Hy4Heat
demonstrating hydrogen for heat

Department for Business, Energy & Industrial Strategy

WORK PACKAGE 7

Safety Assessment:

Experimental Testing - Domestic Pipework Leakage

WP7 SAFETY ASSESSMENT

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

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

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

Safety Assessment:
Conclusions Report
(incorporating Quantitative Risk Assessment)

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

Safety Assessment:
Consequence Modelling Assessment
A comparative modelling assessment of the consequences in the event of a gas leak and ignition event for natural gas and hydrogen gas.

Safety Assessment:
Gas Ignition and Explosion Data Analysis
A review of experimental data focusing on natural gas and hydrogen gas ignition behaviour and a comparison of observed methane and hydrogen deflagrations.

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

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

Safety Assessment:
Gas Escape Frequency and Magnitude Assessment
An assessment of the different causes of existing natural gas leaks and the frequency of such events; and a review of the relevance of this to a hydrogen gas network.

Safety Assessment:
Experimental Testing - Domestic Pipework Leakage
Comparison of leak rates for hydrogen and methane gas from various domestic gas joints and fittings seen in typical domestic gas installations

WP7 SAFETY ASSESSMENT

Safety Assessment:

Experimental Testing – Commercial Pipework Leakage

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

Safety Assessment:

Experimental Testing - Cupboard Level Leakage and Accumulation

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

Safety Assessment:

Experimental Testing - Property Level Leakage and Accumulation

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

Safety Assessment:

Experimental Testing - Ignition Potential

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

“Hy4Heat Work Package 7 – Lot 1”

Safety Assessments for the Suitability of Hydrogen in Existing Buildings

Final Report

v1.3

Client:	BEIS
Ref:	TRN: 1819/02/2019 Lot 1
Project:	156 – H4H WP7 Lot1
Date:	6th May 2020

Authors:	Dr Nick Ryan	Sebastian Roberts
Email:	nick@steerenergy.com	s.roberts@steerenergy.com
Telephone:	07825 169 322	07491 511 133

Executive summary

The Hy4Heat Project aims to establish if it is technically possible and safe to replace methane with hydrogen in commercial and residential buildings and gas appliances. Work Package 7 examines the Safety Assessments for the Suitability of Hydrogen in Existing Buildings. Lot 1 concentrates on leakage from fittings in domestic gas systems.

Specifically, Lot 1 of WP7 compares the leakage from various domestic gas joints and fittings and compares the leak rates for methane and hydrogen. A calculation is then to be made to assess the relative safety of using hydrogen in the home vs methane, the major component of natural gas.

The project involved carrying out an in-depth study of fixtures and fittings likely to be seen in domestic gas networks. A large number of test pieces were made up and the leak flows in hydrogen and methane were measured for each test piece. Many of the test pieces were deliberately damaged to induce leakage. While the damage was intended to represent real incidents, there are an infinite number of ways to cause damage. Gas fitters were consulted to determine the types of damage they would typically find. A range was carefully considered in each case to cover the likely possibilities.

Leak flow theory has been examined to determine the likely differences in flow and leakage between methane and hydrogen and this theory has been compared to the measured data. The main observations of the tests show that:

- a non-leaking fitting in methane will be non-leaking in hydrogen.
- a leak in methane will result in a leak in hydrogen.

At molecular level, methane molecules could be separated from hydrogen molecules using a molecular sieve. The subsequent ‘leakage’ of hydrogen would be classed as permeability, and be too low to be relevant.

Turbulent and laminar flow regimes have been observed, the tests have shown that:

- Laminar flow is characterised by a linear relationship between flow and pressure and a leak flow ratio of 1.2:1 between hydrogen and methane.
- Turbulent flow is characterised by a square root relationship between flow and pressure and a leak flow ratio of 2.8:1 between hydrogen and methane.
- For a given leak flow, transition from laminar to turbulent flow occurs at a lower pressure for methane than for hydrogen. Reynolds number is 6.43 times greater for methane than for hydrogen. This means that for a given leak methane flow will become turbulent at a lower pressure than hydrogen flow.

Leaks derived from accidents such as drilled holes or nail holes are likely to be large leaks with turbulent flow regimes and a volumetric leak ratio of 2.8:1, hydrogen to methane. Leaks from loose and damaged fittings are likely to be small leaks with laminar flow regimes and volumetric leak ratios of 1.2:1 hydrogen to methane.

Many of the leaks observed on damaged fittings resulted in small leak flows of less than $1x10^{-3}$ m^3/hr in both gases. This is close to the boundary between passing and failing the current gas tight tests in domestic system and light commercial systems. For non-damaged fittings the leak rates observed for both gases have been at the limit of the measurement equipment, in the order of 1×10^{-6} m^3/hr.

None of the tests carried out have found a feature or type of fitting that leaked in hydrogen and not in methane. No fittings have been found to be unsuitable for hydrogen.

The current pressure test for gas systems should be valid for hydrogen filled gas systems.

Table of Contents

1 Background

The Hy4Heat project aims to establish if it is technically possible and safe to replace methane with hydrogen in commercial and residential buildings and gas appliances. Work Package 7 examines the safety assessments for the suitability of hydrogen in existing buildings. Lot 1 concentrates on leakage from fittings in domestic gas systems.

Specifically, Lot1 of WP7 examines the leakage from various domestic gas joints and fittings and compares the leak rates for methane and hydrogen.

1.1 Project Scope

The original project scope was to '*test and compare the gas tightness of existing pipework and fittings downstream of the Emergency Control Valve (ECV)*'. This, therefore, relates to pipework in or next to the domestic property (in the case of an external meter). Pipework in the street and risers leading to the building are out of scope as illustrated in Figure 1.

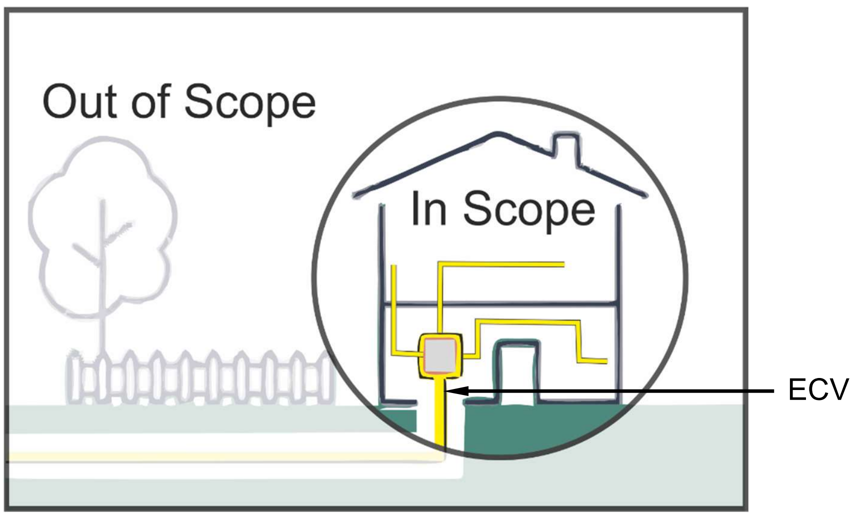


Figure 1: Project scope

The types of pipework to be expected in a domestic property are shown in Figure 2. If UK-wide pipework is to be considered then domestic pipework will include a wide variety of materials. Testing has therefore included: lead, copper, low carbon malleable iron, stainless steel, and polyethylene pipe types. A wide range of fitting and valve types has also been included in the test programme.

These pipes and fittings will also crossover into small commercial systems.

Fittings on MDPE and corrugated semi-flexible steel pipe up to 32 mm diameter, and steel pipe up to ¾ inch diameter have been tested. Copper pipe and fittings have been tested up to 22 mm.

Pressures up to 100 mbar were initially tested and presented in the *50 Test* work. This allowed us to discover the likely flow rates. Following this the tests were kept to 20 mbar as this best represents a typical domestic gas installation. Some further investigations have been carried out to examine the transition from laminar to turbulent flow, and pressure was increased to 400 mbar for these tests.

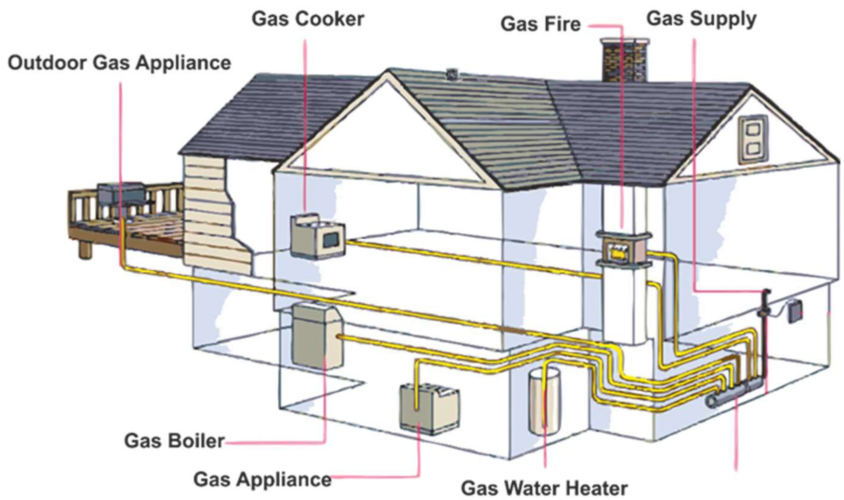


Figure 2: Example of domestic gas pipework

1.2 Project breakdown

The work programme for the project was broken down into five work packages:

- WP1: Project management
- WP2: Literature review
- WP3: Experimental setup
- WP4: Experiments
- WP5: Reporting and documentation

A summary of each section is now provided.

1.2.1 WP1: Project management

This work included running of the project and reporting to the Arup+ Hy4Heat project team.

During the kick off meeting held on the 19 June, a request was made for an early indication look at results. This resulted in the *50 Test* programme of work. The aim of the *50 Test* work was to take a quick look at a small selection of representative fixtures and fittings and report back to the Hy4Heat team. The results would then be used to feed into the test programmes of parallel lots in WP7 and other work packages.

This deviation from the original work programme was managed by Steer and the project plan modified accordingly. A useful outcome of this work was that it enabled the fast commissioning of the test and experimental setup. Shortcomings of the original test equipment were identified and addressed resulting in more accurate tests for the main body of the test programme.

1.2.2 WP2: Literature review

The literature review comprises a number of elements:

- Review of similar published work carried out in other projects
- Development of relevant gas flow and leak flow theory from standard literature

Anecdotal information has been sought from professional gas fitters during the course of the programme of work. This has been used in the manufacture of good and bad joints to create the test pieces and to guide some of the defect choices.

This work is presented in chapter 2 Literature search.

1.2.3 WP3: Experimental setup

The initial test setup was presented in the *50 Test* report. An outcome of the initial *50 test* work was to acquire improved test equipment, specifically calibrated for methane and hydrogen. This report mainly deals with this new experimental setup.

Details of the experimental equipment are presented in Chapter 3 Experimental setup. A breakdown is provided of the various test types used for the different defect types and the method used to generate results.

1.2.4 WP4: Experiments

This chapter reports on the main body of work carried out for the project. The reporting is broken down in the same form as the work. Job sheets have been allocated for the work and this nomenclature has been kept for the raw data and reporting. The test groups are:

- J05 Holes
- J06 Joints and fittings
    - Cold crimp fittings
    - Compression fittings
    - Screwed and threaded fittings
    - Solder fittings
    - Miscellaneous fittings
- J07 Valves
- J08 Damage
- J09 Flow investigations
- J10 Regulators
- J11 Other pieces

The report provides a summary of the tests group by group. Full test details are provided in the appendix, also by group.

2 Literature search

All of the lots of WP7 contain a literature survey to investigate specific elements of literature pertinent to that lot and to the wider work package. A high level literature review was undertaken

2.1.1 Relevant literature

The following documents have been identified and reviewed:

- *Comparison of the Safety-related Physical and Combustion Properties of Liquid Hydrogen and Liquid Natural Gas in the Context of the SF-BREEZE High-Speed Fuel-Cell Ferry. L.E. Klebanoff, J.W. Pratt and C.B. LaFleur.* This document was found to have pertinent references to the project.
- *Estimation of Gas Leak Rates Through Very Small Orifices and Channels. Herbert J. Bomelburg.* This document was found to be a useful source of information but did not contain pertinent references to the project.
- *Hyindoor Final Report. Béatrice L'Hostis.* This document was found to be a useful source of information but did not contain pertinent references to the project
- *H21 Report. Leeds City Gate Team.* This document was found to have pertinent references to the project.
- *Safety in the installation and use of gas systems and appliances. HSE*. This document was found to be a useful source of information but did not contain pertinent references to the project.
- *Fuel Cells. Understand the hazards, control the risks. HSE.* This document was found to have pertinent references to the project.
- *Installation permitting guidance for hydrogen and fuel cell stationary applications: UK version. HSE.* This document was found to have pertinent references to the project.
- *Appraisal of Domestic Hydrogen Appliances. Frazer-Nash Consultancy.* This document was found to have pertinent references to the project.
- *Hydrogen for heating and cooking? Wales & West Utilities.* This document was found to be a useful source of information but did not contain pertinent references to the project.
- *Logistics of Domestic Hydrogen Conversion. Frazer-Nash Consultancy.* This document was found to have pertinent references to the project.
- *Energy Storage Component Research & Feasibility Study Scheme. HyHouse*. This document was found to be a useful source of information but did not contain pertinent references to the project.
- *Safety Issues Surrounding Hydrogen as an Energy Storage Vector. Kiwa Gastec.* This document was found to have pertinent references to the project.
- *A guide to the Gas Safety (Management) Regulations 1996. HSE.* This document was found to be a useful source of information but did not contain pertinent references to the project.

Of the documents identified as containing pertinent information, the most relevant points from the literature review are briefly copied down here with references where appropriate.

The first group of references refer to permeability of materials, some concerns have been raised about the potential for higher permeation of hydrogen through materials but no hard evidence presented.

Comparison of the Safety-related Physical and Combustion Properties of Liquid Hydrogen and Liquid Natural Gas in the Context of the SF-BREEZE High-Speed Fuel-Cell Ferry[1]

> '*Hydrogen permeability is not a leak issue for practical hydrogen systems* - pg1'
>
> '*Many misinterpret hydrogen permeation (even in the absence of embrittlement) as a leak risk.* – pg9'
>
> '*Permeation as a source of leaking is not an issue for the practical performance of tubing, valves or other hardware because the quantities of gas exiting in this way are infinitesimal.* - pg10'
>
> '*The point of this discussion is that permeation in the context of the SF-BREEZE is not an issue for leakage from plumbing systems such as valves, fittings, tubes, pipes, etc. because it is infinitesimal.* - pg10'

H21 Report[2]

> '*Greater ability to permeate through materials and joints, although the actual rate of diffusion through pipes is very small* – pg 157'
>
> '*Bearing in mind the stoichiometric concentration, i.e. the optimum gas mixture for combustion, is only 10% v/v for natural gas and 29% v/v for hydrogen, the independent committee that oversaw the HyHouse work (this included a representative of IGEM), considered that the out-turn risk from unplanned leakage of hydrogen from a gas network was not that dissimilar to a leak of natural gas, through a similar hole.* – pg 159'

The second group of references discuss the need for tighter fittings when using hydrogen, however they do not provide evidence why this should be the case over anecdotal evidence. Some support is drawn however from the ISO standard, ISO/TR 15916:2015(en) basic consideration for the safety of hydrogen systems. Other references are taken from *Fundamentals of hydrogen safety engineering* which discusses the use of high-pressure Swagelok style of compression fittings and their possible overtightening leading to leakage.

Installation permitting guidance for hydrogen and fuel cell stationary applications: UK version[3]

> '*Minimise the number of joints by using continuous lengths of pipe work wherever practicable;* - pg 23'
>
> '*Where possible use fusion joints (welded or brazed) to join pipe work, flange/threaded connectors may be used where necessary;* - pg 23'

---

[1] https://www.osti.gov/pages/biblio/1371474
[2] https://www.northerngasnetworks.co.uk/wp-content/uploads/2017/04/H21-Report-Interactive-PDF-July-2016.compressed.pdf
[3] https://www.hse.gov.uk/research/rrpdf/rr715.pd

> *'Only appropriate pipe work and fittings for the supply of hydrogen should be used. Cupronickel and stainless steel are preferred materials for high-pressure pipe work whereas copper can be used for lower pressures. All pipe work joints should be brazed or welded where possible. Flanged or screwed joints may be used where necessary. Suppliers should be able to provide information on the operating parameters of pipe work and fitting, and the standards used for their manufacture.* - pg 23'

> *'Compression joints are generally not recommended for use on hydrogen systems as it is difficult to achieve and maintain these in a leak-free condition. Where their use is considered essential, such as on small-bore pipe work, they should be suitable for the duty and used in strict accordance with the manufacturer's instructions.* - pg 23 (quotes a withdrawn document)'

> *'Particular attention should be given to the design and location joints in the system that may require regular maintenance, or where mechanical joints will be frequently disturbed or made/broken as the likelihood of leaks in these areas is increased.* – pg24'

> *'The manufacturer must carry out necessary research and tests on components, fittings or the completed equipment to determine whether by its design or construction it is capable of being assembled and put into service safely.* – pg50'

Fuel cells. Understand the hazards, control the risks[4]

> *'Hydrogen gas has a very low viscosity and so it is very difficult to prevent hydrogen systems from developing leaks. Pipework that was 'leak-tight' when pressure-tested with nitrogen will often be found to leak profusely when used on hydrogen duty. This property increases the likelihood of a flammable mixture forming* - pg10'

> *'Compression joints are generally not recommended for use on hydrogen systems as it is difficult to achieve and maintain these in a 'leak-free' condition. Where their use is considered essential, such as on small-bore pipework, they should be suitable for the duty and used in strict accordance with the manufacturer's instructions.* -pg14'

The next references discuss the difference in molecule size between hydrogen and methane and use this as a reason for larger leakage through small openings, however no reference is made to actual sizes of the molecules and openings in question. This is likely to be anecdotal.

Appraisal of Domestic Hydrogen Appliances[5]

'[Hydrogen] *has a much smaller molecular size than natural gas and is therefore more prone to leakage through joints and valves – pg 17'*

> *'Leakage: Hydrogen is the smallest molecule and so has a greater propensity to leak through small openings than natural gas. There is a particular concern with leakage through flanged joints and screwed connections and this may mean more welded joints are necessary.* – pg23'

[4] https://cedrec.com/cedrec_images/upload/acop/hsg/hsg243.pdf
[5] https://www.gov.uk/government/publications/appraisal-of-domestic-hydrogen-appliances

‘Gas valve Gas shut-off and throttling

Potential for hydrogen to leak through seals. Different gas flow rate may be required depending on new burner combustion characteristics and changes to overall energy performance.

Seals may need development to mitigate leakage. Adjust for different flow rate by selecting valves with different flow capacity. - Pg25’

Logistics of Domestic Hydrogen Conversion [6]

‘Hydrogen presents different safety concerns to natural gas – it has a greater propensity to leak through joints – pg3’

‘Gas line tightness test. Gas line tightness test is carried out to ensure that pipework has a leak rate below a level which could ever be considered to form a hazard. It essentially involved pressurising the internal pipework, sealing both ends and monitoring the internal pressure over time and using the drop in pressure to determine the leakage. The Maximum Permissible Leakage Rate (MPLR) is dependent on the combustible energy released and for natural gas is 0.0014 m3/hr (1.4 litres per hour). The duration of the test depends on the internal volume of pipework but typically takes 10-20 mins to complete. The MPLR also depends on the ability to disperse the gas and is higher for buildings of greater internal volume or greater ventilation. – pg16/17’

‘As a result of its small molecular size, hydrogen is much more prone to leakage through joints and component assemblies than natural gas [16]. Evidence from the stakeholders suggested that there is a particular concern with leakage through pressed fitted joints that rely on rubber washers and also compression fittings. Furthermore it will be necessary to determine suitable joint specifications for low pressure domestic (20 mbar) hydrogen pipework. High pressure joint specifications (typically around 350-700 bar operation) already exist and studies will need to identify the extent to which the requirements for low-pressure applications could be relaxed compared with current high-pressure hydrogen – pg18/19’

‘Welded copper is widely used for domestic gas pipework and this is a good starting point as it is likely to be suitable for use with hydrogen. However, other commonly used materials, such as steel and their respective joining techniques should be tested as well. This also provides an opportunity to determine if plastic pipework, which currently cannot be used for fire safety, is suitable for domestic gas applications. It is suggested that tests will need to include the following:

- *Leakage rates through pipework and fixings – initially at the domestic gas pressure of 20 mbar but exploring the effect of variations in driving pressure* - pg40’

Finally, this last reference is of note as it specifically excludes hydrogen in non-domestic applications.

