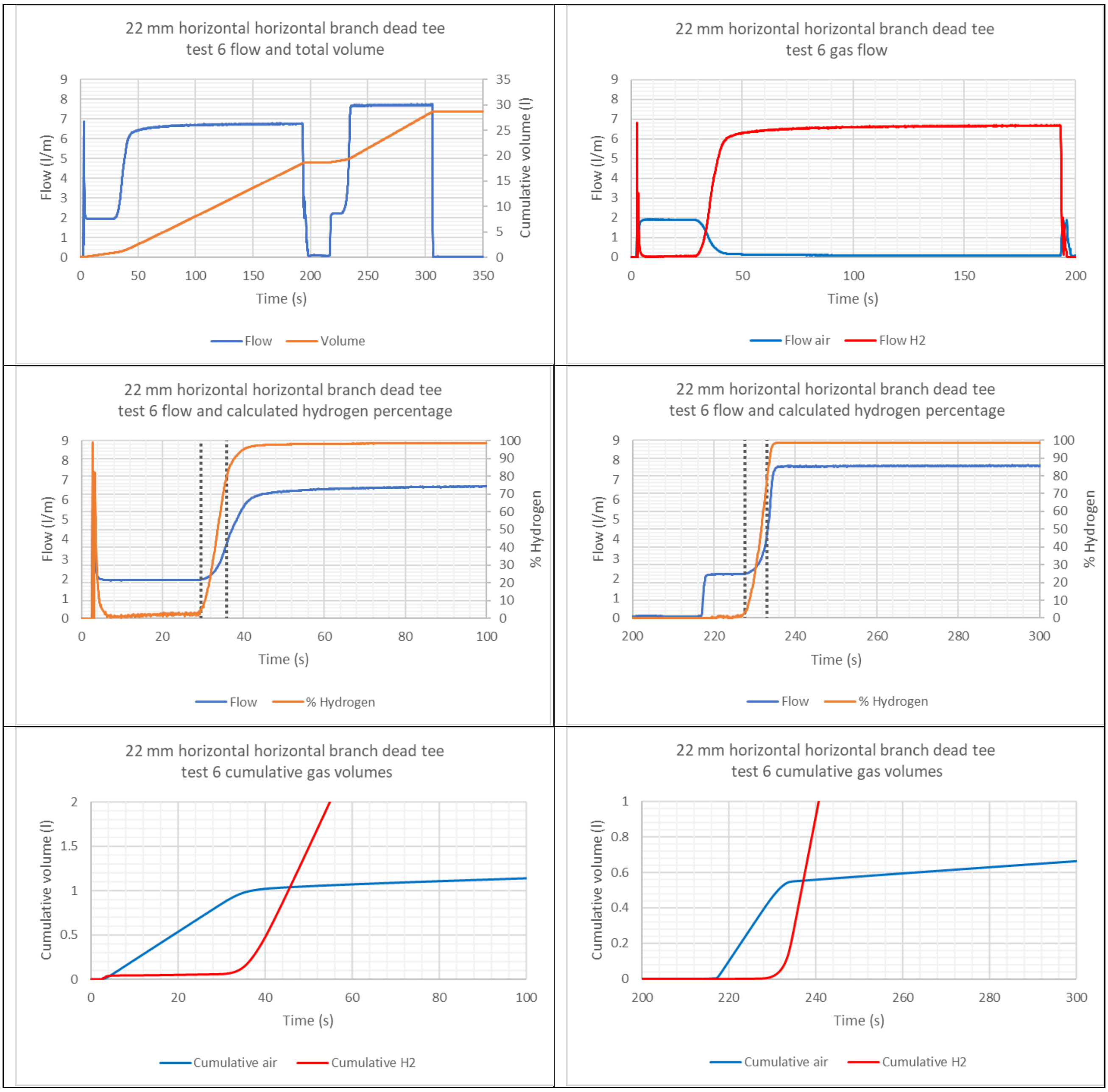


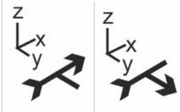
Figure 64: 22 mm horizontal horizontal branch dead tee test 6

1	Time (s)	Volume (l)
To start of transition (>0% H2)	23.9	0.77
Duration of transition	10.3	0.59
To end of transition (95% H2)	34.2	1.36

2	Time (s)	Volume (l)
To start of transition (>0% H2)	11.9	0.37
Duration of transition	6.6	0.34
To end of transition (95% H2)	18.5	0.71

	1	2	Total
Installation volume (l)	0.95	0.63	1.58
Total volume displaced to 95% hydrogen (l)	1.36	0.71	2.08
Calculated volume of air displaced (l)	0.89	0.55	1.44
Calculated volume of hydrogen displaced during purge (l)	0.47	0.17	0.64
Ratio of purge volume to installation volume	1.44	1.13	1.31

065 22 mm horizontal horizontal branch dead tee test 7

Test #	065 22 mm horizontal horizontal branch dead tee test 7	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

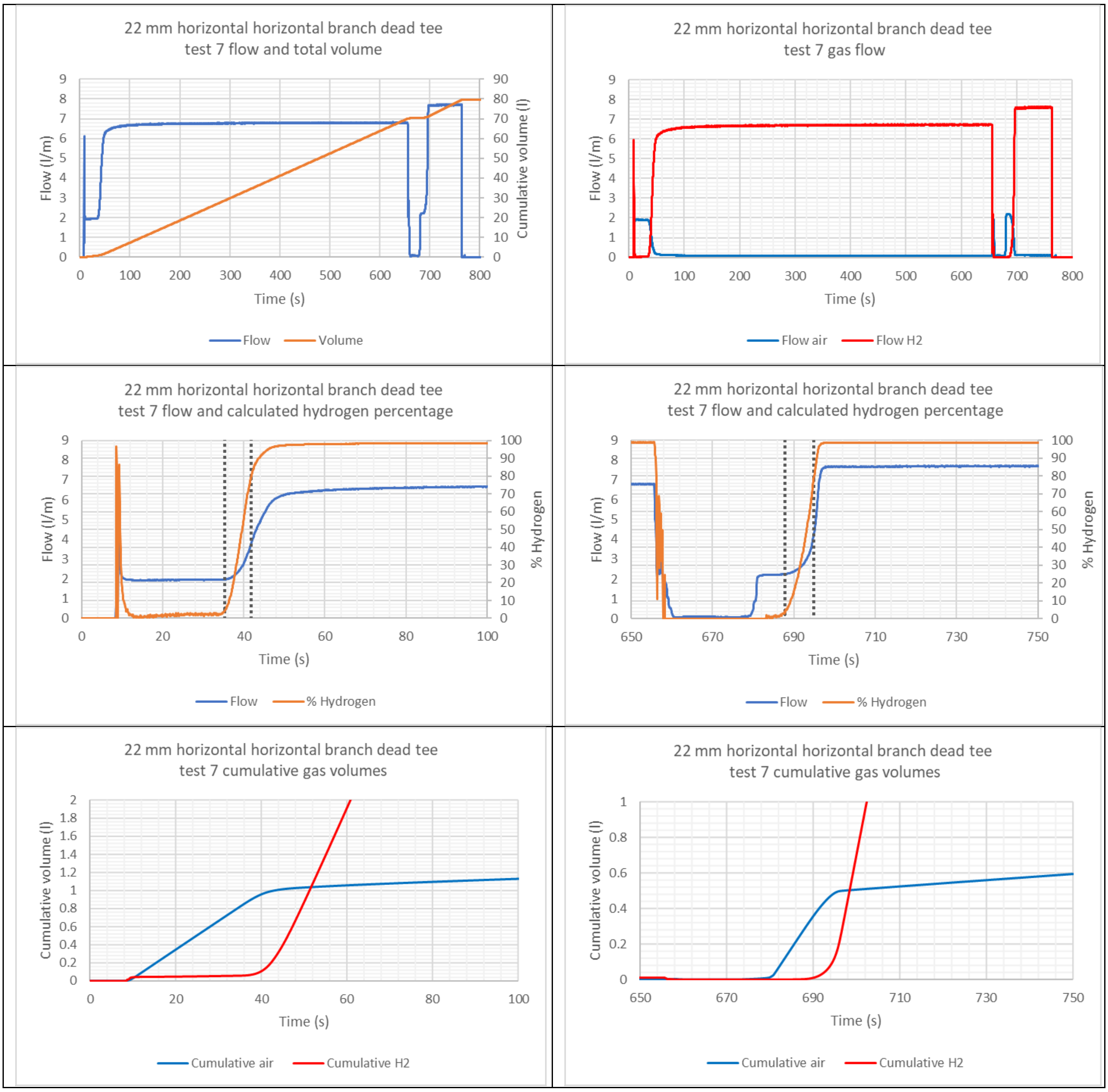


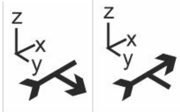
Figure 65: 22 mm horizontal horizontal branch dead tee test 7

1	Time (s)	Volume (l)
To start of transition (>0% H2)	23.7	0.76
Duration of transition	10.5	0.60
To end of transition (95% H2)	34.2	1.36

2	Time (s)	Volume (l)
To start of transition (>0% H2)	9.3	0.24
Duration of transition	9.1	0.46
To end of transition (95% H2)	18.4	0.70

	1	2	Total
Installation volume (l)	0.95	0.63	1.58
Total volume displaced to 95% hydrogen (l)	1.36	0.70	2.06
Calculated volume of air displaced (l)	0.89	0.50	1.39
Calculated volume of hydrogen displaced during purge (l)	0.47	0.21	0.68
Ratio of purge volume to installation volume	1.44	1.10	1.30

066 22 mm horizontal horizontal branch dead straight test 1

Test #	**066 22 mm horizontal horizontal branch dead straight test 1**	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

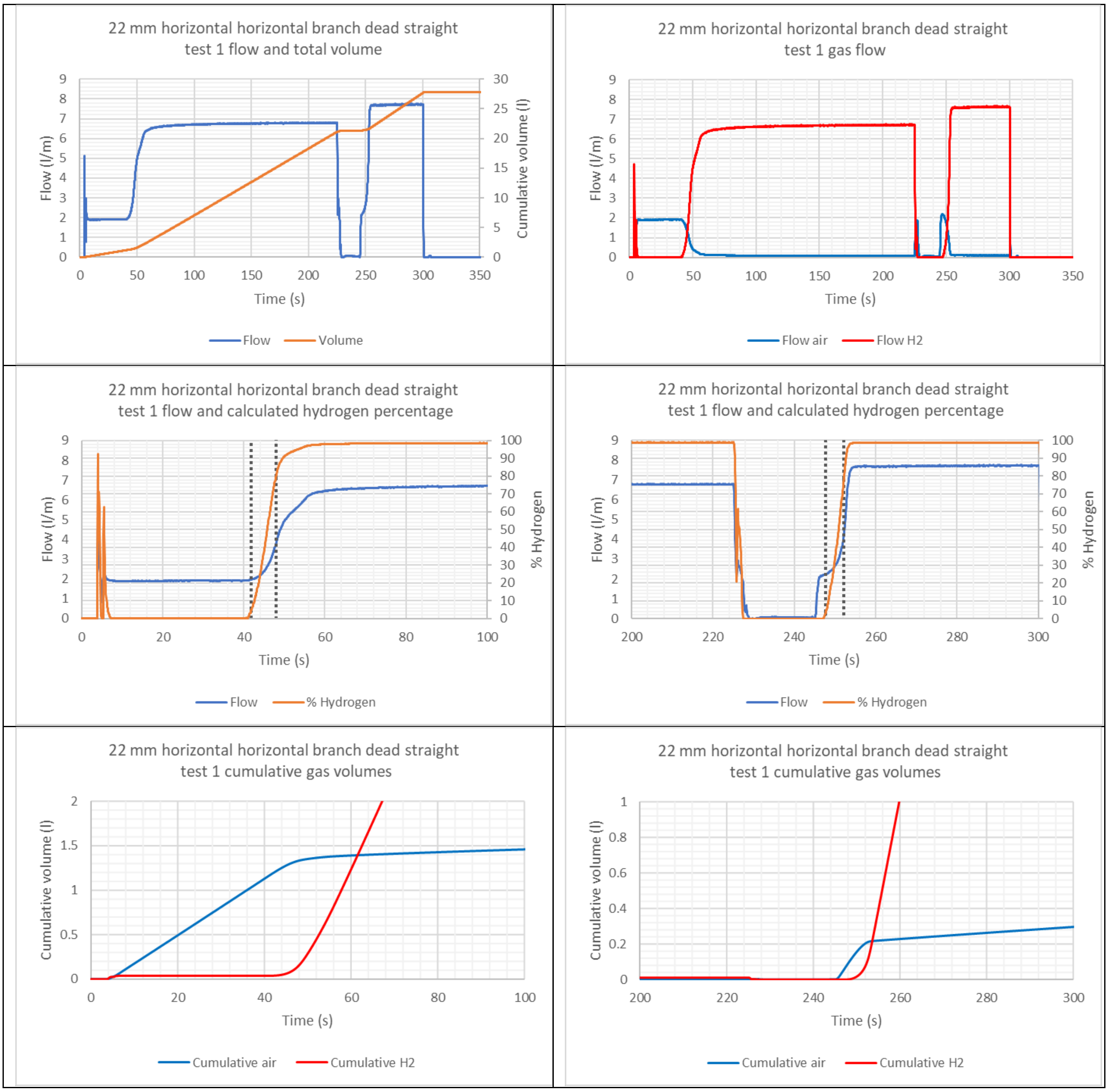


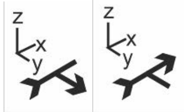
Figure 66: 22 mm horizontal horizontal branch dead straight test 1

1	Time (s)	Volume (l)
To start of transition (>0% H2)	34.6	1.10
Duration of transition	11.4	0.70
To end of transition (95% H2)	46	1.80

2	Time (s)	Volume (l)
To start of transition (>0% H2)	2.3	0.07
Duration of transition	5.5	0.29
To end of transition (95% H2)	7.8	0.36

	1	2	Total
Installation volume (l)	1.26	0.32	1.58
Total volume displaced to 95% hydrogen (l)	1.80	0.36	2.16
Calculated volume of air displaced (l)	1.24	0.21	1.46
Calculated volume of hydrogen displaced during purge (l)	0.56	0.15	0.71
Ratio of purge volume to installation volume	1.43	1.14	1.37

067 22 mm horizontal horizontal branch dead straight test 2

Test #	067 22 mm horizontal horizontal branch dead straight test 2	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

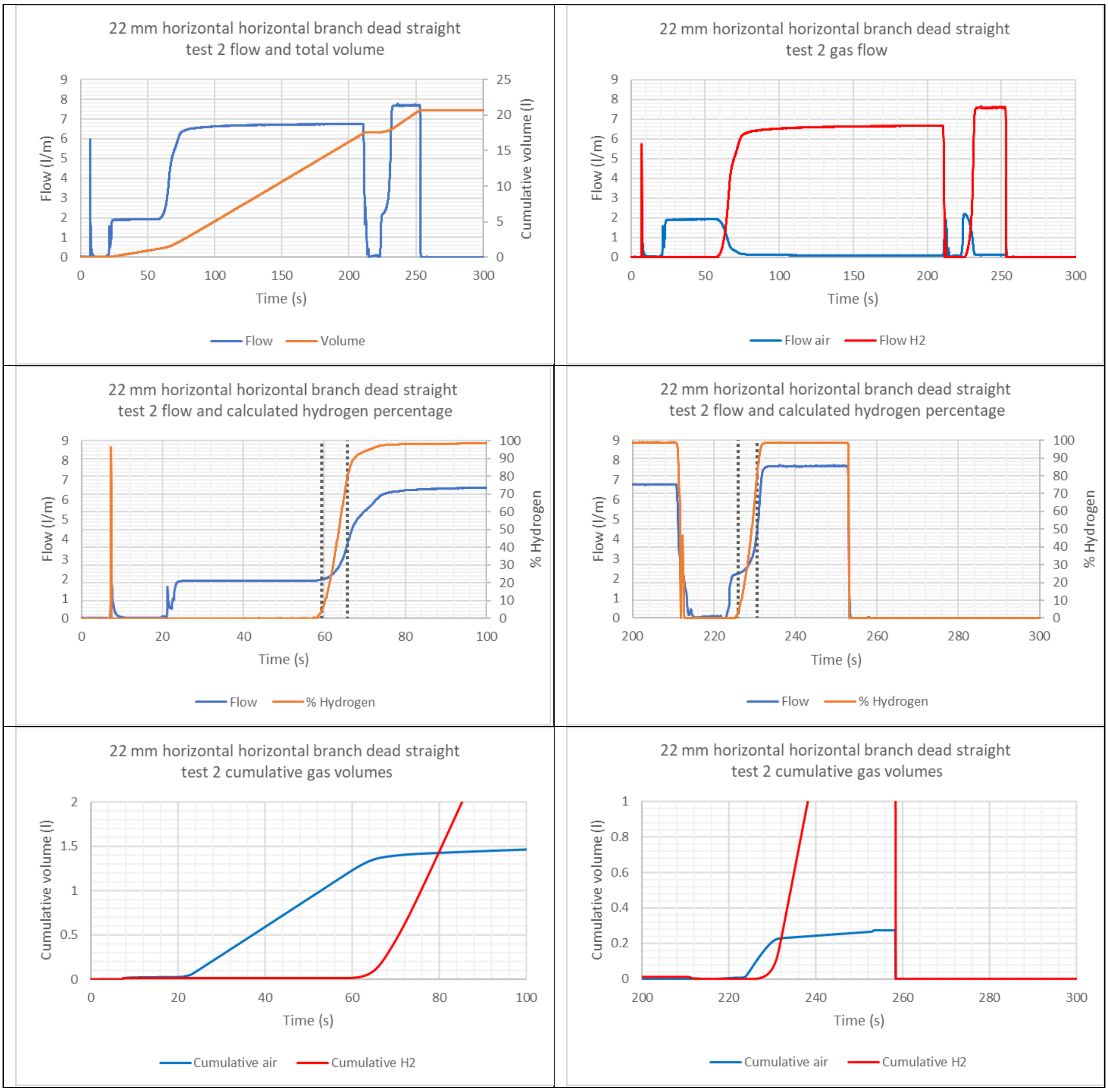


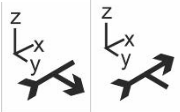
Figure 67: 22 mm horizontal horizontal branch dead straight test 2

1	Time (s)	Volume (l)
To start of transition (>0% H2)	37.7	0.72
Duration of transition	12.2	1.18
To end of transition (95% H2)	49.9	1.90

2	Time (s)	Volume (l)
To start of transition (>0% H2)	2.5	0.07
Duration of transition	5.8	0.30
To end of transition (95% H2)	8.3	0.37

	1	2	Total
Installation volume (l)	1.26	0.32	1.58
Total volume displaced to 95% hydrogen (l)	1.90	0.37	2.27
Calculated volume of air displaced (l)	1.36	0.23	1.59
Calculated volume of hydrogen displaced during purge (l)	0.54	0.15	0.69
Ratio of purge volume to installation volume	1.50	1.17	1.43

068 22 mm horizontal horizontal branch dead straight test 3

Test #	068 22 mm horizontal horizontal branch dead straight test 3	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