Safety in the installation and use of gas systems and appliances [7]

[6] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/760508/hydrogen-logistics.pdf

[7] https://www.hse.gov.uk/pUbns/priced/l56.pdf

> *‘ “gas” means any substance which is or (if it were in a gaseous state) would be gas within the meaning of the Gas Act 1986 except that it does not include gas consisting wholly or mainly of hydrogen when used in non-domestic premises;* - pg 9’

The review carried out on the various items of literature has not been exhaustive, however the documents reviewed did not repeat any of the work carried out in the project. The work in this project provides evidence based knowledge on the nature of hydrogen leakage.

2.2 Overview of gas leak theory

An initial review of the fluid mechanics theory has been carried out. This has looked at small bore pipe flow of methane and hydrogen. This section will outline:

- assumptions that have been made
- details of pipe flow theory
- choked flow calculations
- details of leak flow theory
- and friction and dynamic losses

2.2.1 Assumptions

For a non-ideal gas (as is the case with methane and hydrogen), the ideal gas law is modified by the inclusion of the compressibility factor *Z*,

$$PV = nZRT$$

Where: P = Pressure

V = Volume

n = Number of Moles

Z = Compressibility Factor

R = Specific Gas Constant

T = Temperature

The compressibility of methane and hydrogen in the pressure ranges for the situation being tested are small. It can be justified that the compressibility factor *Z* can be neglected in these calculations with an error introduced of the order of less than 10%.

Therefore, where appropriate, the gases can be thought of as ideal gas, with minor errors. We can therefore assume incompressible gases.

In addition to this, we are assuming that the gases are:

- Adiabatic (no energy transfer other than work, and no work transfer in this case)
- Reversible (no change in entropy e.g. neglecting frictional losses)

The following values have been taken for each of the different gases:

	Air	Methane	Hydrogen	Units
Ratio of Specific Heat[8]	1.4	1.32	1.41	-
Gas Density[9]	1.226	0.680	0.0852	kg/m^3
Absolute Dynamic Viscosity[10]	1.80×10^{-05}	1.08×10^{-05}	8.7×10^{-06}	Pa.s
Universal Gas Constant[11]	287	518	4124.2	J/kgK

Table 1: Specific gas properties

2.2.2 Pipe flow theory

The "Invitation to Tender" highlighted the effect of flow regime on comparative rates of Hydrogen and Methane, particularly relating to laminar and turbulent flow regimes. The following table, Table 2, provides similar figures to those quoted, and outlines the two main models used:

Hagen Poiseuille: this is used in non-ideal fluid dynamics and can be used to calculate the pressure drop in an incompressible Newtonian fluid in laminar flow through a long cylindrical pipe of constant cross section. In our case, this can be applied to the general pipe flow (prior to flow through the leak), or to a thread leak / leak with a long throat. When used with turbulent flows, this equation will underestimate the pressure drops.

Darcy-Weisbach: this provides the pressure drop in an incompressible fluid and contains a dimensionless friction factor which is not constant, but depends on characteristics of the pipe, the fluid, and the velocity. When the flow is laminar, the losses are proportional to the flow velocity and therefore this equation is not appropriate until the flow moves to turbulent flow.

[8] These figures are taken at NTP from https://www.engineeringtoolbox.com/specific-heat-ratio-d_608.html. However, for the purposes of our work, these will not change significantly.
[9] Calculated at 15 Deg C and 1 atm from https://www.engineeringtoolbox.com/gas-density-d_158.html
[10] Calculated at 15 Deg C and 1 atm from https://www.engineeringtoolbox.com/gases-absolute-dynamic-viscosity-d_1888.html
[11] https://www.engineeringtoolbox.com/individual-universal-gas-constant-d_588.html

			H_2	Ratio	CH_4
Model			μ = 0.870 x 10^{-5} Pa.s	1 : 1.24	μ = 1.08 x 10^{-5} Pa.s
			ρ = 0.0852 kg/m^3	1 : 7.98	ρ = 0.680 kg/m^3
Reynolds Number			$Q \propto \frac{\rho}{\mu}$	1 : 6.43	$Q \propto \frac{\rho}{\mu}$
Turbulent flow	High Reynolds	Darcy-Weisbach	$Q \propto \sqrt{\frac{\Delta P}{\rho}}$	2.82 : 1	$Q \propto \sqrt{\frac{\Delta P}{\rho}}$
	Momentum dominates				
	(High speed, unchoked)				
Laminar flow (small leaks)	Low Reynold	Hagen-Poiseuille	$Q \propto \frac{\Delta P}{\mu}$	1.24 : 1	$Q \propto \frac{\Delta P}{\mu}$
	Friction Dominates				
	(Low Speed)				

Table 2: Ratios from flow models

Table 2 indicates the flow conditions in the cases where turbulent and laminar flow exist. In laminar conditions, flow is dominated by friction and the flow ratio of hydrogen to methane is 1.24:1. In turbulent conditions this flow ratio of hydrogen to methane rises to 2.82:1 and the flow is dominated by momentum. The Reynolds number indicates the flow regime: laminar, transition or turbulent. Fluid mechanics theory states that the transition point between laminar and turbulent flow occurs at Reynolds numbers between 2300 and 2900, with the flow not fully turbulent before a Reynolds number of 4000. Typically transition points are taken at a Reynolds number of 2500.

The table also indicates the difference in Reynolds number between hydrogen and methane and indicates that transition will occur at lower flow speeds for methane than hydrogen.

One of the challenges set in the "Invitation to Tender" was to carry out experiments which "*demonstrates the conditions necessary to cause both types of flow and focus on the scenarios which illustrate the transition from laminar flow to turbulent flow. For guidance we would expect this to occur between 0.01 and 6.4m*^{3}*/h of G20 (Natural Gas) and Hydrogen (ISO14687 Type A)*".

Using this figure within the Reynolds calculation, and standard chemical values for density and absolute viscosity we would expect the turbulence transition to occur at around 2.2 m^3/h for methane and above 14 m^3/h for hydrogen in a 20 mm internal diameter pipe. Note that this calculation is for main pipe flow rather than leak flow.

2.2.3 When does choked flow occur?

Choked flow is a compressible flow effect, and occurs when the gas particle velocity reaches the speed of sound (Mach 1). At this point, upstream conditions cannot propagate forwards any faster than the particles are physically moving, and therefore the flow is "choked". This occurs when:

$$P_2 = P_1\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$$

$i.e.\frac{P_2}{P_1} \leq P_{Critical}\ (For\ Air, Hydrogen = 0.53, for\ Methane = 0.54)$

where Υ= *Ratio of Specific Heat*

P_2 = *Downstream Pressure (Outside of the pipe)*

P_1 = *Upstream Pressure (Inside of the pipe)*

In our case, we envisage a maximum of 100 mbar difference between P_1 and P_2, which over 1 bar g equates to a 10% drop. Therefore, due to the pressure regime being tested, we cannot envisage a situation where the leak flow would become choked. At a gauge pressure of 20 mbar the chance of choked flow is even less.

2.2.4 Leak flow

Working through Bernoulli's equation, isentropic orifice flow *below* the critical (choked) pressure ratio can be calculated as:

$$\dot{m} = C_d\, A_2 \sqrt{2\,\rho_1\, P_1\left(\frac{\gamma}{\gamma-1}\right)\left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{\gamma}} - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma+1}{\gamma}}\right]}$$ [12]

Where C_d, coefficient of discharge,

$$0.6 \leq C_d \leq 0.85$$ [13]

Note that this value is affected by various parameters of the orifice and given shape variation is likely to vary even more widely in the current work. We have used 0.611 in this work.

Isentropic orifice flow *at or above* the critical (choked) pressure ratio can be calculated as:

$$\dot{m} = C_d\, A_2 \sqrt{\gamma\,\rho_1\, P_1\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}$$ [14]

For the following figures, we use the sub-critical equation to calculate the mass flow rate for air, methane and hydrogen from a 6mm leak, assuming a C_d of 0.611.

[12] https://en.wikipedia.org/wiki/Orifice_plate

[13] https://en.wikipedia.org/wiki/Orifice_plate#Coefficient_of_discharge

[14] https://en.wikipedia.org/wiki/Orifice_plate

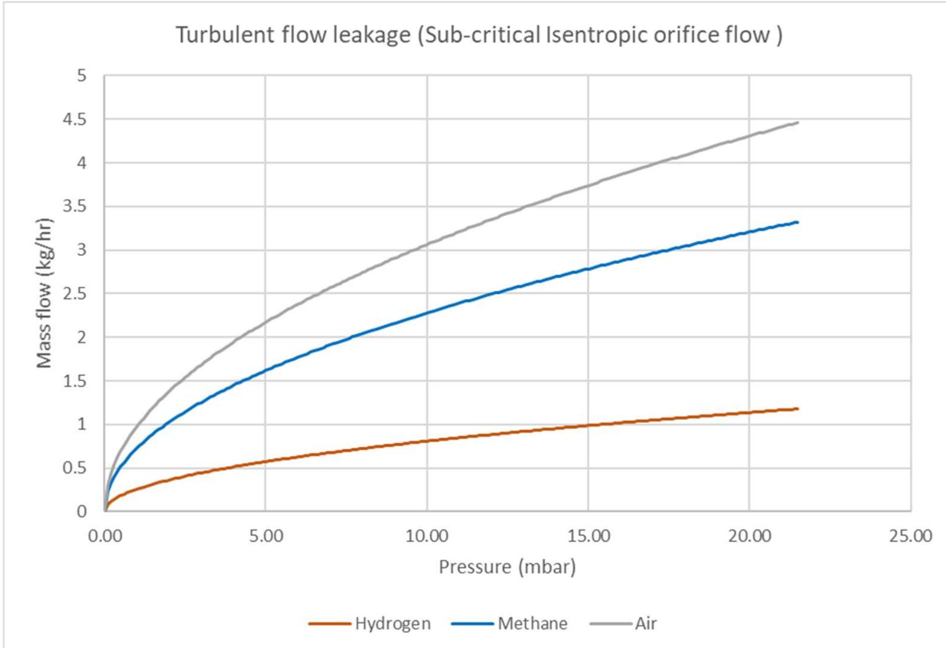


Figure 3: Mass flow vs pressure for turbulent flow regime

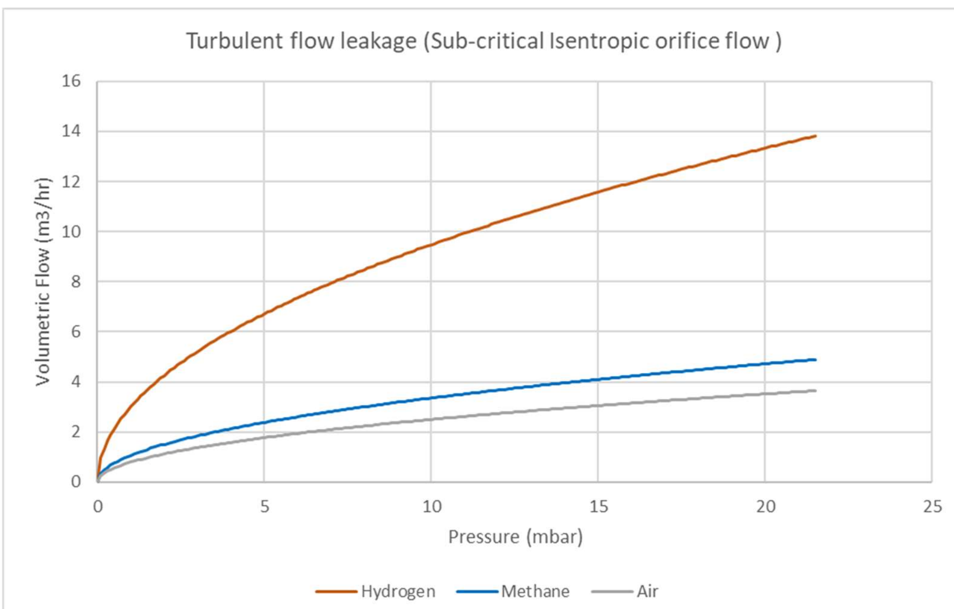


Figure 4: Volumetric flow vs pressure for turbulent flow regime

This is calculated out for circular leaks or more specifically leaks where the flow is turbulent. However, certain leak types such as thread leaks lead not to turbulent but laminar flow conditions. The Hagen-Poiseuille model can be used to for these laminar flows. These leaks could be expressed as an equivalent area of circular leak for a reasonable approximation to compare theory with measured data.

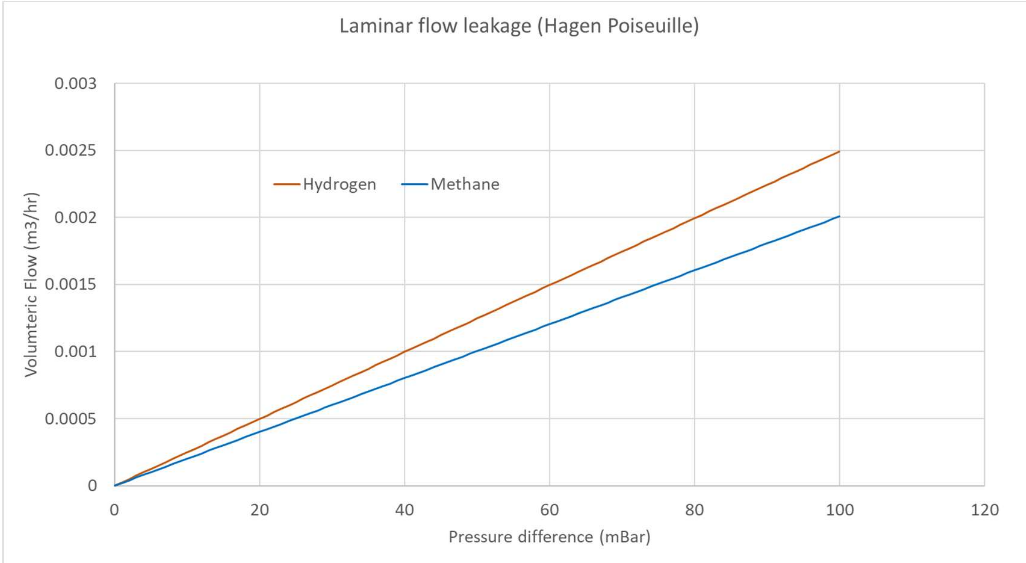


Figure 5: Volumetric flow vs pressure for laminar flow regime

An example of laminar flow calculations (using Hagen Poiseuille) has been shown in Figure 5 above. Here, using the example of a 0.3 mm diameter leak with a throat length of 3.3 mm (equivalent of a 32mm diameter MDPE pipe), we can see that for a given pressure in laminar flow, hydrogen will have a higher volumetric flow rate. We can expect that a graph containing laminar, transition, and turbulent flow would start off similarly to Figure 5 before moving towards the volumetric flow shapes given in Figure 4.

2.2.5 Onset of turbulence in leak

Similar to the methodology used above, we can calculate when turbulent flow is likely to occur through a leak. In the case of a 6 mm diameter leak, this is likely to occur at a flow rate of 0.67 m^3/h for Methane and 4.3 m^3/h for Hydrogen. Figure 6 outlines how Reynolds number changes as the leak hole sizes increase for a range of flow rates in Hydrogen and Methane.

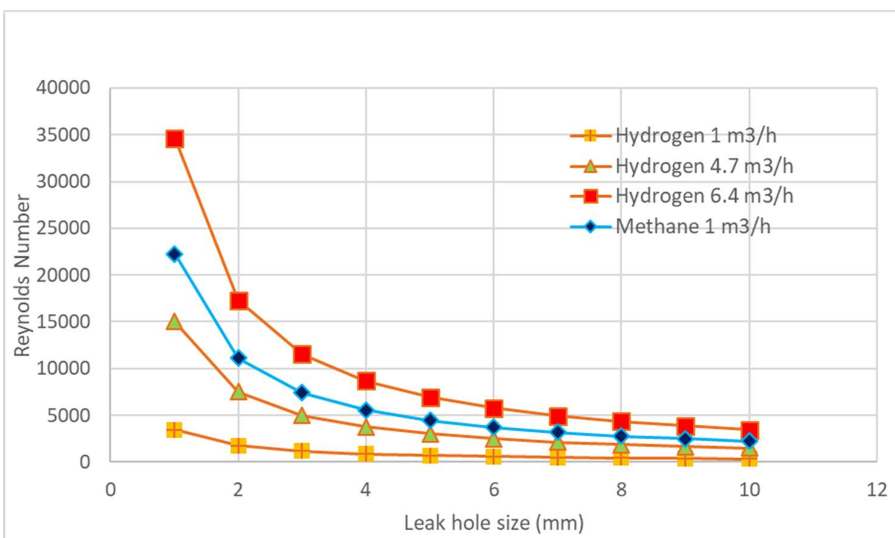


Figure 6: Demonstrating how Reynolds number changes with leak size

Finally, we can plot Reynolds number against velocity for a given pipeline diameter (20mm) as shown in Figure 7. This indicates that the transition for hydrogen is always later than for methane given the same flow conditions.

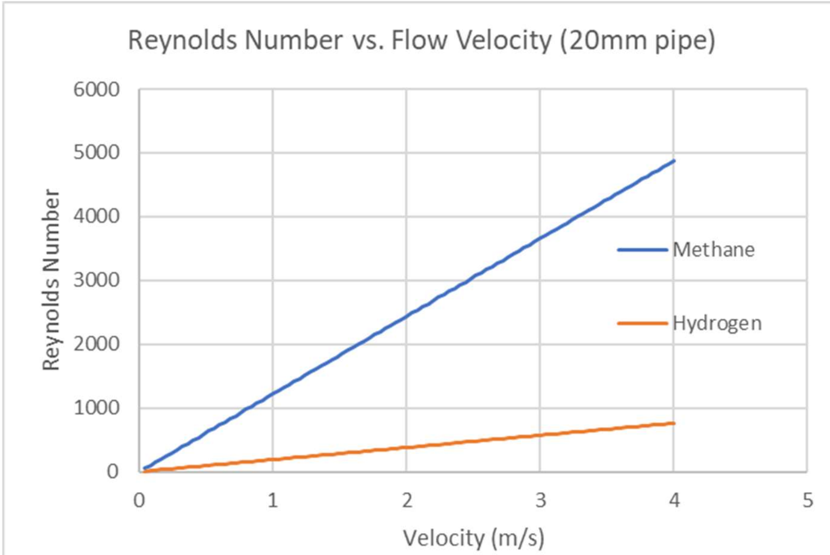


Figure 7: Reynolds Number against Velocity

2.3 Losses

Head losses are generally the result of two mechanisms:

- Friction along the pipe walls
- Turbulence due to flow through fittings, valves, etc.

2.3.1 Frictional losses

For incompressible fluids, the Darcy-Weisbach equation is commonly used for computing the frictional loss in a given pipe for a given discharge:

$$h_f = f\frac{L}{D}\frac{v^2}{2g}$$

Where:

- h_f is the head loss due to friction that has the unit of length (*L*),
- *f* is a dimensionless friction factor,
- L is the length of the pipe (L),
- *D* is the internal diameter (L),
- *v* is the average velocity (LT^{-1}), and
- *g* is the acceleration due to gravity (LT^{-2}).

The friction factor is not a constant but depends on the characteristics of the pipe, the fluid, and the velocity of the flow, and can be found from Moody diagrams.