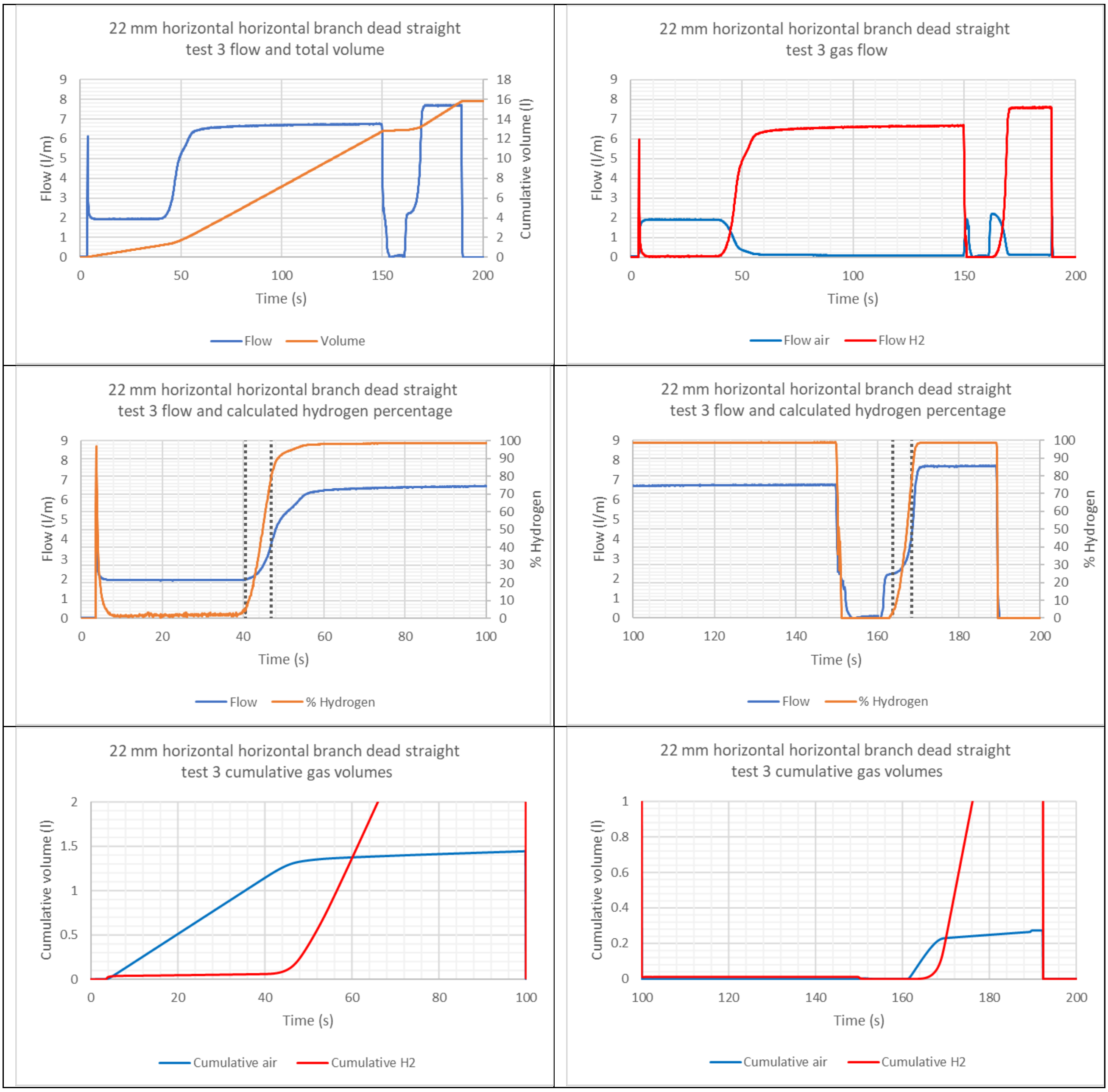


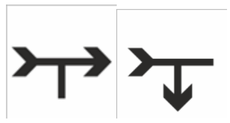
Figure 68: 22 mm horizontal horizontal branch dead straight test 3

1	Time (s)	Volume (l)
To start of transition (>0% H2)	31	1.03
Duration of transition	14	0.75
To end of transition (95% H2)	45	1.79

2	Time (s)	Volume (l)
To start of transition (>0% H2)	2.4	0.07
Duration of transition	5.9	0.30
To end of transition (95% H2)	8.3	0.38

	1	2	Total
Installation volume (l)	1.26	0.32	1.58
Total volume displaced to 95% hydrogen (l)	1.79	0.38	2.17
Calculated volume of air displaced (l)	1.21	0.23	1.44
Calculated volume of hydrogen displaced during purge (l)	0.57	0.15	0.72
Ratio of purge volume to installation volume	1.41	1.20	1.37

069 22 mm horizontal vertical downwards branch dead tee test 1

Test #	069 22 mm horizontal vertical downwards branch dead tee test 1	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

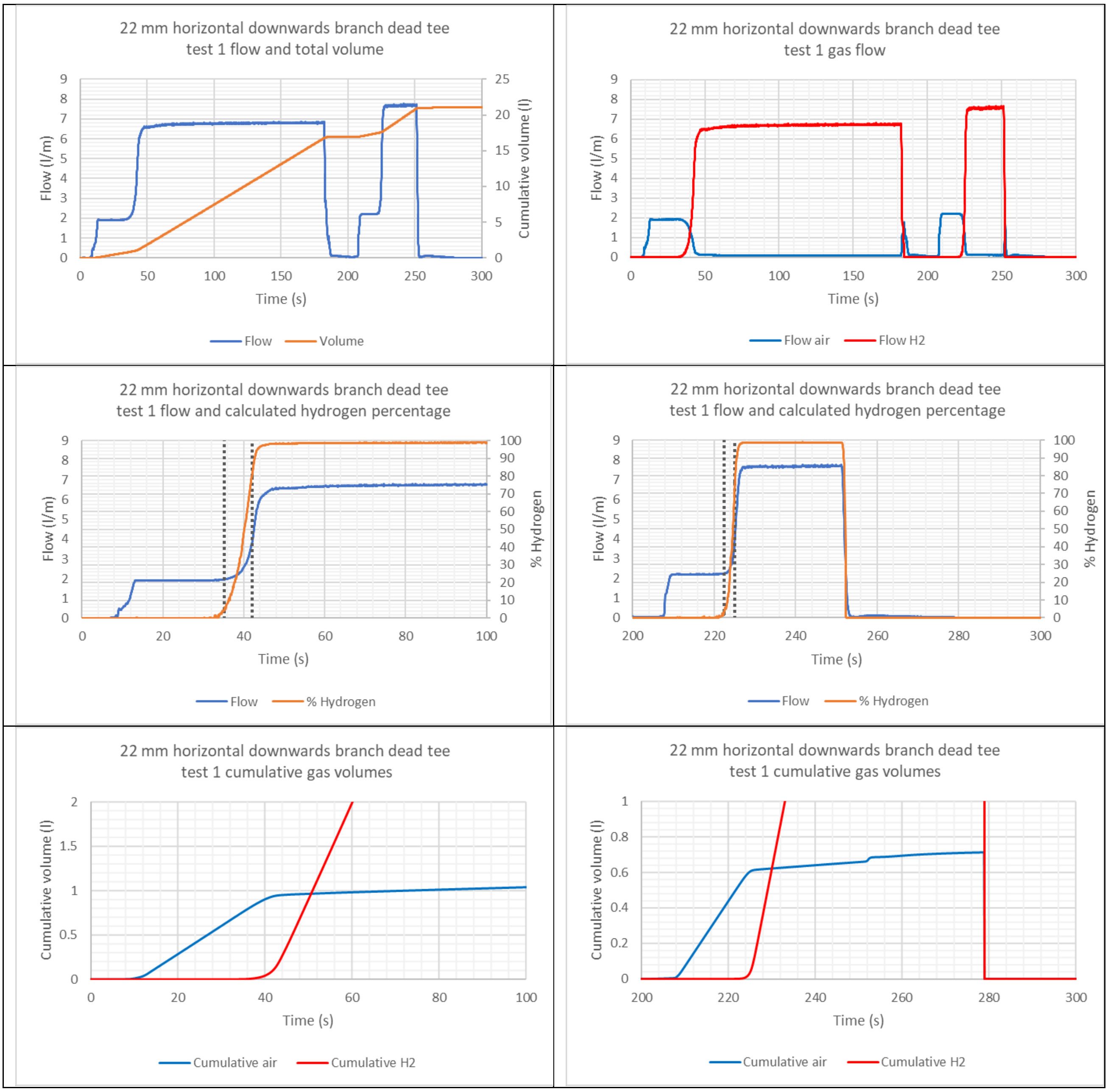


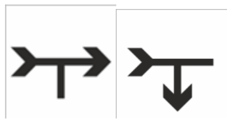
Figure 69: 22 mm horizontal vertical downwards branch dead tee test 1

1	Time (s)	Volume (l)
To start of transition (>0% H2)	25.3	0.74
Duration of transition	9.1	0.41
To end of transition (95% H2)	34.4	1.15

2	Time (s)	Volume (l)
To start of transition (>0% H2)	14.7	0.51
Duration of transition	3.9	0.20
To end of transition (95% H2)	18.6	0.71

	1	2	Total
Installation volume (l)	0.95	0.63	1.58
Total volume displaced to 95% hydrogen (l)	1.15	0.71	1.86
Calculated volume of air displaced (l)	0.95	0.61	1.56
Calculated volume of hydrogen displaced during purge (l)	0.20	0.10	0.30
Ratio of purge volume to installation volume	1.21	1.12	1.18

070 22 mm horizontal vertical downwards branch dead tee test 2

Test #	070 22 mm horizontal vertical downwards branch dead tee test 2	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

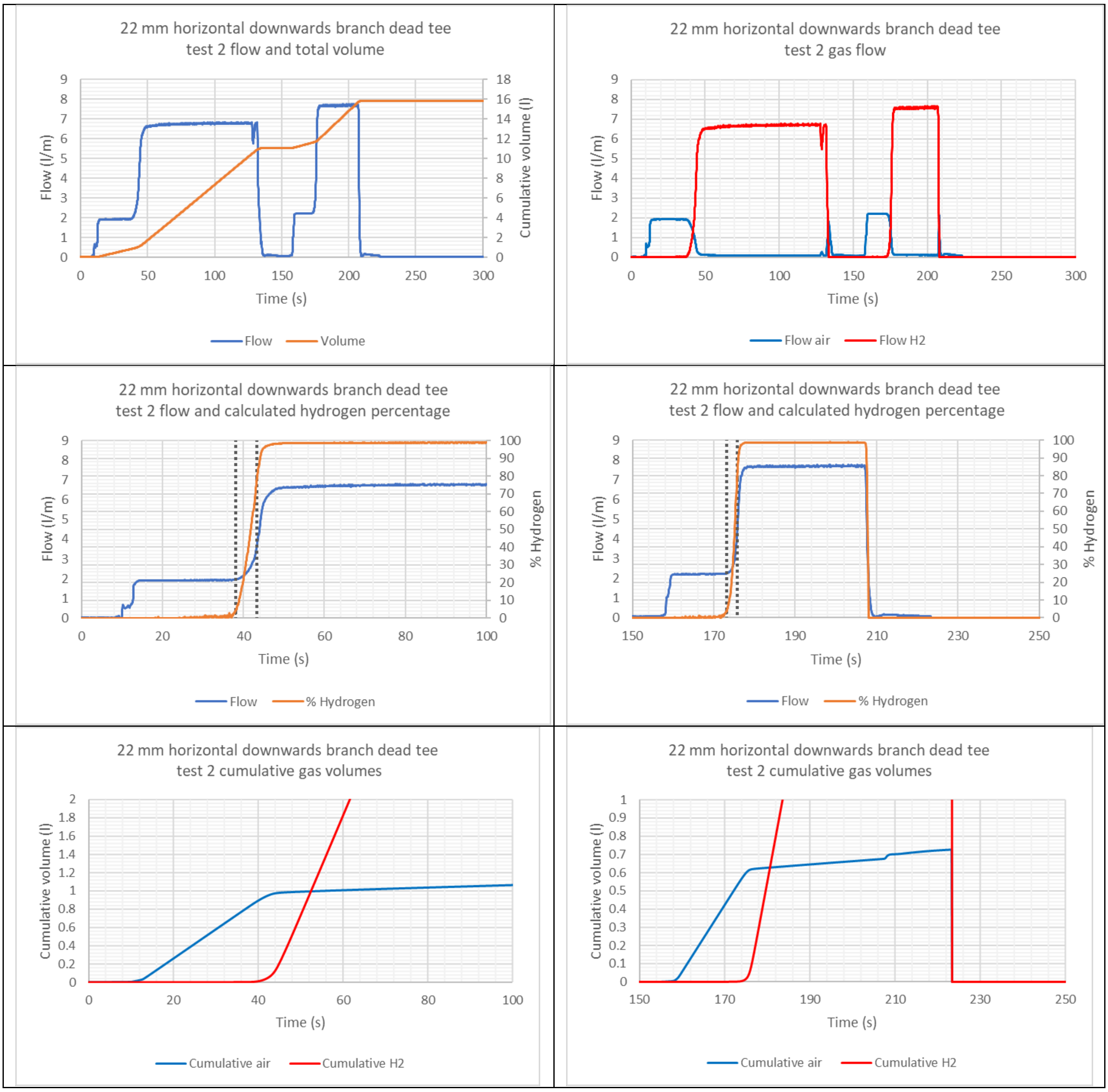


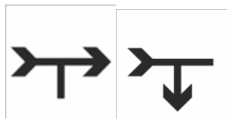
Figure 70: 22 mm horizontal vertical downwards branch dead tee test 2

1	Time (s)	Volume (l)
To start of transition (>0% H2)	27.6	0.83
Duration of transition	7.1	0.33
To end of transition (95% H2)	34.7	1.16

2	Time (s)	Volume (l)
To start of transition (>0% H2)	15.6	0.52
Duration of transition	3.7	0.19
To end of transition (95% H2)	19.3	0.71

	1	2	Total
Installation volume (l)	0.95	0.63	1.58
Total volume displaced to 95% hydrogen (l)	1.16	0.71	1.87
Calculated volume of air displaced (l)	0.98	0.62	1.60
Calculated volume of hydrogen displaced during purge (l)	0.18	0.09	0.27
Ratio of purge volume to installation volume	1.22	1.12	1.18

071 22 mm horizontal vertical downwards branch dead tee test 3

Test #	071 22 mm horizontal vertical downwards branch dead tee test 3	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

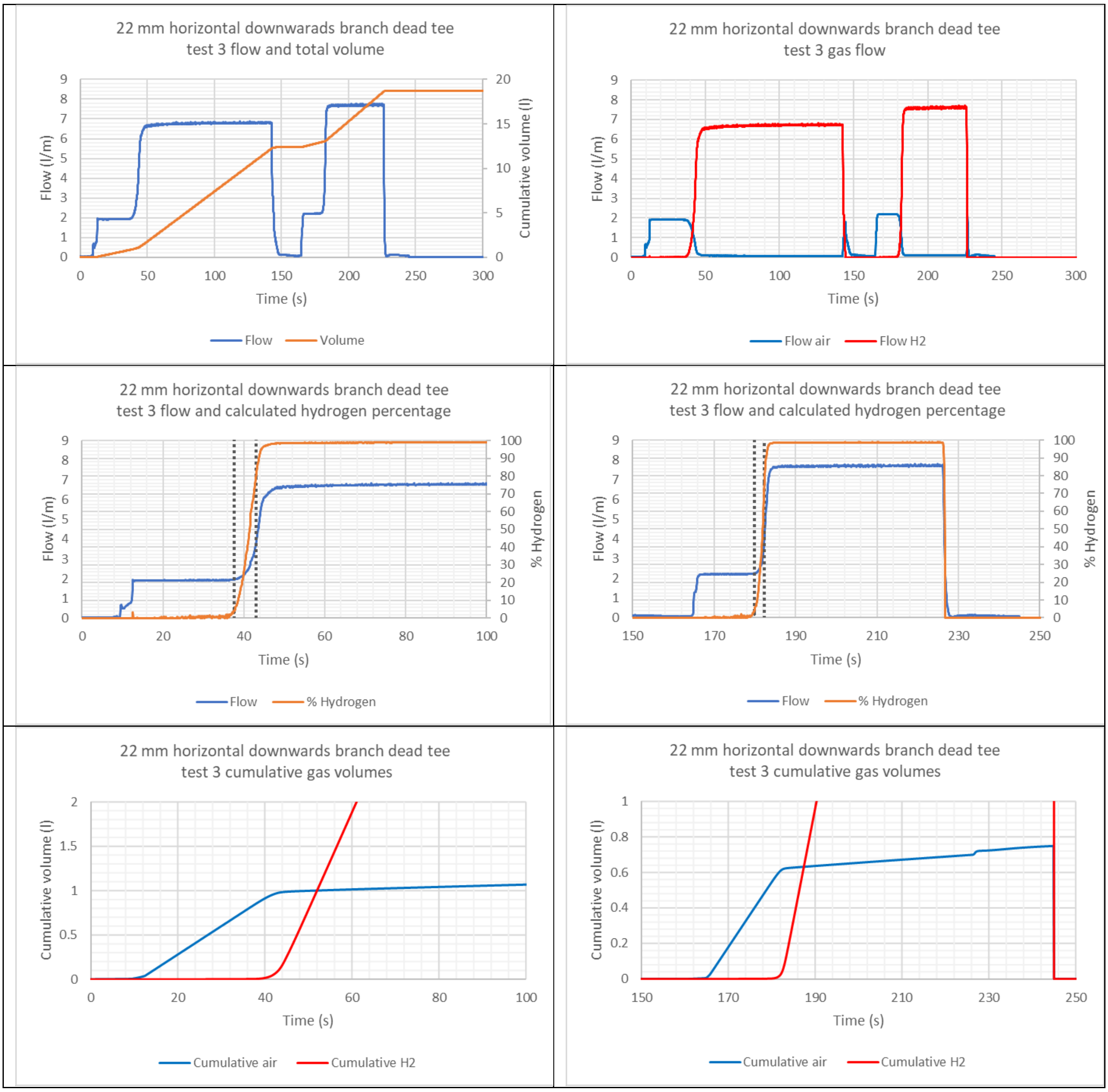


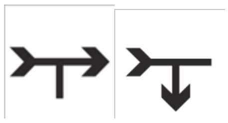
Figure 71: 22 mm horizontal vertical downwards branch dead tee test 3

1	Time (s)	Volume (l)
To start of transition (>0% H2)	27.7	0.81
Duration of transition	7.1	0.35
To end of transition (95% H2)	34.8	1.16

2	Time (s)	Volume (l)
To start of transition (>0% H2)	15.1	0.51
Duration of transition	3.7	0.19
To end of transition (95% H2)	18.8	0.70

	1	2	Total
Installation volume (l)	0.95	0.63	1.58
Total volume displaced to 95% hydrogen (l)	1.16	0.70	1.86
Calculated volume of air displaced (l)	0.97	0.62	1.60
Calculated volume of hydrogen displaced during purge (l)	0.19	0.09	0.27
Ratio of purge volume to installation volume	1.22	1.11	1.18

072 22 mm horizontal vertical downwards branch dead tee test 4 (pause)