2.3.2 Losses Due to Fittings

A body of work exists to quantify the losses that are due to the turbulent effects of flowing through flanges, valves, etc. These are commonly called minor or dynamic loss coefficients.

$$\Delta P_{Minor\ Loss} = \xi \rho_f \frac{v^2}{2}$$

Where:

ξ = minor loss coefficient

ρ_f = density

$\Delta P_{Minor\ Loss}$ = minor pressure loss

v = flow velocity

A number of pipe manufacturers create friction loss tables[15]. These tables detail the loss per unit length of pipe for given flow rates, media and pipe diameter. The tables also detail the minor loss coefficients and equivalent length for various fixtures and fittings.

For example, a 22 mm elbow may have a loss coefficient of 1.29 or an equivalent length of 1.04 m. A radius bend of the same size has a quoted minor loss coefficient of 0.44 and an equivalent length of 0.35 m. The equivalent length is the equivalent length of straight pipe that would incur the same pressure drop.

2.4 Leak characterisation

The test matrix involved testing a wide range of fittings, fixtures and leak types. To ensure that all the main leak types were covered, the leak types have been characterised by geometry. This geometric characterisation has led to a theoretical analysis of the leak types. The key leak shapes are:

- circular holes in thin and thick wall pipes
- thin cracks, circumferentially and longitudinally oriented
- thin annular gap such as an unsoldered solder joint
- thread leaks resulting in a helical leak path

Each of these leak types can be characterised by basic length, width and depth as seen by the gas. Understanding the dominant dimension, e.g. length or width enables a prediction to be made on the likely gas flow behaviour as it passes through the leak. This should facilitate understanding of the Reynolds number for the leak flow and hence the flow mode for the different leak types.

The leak types have been broken up into:

- circular holes
- circumferential and longitudinal cracks
- annular tube gaps
- helical thread leaks

[15] https://www.pegleryorkshire.co.uk/MEDIA/Downloads/CC_004/82498733_Pressure_Loss_Tables.pdf

2.4.1 Circular holes

Circular holes are the simplest feature to characterise, indeed much of the literature examines leaks in terms of round holes. Round holes are a simple method of characterising leak sizes and of creating a leak by accident.

The two main dimensions of a hole are the diameter of the hole and the depth of the hole which is in turn is determined by the thickness of the pipe. Two hole types have been investigated; thin wall holes in copper tube and thick walled small diameter holes in MDPE pipe. Figure 8 shows a 4 mm diameter hole in copper tube and a 1 mm diameter hole in MDPE pipe to demonstrate the difference in aspect ratio of diameter to length in the two materials.

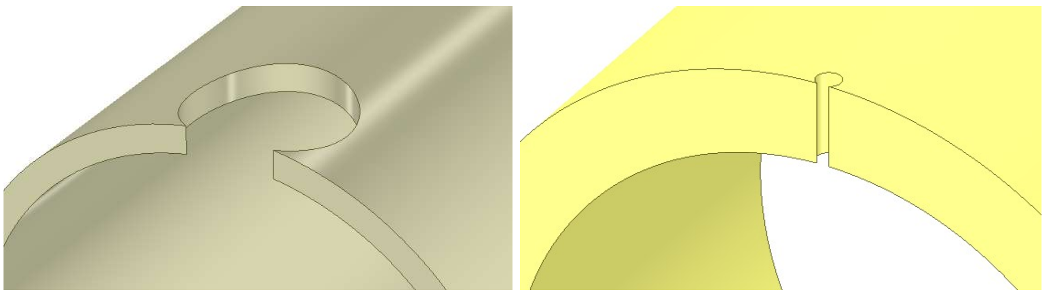


Figure 8: Thin wall hole in copper and thick wall hole in MDPE

The 4 mm hole in the copper tube has a short flow length and a long width across the flow. The gas/defect interaction occurs at the sharp edges of the holes which is likely to create large eddies, hence turbulence. This hole is likely to have been made by accident, therefore the hole is likely to have large amounts of swarf and burrs on the inside of the pipe which provides a very sharp edge. The 1 mm hole in MDPE has a longer flow length than flow width, this moves to a shape closer to thin pipe flow. In this instance the gas/defect interaction will start to be influenced by the friction resistance of the flow interacting with the wall of the hole. This frictional loss will significantly reduce the leak flow and move the flow towards laminar.

Corrosion pitting, which is a likely cause of pinhole, or small leaks, is associated with pipe wall thinning so these real-world cases are unlikely to mimic a pipe flow.

2.4.2 Circumferential and longitudinal cracks

Crack defects have width and length which are very different from each other, Figure 9. The result is a wide, narrow slot where the walls of the slot are close to each other. The flow path is more parallel than in the round hole defects and there is more opportunity for gas/wall interaction. Like the round hole, the slot is likely to result in eddies and hence turbulent flow. The slot leak is likely to be formed by mechanical damage such as caused by a saw. This is likely to have large burrs on the inside of the pipe.

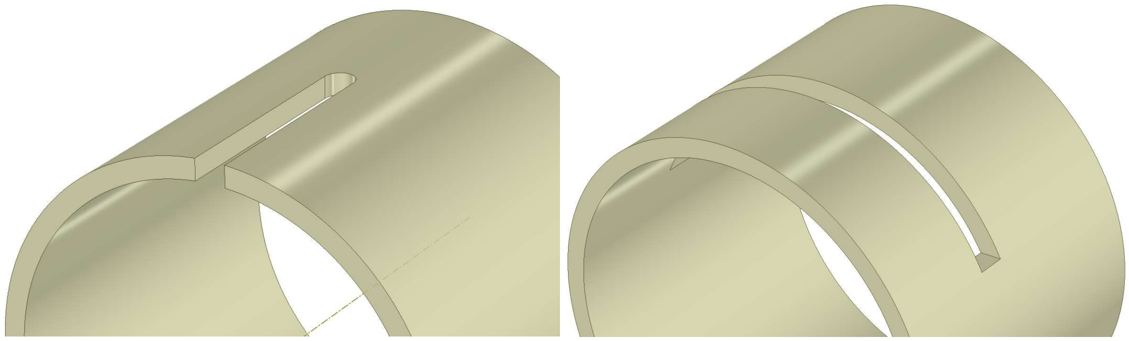


Figure 9: Longitudinal and circumferential cuts

Longitudinal and circumferential cuts have already been reported in the *50 Test* work. The resulting behaviour is, as predicted, like a hole. These tests have not been repeated in the data presented in this report.

2.4.3 Annular tube gap

The annular leak is in the form of a thin wide passage between the outside of the tube wall and the inside of the fitting. The annular gap leak is likely to be similar to a thin narrow walled duct when comparing the flow to a round leak. The flow path will have a very large amount of gas/wall interaction and the potential for slow flow through the gap. The length of the leak is long compared to the thin annular gap width. Frictional effects are likely to dominate, which would be likely to result in laminar flow. This type of leak is likely to be found inside a fitting as illustrated in Figure 10 and will have a significantly restricted flow compared to the large damage hole and crack defects.

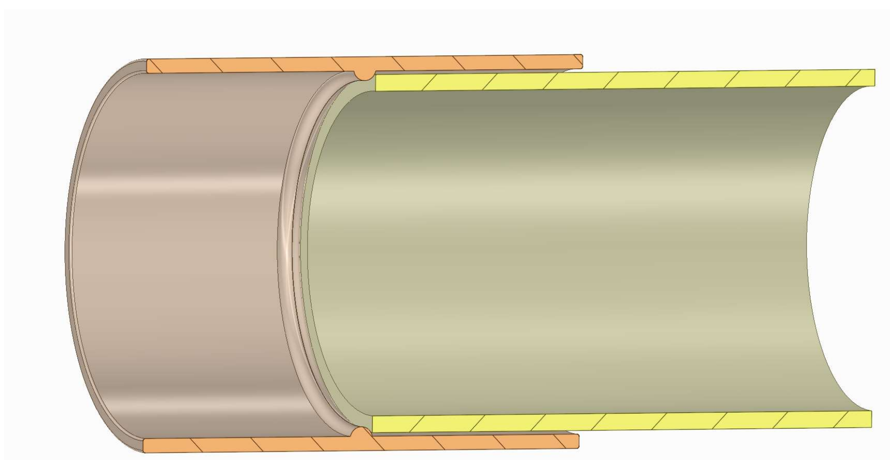


Figure 10: Annular gap leak

It should be noted that in the instance of a ‘flux’ joint, where the annular gap is filled with flux paste and the gas has broken through in only one or two points, the leak is likely to be in the form of one or two very narrow tube-like flow paths. It could also be in the form of multi-parallel flow paths such as is seen in the delta of a river.

2.4.4 Thread leak

The thread leak, such as would be seen in a BSPT fitting without jointing compound or a BSPP fitting without a sealing washer, results in a long tubular helical leak path. In this instance the leak has to pass around the entire helix formed between the male and female thread components. The leak path is illustrated in Figure 11, and in greater detail in Figure 12. The resulting leak is in the form of a very long tube-like leak where the flow length of the leak is vastly longer than the width of the leak. Frictional effects dominate the leak and the result is a laminar leak flow.

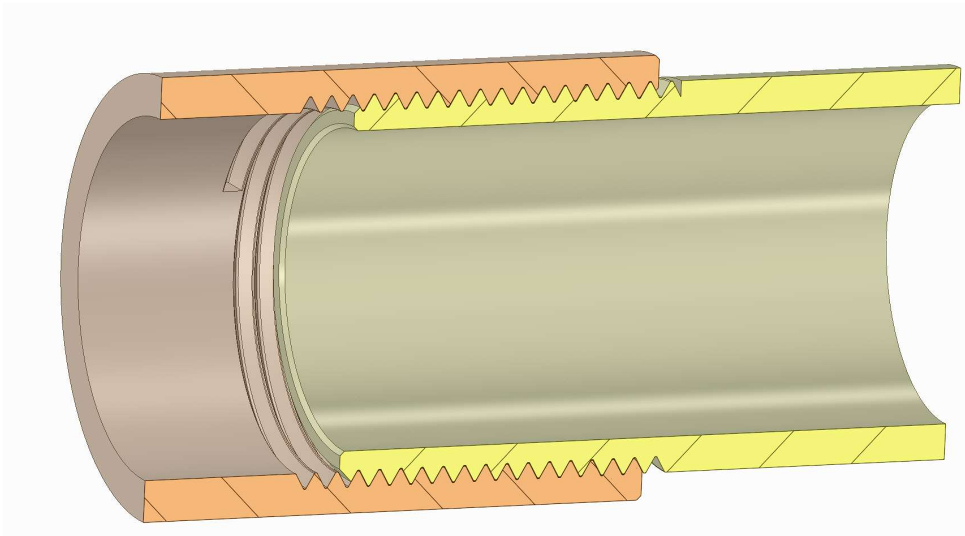


Figure 11: Helical Thread Leak

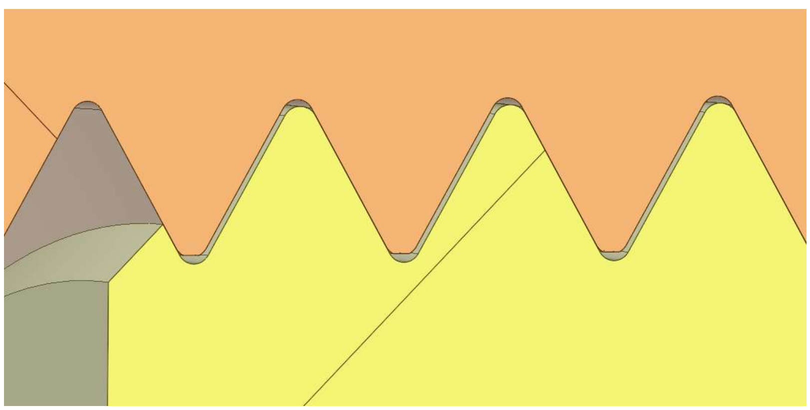


Figure 12: Detail of thread leak path

When developing an understanding of leakage, consideration of these discrete geometric flow paths is useful. This consideration can also be applied to different leak scenarios; however in reality a leak such as an annular gap leak in a 'flux joint' in the field will result in a wide variety of actual leak shapes, sizes and flow paths. We can only therefore gain an understanding of the generic behaviour when comparing hydrogen to methane discharge severity for all of the idealised leak types and then consider the statistical likelihood of each leak type in the field.

2.4.5 Complex leak example

An example of leak path analysis is given in the case of a 15 mm compression joint. The sectional view illustrates that the leak path in a failed compression joint will result in an annular leak gap to get from the inside to the outside of the tube. The seal itself is created between the olive, tube and fitting body so this will be where the failure is situated. This failure may be a score, cut or other damage. The exit to atmosphere will be via the thread or past the olive and the compression nut. In this manner it is possible to examine many different fitting and leak types.

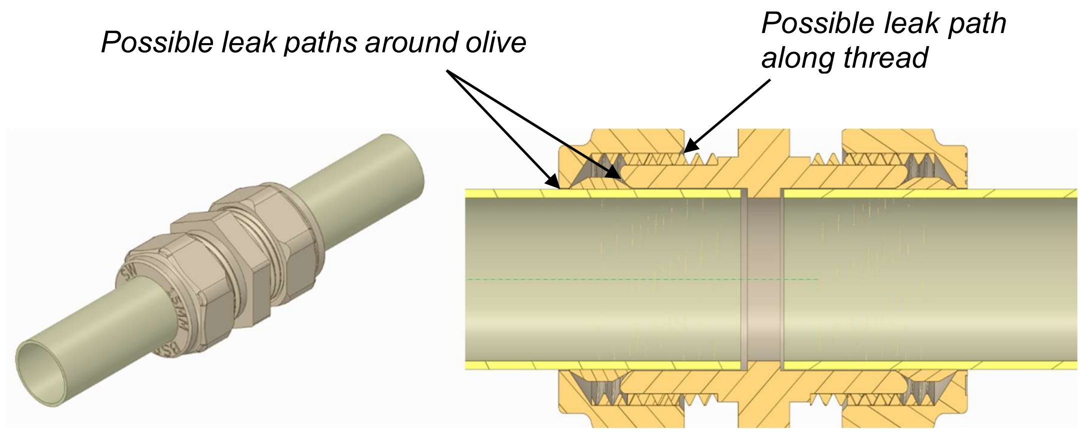


Figure 13: 15 mm compression joint and sectional view showing leak path

3 Experimental setup

The experimental setup comprised gas supply, flow control, logging and a range of individual test sections. The test sections were mounted in a fume cabinet to allow the exhaust gases to be extracted from the building.

Figure 14: Overview of Hy4Heat test setup at Steer

3.1 Equipment

Details of the equipment are broken down into discrete sections:

- Gas supplies
- Flow control and measurement
- Pressure measurement
- Test sections
- Logging

A schematic of the equipment is shown in Figure 15 to indicate how the equipment fits together. The individual equipment elements are then broken down and discussed in more detail.

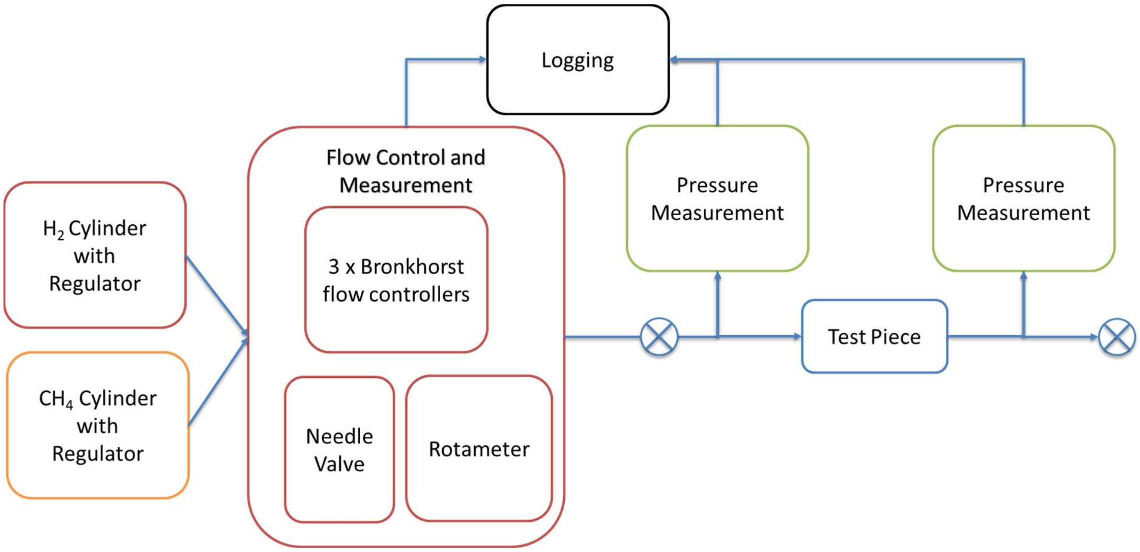


Figure 15: Schematic of the test equipment

3.1.1 Gas supplies

The gas supplies were via bottled gas cylinders with 4 bar regulators to step the pressure down from the cylinder pressure to a nominal 2 bar pressure. For methane, the gas supply was G20 test gas whilst for hydrogen, high purity hydrogen from BOC was used.

Figure 16: Gas cylinders with 4 bar regulators

3.1.2 Flow measurement and control

The gas supply was fed to a number of different flow control systems. Initially, Honeywell air mass flow sensors were used, as reported in the *50 Test* report. Challenges were found in the use of these flow sensors and consequently three Bronkhörst mass flow controllers were used for the main body of work. The Bronkhörst controllers were calibrated for methane and hydrogen. These three controllers provided flow control across the range from 0.00024 m^3/hr to 6.49 m^3/hr in hydrogen and from 0.00019 m^3/hr to 2.95 m^3/hr in methane, indicated in Table 3. The flow controllers were operated using bespoke software on a dedicated computer. They also had a 4-20 mA analogue output which was logged to record the flow data during tests.

Figure 17: Bronkhörst flow controllers

Controller type	Minimum flow (normal m^3/hr)		Maximum flow (normal m^3/hr)	
	Methane	Hydrogen	Methane	Hydrogen
F-202AV-M10	0.059	0.13	2.95	6.49
F-201CV-10K	0.0094	0.012	0.472	0.59
F201CV-200	0.00019	0.00024	0.009	0.012

Table 3: Calibrated range of the three Bronkhörst flow controllers

High flow tests to determine regulator behaviour in extreme conditions required a greater flow measurement than that provided by the largest Bronkhörst controller. Two rotameters were used instead to provide manual measurements of flow. The rotameters, shown in Figure 18, measured 10 to 100 l/m and 30 to 300 l/m in air respectively. Conversion factors were measured for methane and hydrogen using the largest of the Bronkhörst flow controllers. These data have produced graphs which have enabled extrapolation of the conversion factors for the higher flows of both gases.