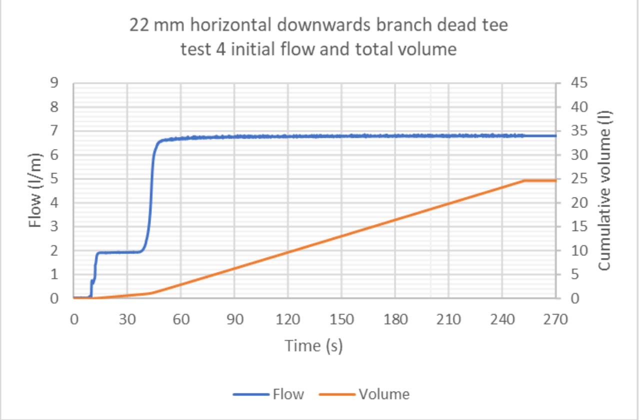
Test #	072 22 mm horizontal vertical downwards branch dead tee test 4	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

See graphs overleaf

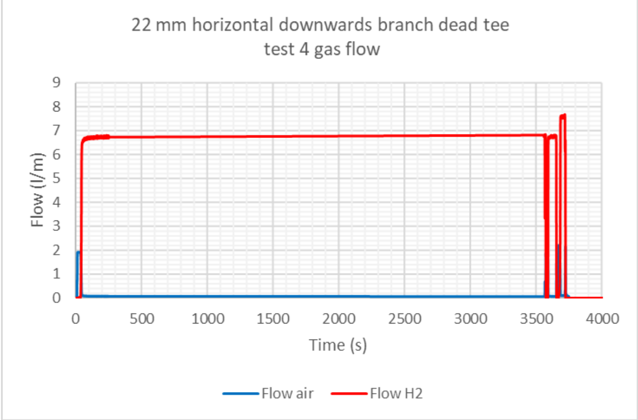
1	Time (s)	Volume (l)
To start of transition (>0% H2)	27.3	0.047
Duration of transition	7.1	1.11
To end of transition (95% H2)	34.4	1.16

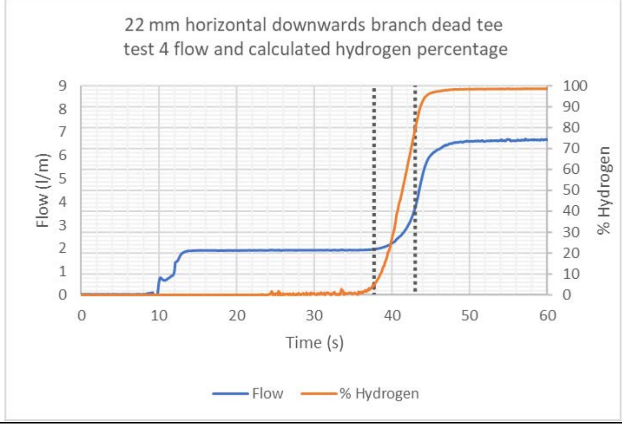
2	Time (s)	Volume (l)
To start of transition (>0% H2)	2.1	0.046
Duration of transition	13.6	0.63
To end of transition (95% H2)	15.7	0.67

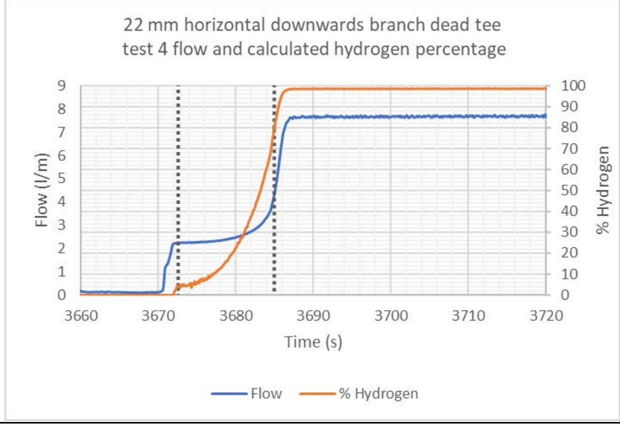
	1	2	Total
Installation volume (l)	0.95	0.63	1.58
Total volume displaced to 95% hydrogen (l)	1.16	0.67	1.83
Calculated volume of air displaced (l)	0.98	0.45	1.43
Calculated volume of hydrogen displaced during purge (l)	0.19	0.22	0.41
Ratio of purge volume to installation volume	1.22	1.07	1.14

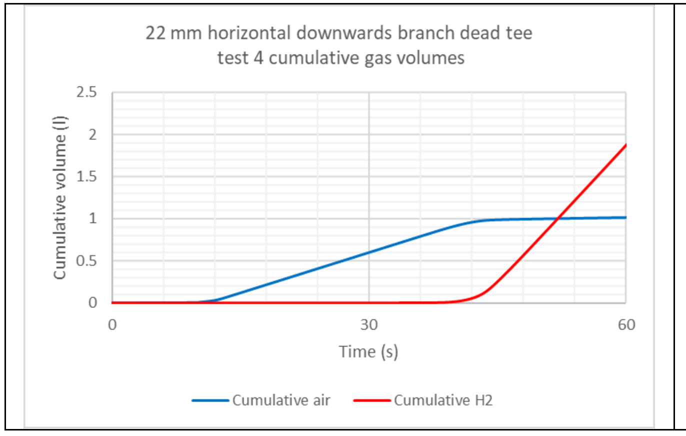

22 mm horizontal downwards branch dead tee
test 4 initial flow and total volume
Flow (l/m)
Cumulative volume (l)
Time (s)
Flow
Volume

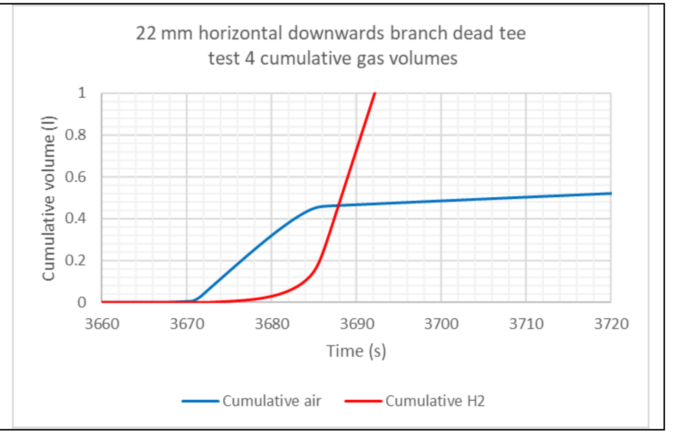

22 mm horizontal downwards branch dead tee
test 4 flow and total volume
Flow (l/m)
Cumulative volume (l)
Time (s)
Flow
Volume


22 mm horizontal downwards branch dead tee
test 4 gas flow
Flow (l/m)
Time (s)
Flow air
Flow H2

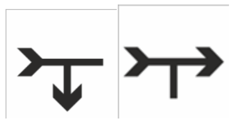

22 mm horizontal downwards branch dead tee
test 4 flow and calculated hydrogen percentage
Flow (l/m)
% Hydrogen
Time (s)
Flow
% Hydrogen


22 mm horizontal downwards branch dead tee
test 4 flow and calculated hydrogen percentage
Flow (l/m)
% Hydrogen
Time (s)
Flow
% Hydrogen


22 mm horizontal downwards branch dead tee
test 4 cumulative gas volumes
Cumulative volume (l)
2.5
2
1.5
1
0.5
0
0
30
60
Time (s)
Cumulative air
Cumulative H2


22 mm horizontal downwards branch dead tee
test 4 cumulative gas volumes
Cumulative volume (l)
1
0.8
0.6
0.4
0.2
0
3660
3670
3680
3690
3700
3710
3720
Time (s)
Cumulative air
Cumulative H2

073 22 mm horizontal vertical downwards branch dead straight test 1

Test #	073 22 mm horizontal vertical downwards branch dead straight test 1	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

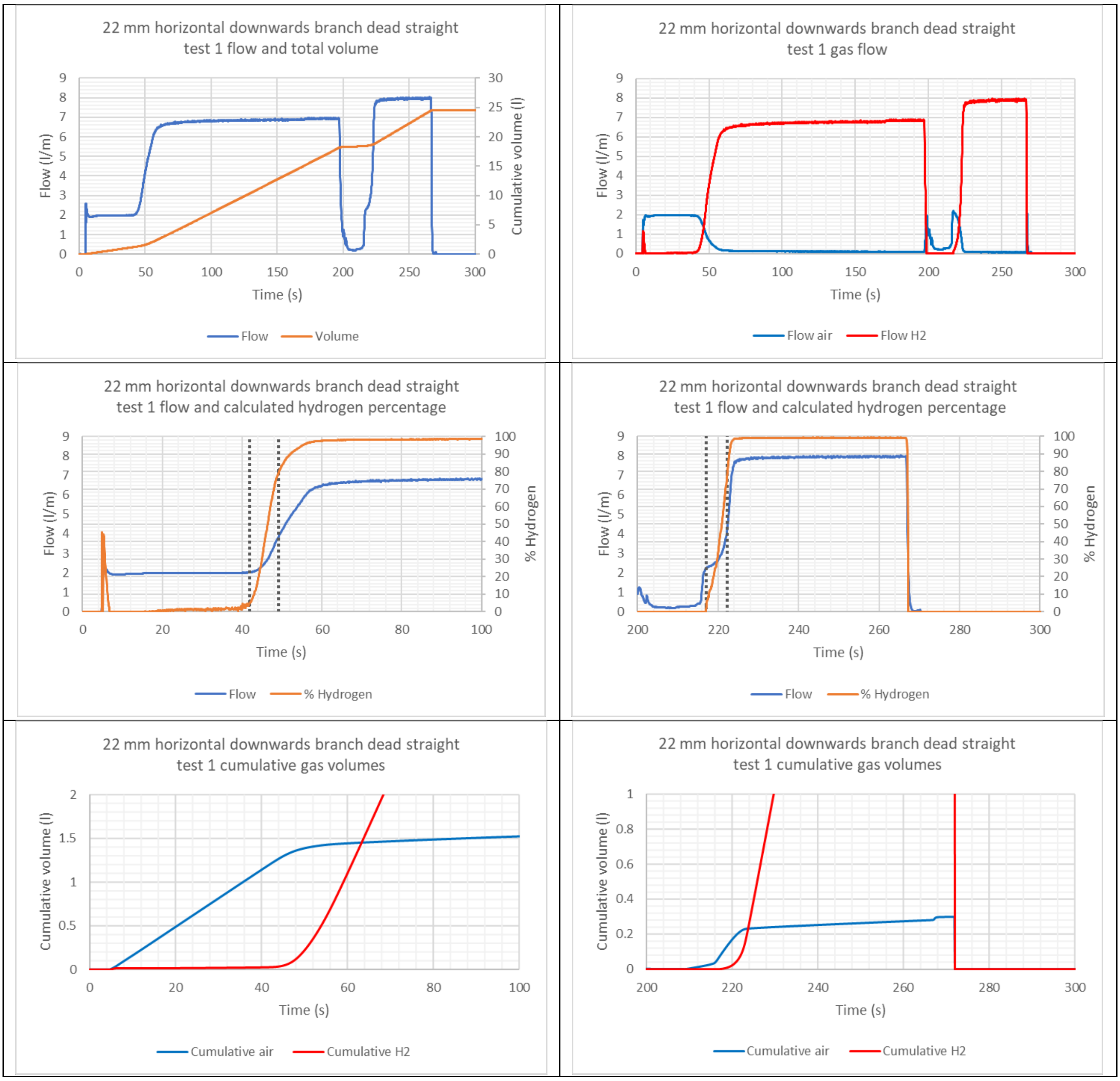


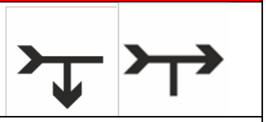
Figure 72: 22 mm horizontal vertical downwards branch dead straight test 1

1	Time (s)	Volume (l)
To start of transition (>0% H2)	28.9	1.01
Duration of transition	19	0.93
To end of transition (95% H2)	47.9	1.94

2	Time (s)	Volume (l)
To start of transition (>0% H2)	7.4	0.07
Duration of transition	6.1	0.32
To end of transition (95% H2)	13.5	0.39

	1	2	Total
Installation volume (l)	1.26	0.32	1.58
Total volume displaced to 95% hydrogen (l)	1.94	0.39	2.33
Calculated volume of air displaced (l)	1.34	0.23	1.57
Calculated volume of hydrogen displaced during purge (l)	0.60	0.16	0.76
Ratio of purge volume to installation volume	1.53	1.22	1.47

074 22 mm horizontal vertical downwards branch dead straight test 2

Test #	**074 22 mm horizontal vertical downwards branch dead straight test 2**	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

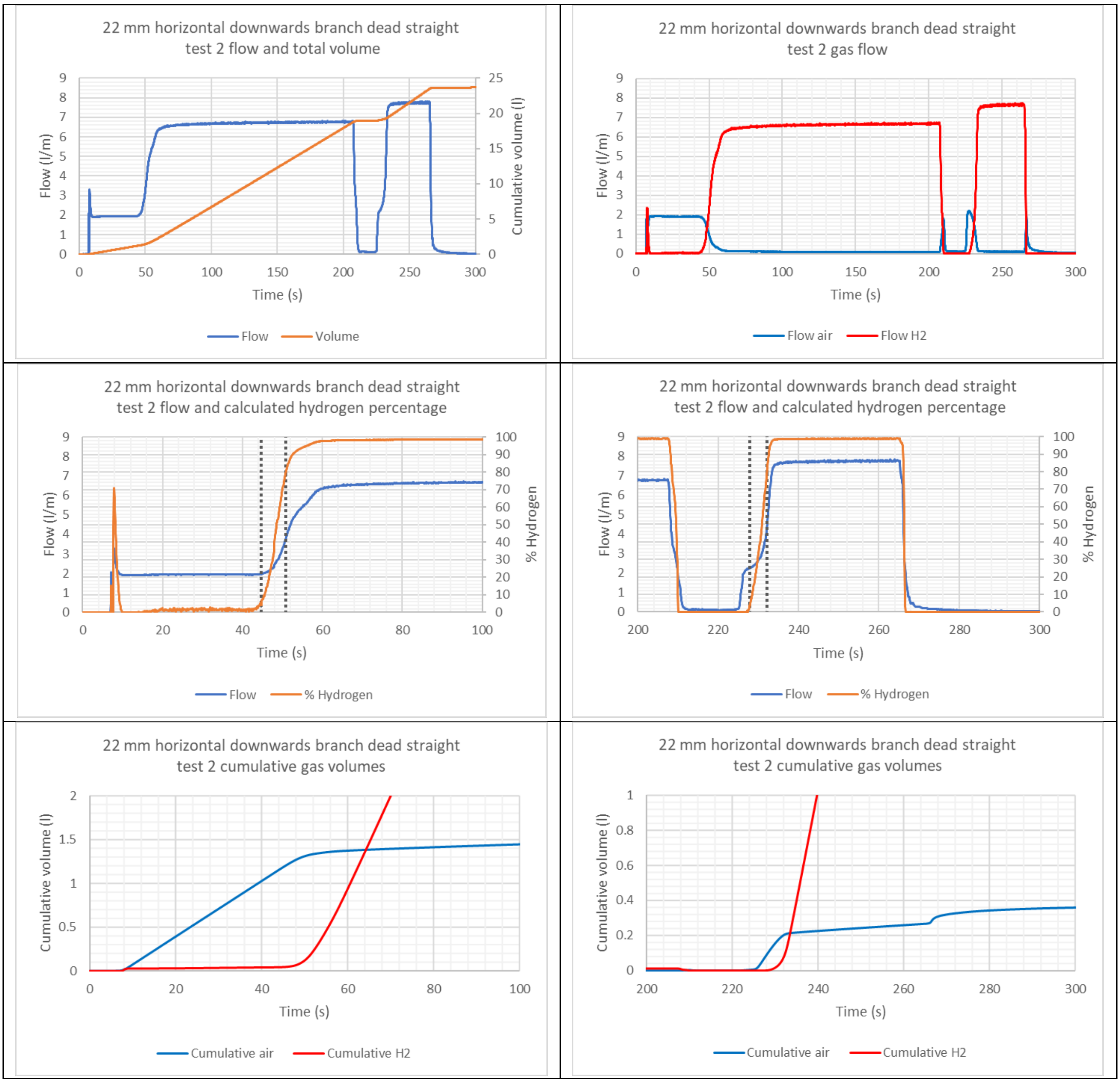


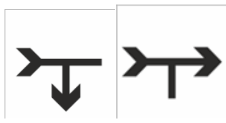
Figure 73: 22 mm horizontal vertical downwards branch dead straight test 2

1	Time (s)	Volume (l)
To start of transition (>0% H2)	33.4	1.08
Duration of transition	12.8	0.74
To end of transition (95% H2)	46.2	1.81

2	Time (s)	Volume (l)
To start of transition (>0% H2)	3.4	0.07
Duration of transition	5.3	0.28
To end of transition (95% H2)	8.7	0.35

	1	2	Total
Installation volume (l)	1.26	0.32	1.58
Total volume displaced to 95% hydrogen (l)	1.81	0.35	2.16
Calculated volume of air displaced (l)	1.26	0.21	1.47
Calculated volume of hydrogen displaced during purge (l)	0.55	0.14	0.70
Ratio of purge volume to installation volume	1.43	1.11	1.37

075 22 mm horizontal vertical downwards branch dead straight test 3

Test #	075 22 mm horizontal vertical downwards branch dead straight test 3	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