Rotameter	Minimum flow (normal m^3/hr)		Maximum flow (normal m^3/hr)	
	Methane	Hydrogen	Methane	Hydrogen
300 l/m	2.5	6.3	25.2	62.6
100 l/m	0.8	2	7.6	20

Table 4: Scaled flow rates for the two rotameters

Figure 18: 100 l/m and 300 l/m rotameters

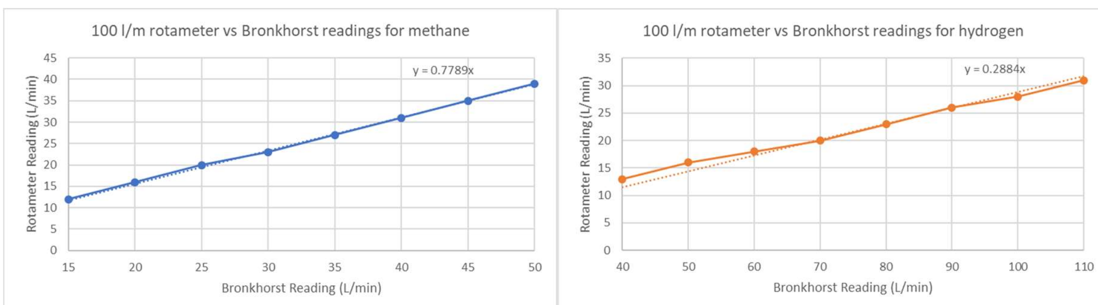


Figure 19 Scaling factors for 100 l/m rotameter

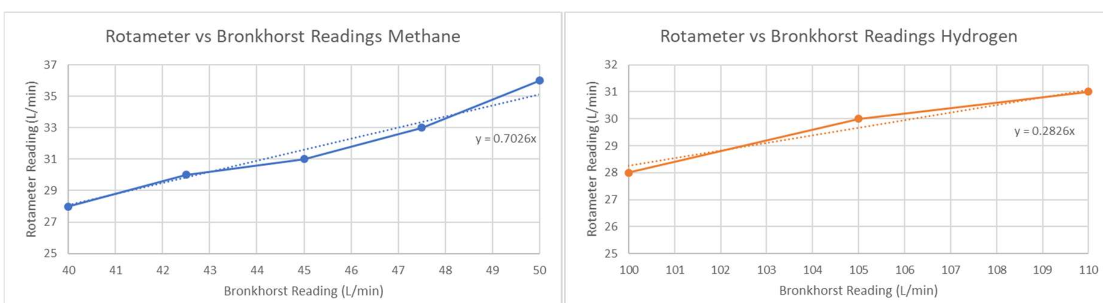


Figure 20: Scaling factors for 300 l/m rotameter

The flow during the high flow tests was achieved using a needle valve incorporated into the rotameter. For the upper end of flow, the cylinder regulator was increased from 2 bar to 4 bar feed pressure. This was required to overcome the pressure losses in the system from the cylinder to the rotameter.

3.1.3 Pressure measurement

The pressure measurement was carried out as close to the test pieces as possible to minimise inaccuracy due to frictional losses in the adjacent pipe sections. Two electronic pressure sensors manufactured by ifm were used for the majority of the tests. The pressure sensors were rated to 100 mbar and 1000 mbar respectively.

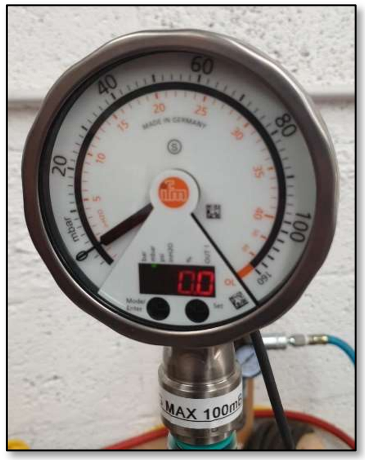


Figure 21: ifm electronic pressure sensor

The ifm pressure sensors provided an analogue style gauge and a digital readout of the pressure in addition to a 4-20mA analogue output which was logged during the flow tests.

A range of high flow tests were carried out to measure the frictional losses along straight pipe lengths and fittings such as elbows and tees. These tests used an Extech HD360 differential manometer which measured differential pressure up to 50.00 mbar with a maximum resolution of 0.01 mbar.

Figure 22: Extech HD350 differential manometer

3.1.4 Logging equipment

A 16-channel bespoke datalogger was used to log the two pressure readings, the flow readings, and ambient temperature. The datalogger is shown in Figure 23 and was connected to Steer's intranet via wifi to enable efficient capture and processing of data.

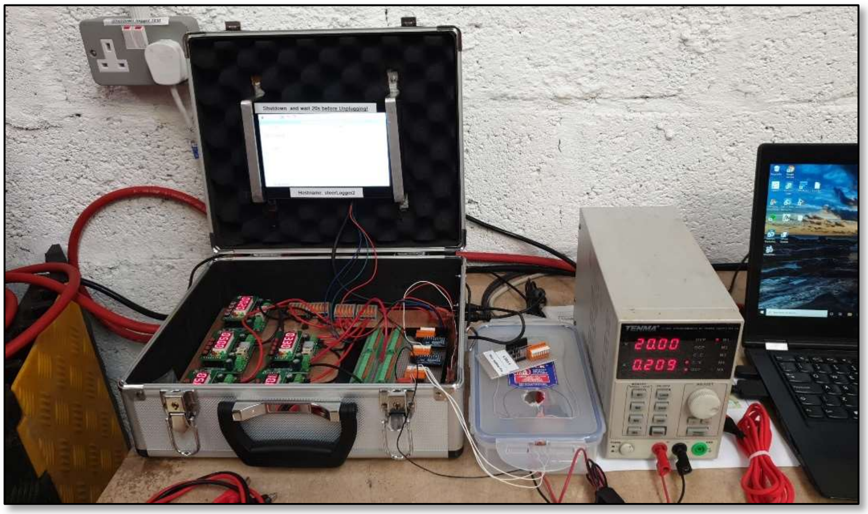


Figure 23: Datalogger used for the tests

3.1.5 Test Pieces

The project used a large number of test pieces. Each of the test pieces was physically mounted into the experimental equipment and then subjected to one of a number of formal test procedures as determined by leak behaviour.

Figure 24: Example test piece

3.2 Test configurations

There have been a number of different test configurations used for the main body of testing, however they can be summarised as three main configurations of test setup and equipment. A separate configuration was used and reported in the *50 Test* report.

In the majority of tests where there was a discernible leak, the main flow-controlled test setup was used. This involved controlling the flow into the test piece and logging the system flow and the pressure at the test piece. If the flow was too small to control then the system was charged to a given pressure and the pressure locked in. The drop in pressure over time was logged and used to calculate a leak flow. The third type of test was the large flow test which was used when the flow was too great to control with the Bronkhörst flow controllers. For this test type, manual readings of flow and pressure were taken with the rotameters and the differential manometer.

3.2.1 Main flow-controlled test setups

The main flow control setup used the Bronkhörst flow controllers, ifm pressure sensors and the data was logged either every 0.2 seconds or every second. The schematic for the main flow tests is shown in Figure 25.

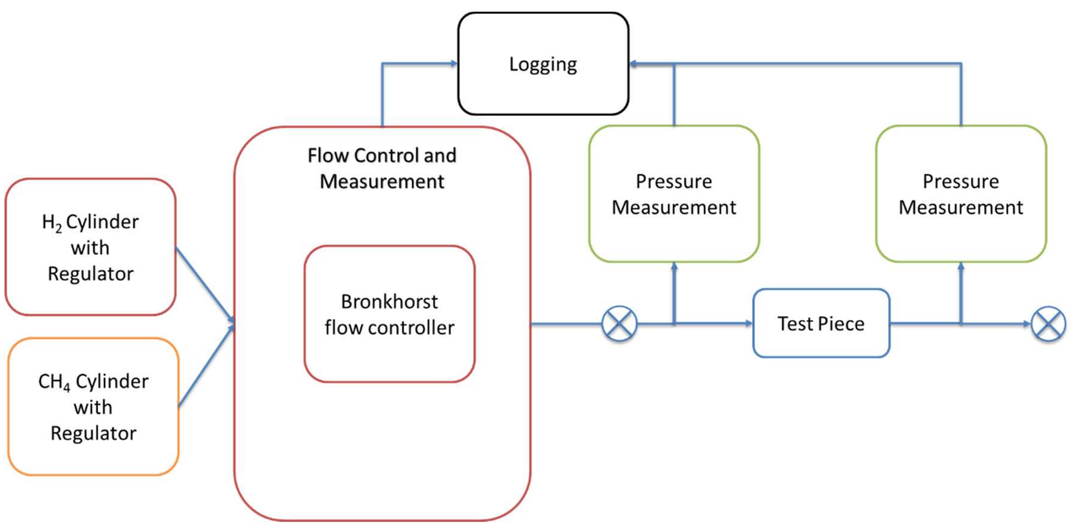


Figure 25: Schematic for main flow tests

The tests were driven by the flow controller which had the ability to run automated test scripts that controlled the flow to a number of specific setpoints. The test procedure followed a number of specific steps:

- Select the correct scale of flow controller for the leak section, this may involve initial investigation of the pressure / flow relationship.
- Select one of the test gases and set the flow controller and logger to the correct parameters for that gas and controller.
- Manually adjust the controller setpoint, therefore flow, until a stable pressure of 20 mbar is seen in the test section.

- Load automated script file into the controller with a maximum setpoint above the 20 mbar setpoint.
- Start the flow and pressure log.
- After 20 seconds of logging, stop the flow and run the automated script on the controller.
- Once the script is completed, stop the log.
- Select the second test gas and repeat.
- Download the logged data, convert to a scaled CSV file and import into the excel test template.

The data collected from the scaled CSV test file is then pasted into the excel test template. The template plots the logged data which is referenced to 20°C, and produces test plots of the pressure and flow data for each test gas. Examples of these are given below in Figure 26 and Figure 27.

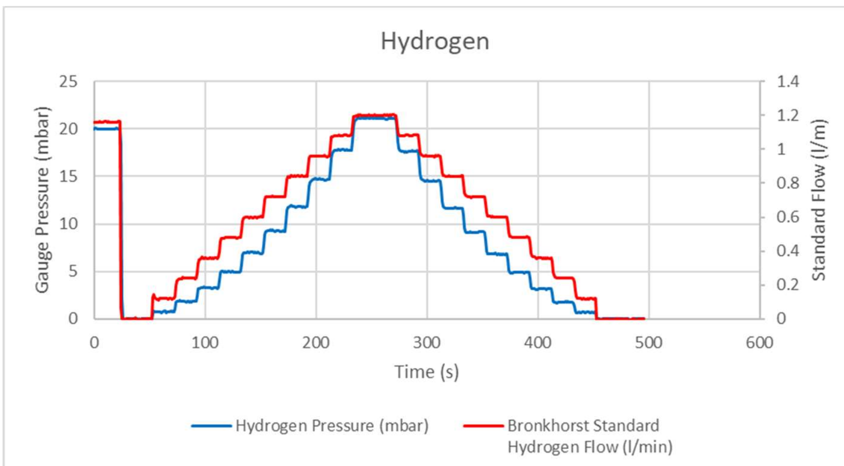


Figure 26: Sample hydrogen test result, 0.5 mm hole in MDPE

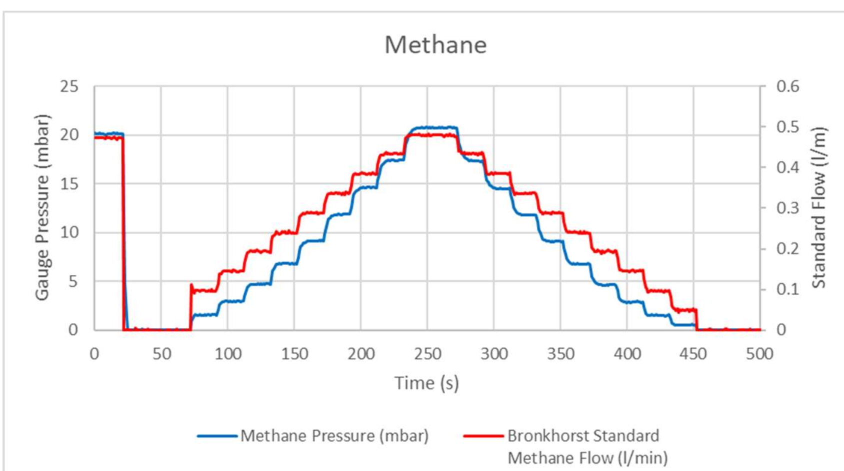


Figure 27: Sample methane test result, 0.5 mm hole in MDPE

The two sets of data are then converted from standard l/m to normal m^3/hr and plotted onto a graph to give pressure vs. flow, see Figure 28.

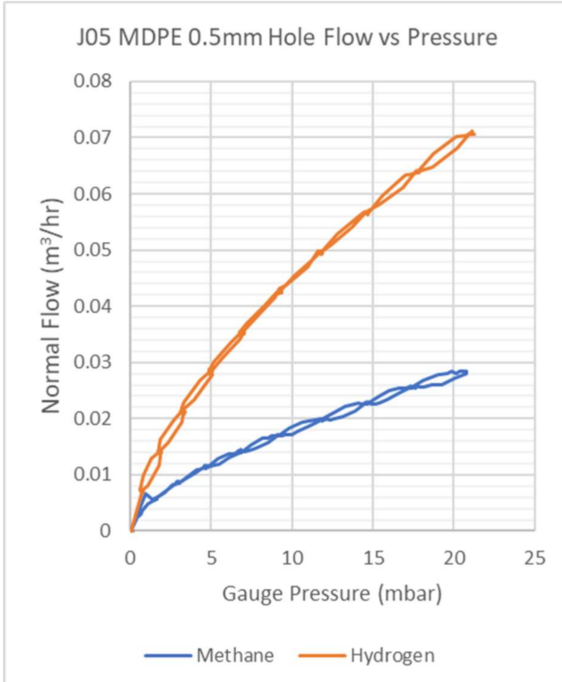


Figure 28: Sample test output, 0.5 mm hole in MDPE

Finally, datapoints for the 20 mbar test pressure are calculated to give accurate comparative data between all of the different test sections.

	Ls/min	Nm3/hr
Methane Flow at 20.12 mbar	0.473	0.028
Hydrogen Flow at 19.99 mbar	1.160	0.068
Ratio of H2 to CH4	2.456	

Table 5: Sample results table, 0.5 mm hole in MDPE

The results taken from the table have been collated and are presented in the experiments section of the report, Chapter 0. Individual test sheets are presented as an appendix to the report.

3.2.2 Lock off test

If the leak rate was too small to be managed by the smallest flow controller, then a lock off test was carried out. This involved charging the test section up to a given pressure in the test gas. The test section was then isolated with lock off valves and the pressure drop in the test section monitored over a given time period as the gas leaked out of the test section. The schematic for the lock off tests is shown in Figure 29. In reality the pressure was applied using the flow controllers manually before locking in the pressure but these are not included in the schematic.

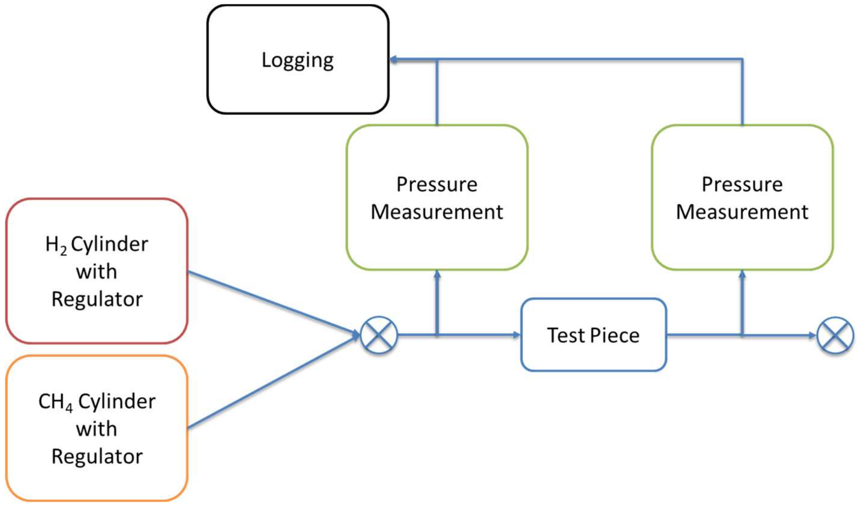


Figure 29: Schematic for lock off tests

The test steps for the lock off test were:

- Start the logger.
- Charge pressure in the test section to 22 mbar.
- Close the valves adjacent to the test section.
- Monitor the pressure drop over the 5 minute test period.
- Open the valves and purge to the second test gas.
- Repeat the tests.
- Download the logged data, convert to a scaled CSV file and import into the excel test template.

The two sets of data were then plotted on a single graph, see Figure 30, and an average calculation made to assess the equivalent flow rate for a pressure of 20 mbar.

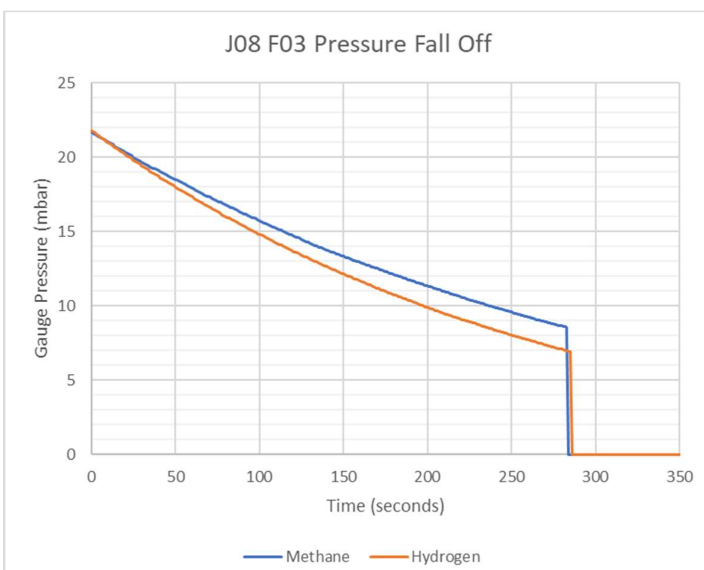


Figure 30: Sample lock off test result

The equivalent flow rate and pressure is then presented in a results table for the individual test output.

	Flow (ml/hr)	Average Pressure (mbar)
Methane	67.46	20.0
Hydrogen	80.74	20.0
Ratio of H2 to CH4 Flow	1.197	

Table 6: Sample lock off test results table

The results taken from the table have been collated and are presented in the experiments section of the report, Chapter 0. Individual test sheets are presented as an appendix to the report.

In the case of a solid test, indicating no leakage, the equivalent flow rate is negligible and it is not possible to calculate the leak ratio, see Figure 31.

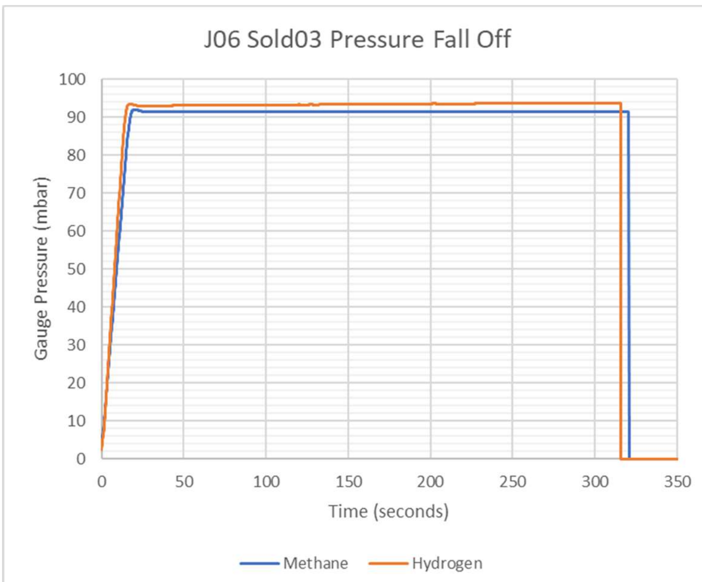


Figure 31: Sample lock off test with no leak

Earlier tests charged the test section to 90 mbar, being a more stringent test pressure than 20 mbar. Once it was determined that a system that does not leak in methane also does not leak in hydrogen, the test pressure was dropped to 20 mbar to enable more direct comparison of leak rates with the flow tests that were set at 20 mbar.

3.2.3 High flow tests

The last of the standard set of tests was a high flow test. This test used a rotometer to measure the high flow rates and either the ifm pressure sensors or the more sensitive Extech HD350 differential manometer. The ifm pressure sensors were used with large test leaks, such as the 5 mm to 10 mm holes. The differential manometer was used in the frictional loss tests where the test pressure was not set to 20 mbar. The schematic for the high flow frictional tests is shown in Figure 32.