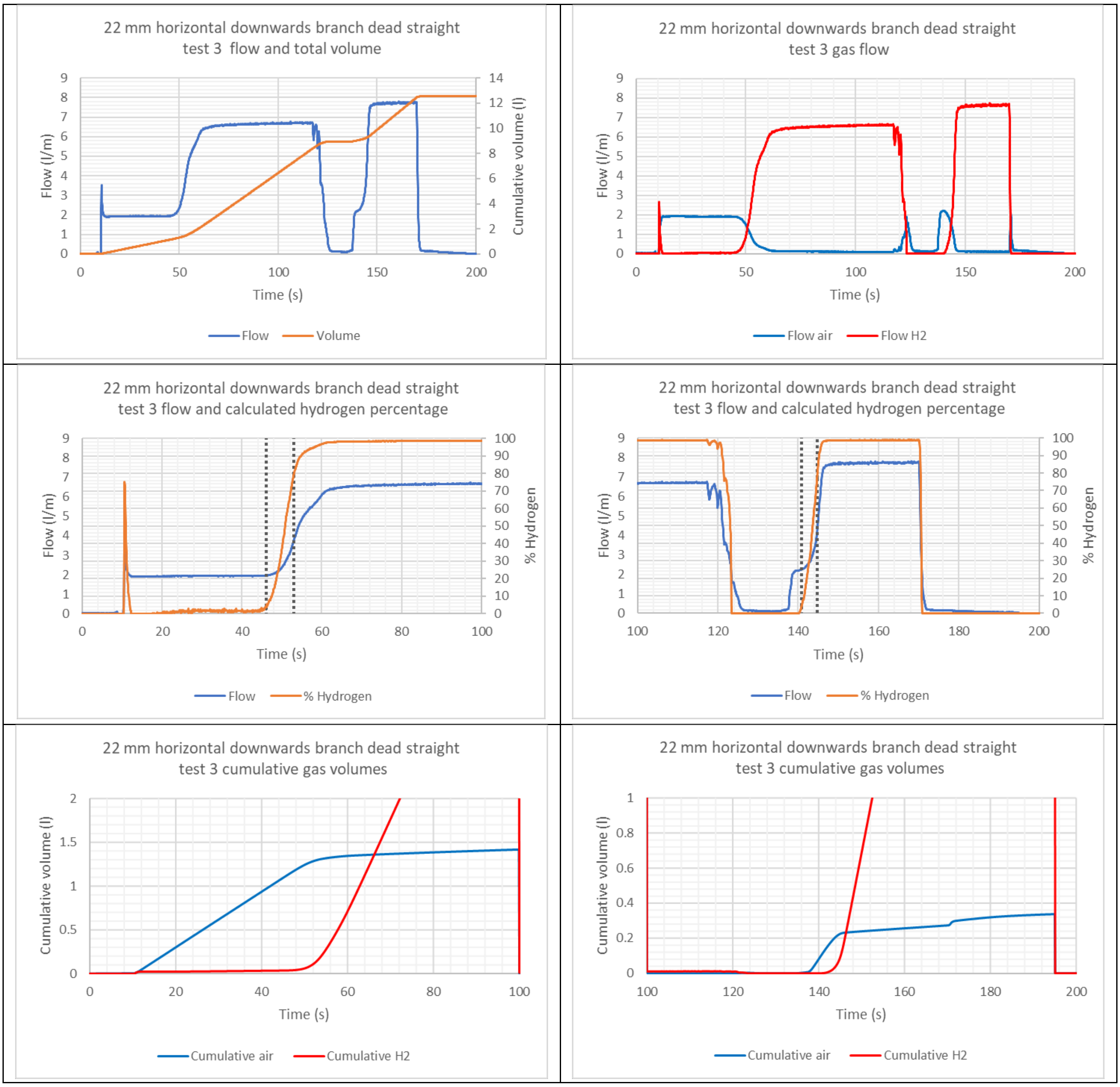


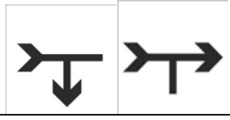
Figure 74: 22 mm horizontal vertical downwards branch dead straight test 3

1	Time (s)	Volume (l)
To start of transition (>0% H2)	32.1	1.03
Duration of transition	13.7	0.76
To end of transition (95% H2)	45.8	1.79

2	Time (s)	Volume (l)
To start of transition (>0% H2)	4.7	0.10
Duration of transition	5	0.27
To end of transition (95% H2)	9.7	0.37

	1	2	Total
Installation volume (l)	1.26	0.32	1.58
Total volume displaced to 95% hydrogen (l)	1.79	0.37	2.16
Calculated volume of air displaced (l)	1.26	0.23	1.49
Calculated volume of hydrogen displaced during purge (l)	0.53	0.14	0.68
Ratio of purge volume to installation volume	1.42	1.18	1.37

076 22 mm horizontal vertical downwards branch dead straight test 4 (pause)

Test #	076 22 mm horizontal vertical downwards branch dead straight test 4 (pause)	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

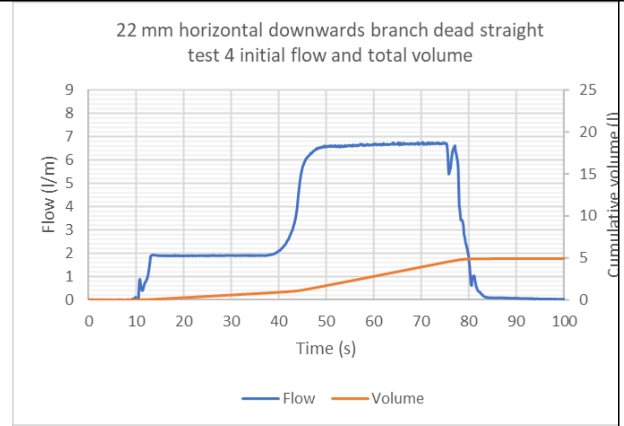
See graphs overleaf

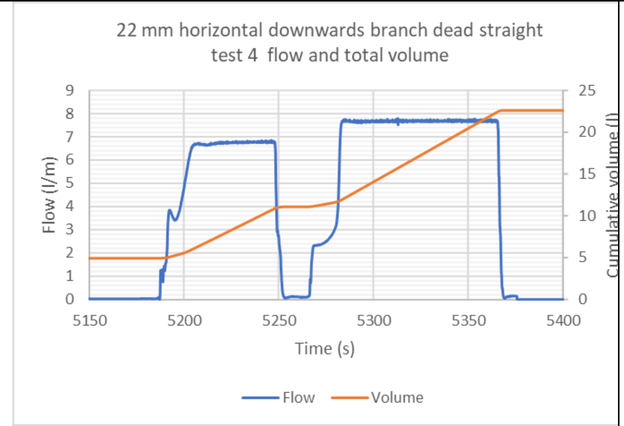
1	Time (s)	Volume (l)
Start injection	10.6	0.002
End injection	57.7	2.537
Total injection	47.1	2.535
%age of H2 in installation	100.0	

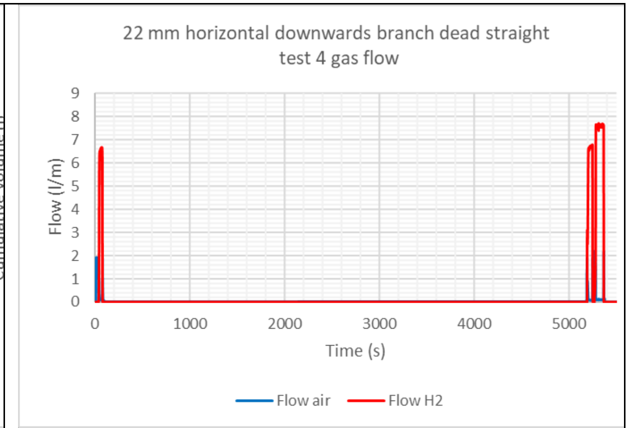
2	Time (s)	Volume (l)
To start of transition (>0% H2)	3.6	0.074
Duration of transition	10.8	0.713
To end of transition (95% H2)	14.4	0.787

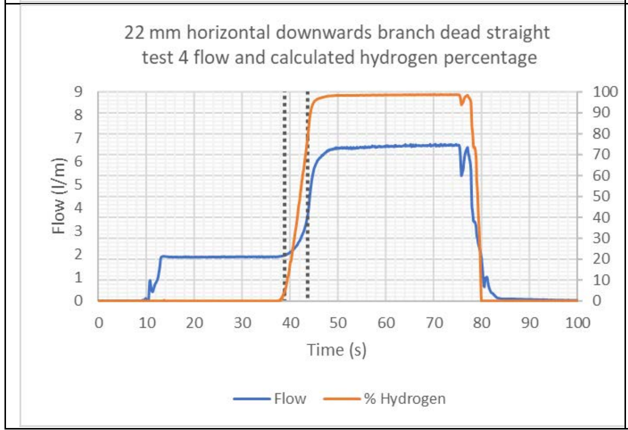
3	Time (s)	Volume (l)
To start of transition (>0% H2)	2.3	0.043
Duration of transition	14.1	0.654
To end of transition (95% H2)	16.4	0.697

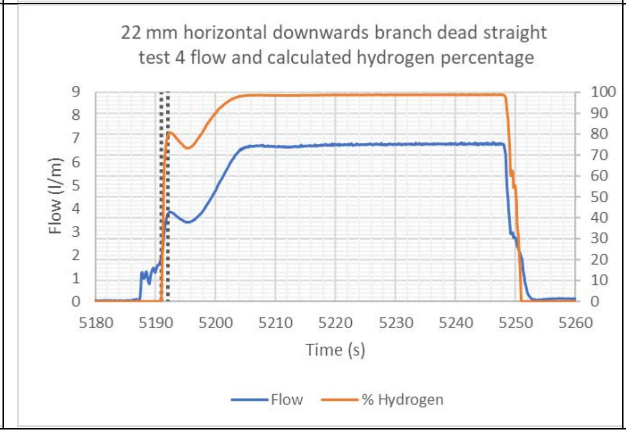
	1	2	3	Total
Installation volume (l)	1.26	1.26	0.32	1.58
Total volume displaced to 95% hydrogen (l)	2.53	0.79	0.70	4.02
Calculated volume of air displaced (l)	1.01	0.21	0.46	1.68
Calculated volume of hydrogen displaced during purge (l)	1.53	0.58	0.24	2.35
Ratio of purge volume to installation volume	N/A	0.62	2.21	2.54

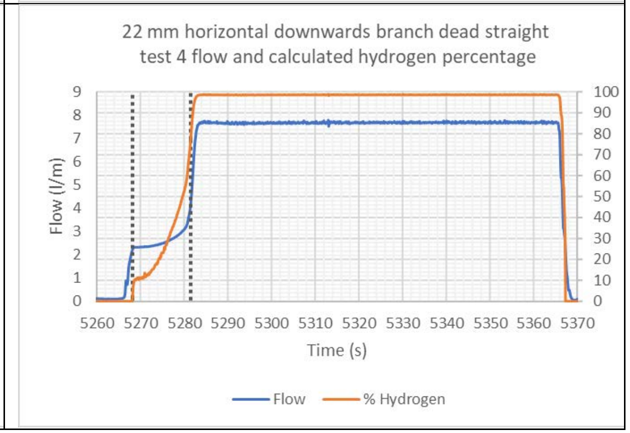

22 mm horizontal downwards branch dead straight
test 4 initial flow and total volume
Flow (l/m)
Cumulative volume (l)
Time (s)
Flow
Volume

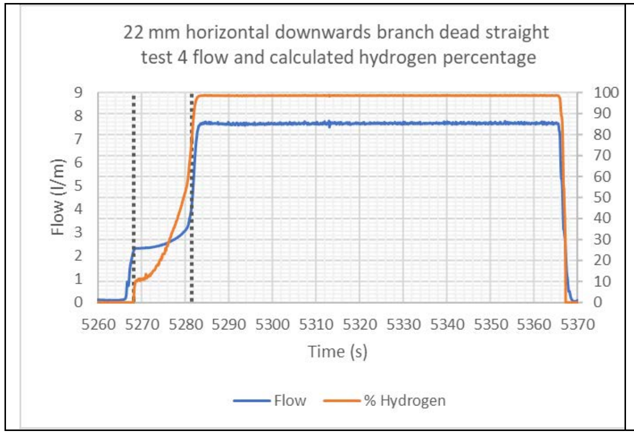

22 mm horizontal downwards branch dead straight
test 4 flow and total volume
Flow (l/m)
Cumulative volume (l)
Time (s)
Flow
Volume

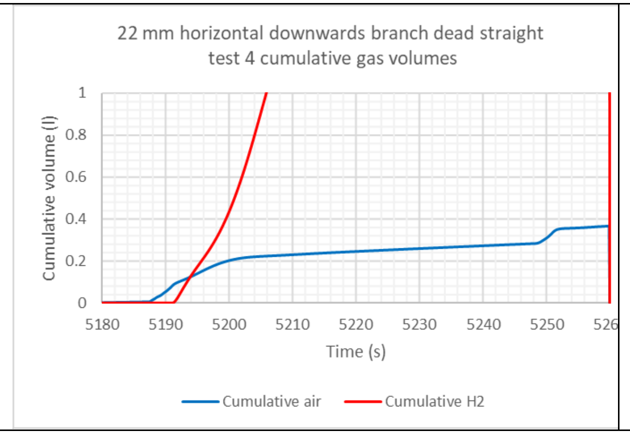

22 mm horizontal downwards branch dead straight
test 4 gas flow
Flow (l/m)
Time (s)
Flow air
Flow H2

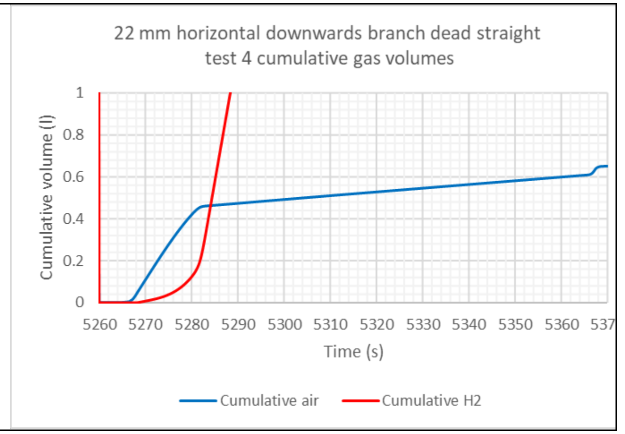

22 mm horizontal downwards branch dead straight
test 4 flow and calculated hydrogen percentage
Flow (l/m)
Time (s)
Flow
% Hydrogen


22 mm horizontal downwards branch dead straight
test 4 flow and calculated hydrogen percentage
Flow (l/m)
Time (s)
Flow
% Hydrogen

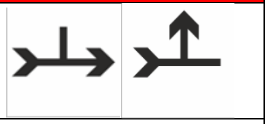

22 mm horizontal downwards branch dead straight
test 4 flow and calculated hydrogen percentage
Flow (l/m)
Time (s)
Flow
% Hydrogen


22 mm horizontal downwards branch dead straight
test 4 flow and calculated hydrogen percentage
Flow (l/m)
Time (s)
Flow
% Hydrogen


22 mm horizontal downwards branch dead straight
test 4 cumulative gas volumes
Cumulative volume (l)
Time (s)
Cumulative air
Cumulative H2


22 mm horizontal downwards branch dead straight
test 4 cumulative gas volumes
Cumulative volume (l)
Time (s)
Cumulative air
Cumulative H2

077 22 mm horizontal vertical upwards branch dead tee test 1

Test #	077 22 mm horizontal vertical upwards branch dead tee test 1	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

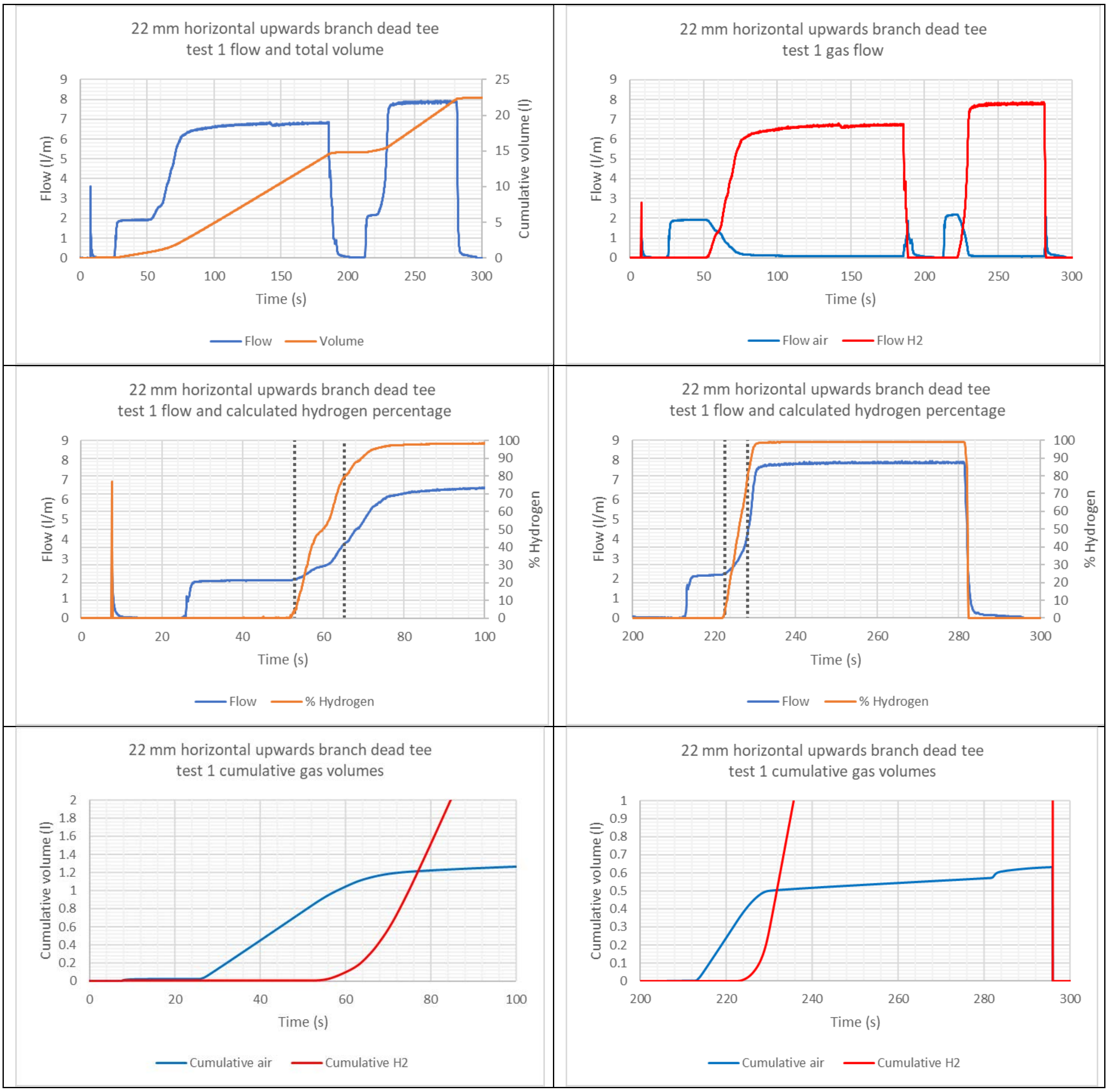


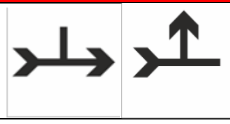
Figure 75: 22 mm horizontal vertical upwards branch dead tee test 1

1	Time (s)	Volume (l)
To start of transition (>0% H2)	14.3	0.20
Duration of transition	19.3	1.35
To end of transition (95% H2)	33.6	1.55

2	Time (s)	Volume (l)
To start of transition (>0% H2)	10	0.33
Duration of transition	7.1	0.40
To end of transition (95% H2)	17.1	0.73

	1	2	Total
Installation volume (l)	0.95	0.63	1.58
Total volume displaced to 95% hydrogen (l)	1.55	0.73	2.28
Calculated volume of air displaced (l)	0.79	0.50	1.29
Calculated volume of hydrogen displaced during purge (l)	0.76	0.22	0.99
Ratio of purge volume to installation volume	1.64	1.15	1.44

078 22 mm horizontal vertical upwards branch dead tee test 2

Test #	078 22 mm horizontal vertical upwards branch dead tee test 2	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

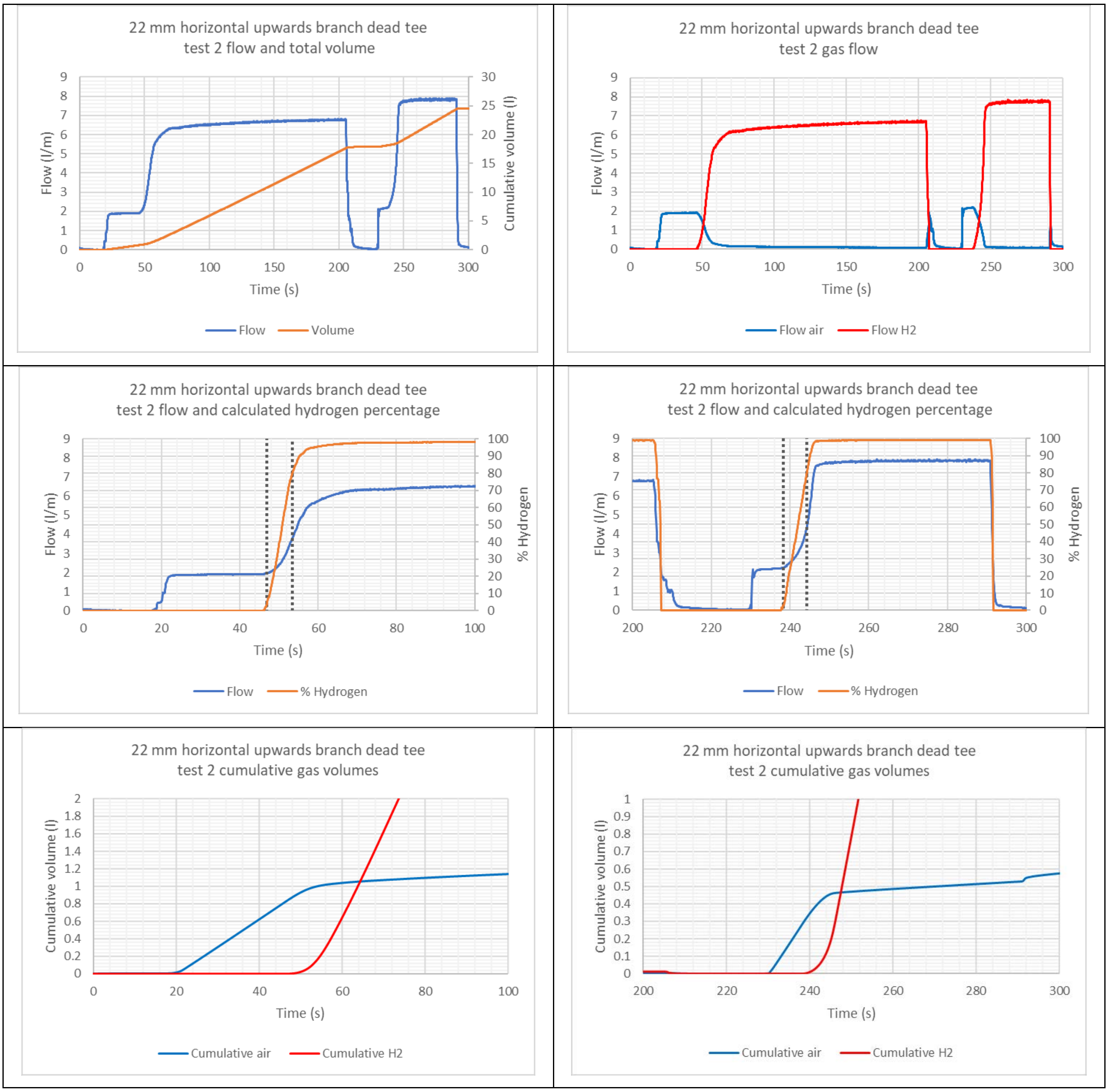


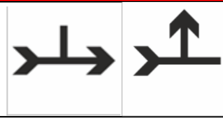
Figure 76: 22 mm horizontal vertical upwards branch dead tee test 2

1	Time (s)	Volume (l)
To start of transition (>0% H2)	28.2	0.76
Duration of transition	12.1	0.82
To end of transition (95% H2)	40.3	1.58

2	Time (s)	Volume (l)
To start of transition (>0% H2)	8.6	0.27
Duration of transition	7.8	0.43
To end of transition (95% H2)	16.4	0.70

	1	2	Total
Installation volume (l)	0.95	0.63	1.58
Total volume displaced to 95% hydrogen (l)	1.58	0.70	2.28
Calculated volume of air displaced (l)	1.02	0.46	1.48
Calculated volume of hydrogen displaced during purge (l)	0.56	0.24	0.80
Ratio of purge volume to installation volume	1.67	1.11	1.44

079 22 mm horizontal vertical upwards branch dead tee test 3

Test #	079 22 mm horizontal vertical upwards branch dead tee test 3	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

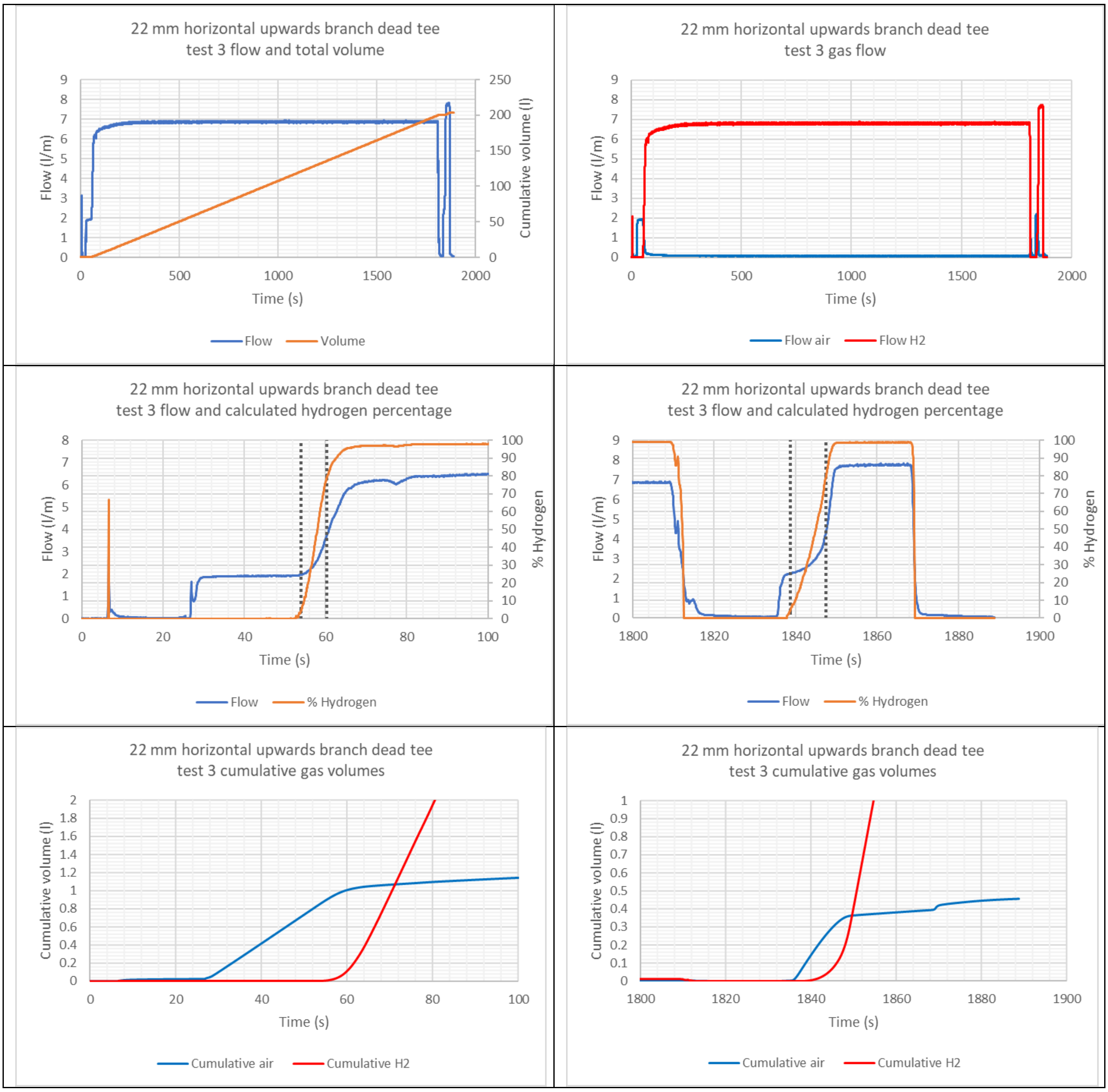


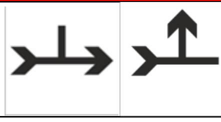
Figure 77: 22 mm horizontal vertical upwards branch dead tee test 3

1	Time (s)	Volume (l)
To start of transition (>0% H2)	27.2	0.54
Duration of transition	10.7	0.91
To end of transition (95% H2)	37.9	1.45

2	Time (s)	Volume (l)
To start of transition (>0% H2)	3	0.07
Duration of transition	10.7	0.55
To end of transition (95% H2)	13.7	0.63

	1	2	Total
Installation volume (l)	0.95	0.63	1.58
Total volume displaced to 95% hydrogen (l)	1.45	0.63	2.08
Calculated volume of air displaced (l)	1.02	0.36	1.38
Calculated volume of hydrogen displaced during purge (l)	0.44	0.27	0.70
Ratio of purge volume to installation volume	1.53	0.99	1.32

080 22 mm horizontal vertical upwards branch dead tee test 4 (pause)

Test #	080 22 mm horizontal vertical upwards branch dead tee test 4	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

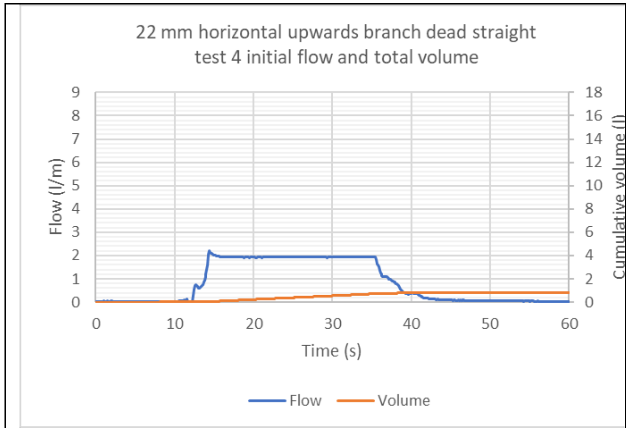
See graphs overleaf

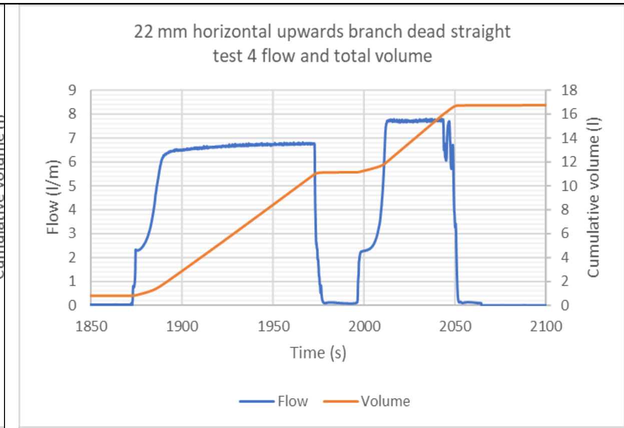
1	Time (s)	Volume (l)
Start injection	12.4	0.008
End injection	45.8	0.801
Total injection	33.4	0.793
%age of H2 in installation	50.2	

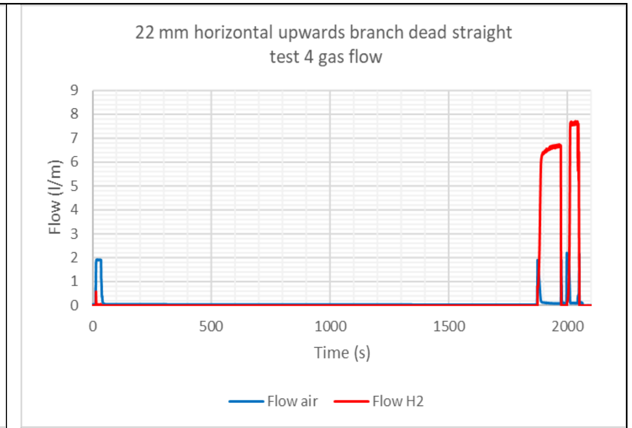
2	Time (s)	Volume (l)
To start of transition (>0% H2)	1.5	0.024
Duration of transition	13.1	0.713
To end of transition (95% H2)	14.6	0.737

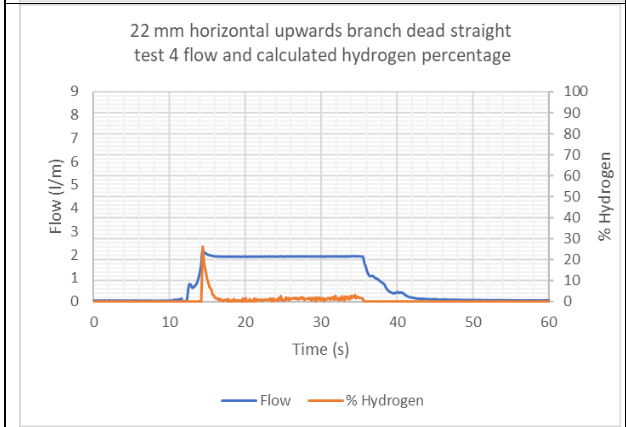
3	Time (s)	Volume (l)
To start of transition (>0% H2)	2	0.048
Duration of transition	13.1	0.646
To end of transition (95% H2)	15.1	0.694

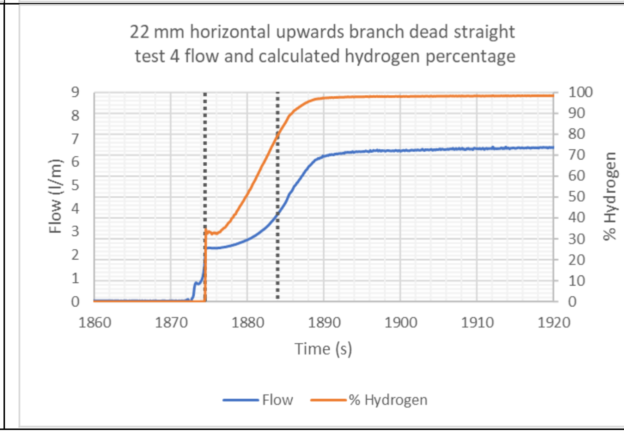
	1	2	3	Total
Installation volume (l)	0.95	0.95	0.63	1.58
Total volume displaced to 95% hydrogen (l)	0.79	0.74	0.69	2.22
Calculated volume of air displaced (l)	0.78	0.27	0.42	1.47
Calculated volume of hydrogen displaced during purge (l)	0.01	0.48	0.28	0.77
Ratio of purge volume to installation volume	N/A	0.78	1.10	1.41

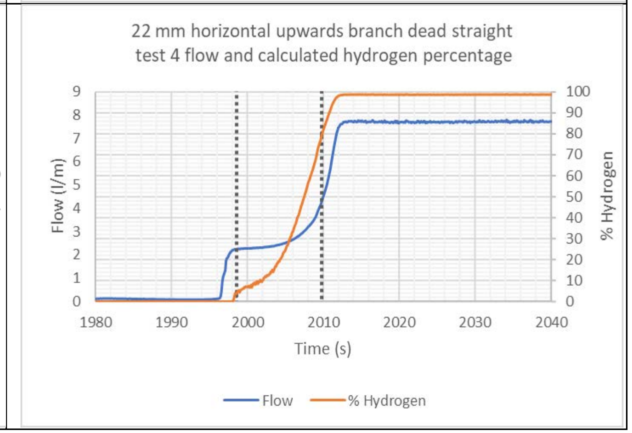

22 mm horizontal upwards branch dead straight
test 4 initial flow and total volume
Flow (l/m)
Cumulative volume (l)
Time (s)
Flow
Volume

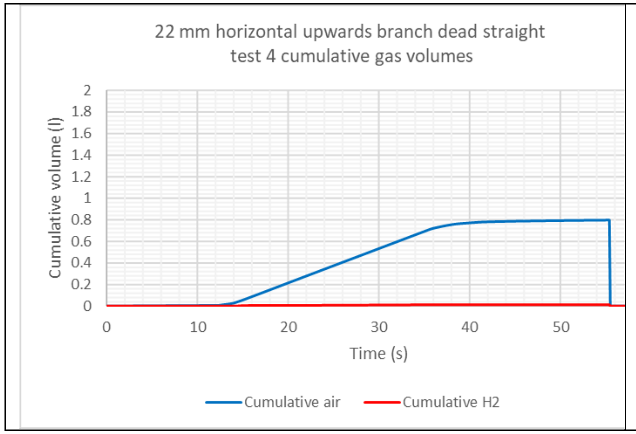

22 mm horizontal upwards branch dead straight
test 4 flow and total volume
Flow (l/m)
Cumulative volume (l)
Time (s)
Flow
Volume

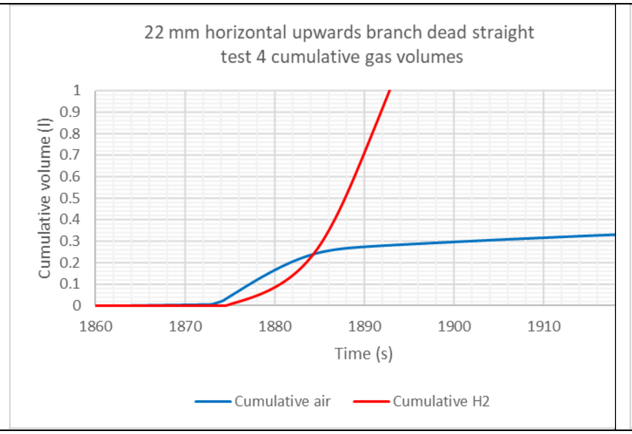

22 mm horizontal upwards branch dead straight
test 4 gas flow
Flow (l/m)
Time (s)
Flow air
Flow H2

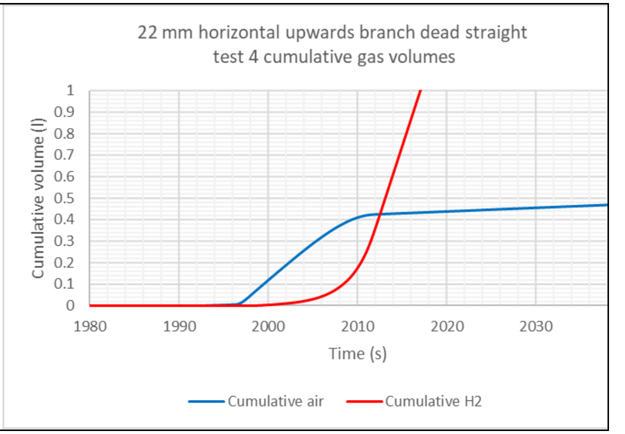

22 mm horizontal upwards branch dead straight
test 4 flow and calculated hydrogen percentage
Flow (l/m)
% Hydrogen
Time (s)
Flow
% Hydrogen


22 mm horizontal upwards branch dead straight
test 4 flow and calculated hydrogen percentage
Flow (l/m)
% Hydrogen
Time (s)
Flow
% Hydrogen

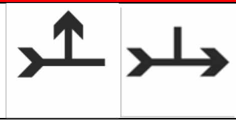

22 mm horizontal upwards branch dead straight
test 4 flow and calculated hydrogen percentage
Flow (l/m)
% Hydrogen
Time (s)
Flow
% Hydrogen


22 mm horizontal upwards branch dead straight
test 4 cumulative gas volumes
Cumulative volume (l)
Time (s)
Cumulative air
Cumulative H2


22 mm horizontal upwards branch dead straight
test 4 cumulative gas volumes
Cumulative volume (l)
Time (s)
Cumulative air
Cumulative H2