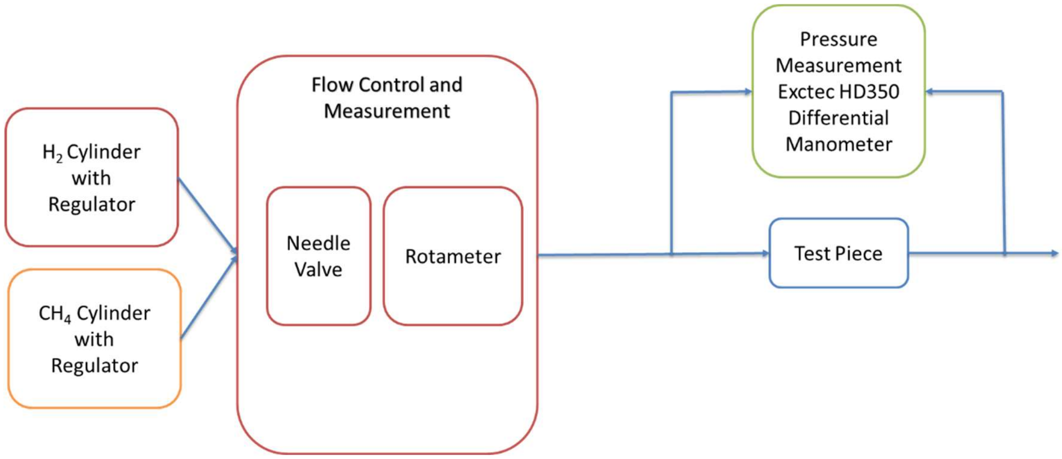


Figure 32: Schematic for high flow tests

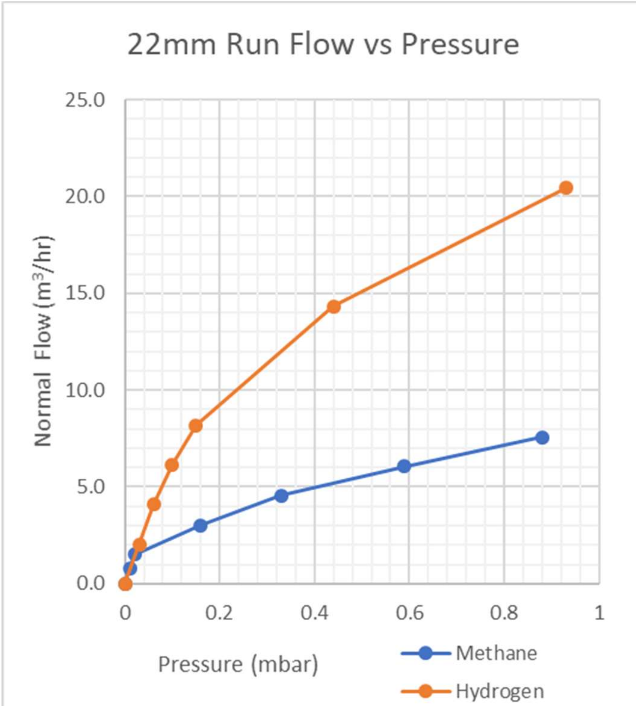
The high gas flow was taken from the cylinders at 4 bar and fed directly to the rotameter needle valve which was used to control flow. The pipe section downstream of the rotameter then opened out from the ¼ inch NPT fitting to 22 mm copper tube where the pressure was measured upstream of the test section. The high flow tests were used for frictional loss tests, regulator tests and large defect tests.

The high flow test procedure comprised the following steps:

- Apply 4 bar test gas pressure to rotameter inlet.
- Adjust rotameter needle valve to give desired flow rate.
- Note down the flow rate and indicated pressure.
- Repeat flow adjustment and note pressure and flow for full range of tests.
- Close off flow.
- Change test gas and repeat.
- Manually add data to excel template.

The excel template then converts the flow indicated on the rotameter to delivered flow.

An example of this data is given in Figure 33 which shows the data for 3 m of 22 mm copper tube and the calculated pressure loss per meter for the tube.



Normal flow m3/hr	Pressure loss per metre	
	CH4	H2
0.00	0.000	
4.20	0.083	
8.39	0.287	
12.59	0.603	
16.79	1.037	
19.31	1.333	
20.99	1.543	
0.00		0.000
10.43		0.070
20.87		0.320
31.30		0.690
41.74		1.110
48.00		1.467
52.17		1.740

Figure 33: Example high flow test results for 3 m of 22 mm pipe

3.3 Conventions

Initially the test data was presented in units of l/m and pressure in mbar. The Bronkhörst flow controllers use the following notation:

- Normal conditions (ln/min): references a temperature of 0 °C and a pressure of 1013.25 hPa(a)
- Standard conditions (ls/min): references a temperature of 20 °C and a pressure of 1013.25 hPa(a)

The controllers were factory set to deliver output in terms of Bronkhörst standard conditions, namely 1.01325 bar and 20°C.

During the presentation to BEIS on 10 October 2019 a request was made to present the data in referenced to 15°C and flow in units of m^3/hr. This reference comes from the GSMR 1995 Gas Safety (Management) Regulations. A conversion has been made to present the final data in this form.

3.4 Comparison to permitted leakage rates

We can compare the lock off testing carried out for domestic gas systems. Details of the current required testing procedure for domestic gas systems can be found in the 'Installer Online' document Testing Procedure[16] which states: '*The test pressure for natural gas would be 20–21 mbar for low pressure installations and 18–19mbar for medium pressure installations.*' The hold time is 2 minutes for these tests. Figure 34 provides the allowable pressure drop after 2 minutes.

[16] https://www.installeronline.co.uk/wp-content/uploads/2014/07/Testing-procedure.pdf

Table 2. Maximum permissible pressure drops – natural gas.

Meter designation	Pipework diameter (mm)	Maximum permissible pressure drop (mbar)
No meter and ultrasonic meter (E6)	≤28	8
	>28, ≤35	4
Diaphragm ≤6m³/h	≤28	4
	>28, ≤35	2.5
Diaphragm 6m³/h ≤16m³/h	≤35	1

Figure 34: Max allowable pressure drop for pressure tests

The maximum allowable volume for a domestic system is 0.035 m^3 this gives us a calculated maximum allowable leakage in a current domestic system for methane. If we take the maximum system size, 0.035 m^3 and the most stringent 1 mbar allowable pressure drop we have a permitted leakage of 1.03 l/hr of gas. Hydrogen volumetric leakage is likely to be at least 1.2 times greater than methane for a system with one or more leaking fittings. For this 'just passing' example system and leak, there would be a hydrogen leak of 1.236 l/hr, and a resultant pressure drop of 1.2 mbar.

Based on the current allowable pressure drop, tightness tests such as this which are borderline passes with methane would not pass with hydrogen. This means if the current allowable pressure drop off is kept for hydrogen this will result in a more stringent test due to the larger hydrogen flow for a given leak size.

The majority of lock off tests carried out in this report have demonstrated a significantly lower flow than is currently permissible. These leaks are therefore very unlikely to cause unsafe situations.

For comparison, a leak of 0.025 mm diameter fed by 20 mbar of methane would result in a 0.1 l/hr leak of gas.

Experiments

The majority of the project programme of work has involved testing the wide range of test pieces determined by the test matrix as agreed with the Hy4Heat team at the kick off meeting and refined during subsequent steering group meetings.

The test matrix has been split into individual job sheet categories for convenience of carrying out and documenting the work. The reporting has followed these groupings, these are:

- J05 Holes
- J06 Joints and Fittings
    - Cold compression fittings
    - Compression fittings
    - Screwed and threaded fittings
    - Solder fittings
    - Miscellaneous fittings
- J07 Valves
- J08 Damage
- J09 Flow Investigations
- J10 Regulators
- J11 Other Pieces

The results for all of the tests groups are presented in this chapter in a similar format.

A write up of individual tests is presented in the relevant appendix, referenced by the job sheet number, (Jxx). Data from the individual tests can be seen on the individual tabs in the relevant spreadsheets submitted alongside this report again, these spreadsheet tabs are all identified by job number (Jxx).

3.5 Presentation of test results

The grouped test results presented in the main body of the report are presented in three different ways. Firstly, a 3D bar chart is provided to enable a comparison between tests to be made. An example of the comparison bar chart is provided in Figure 35. The comparison charts have the 0.3 mm hole included as a reference point on all of the charts. The 0.3 mm hole results in a leak rate that is approximately ten times the magnitude that would pass a 1 mbar leak off test in a 0.035 m^3 installation in methane.

The 3D chart was chosen as it indicates very low values as a square base with no apparent height.

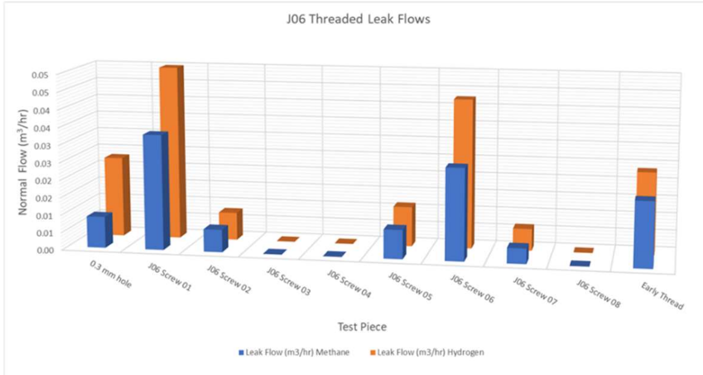


Figure 35: Example comparison bar chart

A second bar chart is provided without the reference hole data. This second chart is included to allow results to be read off the axes of the chart. An example of the second chart type is given in Figure 36. This data is presented on a linear y axis, it would be possible to change this to a logarithmic axis to display all of the values if desired.

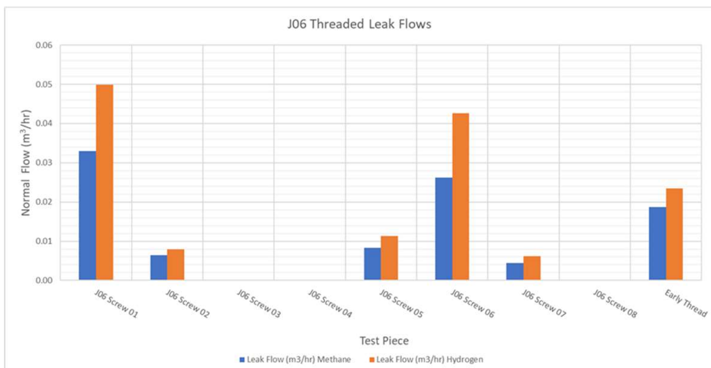


Figure 36: Example leak rate chart

Finally, the data are also presented in results tables with numeric results and pertinent comments on flow regime. The comparison between the flow rates of the two gases is given but it should be noted that in the case of very low flows these results may not be relevant or misleading.

Test Piece	Leak Flow (m^3/hr)		Test Type	Nominal Pressure (mbar)	Leak Flow Ratio	Flow Type
	Methane	Hydrogen				
J06 Screw 01	3.29E-02	4.99E-02	Flow	20	1.51	Transition Flow
J06 Screw 02	6.44E-03	7.90E-03	Flow	20	1.23	Laminar Flow
J06 Screw 03	1.69E-06	4.69E-06	Lock Off	22	2.78	Negligible Flow

Table 7: Sample of results table

Where appropriate, line graphs are also included to aid discussions on particular findings or a particular grouping.

3.6 Test practicalities

Working through the tests required physical changes to be made to the test setup to insert and remove each test section. During these changes certain joints and fittings required repeated breaking and remaking. Consequently, additional leaks occasionally crept into the test system. A practical balance had to be drawn between ensuring background leakage was kept to a minimum whilst efficiently carrying out the very large number of tests in the test matrix. Care has been taken to ensure that any leaks in the test equipment are orders of magnitude below the leakage of the test component and such leaks are smaller in magnitude than permitted leaks in current domestic gas systems. The full test system was regularly re-tested for background leaks during the course of the programme of work.

The test results have been reviewed at the time of testing and during the post processing and reporting. Unexpected test results have been investigated and this has led to a small percentage of tests being repeated.

Certain of the tests involved moveable assemblies such as valves. The requirement to purge from one test gas to another, required adjustments to be made to the physical test piece to achieve this purge. This has made carrying out repeat tests from one gas to another challenging. These instances mainly involve valve test pieces and are noted in the test documents.

Please note that due care has been taken to ensure accurate copying and processing of the data and every effort has been made to prevent typos and errors in this work.

3.7 J05: Hole results

Two types of holes were examined; thin wall holes in copper tube and thick wall holes in MDPE pipe. The pipe material will not have a significant impact on the leakage rate or type of flow, this will be determined by the hole geometry.

3.7.1 Thin wall hole results summary

The thin wall hole tests comprised a range of holes from 0.3 mm diameter to 10 mm diameter. Holes can generally be defined as *gross leaks* and these gross leaks will almost always result in turbulent flow at 20 mbar. Cuts and gashes in pipes can be treated as a hole of equivalent area. The flow will be turbulent and the hydrogen to methane ratio will be 2.8:1.

The hole flow data follows a linear relationship between flow and leak area for a given pressure. It should be noted that for the larger flows, a domestic pipework system would struggle to maintain a 20 mbar pressure supply to the leak so it is likely that in a real world scenario the actual leak flow into the building would be reduced.

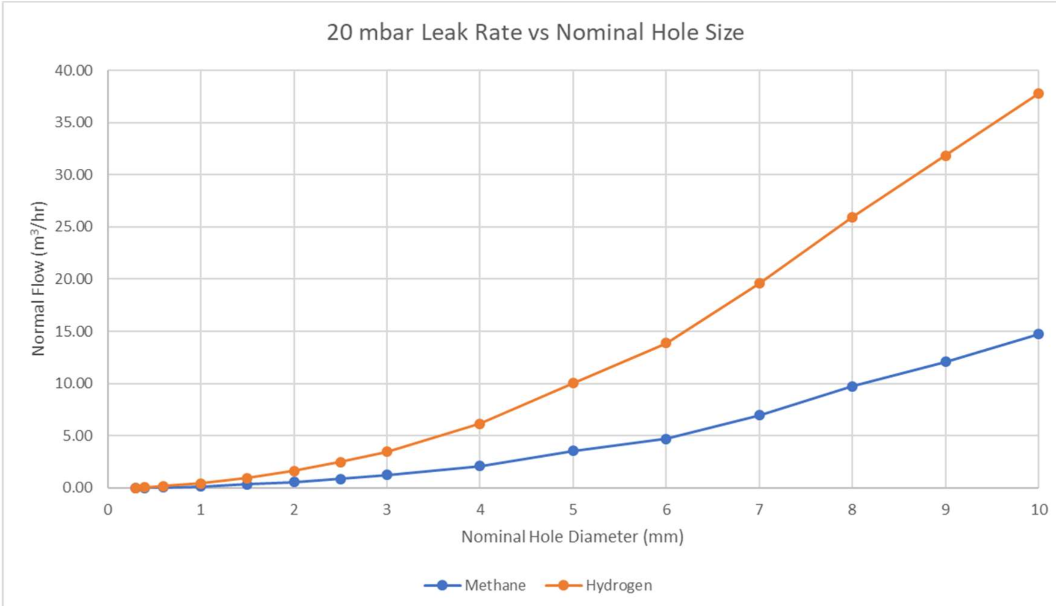


Figure 37: Combined leak rate vs nominal hole diameter

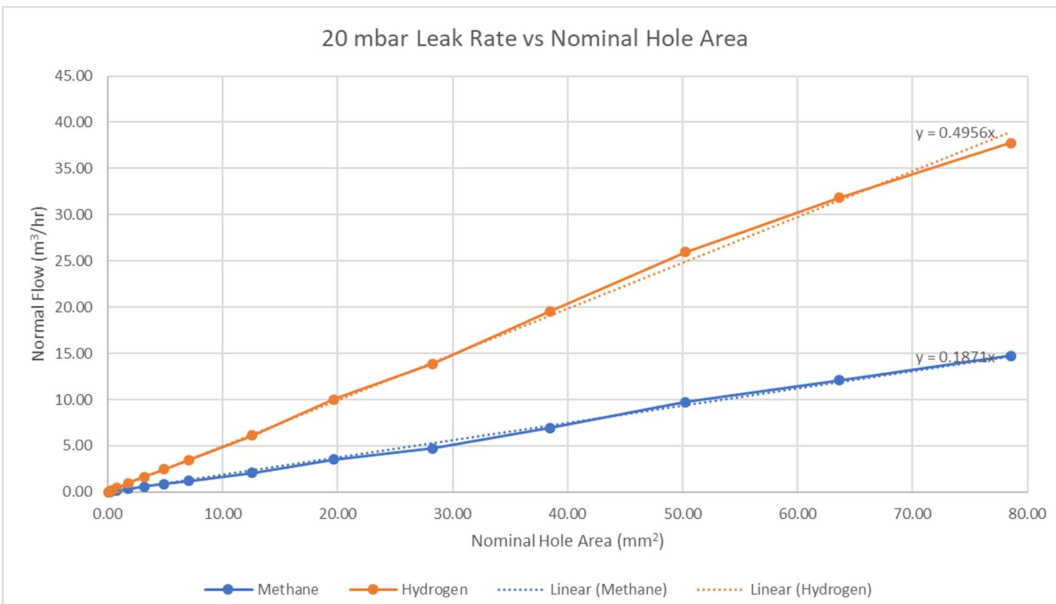


Figure 38:Combined leak rate vs. nominal hole area

3.7.2 Thin and thick wall hole comparison

All of the thin wall holes were tested in 15 mm copper tube with 0.7 mm wall thickness, all of the thick wall holes were tested in 32 mm MDPE pipe with 3.3 mm wall thickness. An illustration of the two pipes with 1mm holes is shown in Figure 39.

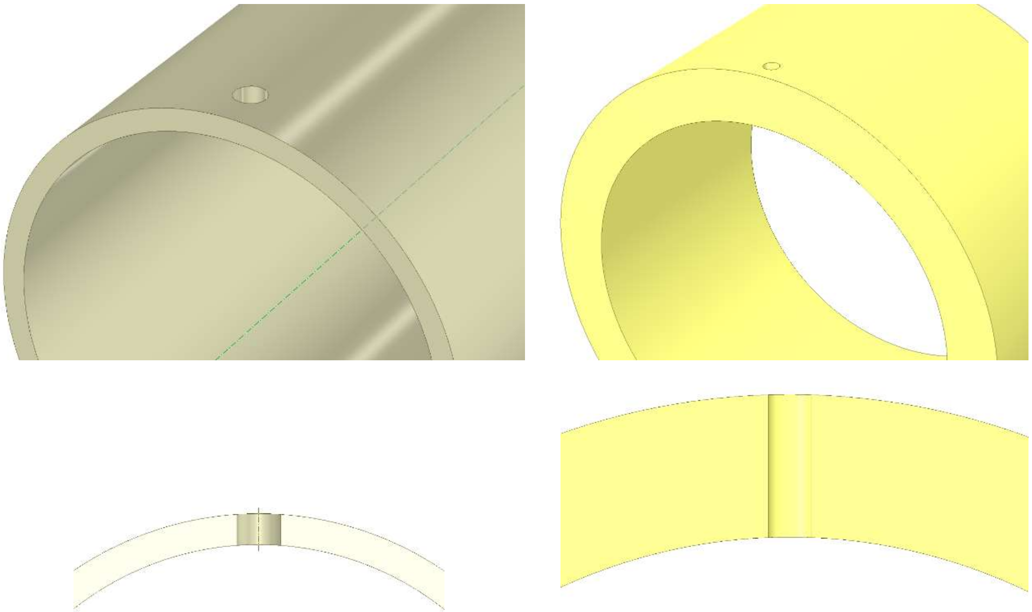


Figure 39: Leak aspect ratio for 1 mm holes in copper and MDPE

The effect of the thicker pipe wall is to increase the frictional loss incurred by the gas passing through the hole, or thin channel. This is reflected in the results, given by leak diameter in Figure 40 and by leak area in Figure 41. The relationship between hydrogen and methane is similar for the thin and thick wall tests, but the flow rates are reduced for both gases passing though the longer flow path with the greater wall thickness.

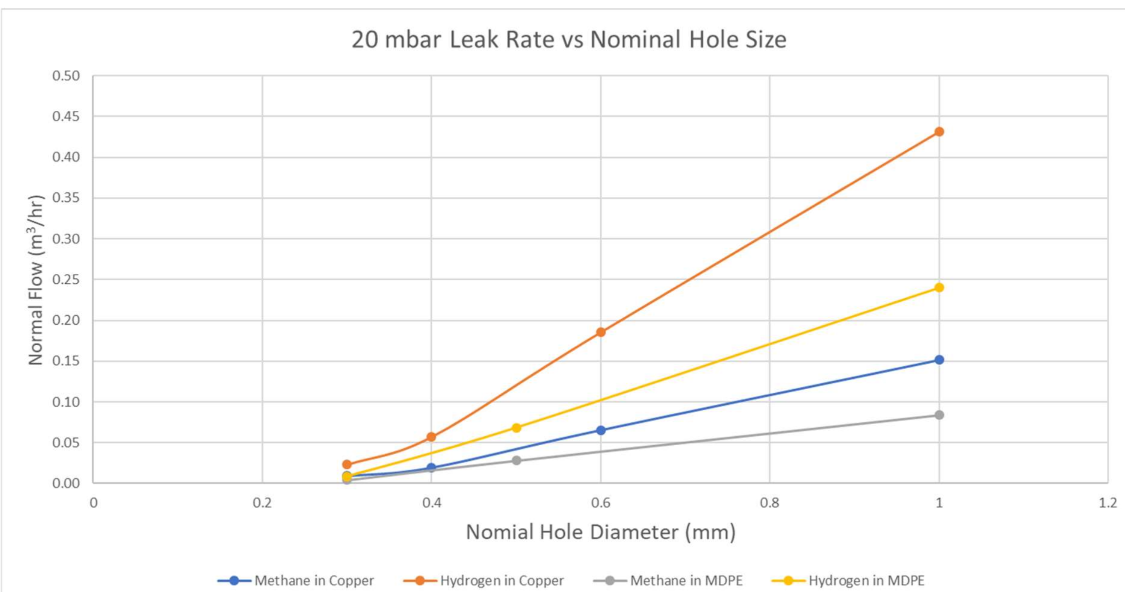


Figure 40: Thin and thick pipe wall leak data comparison by leak diameter

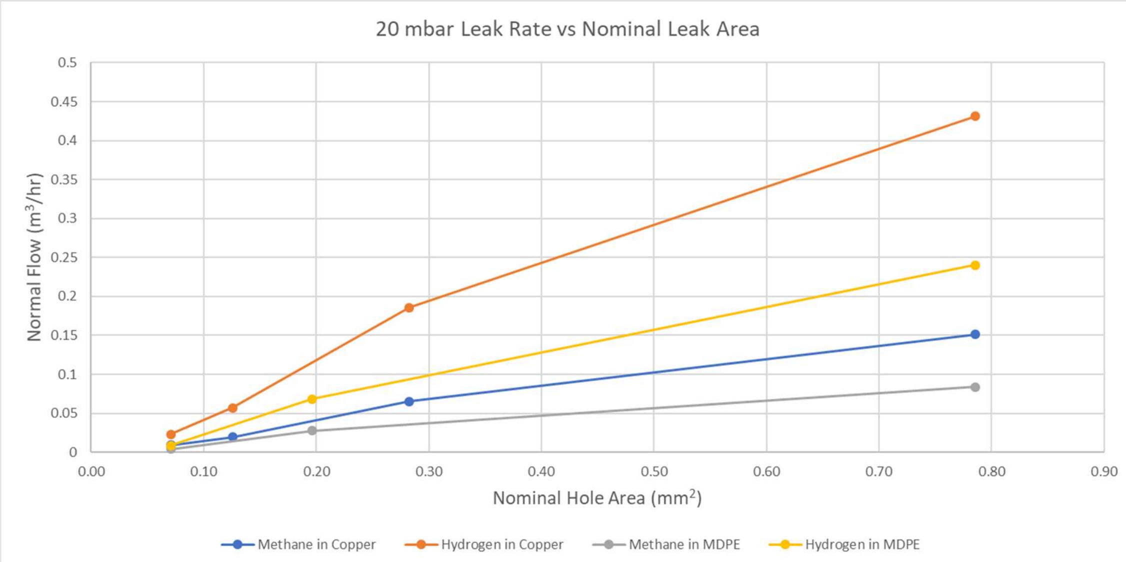


Figure 41: Thin and thick pipe wall leak data comparison by leak area

Test Piece	Leak Flow (m^3/hr)		Test Type	Nominal Pressure (mbar)	Leak Flow Ratio	Flow Type
	Methane	Hydrogen				
J05 0.3 mm Cu	8.94E-03	2.30E-02	Flow	20	2.574	Transition Flow
J05 0.4 mm Cu	1.95E-02	5.73E-02	Flow	20	2.942	Turbulent Flow
J05 0.6 mm Cu	6.55E-02	1.86E-01	Flow	20	2.834	Turbulent Flow
J05 1 mm Cu	1.51E-01	4.31E-01	Flow	20	2.848	Turbulent Flow
J05 1.5 mm Cu	3.46E-01	9.60E-01	Flow	20	2.776	Turbulent Flow
J05 2 mm Cu	5.81E-01	1.65E+00	Flow	20	2.838	Turbulent Flow
J05 2.5 mm Cu	8.74E-01	2.49E+00	Flow	20	2.844	Turbulent Flow
J05 3 mm Cu	1.23E+00	3.45E+00	Flow	20	2.812	Turbulent Flow
J05 4 mm Cu	2.10E+00	6.13E+00	Flow	20	2.927	Turbulent Flow
J05 5 mm Cu	3.54E+00	1.00E+01	Flow	20	2.833	Turbulent Flow
J05 6 mm Cu T02	4.72E+00	1.39E+01	Flow	20	2.938	Turbulent Flow
J05 7 mm Cu	6.96E+00	1.96E+01	Flow	20	2.814	Turbulent Flow
J05 8 mm Cu	9.73E+00	2.59E+01	Flow	20	2.667	Turbulent Flow
J05 9 mm Cu	1.21E+01	3.18E+01	Flow	20	2.634	Turbulent Flow
J05 10 mm Cu	1.47E+01	3.77E+01	Flow	20	2.560	Turbulent Flow
J05 0.3 mm MDPE	4.14E-03	8.49E-03	Flow	20	2.051	Transition Flow
J05 0.4 mm MDPE	2.43E-02	6.32E-02	Flow	20	2.602	Transition Flow
J05 0.5 mm MDPE	2.79E-02	6.84E-02	Flow	20	2.456	Transition Flow
J05 1.0 mm MDPE	8.36E-02	2.40E-01	Flow	20	2.871	Turbulent Flow

Table 8: Hole results table

3.8 J06: Joints and fitting results

This is by far the largest group of test pieces and as such has been broken down into sub groups to keep the collated document size down. The sub groups are:

- Cold crimp press fittings
- Compression fittings
- Screwed and thread fittings
- Solder fittings
- Miscellaneous Joints

These groups are now presented one at a time.

3.8.1 Cold crimp press fittings

Cold crimp press fittings are a relatively new jointing system. The fittings are applied using a bespoke crimping machine. The cost of crimpers is approaching £1,000 and so will prohibit this technology for most DIY enthusiasts. The sealing system relies on O-rings being slid over the tubes to be joined and then held in place by compressing the surrounding fitting onto the tube.

Figure 42: Cold crimp fitting, before and after fitting

The majority of the cold crimp fitting tests performed well, resulting in successful pressure holding even with the O-ring removed from the fitting. The worst test result was achieved with an uncrimped fitting followed by a partially crimped fitting. Tests have included: damage to the pipe and the O-rings, use on incorrect pipe types, incorrect insertion and incorrect use of the crimp tooling.

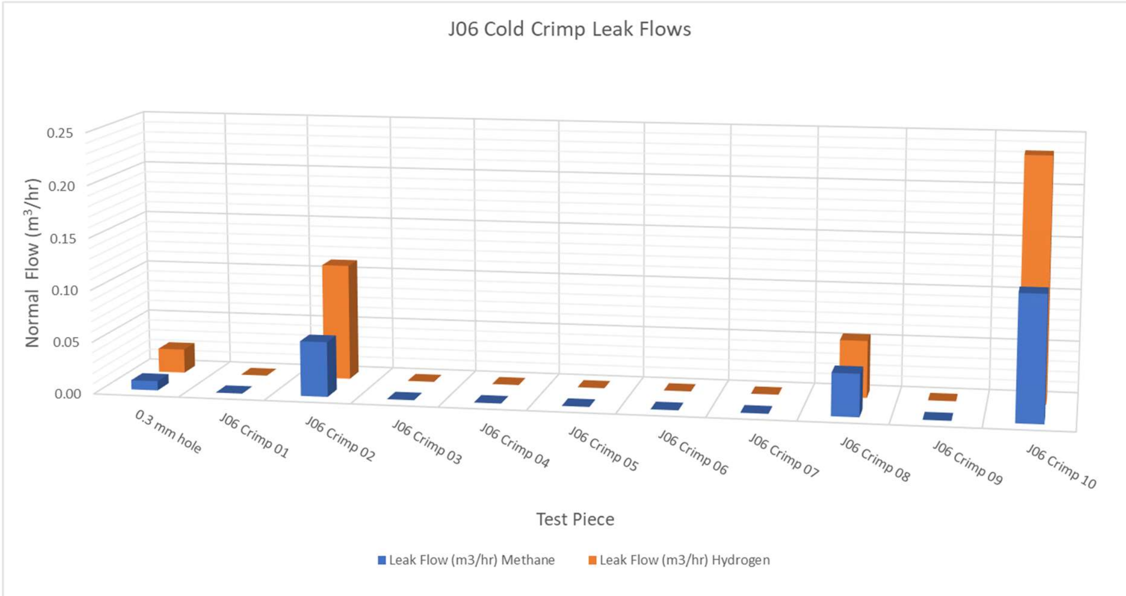


Figure 43: Cold crimp fittings comparison chart

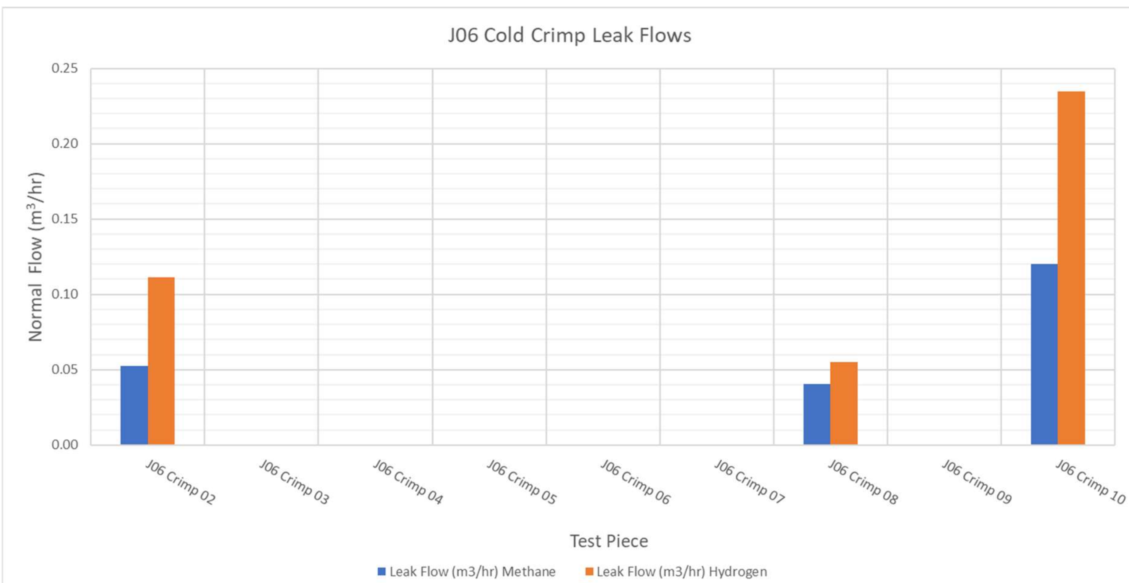


Figure 44: Cold crimp fittings leak rates

Test Piece	Leak Flow (m^3/hr)		Test Type	Nominal Pressure (mbar)	Leak Flow Ratio	Flow Type
	Methane	Hydrogen				
J06 Crimp 01	5.30E-07	-7.55E-07	Lock Off	22.6	-1.43	Negligible Flow
J06 Crimp 02	5.27E-02	1.11E-01	Flow	20.0	2.11	Transition Flow
J06 Crimp 03	3.99E-06	-1.13E-08	Lock Off	21.2	0.00	Negligible Flow
J06 Crimp 04	1.30E-06	1.34E-06	Lock Off	21.5	1.03	Negligible Flow
J06 Crimp 05	3.92E-06	5.99E-07	Lock Off	22.2	0.15	Negligible Flow
J06 Crimp 06	1.15E-05	5.76E-06	Lock Off	20.5	0.50	Negligible Flow
J06 Crimp 07	4.10E-06	4.61E-06	Lock Off	22.0	1.12	Negligible Flow
J06 Crimp 08	4.07E-02	5.48E-02	Flow	20.0	1.35	Laminar Flow
J06 Crimp 09	7.44E-06	1.57E-06	Lock Off	21.7	0.21	Negligible Flow
J06 Crimp 10	1.20E-01	2.35E-01	Flow	20.0	1.95	Transition Flow

Table 9: Cold crimp fittings results table

3.8.2 Compression fittings

Brass compression fittings are used ubiquitously in domestic gas systems to connect copper tubing. A nut is tightened over an olive, which deforms and cuts into the copper. A seal is created between the shoulder of the olive and the socket of the fitting. Once compressed, the nut holds the fitting in place and ensures the olive is pressed against the shoulder. Many of the early configurations tested did not leak in either gas. Significant damage had to be inflicted upon the test sections to create leakage.

Figure 45: Compression fitting showing olive and compression nut

Much of the test rig was made using compression fittings and these showed wear over time. They can stand breaking and remaking, however there is a limit to the amount of times this can be carried out before leakage starts. It should, however be noted that these are small leaks and are unlikely to be noticed in a conventional domestic system.

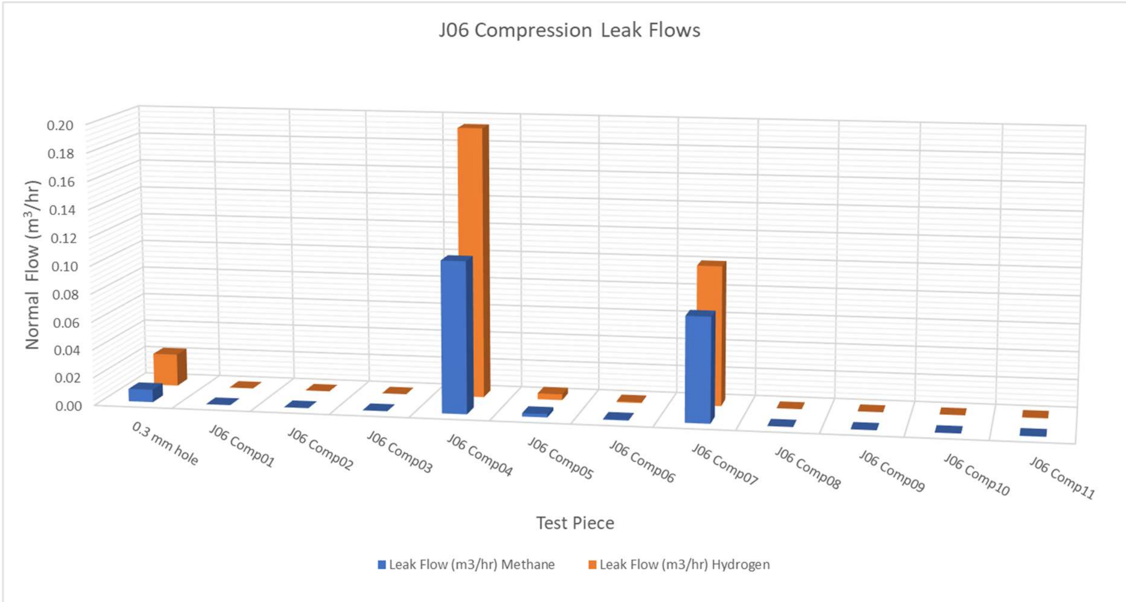


Figure 46: Compression fittings comparison chart

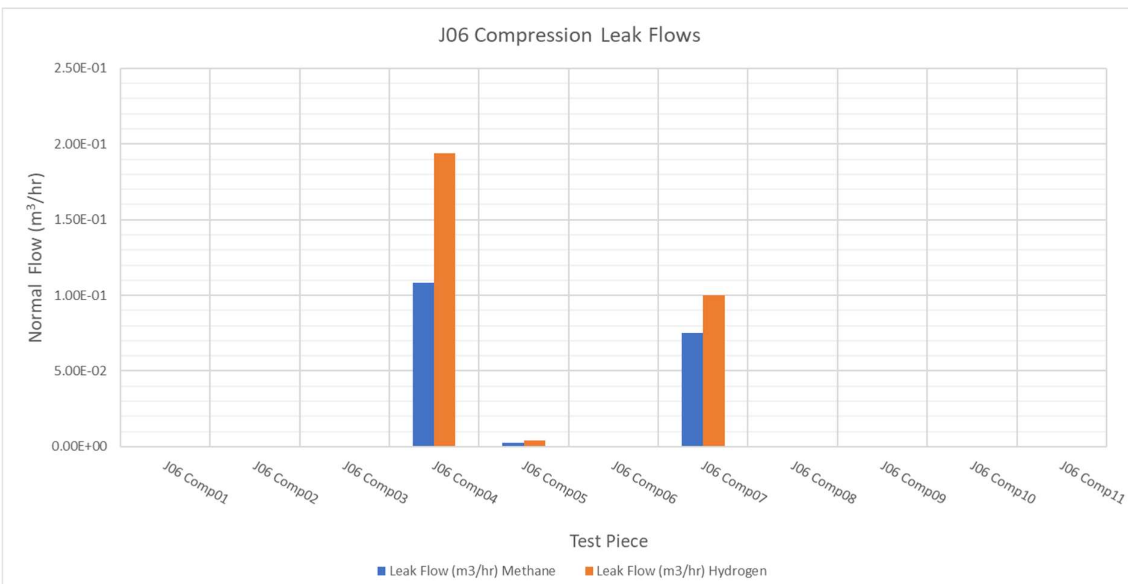


Figure 47: Compression fittings leak rates

Test Piece	Leak Flow (m^3/hr)		Test Type	Nominal Pressure (mbar)	Leak Flow Ratio	Flow Type
	Methane	Hydrogen				
J06 Comp01	3.42E-07	-2.63E-07	Lock Off	92.0	-0.77	Negligible Flow
J06 Comp02	3.42E-06	1.14E-06	Lock Off	93.0	0.33	Negligible Flow
J06 Comp03	-1.23E-06	-1.61E-06	Lock Off	22.3	1.31	Negligible Flow
J06 Comp04	1.08E-01	1.94E-01	Flow	20.0	1.79	Transition Flow
J06 Comp05	2.34E-03	4.22E-03	Flow	20.0	1.80	Transition Flow
J06 Comp06	4.34E-04	6.45E-04	Flow	20.0	1.49	Laminar Flow
J06 Comp07	7.50E-02	1.00E-01	Flow	20.0	1.34	Transition Flow
J06 Comp08	-9.22E-07	6.21E-07	Lock Off	21.4	-0.67	Negligible Flow
J06 Comp09	1.23E-07	-3.49E-07	Lock Off	21.8	-2.84	Negligible Flow
J06 Comp10	4.16E-05	3.36E-05	Lock Off	20.0	0.81	Negligible Flow
J06 Comp11	3.04E-04	3.74E-04	Flow	20.0	1.23	Laminar Flow

Table 10: Compression fittings results table

A 15 mm compression fitting was used in an early investigation into the transition between laminar and turbulent flow regimes. This test is demonstrated by comparison between the two graphs of Figure 48. The left-hand graph shows the flow vs. pressure response up to 20 mbar. Hydrogen flow is laminar as indicated by a linear response. Methane is starting to transition to turbulent flow as indicated by a deviation from a linear response. The ratio of the two leak flows is 1.4:1, which again indicates a transition flow. The right-hand graph shows the flow vs. pressure response up to 500 mbar. Both of the gases are now indicating a non-linear response indicating transition or turbulent flow. The leak flow ratio is now 2.3:1 which is close to fully turbulent flow.