22 mm horizontal upwards branch dead straight
test 4 cumulative gas volumes
Cumulative volume (l)
Time (s)
Cumulative air
Cumulative H2

081 22 mm horizontal vertical upwards branch dead straight test 1

Test #	081 22 mm horizontal vertical upwards branch dead straight test 1	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

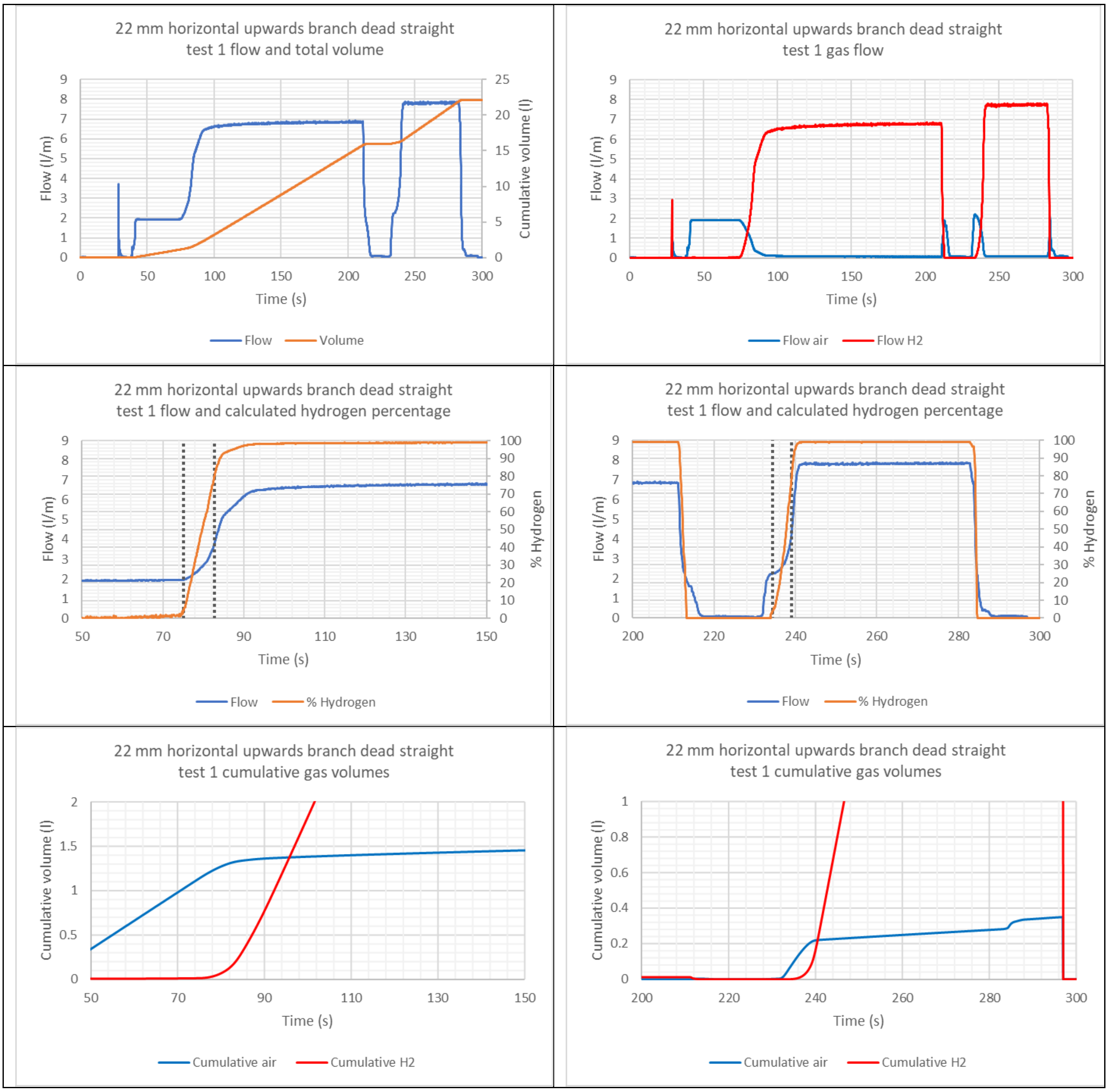


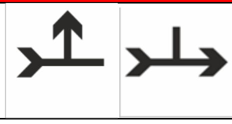
Figure 78: 22 mm horizontal vertical upwards branch dead straight test 1

1	Time (s)	Volume (l)
To start of transition (>0% H2)	36	0.15
Duration of transition	12.3	1.65
To end of transition (95% H2)	48.3	1.81

2	Time (s)	Volume (l)
To start of transition (>0% H2)	3	0.05
Duration of transition	6.2	0.32
To end of transition (95% H2)	9.2	0.37

	1	2	Total
Installation volume (l)	1.26	0.32	1.58
Total volume displaced to 95% hydrogen (l)	1.81	0.37	2.18
Calculated volume of air displaced (l)	1.32	0.22	1.54
Calculated volume of hydrogen displaced during purge (l)	0.49	0.15	0.64
Ratio of purge volume to installation volume	1.43	1.17	1.38

082 22 mm horizontal vertical upwards branch dead straight test 2

Test #	082 22 mm horizontal vertical upwards branch dead straight test 2	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

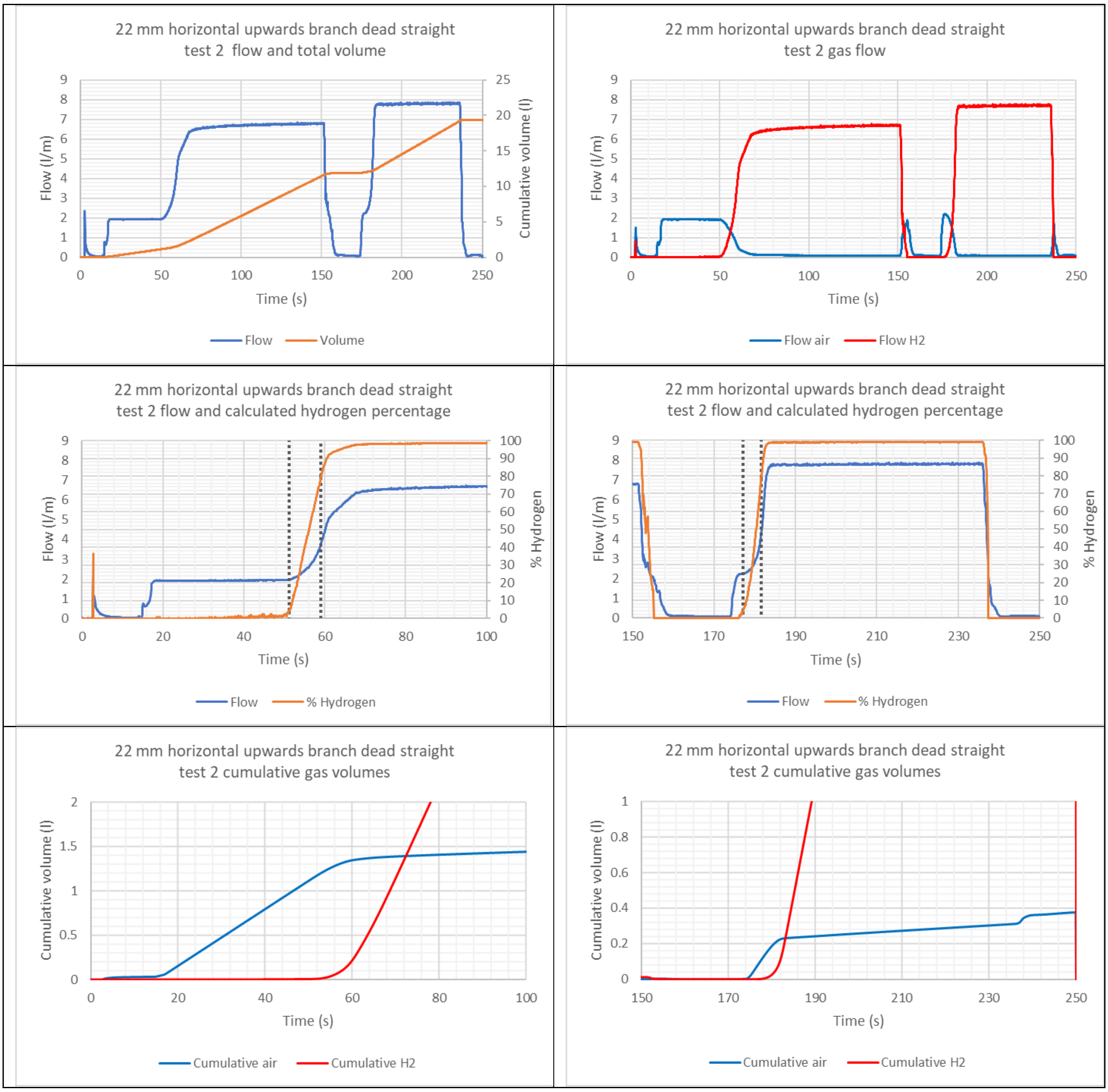


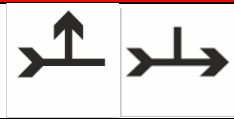
Figure 79: 22 mm horizontal vertical upwards branch dead straight test 2

1	Time (s)	Volume (l)
To start of transition (>0% H2)	29.9	0.73
Duration of transition	18.7	1.09
To end of transition (95% H2)	48.6	1.83

2	Time (s)	Volume (l)
To start of transition (>0% H2)	2.4	0.06
Duration of transition	6.2	0.31
To end of transition (95% H2)	8.6	0.37

	1	2	Total
Installation volume (l)	1.26	0.32	1.58
Total volume displaced to 95% hydrogen (l)	1.83	0.37	2.20
Calculated volume of air displaced (l)	1.34	0.23	1.56
Calculated volume of hydrogen displaced during purge (l)	0.49	0.14	0.64
Ratio of purge volume to installation volume	1.45	1.18	1.39

083 22 mm horizontal vertical upwards branch dead straight test 3

Test #	083 22 mm horizontal vertical upwards branch dead straight test 3	
Installation configuration	3 m x 22 mm + 2m x 22 mm branch	
Installation volume	1.58 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s

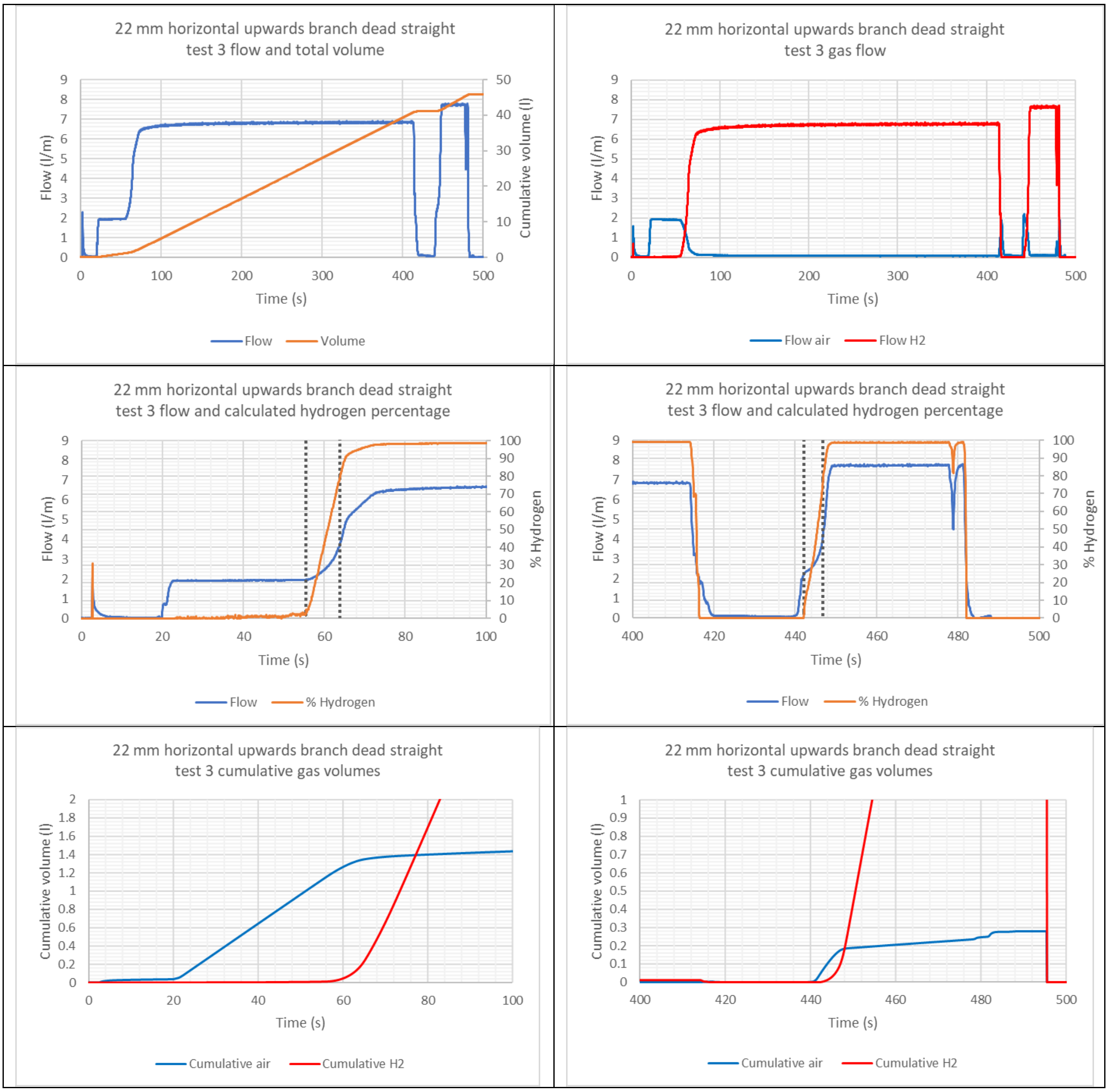


Figure 80: 22 mm horizontal vertical upwards branch dead straight test 3

1	Time (s)	Volume (l)
To start of transition (>0% H2)	16	0.72
Duration of transition	32.5	1.13
To end of transition (95% H2)	48.5	1.85

2	Time (s)	Volume (l)
To start of transition (>0% H2)	2.9	0.04
Duration of transition	5.8	0.32
To end of transition (95% H2)	8.7	0.36

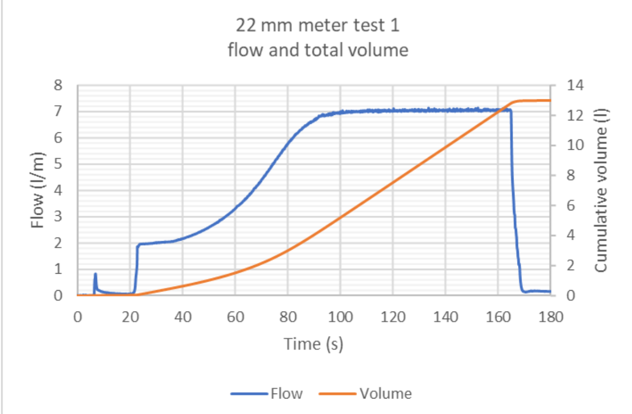
	1	2	Total
Installation volume (l)	1.26	0.32	1.58
Total volume displaced to 95% hydrogen (l)	1.85	0.36	2.21
Calculated volume of air displaced (l)	1.33	0.18	1.51
Calculated volume of hydrogen displaced during purge (l)	0.52	0.17	0.69
Ratio of purge volume to installation volume	1.46	1.13	1.40

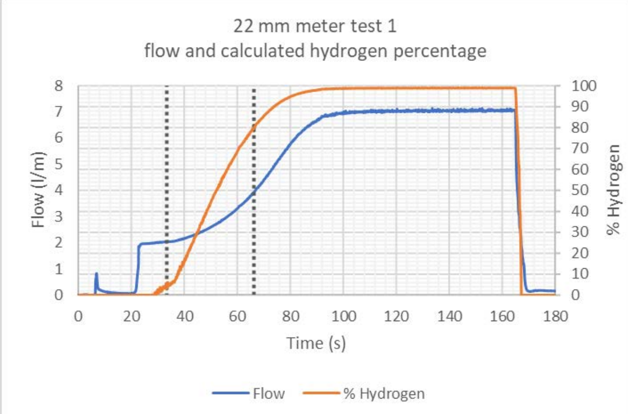
Meter tests

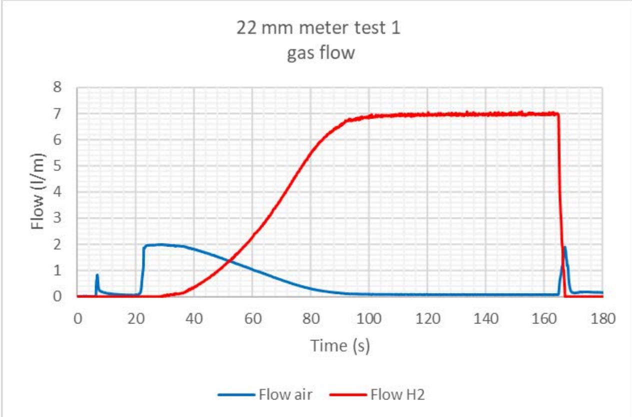
Smart Meter

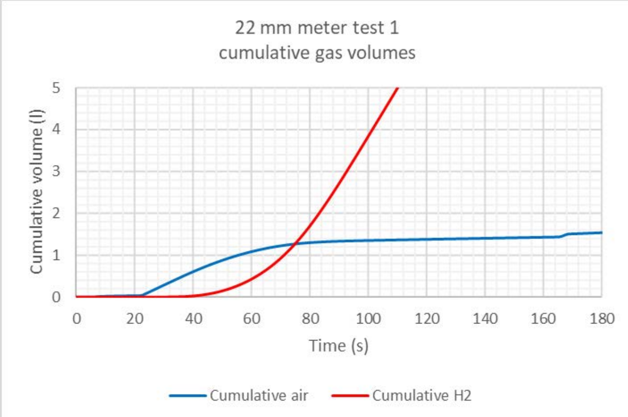
084 22 mm meter test 1

Test #	084 22 mm meter test 1	
Installation configuration	97 cm x 22 mm pipe plus meter	
Installation volume	1.32 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s







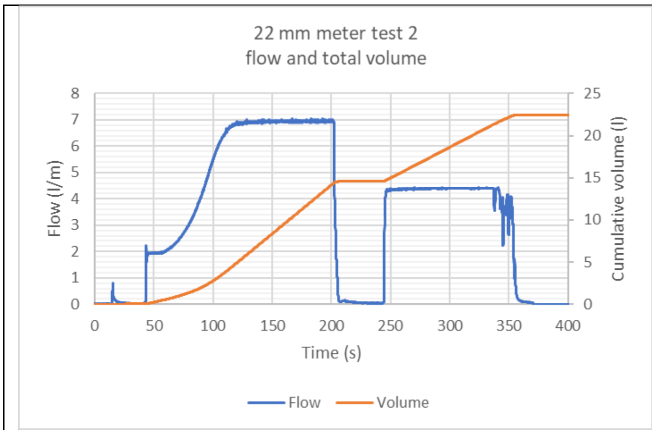


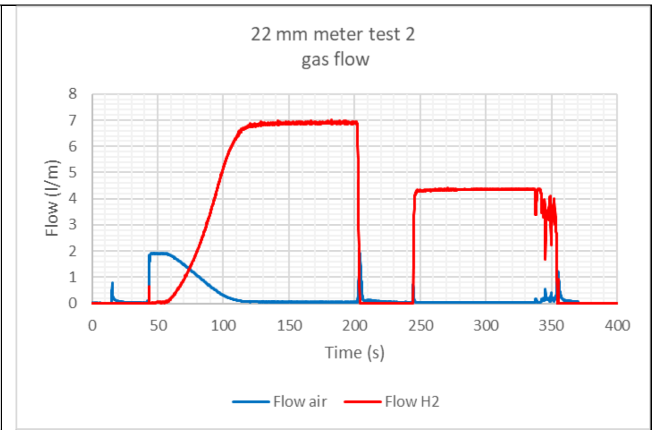
	Time (s)	Volume (l)
To start of transition (>0% H2)	9.8	0.26
Duration of transition	49.7	2.74
To end of transition (95% H2)	59.5	3.00