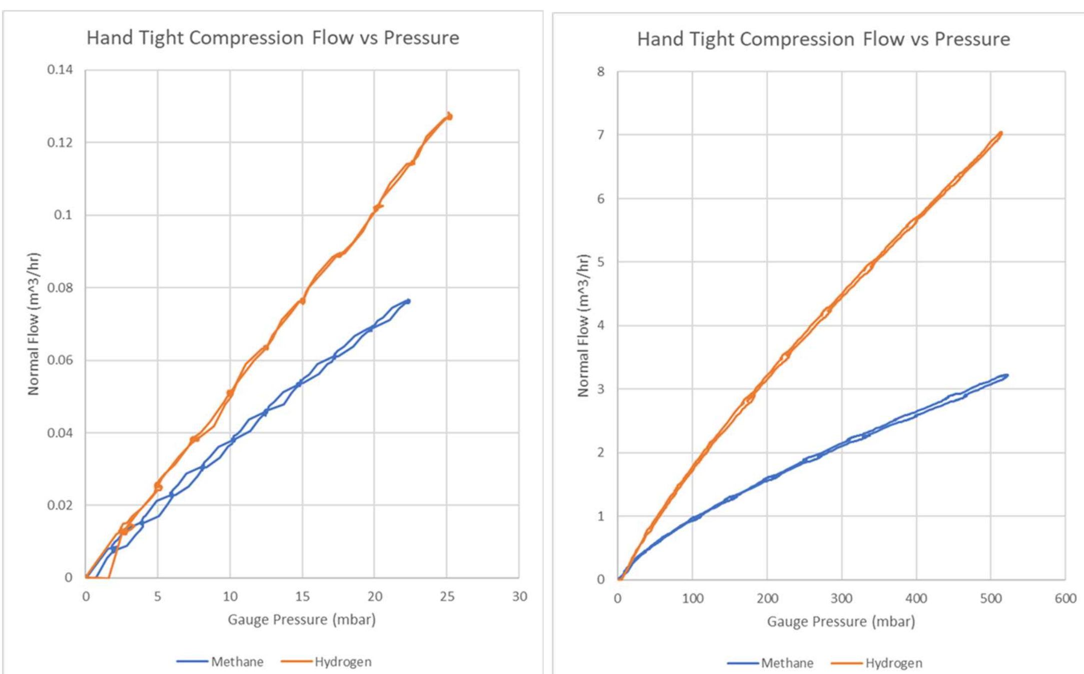


Figure 48: Demonstrating transition from laminator to turbulent flow

The comparison also indicates that the transition to turbulent flow occurs at a lower pressure regime for methane than for hydrogen.

3.8.3 Screwed and threaded fittings

Threaded fittings are common in thick wall steel pipes. They are also a common method for connecting items of infrastructure such as valves and meters. Thread leaks result in a long helical leak path around the thread which will tend towards laminar flows. Threaded connections seal using specific thread sealants which aim to block the flow path around the thread. The worst leaks were found to be on hand tight threaded connections with no sealant applied. These leaks were comparable to a 0.4 mm hole.

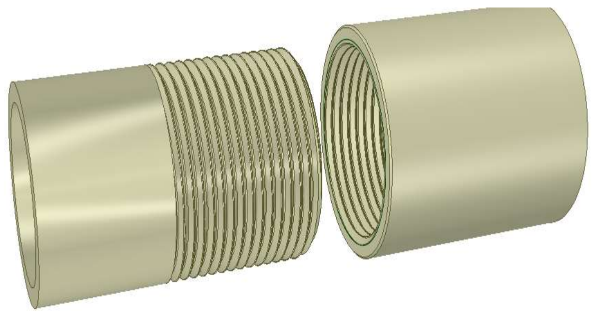


Figure 49: Thread joint

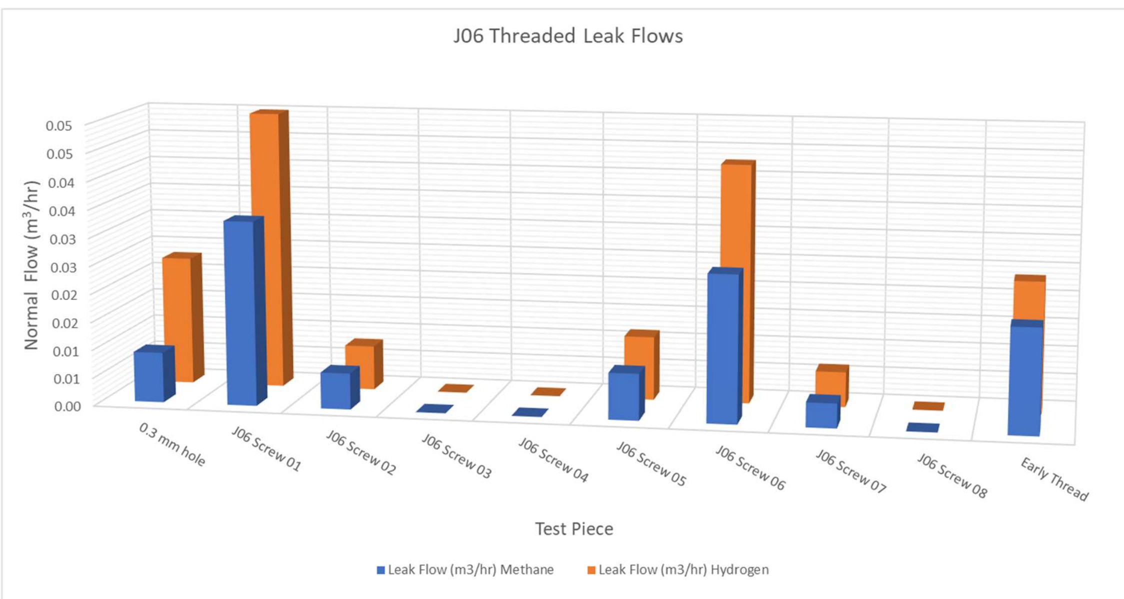


Figure 50: Threaded fittings comparison chart

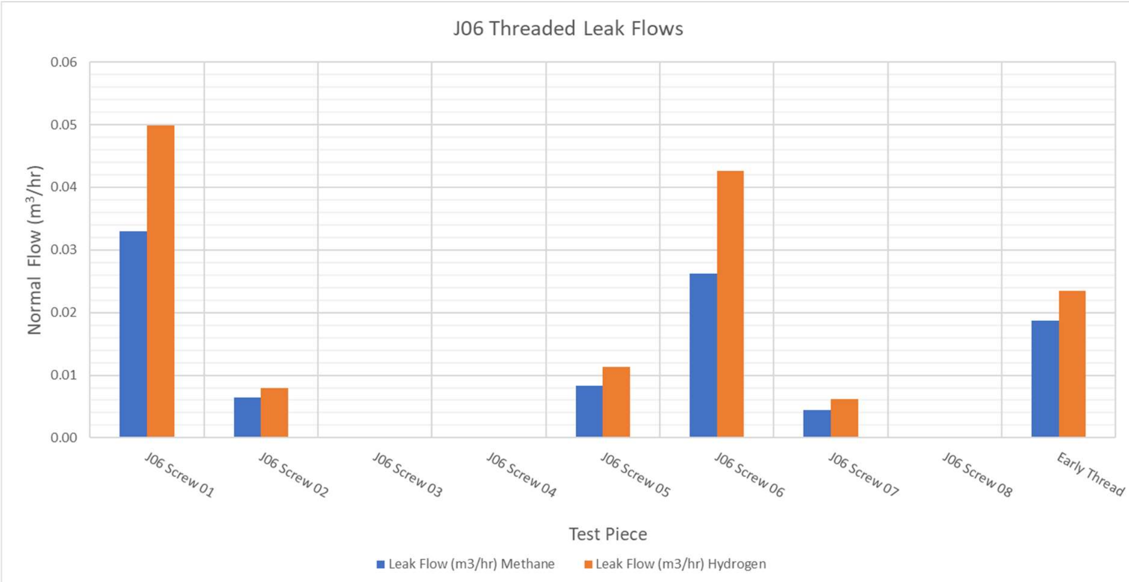


Figure 51: Threaded fitting leak rates

Test Piece	Leak Flow (m^3/hr)		Test Type	Nominal Pressure (mbar)	Leak Flow Ratio	Flow Type
	Methane	Hydrogen				
J06 Screw 01	3.29E-02	4.99E-02	Flow	20	1.51	Transition Flow
J06 Screw 02	6.44E-03	7.90E-03	Flow	20	1.23	Laminar Flow
J06 Screw 03	1.69E-06	4.69E-06	Lock Off	22	2.78	Negligible Flow
J06 Screw 04	2.76E-06	1.14E-06	Lock Off	22	0.42	Negligible Flow
J06 Screw 05	8.29E-03	1.14E-02	Flow	20	1.37	Laminar Flow
J06 Screw 06	2.62E-02	4.27E-02	Flow	20	1.63	Transition Flow
J06 Screw 07	4.38E-03	6.25E-03	Flow	20	1.43	Transition Flow
J06 Screw 08	3.78E-06	2.86E-06	Lock Off	22	0.76	Negligible Flow
Early Thread	1.87E-02	2.35E-02	Flow	20	1.26	Laminar Flow
Early Thread 40 mbar	3.68E-02	5.02E-02	Flow	40	1.36	Transition Flow
Early Thread 80 mbar	7.06E-02	1.00E-01	Flow	80	1.42	Transition Flow
Early Thread 400 mbar	2.95E-01	5.17E-01	Flow	400	1.75	Transition Flow

Table 11: Threaded fitting results table

Thread leaks were also used for an early investigation into flow regimes. Thread leaks demonstrated a laminar flow that moved through transition to turbulent flow as the pressure in the leak was increased. Figure 52 shows a laminar flow regime at 20 mbar that moves to a transition flow regime at 400 mbar. Transition is indicated by a non-linear curve, more prevalent in methane. Eventually if the pressure was increased this deviation from a linear response would also be evident in the hydrogen graph. This effect is shown in the increase in ratio of leak flow from hydrogen to methane in the early thread tests from 20 mbar to 400 mbar at the bottom of Table 11.

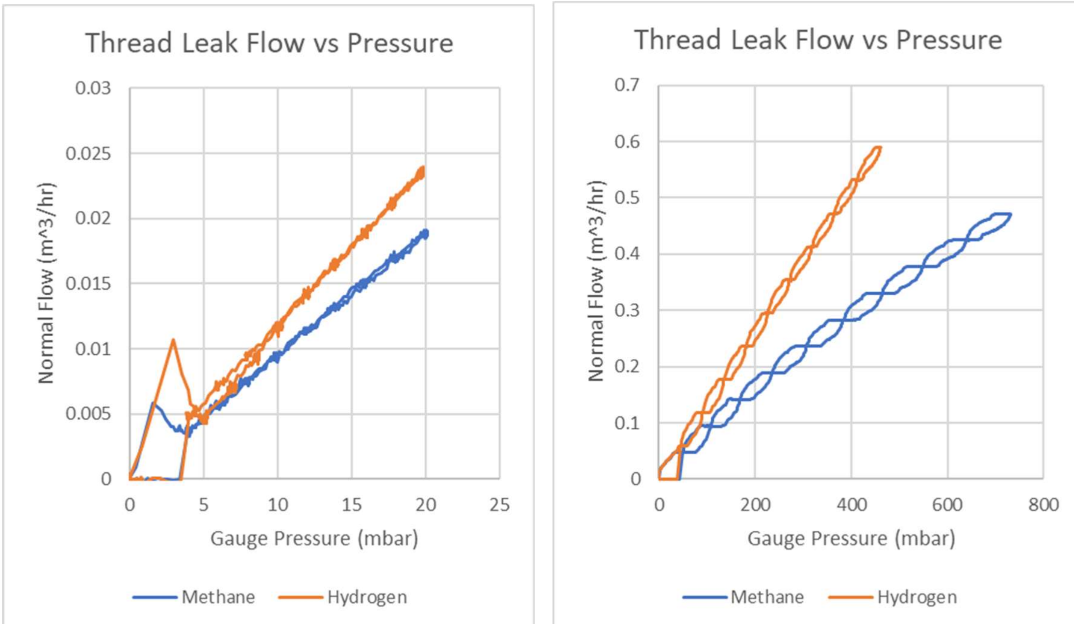


Figure 52: Thread leak flow up to 20 and 400 mbar

3.8.4 Solder fittings

Solder fittings are probably one of the most commonly used fitting type. They are cheap to buy and simple to install with relatively inexpensive equipment. They are also small in size and so result in a neat finish. They provide good sealing and are semi-permanent so de-mounting would often involve cutting out fittings.

Soldered joints are commonly used to join lengths of copper tube. Flux is applied to the tube and the fitting, then heat applied with a blowtorch. Solder is melted into one side of the joint, and in the right conditions it fills the annular gap between the tube and fitting entirely. A pre-soldered fitting type is shown in Figure 53.

Figure 53: Solder fitting, before and after installation

Experiments have included joints with no flux or solder, joints with flux only and no solder, dirty joints and jointing to incorrect materials. The solder fittings result in a leak type which will generally lead to laminar flow.

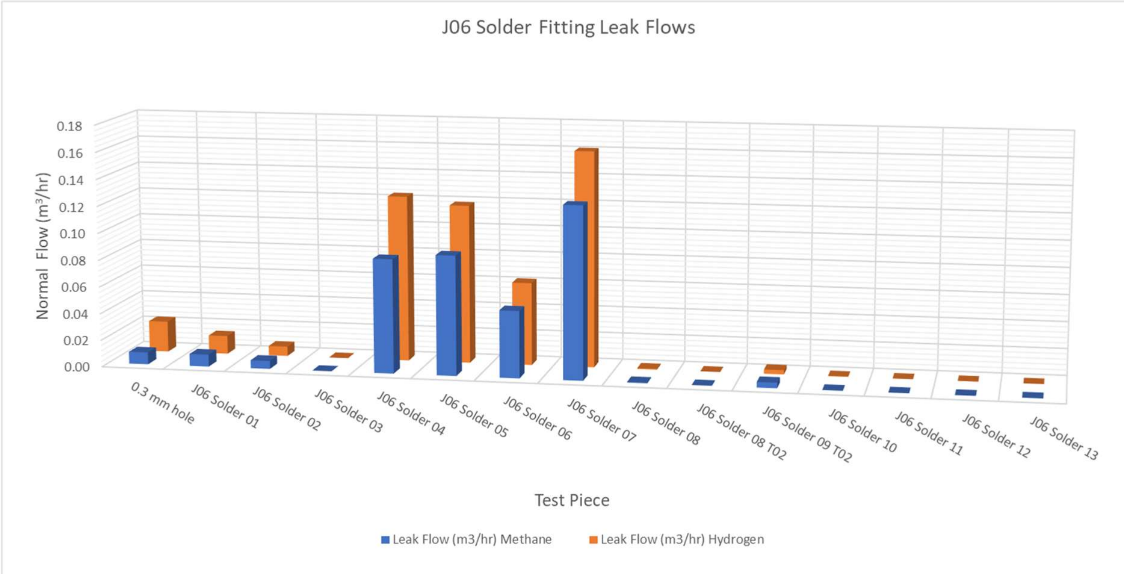


Figure 54: Solder fitting comparison chart

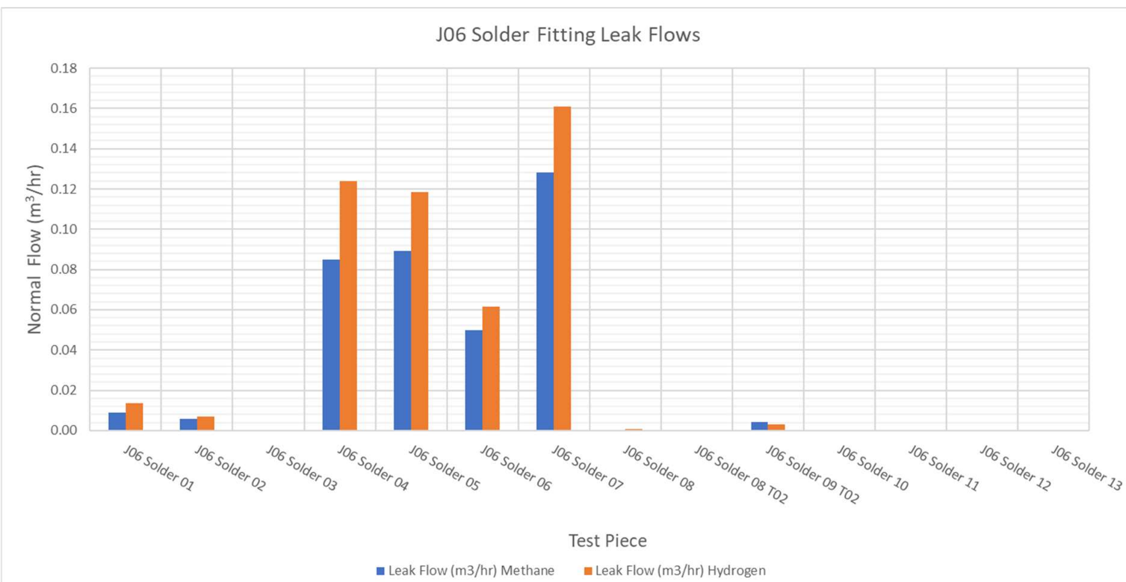


Figure 55: Solder fitting leak rates

Test Piece	Leak Flow (m^3/hr)		Test Type	Nominal Pressure (mbar)	Leak Flow Ratio	Flow Type
	Methane	Hydrogen				
J06 Solder 01	9.00E-03	1.36E-02	Flow	20.0	1.51	Laminar Flow
J06 Solder 02	5.99E-03	7.10E-03	Flow	20.0	1.18	Laminar Flow
J06 Solder 03	3.10E-07	-2.52E-06	Lock Off	92.4	-8.15	Negligible Flow
J06 Solder 04	8.49E-02	1.24E-01	Flow	20.0	1.46	Transition flow
J06 Solder 05	8.90E-02	1.18E-01	Flow	20.0	1.33	Laminar Flow
J06 Solder 06	4.98E-02	6.17E-02	Flow	20.0	1.24	Laminar Flow
J06 Solder 07	1.28E-01	1.61E-01	Flow	20.0	1.25	Laminar Flow
J06 Solder 08	4.96E-04	5.88E-04	Lock Off	20.0	1.19	Laminar Flow
J06 Solder 08 T02	-5.96E-07	1.33E-06	Lock Off	21.8	-2.22	Negligible Flow
J06 Solder 09 T02	4.07E-03	3.13E-03	Flow	20.0	0.77	Laminar Flow
J06 Solder 10	8.28E-05	9.24E-05	Lock Off	20.0	1.12	Laminar Flow
J06 Solder 11	6.85E-05	7.22E-05	Lock Off	20.0	1.05	Laminar Flow
J06 Solder 12	7.04E-05	7.20E-05	Lock Off	20.0	1.02	Laminar Flow
J06 Solder 13	6.79E-05	8.14E-05	Lock Off	20.0	1.20	Laminar Flow

Table 12: Solder fitting results table

3.8.5 Miscellaneous test pieces

This section captures the various fixtures and fittings that don't fit into any obvious grouping. This included sweated solder joints, PE fittings, PE pipe squeeze off and corrugated fittings.

Sweated fittings involve the use of solder to join dissimilar pipe materials, in particular lead pipe to copper where the solder fills in large gaps between the pipes, see Figure 56.