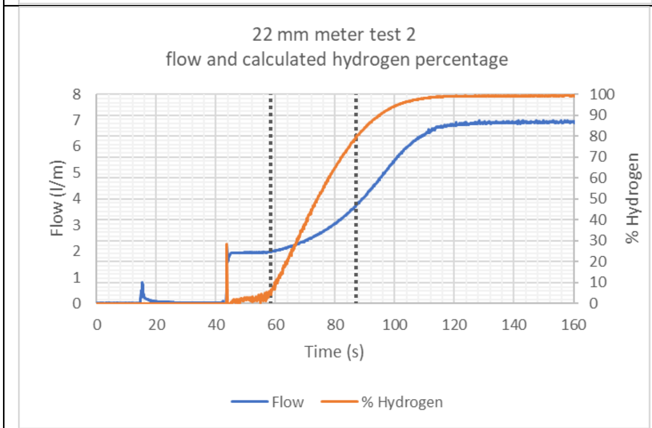
Installation volume (l)	1.32
Total volume displaced to 95% hydrogen (l)	3.00
Calculated volume of air displaced (l)	1.27
Calculated volume of hydrogen displaced during purge (l)	1.73
Ratio of purge volume to installation volume	2.27

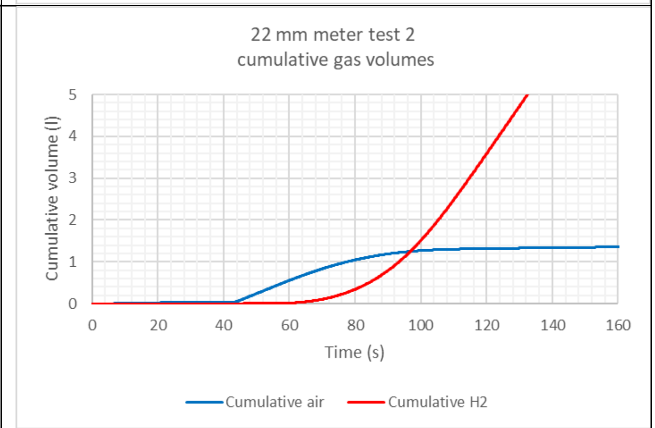
085 22 mm meter test 2

Test #	085 22 mm meter test 2	
Installation configuration	97 cm x 22 mm pipe plus meter	
Installation volume	1.32 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s







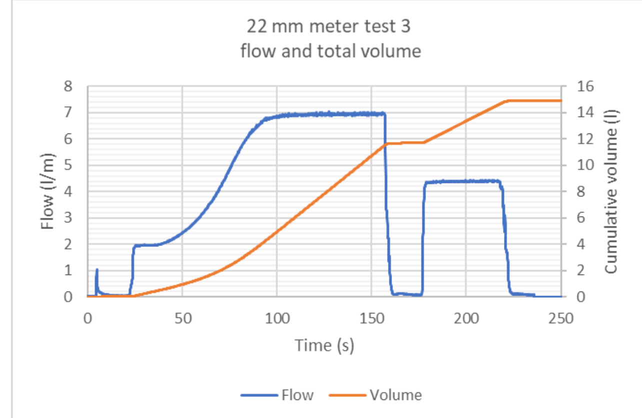


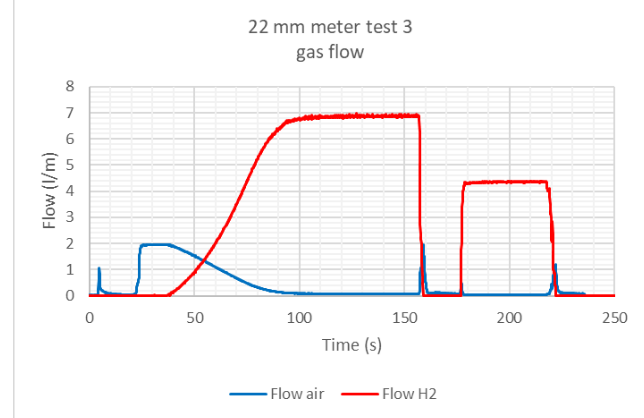
1	Time (s)	Volume (l)
To start of transition (>0% H2)	6	0.04
Duration of transition	50.4	2.68
To end of transition (95% H2)	56.4	2.72

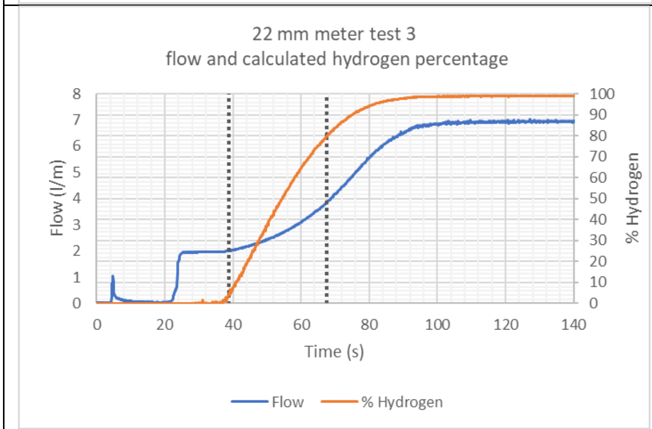
	1
Installation volume (l)	1.32
Total volume displaced to 95% hydrogen (l)	2.72
Calculated volume of air displaced (l)	1.23
Calculated volume of hydrogen displaced during purge (l)	1.49
Ratio of purge volume to installation volume	2.06

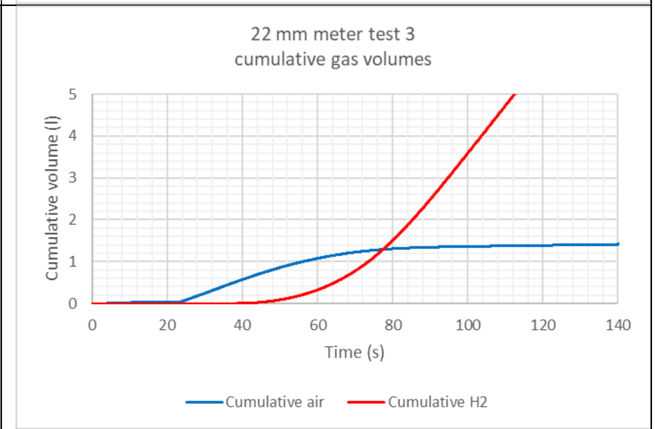
086 22 mm meter test 3

Test #	086 22 mm meter test 3	
Installation configuration	97 cm x 22 mm pipe plus meter	
Installation volume	1.32 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s







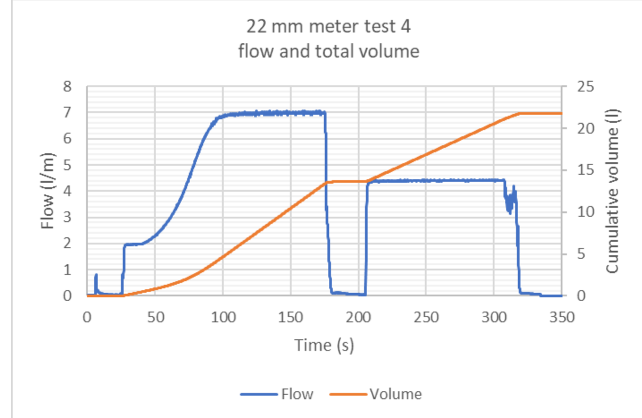


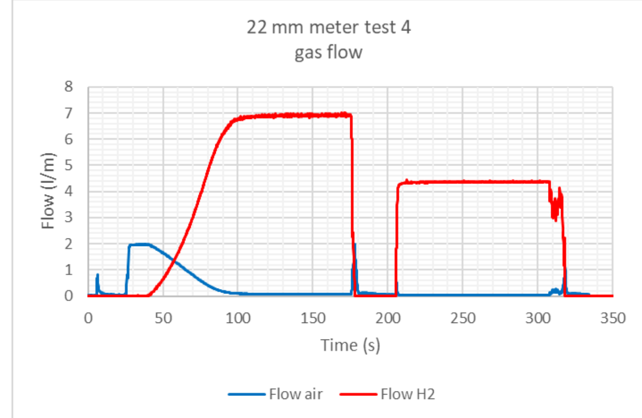
1	Time (s)	Volume (l)
To start of transition (>0% H2)	16.3	0.47
Duration of transition	43.4	2.46
To end of transition (95% H2)	59.7	2.92

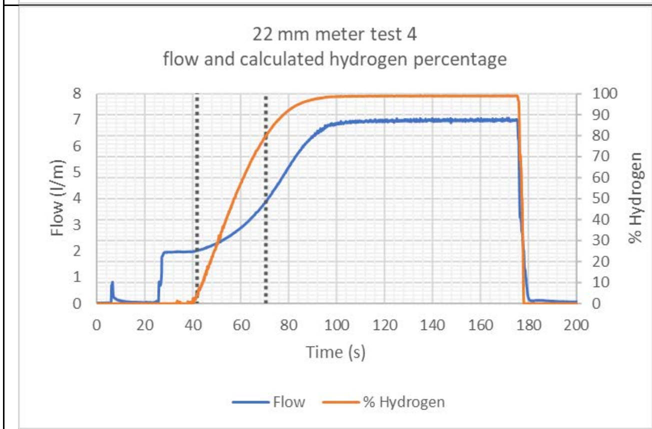
	1
Installation volume (l)	1.32
Total volume displaced to 95% hydrogen (l)	2.92
Calculated volume of air displaced (l)	1.28
Calculated volume of hydrogen displaced during purge (l)	1.64
Ratio of purge volume to installation volume	2.21

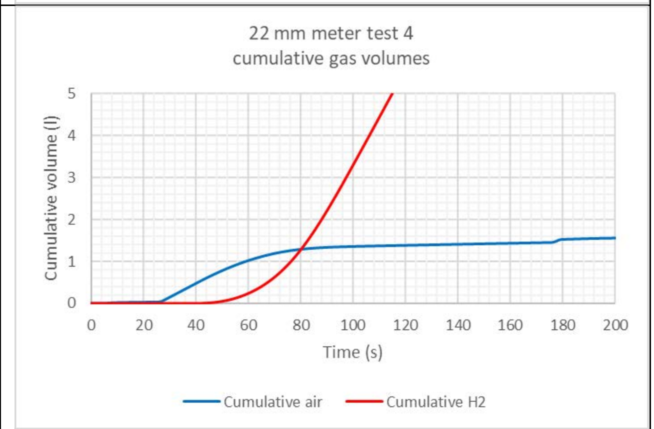
087 22 mm meter test 4

Test #	087 22 mm meter test 4	
Installation configuration	97 cm x 22 mm pipe plus meter	
Installation volume	1.32 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s







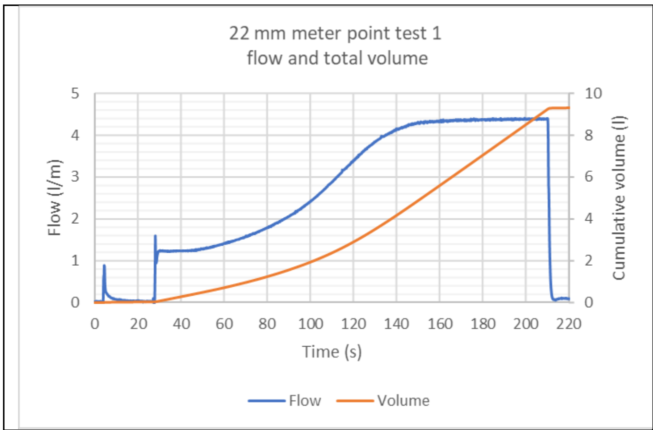


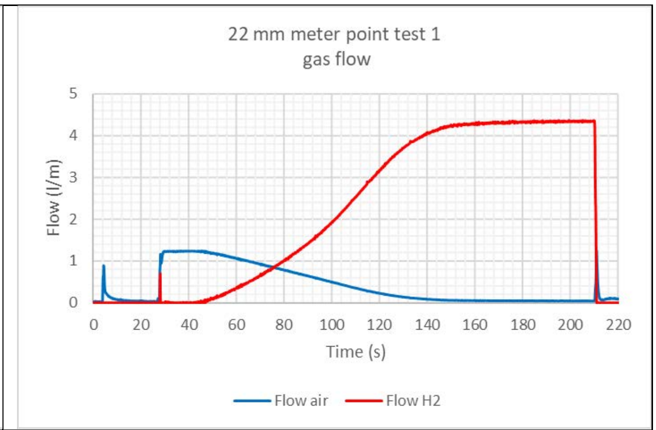
1	Time (s)	Volume (l)
To start of transition (>0% H2)	15.3	0.48
Duration of transition	43.3	2.45
To end of transition (95% H2)	58.6	2.92

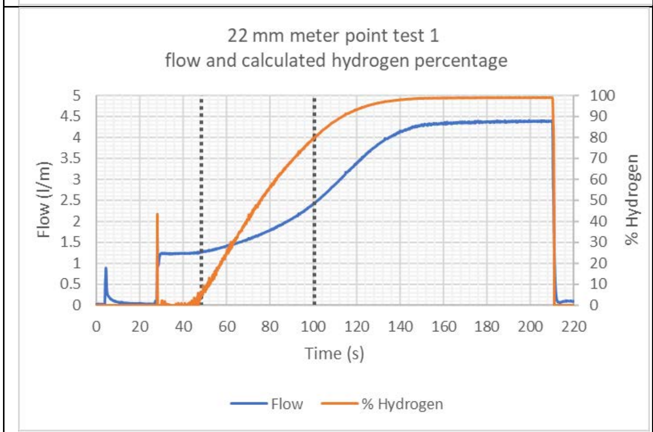
	1
Installation volume (l)	1.32
Total volume displaced to 95% hydrogen (l)	2.92
Calculated volume of air displaced (l)	1.28
Calculated volume of hydrogen displaced during purge (l)	1.64
Ratio of purge volume to installation volume	2.21

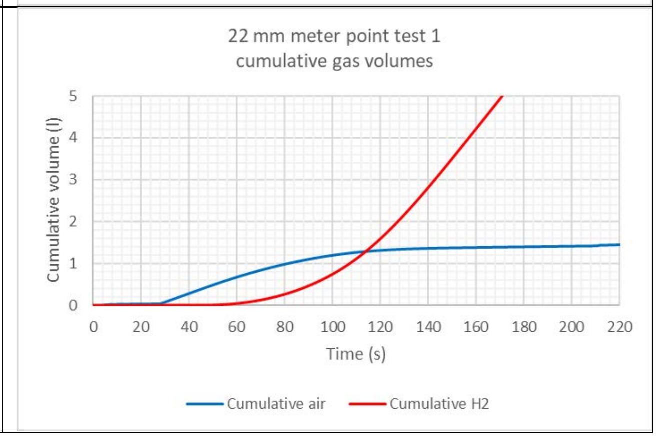
088 22 mm meter point test 1

Test #	088 22 mm meter point test 1	
Installation configuration	97 cm x 22 mm pipe plus meter	
Installation volume	1.32 l	
Flow and speed with pure air	1.25 l/m	0.066 m/s
Flow and speed with pure hydrogen	4.3 l/m	0.228 m/s







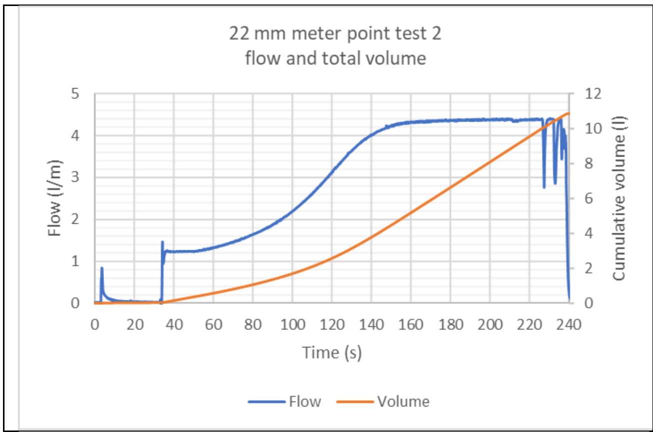


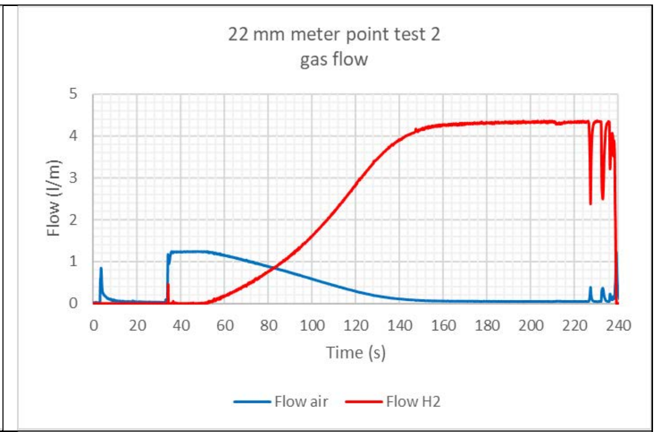
	Time (s)	Volume (l)
To start of transition (>0% H2)	16.3	0.31
Duration of transition	80.4	2.81
To end of transition (95% H2)	96.7	3.12

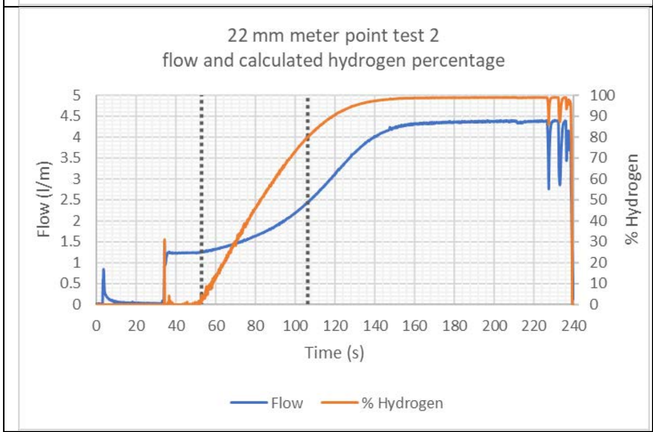
Installation volume (l)	1.00
Total volume displaced to 95% hydrogen (l)	3.12
Calculated volume of air displaced (l)	1.29
Calculated volume of hydrogen displaced during purge (l)	1.84
Ratio of purge volume to installation volume	3.12

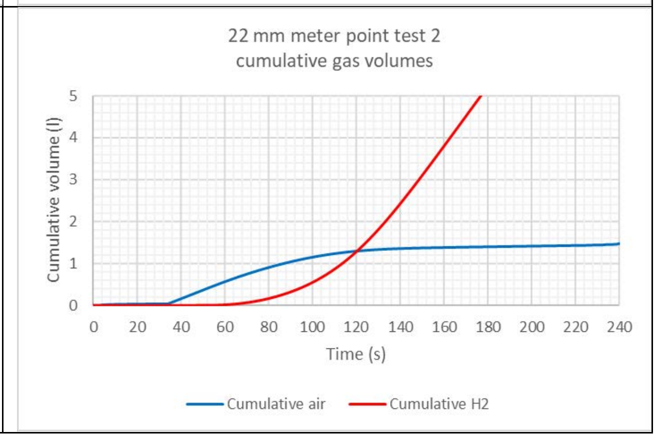
089 22 mm meter point test 2

Test #	089 22 mm meter point test 2	
Installation configuration	97 cm x 22 mm pipe plus meter	
Installation volume	1.32 l	
Flow and speed with pure air	1.25 l/m	0.066 m/s
Flow and speed with pure hydrogen	4.3 l/m	0.228 m/s







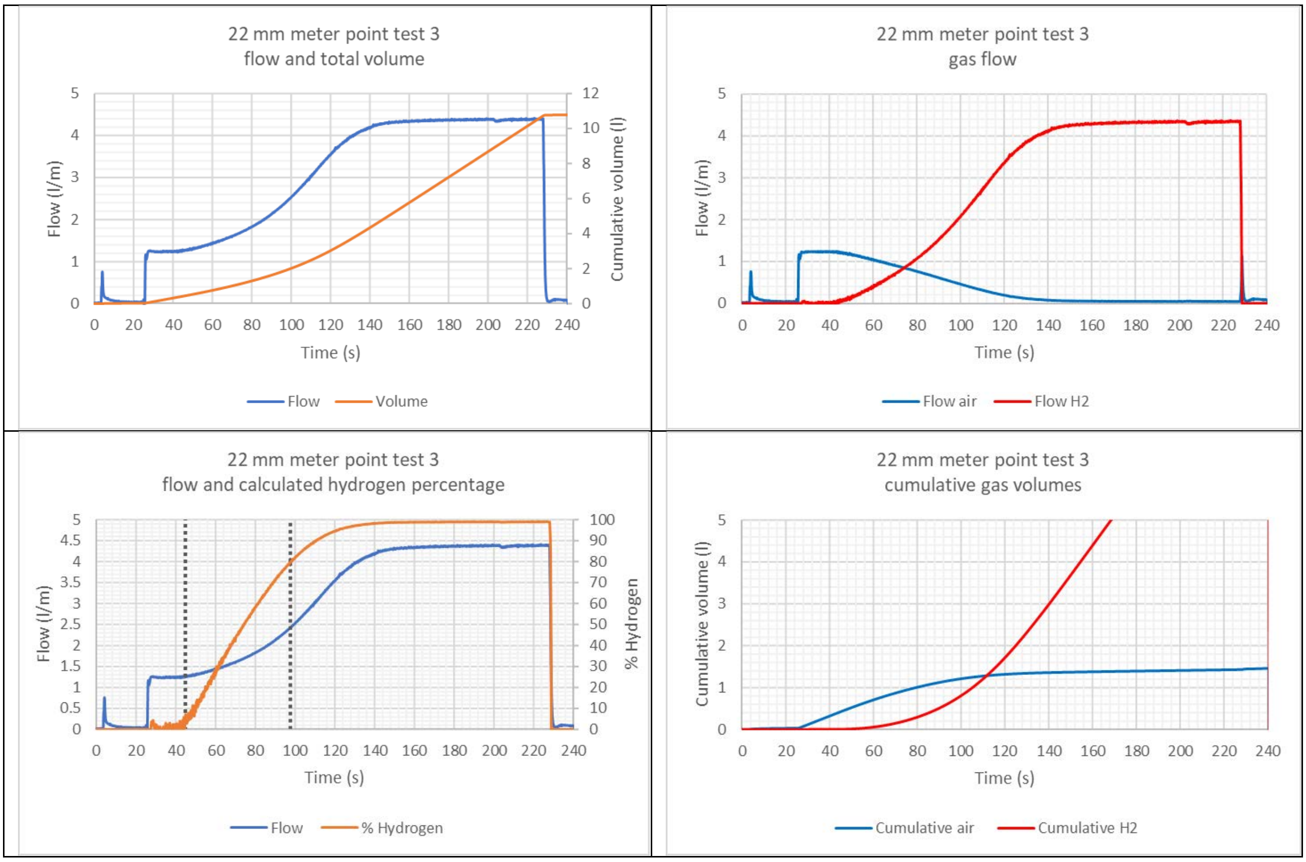


	Time (s)	Volume (l)
To start of transition (>0% H2)	17.8	0.22
Duration of transition	77.7	2.85
To end of transition (95% H2)	95.5	3.07

Installation volume (l)	1.00
Total volume displaced to 95% hydrogen (l)	3.07
Calculated volume of air displaced (l)	1.29
Calculated volume of hydrogen displaced during purge (l)	1.77
Ratio of purge volume to installation volume	3.07

090 22 mm meter point test 3

Test #	089 22 mm meter point test 3	
Installation configuration	97 cm x 22 mm pipe plus meter	
Installation volume	1.32 l	
Flow and speed with pure air	1.25 l/m	0.066 m/s
Flow and speed with pure hydrogen	4.3 l/m	0.228 m/s

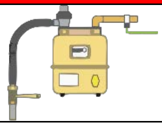


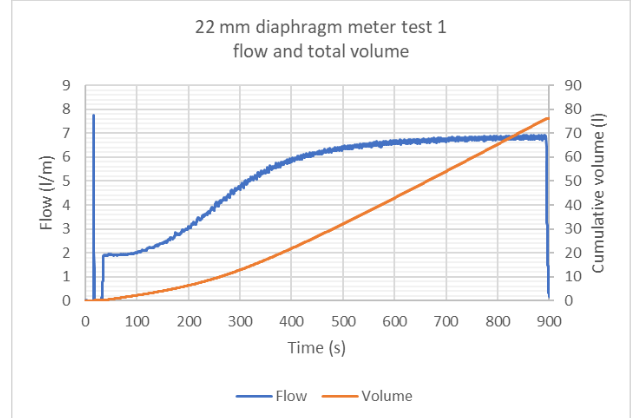
	Time (s)	Volume (l)
To start of transition (>0% H2)	19.1	0.33
Duration of transition	76.5	2.74
To end of transition (95% H2)	95.6	3.07

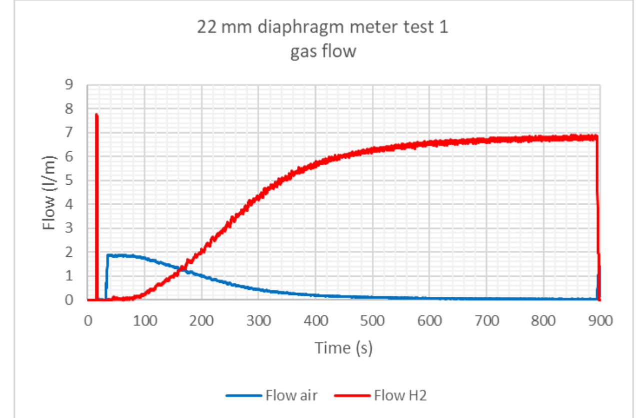
Installation volume (l)	1.00
Total volume displaced to 95% hydrogen (l)	3.07
Calculated volume of air displaced (l)	1.29
Calculated volume of hydrogen displaced during purge (l)	1.78
Ratio of purge volume to installation volume	3.07

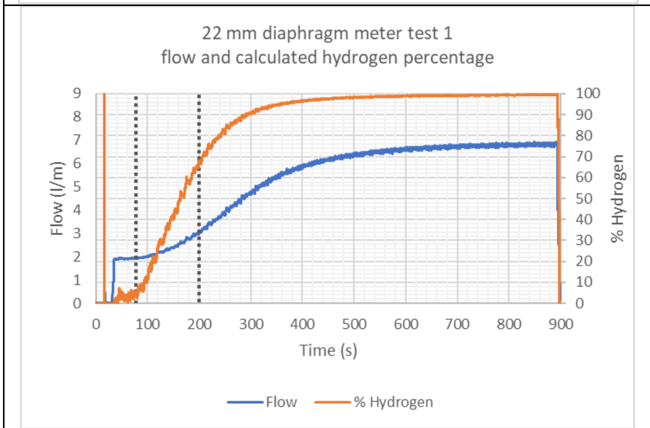
Diaphragm meter

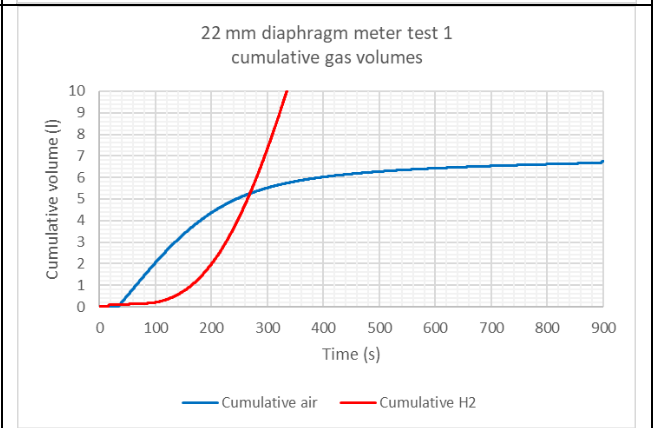
091 22 mm diaphragm meter test 1

Test #	091 22 mm diaphragm meter test 1	
Installation configuration	97 cm x 22 mm pipe plus meter	
Installation volume	8.32 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s





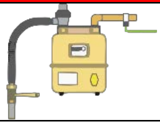


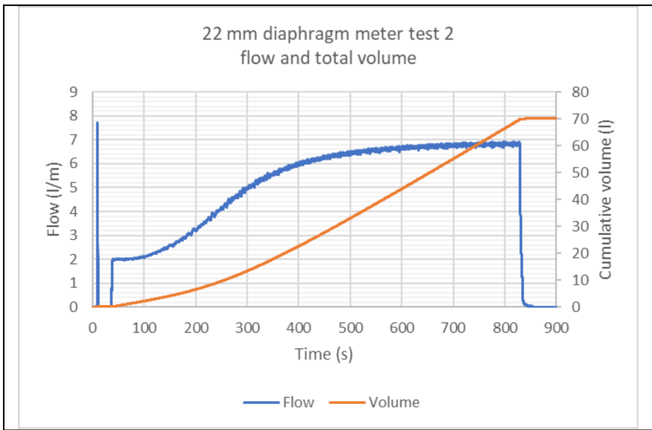


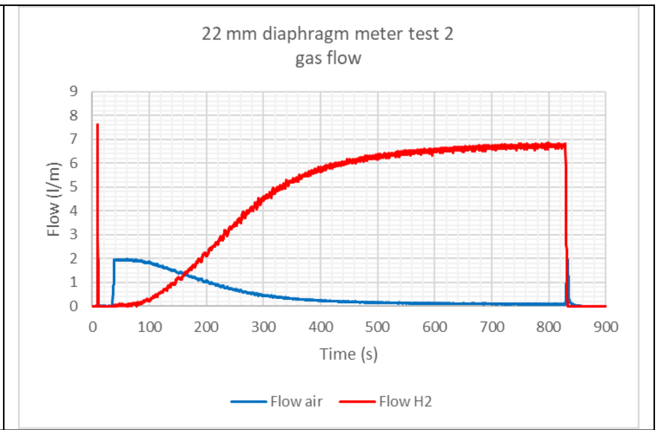
	Time (s)	Volume (l)
To start of transition (>0% H2)	22.4	0.32
Duration of transition	302.7	17.31
To end of transition (95% H2)	325.1	17.63

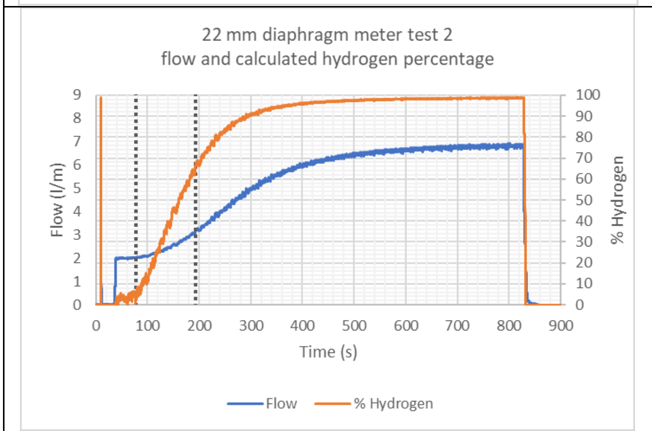
Installation volume (l)	8.32
Total volume displaced to 95% hydrogen (l)	17.63
Calculated volume of air displaced (l)	5.73
Calculated volume of hydrogen displaced during purge (l)	11.90
Ratio of purge volume to installation volume	2.12

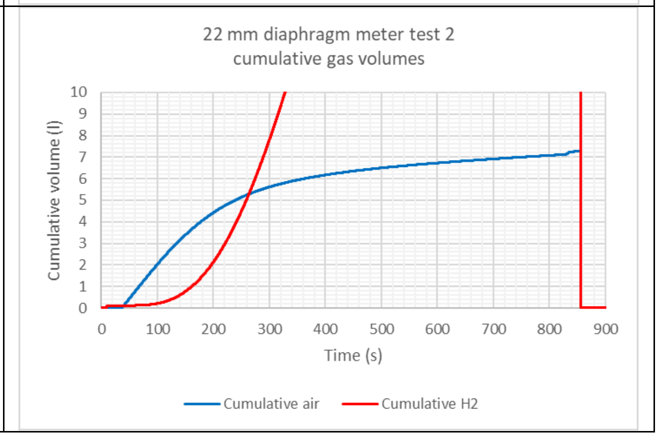
092 22 mm diaphragm meter test 2

Test #	092 22 mm diaphragm meter test 2	
Installation configuration	97 cm x 22 mm pipe plus meter	
Installation volume	8.32 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s





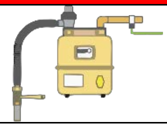


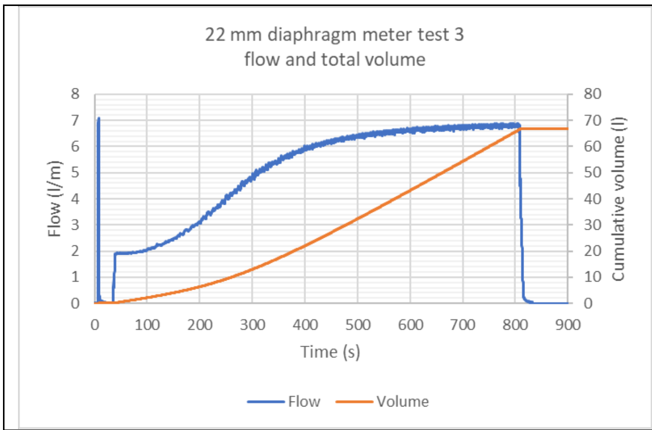


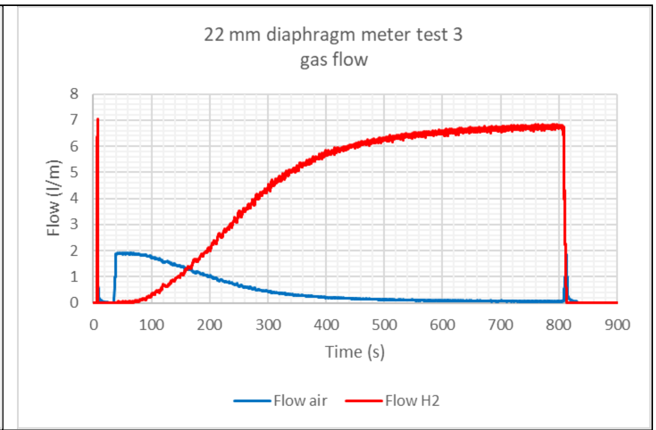
	Time (s)	Volume (l)
To start of transition (>0% H2)	8.7	0.06
Duration of transition	318.3	18.76
To end of transition (95% H2)	327	18.82

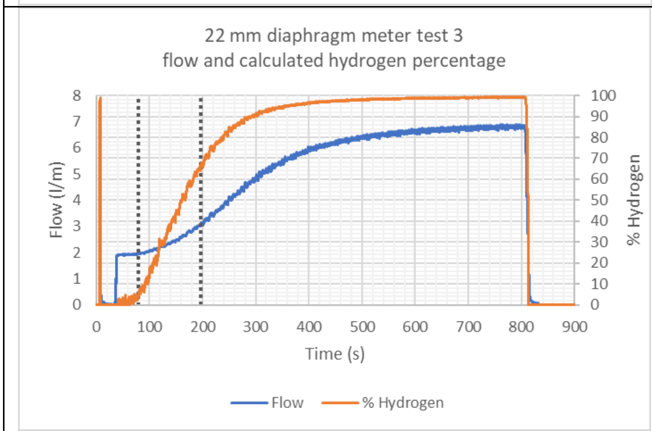
Installation volume (l)	8.32
Total volume displaced to 95% hydrogen (l)	18.82
Calculated volume of air displaced (l)	5.87
Calculated volume of hydrogen displaced during purge (l)	12.95
Ratio of purge volume to installation volume	2.26

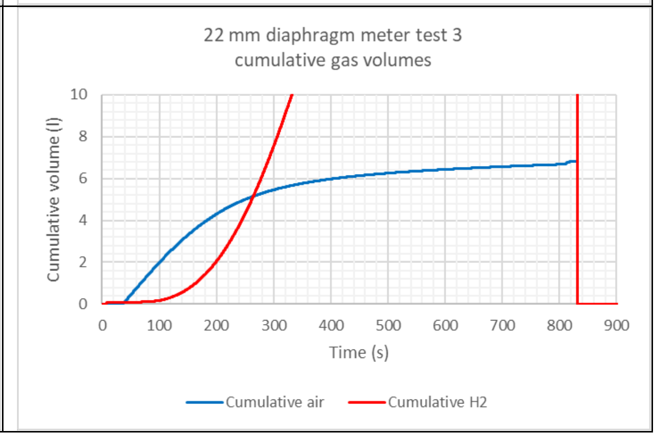
093 22 mm diaphragm meter test 3

Test #	093 22 mm diaphragm meter test 3	
Installation configuration	97 cm x 22 mm pipe plus meter	
Installation volume	8.32 l	
Flow and speed with pure air	2 l/m	0.11 m/s
Flow and speed with pure hydrogen	7 l/m	0.37 m/s









	Time (s)	Volume (l)
To start of transition (>0% H2)	34.6	0.23
Duration of transition	283.3	17.31
To end of transition (95% H2)	317.9	17.54

Installation volume (l)	8.32
Total volume displaced to 95% hydrogen (l)	17.54
Calculated volume of air displaced (l)	5.65
Calculated volume of hydrogen displaced during purge (l)	11.89
Ratio of purge volume to installation volume	2.11