Figure 56: Sweated lead to copper

MDPE compression fittings have elastomeric sealing washers which are compressed as the fitting is screwed together, see Figure 57.

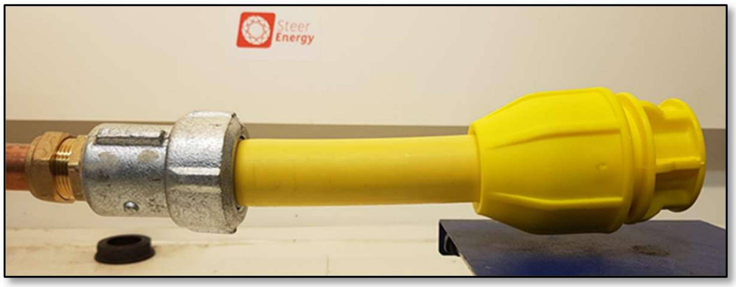


Figure 57: MDPE pipe and fittings

MDPE squeeze, shown in Figure 58, off uses a squeeze-off tool to clamp a piece of MDPE pipe as is commonly used for temporarily stopping flow in MDPE and PE pipes.

Figure 58: MDPE Squeeze-off tool

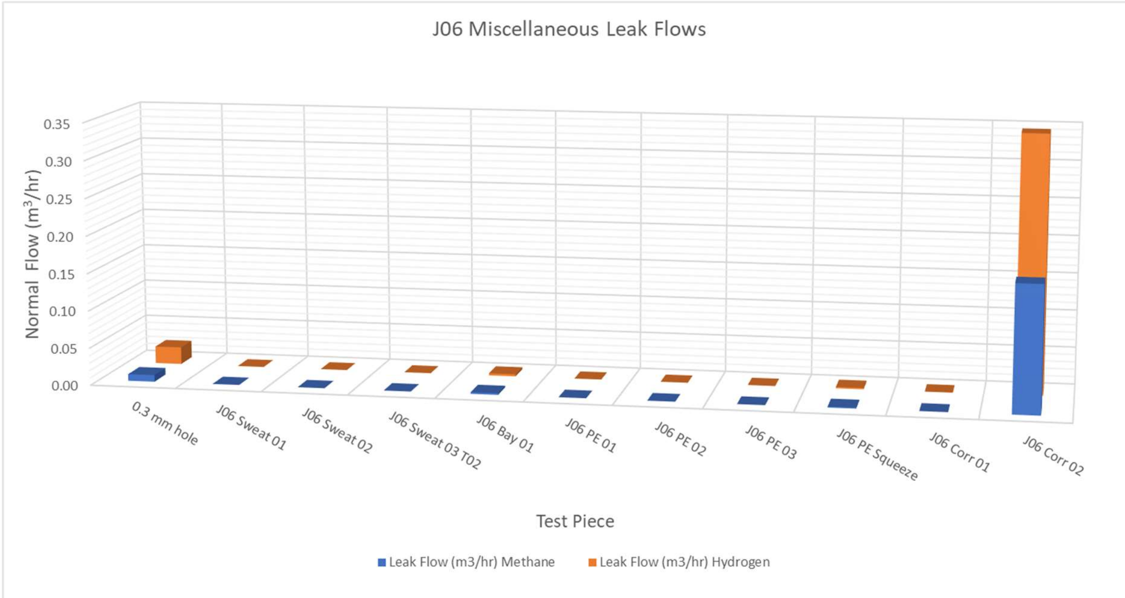


Figure 59: Miscellaneous fitting comparison chart

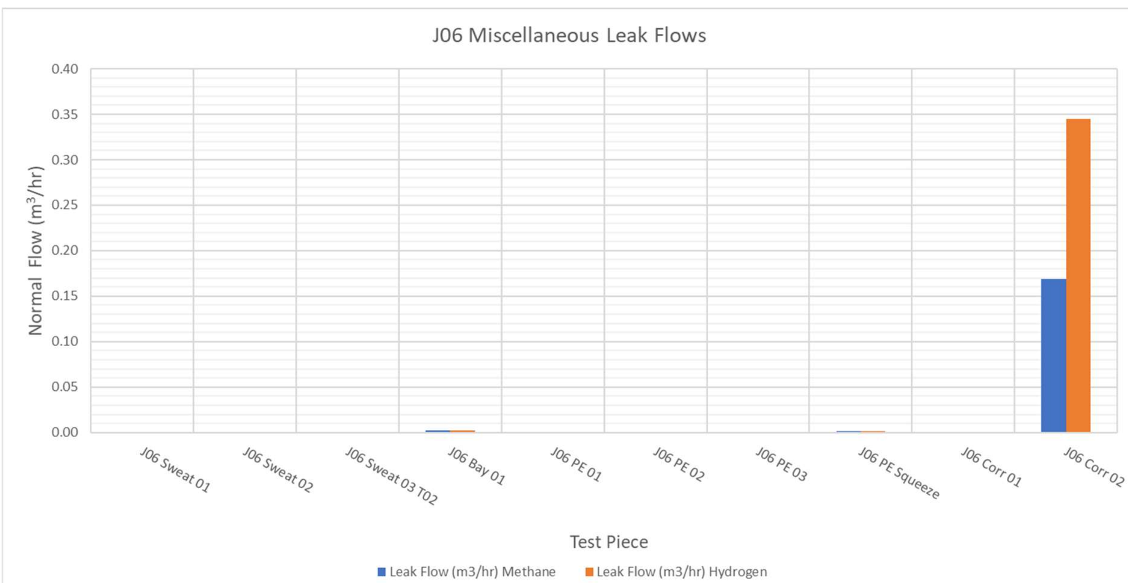


Figure 60: Miscellaneous fitting leak rates

Test Piece	Leak Flow (m^3/hr)		Test Type	Nominal Pressure (mbar)	Leak Flow Ratio	Flow Type
	Methane	Hydrogen				
J06 Sweat 01	-1.68E-06	-1.09E-07	Lock Off	91.9	0.07	Negligible Flow
J06 Sweat 02	2.57E-06	-2.58E-06	Lock Off	91.9	-1.00	Negligible Flow
J06 Sweat 03 T02	-1.32E-06	-1.26E-07	Lock Off	22.4	0.10	Negligible Flow
J06 Bay 01	2.15E-03	2.78E-03	Lock Off	20.4	1.29	Laminar Flow
J06 PE 01	7.17E-06	8.11E-06	Lock Off	20.0	1.13	Laminar Flow
J06 PE 02	1.30E-06	1.95E-07	Lock Off	22.2	0.15	Negligible Flow
J06 PE 03	5.87E-07	-3.68E-07	Lock Off	22.2	-0.63	Negligible Flow
J06 PE Squeeze	1.42E-03	1.71E-03	Flow	20.0	1.20	Laminar Flow
J06 Corr 01	-1.10E-07	1.47E-06	Lock Off	21.9	-13.36	Negligible Flow
J06 Corr 02	1.69E-01	3.45E-01	Flow	20.0	2.04	Transition Flow

Table 13: Miscellaneous fitting results table

3.9 J07: Valve results

The valve results comprise a large group of data, therefore the results are split up and presented in a number of graphs and tables. Each of the valves has been tested in a number of different configurations such as leakage through a closed valve and leakage out of a valve body to atmosphere. Different valves offered different options for leakage scenarios resulting in a variety of tests for each valve. An effort was made to avoid excessive repeat tests on similar valves.

3.9.1 Valves 01, 02 and 03

Valve 01 is an inline ball valve with a test port downstream of the ball valve. Valve 02 is a domestic meter control valve certified to GIS/V7-3:2007. This valve has high temperature seals and is designed as an emergency fire safety lock off valve. This valve type was one of the leakiest of all the valves tested. A repeat set of tests was carried out on a separated valve of the same type, valve 04. Valve 03 was a brass disc on seat valve, typically used for gas fires.

Figure 61: Valves 01, 02 and 03

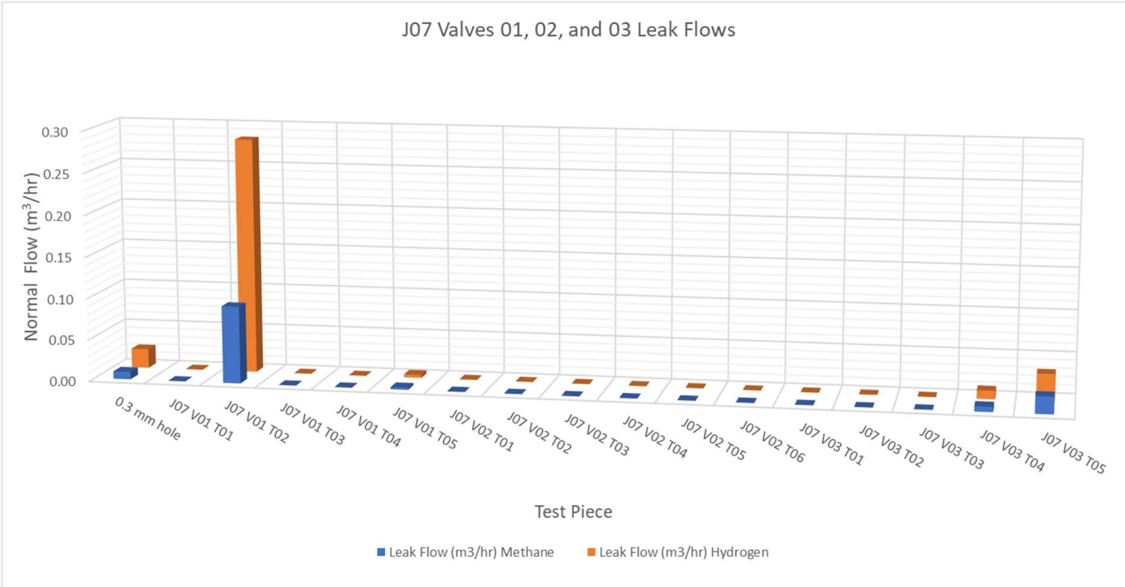


Figure 62: Valve 01, 02 and 03 comparison chart

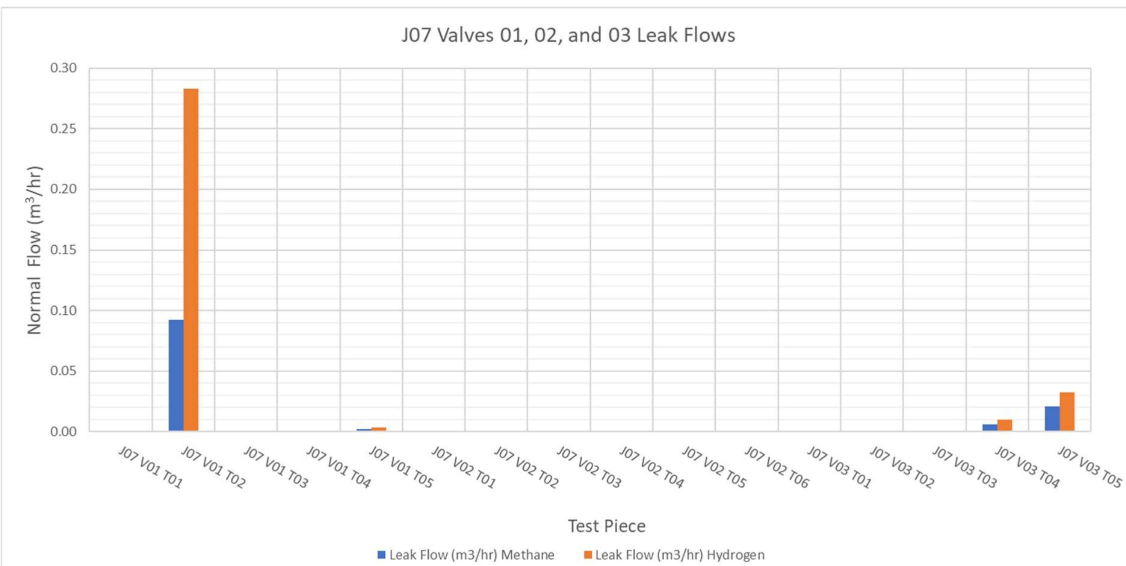


Figure 63: Valve 01, 02 and 03 leak rates

Test Piece	Leak Flow (m^3/hr)		Test Type	Nominal Pressure (mbar)	Leak Flow Ratio	Flow Type
	Methane	Hydrogen				
J07 V01 T01	4.76E-06	4.15E-06	Lock Off	89.9	0.87	Negligible Flow
J07 V01 T02	9.27E-02	2.83E-01	Flow	20.0	3.05	Turbulent Flow
J07 V01 T03	1.33E-06	2.65E-07	Lock Off	90.7	0.20	Negligible Flow
J07 V01 T04	1.05E-06	-5.51E-08	Lock Off	93.1	-0.05	Negligible Flow
J07 V01 T05	2.48E-03	3.54E-03	Flow	20.0	1.43	Laminar Flow
J07 V02 T01	3.87E-05	5.38E-05	Lock Off	20.0	1.39	Negligible Flow
J07 V02 T02	5.54E-05	2.63E-05	Lock Off	20.0	0.48	Negligible Flow
J07 V02 T03	4.64E-05	5.59E-05	Lock Off	20.0	1.20	Negligible Flow
J07 V02 T04	8.08E-05	7.13E-05	Lock Off	20.0	0.88	Negligible Flow
J07 V02 T05	2.17E-05	2.56E-05	Lock Off	20.0	1.18	Negligible Flow
J07 V02 T06	1.93E-05	2.17E-05	Lock Off	20.0	1.12	Negligible Flow
J07 V03 T01	1.87E-07	-1.51E-06	Lock Off	21.2	-8.07	Negligible Flow
J07 V03 T02	-8.51E-07	-2.10E-07	Lock Off	19.5	0.25	Negligible Flow
J07 V03 T03	3.15E-07	-2.84E-07	Lock Off	19.8	-0.90	Negligible Flow
J07 V03 T04	6.19E-03	1.00E-02	Flow	20.0	1.62	Transition Flow
J07 V03 T05	2.06E-02	3.24E-02	Flow	20.0	1.57	Transition Flow

Table 14: Valve 01, 02 and 03 results table

3.9.2 Valves 04, 05 and 06

Valve 04 is a set of tests carried out on the same type as valve 02. This valve had significantly better sealing properties than valve 02. Valve 05 was a disc on seat cooker bayonet fitting socket, the cooker hose has a pin which unseats the valve and permits flow of gas. Valve 06 is a brass taper plug valve; the taper plug is pulled down into the body of the valve to provide a seal. Testing this valve in fault modes was particularly challenging as any movement of the valve resulted in a change in the leak.

Figure 64: Valves 04, 05 and 06

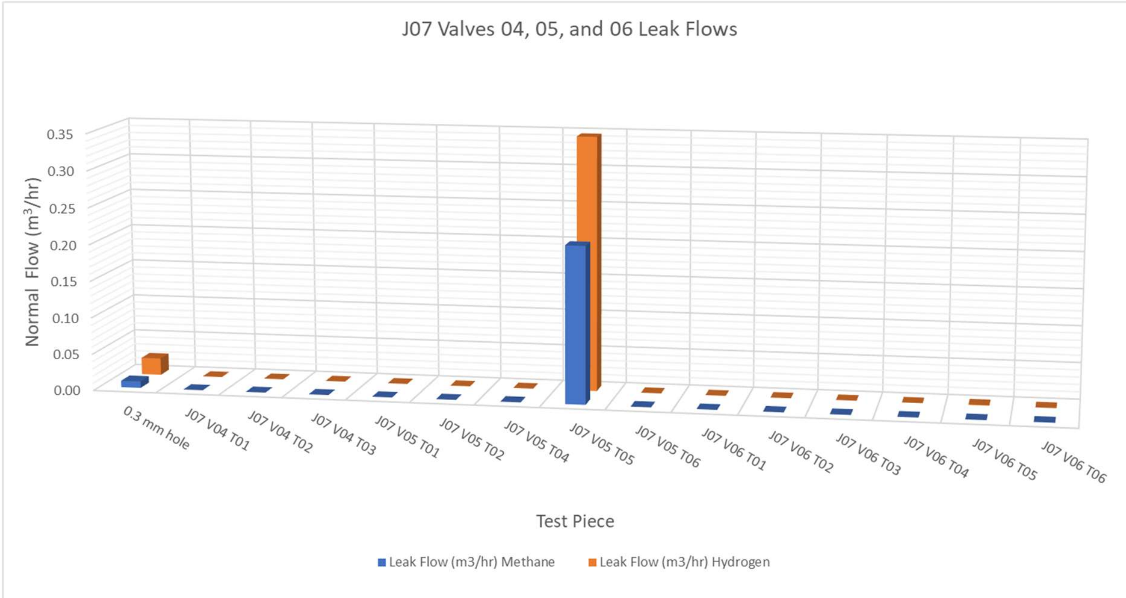


Figure 65: Valves 04, 05 and 06 comparison chart

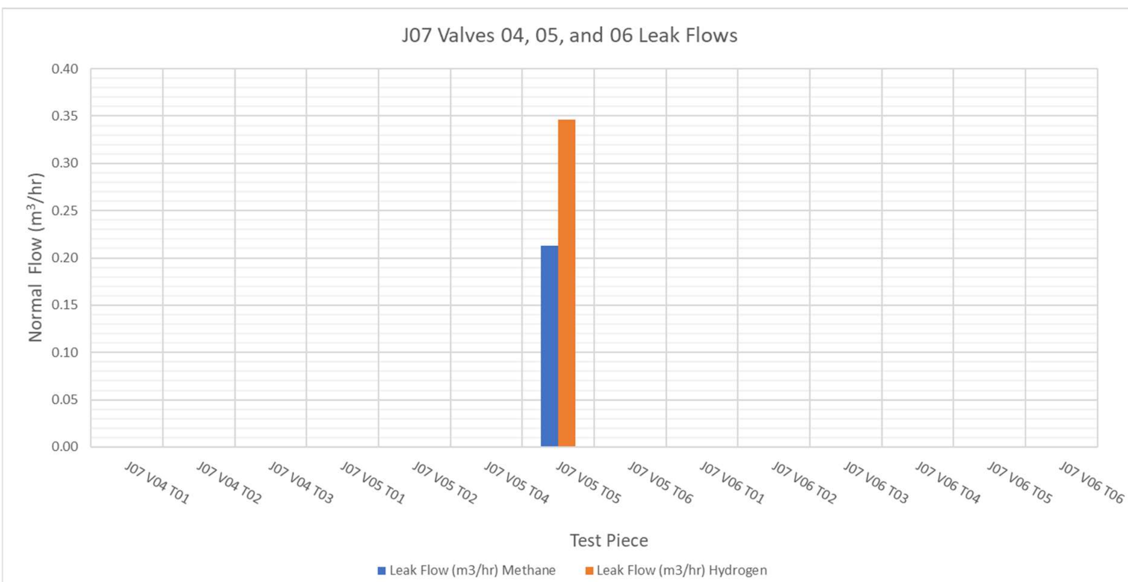


Figure 66: Valves 04, 05 and 06 leak rates

Test Piece	Leak Flow (m^3/hr)		Test Type	Nominal Pressure (mbar)	Leak Flow Ratio	Flow Type
	Methane	Hydrogen				
J07 V04 T01	4.37E-07	1.87E-06	Lock Off	21.7	4.28	Negligible Flow
J07 V04 T02	-8.27E-07	-3.19E-06	Lock Off	22.2	3.86	Negligible Flow
J07 V04 T03	3.62E-06	6.46E-07	Lock Off	22.6	0.18	Negligible Flow
J07 V05 T01	3.99E-07	-3.16E-07	Lock Off	22.2	-0.79	Negligible Flow
J07 V05 T02	3.55E-07	-2.37E-07	Lock Off	22.5	-0.67	Negligible Flow
J07 V05 T04	4.24E-08	-1.19E-06	Lock Off	22.3	-28.15	Negligible Flow
J07 V05 T05	2.13E-01	3.46E-01	Flow	20.0	1.62	Transition Flow
J07 V05 T06	6.70E-07	4.94E-07	Lock Off	22.1	0.74	Negligible Flow
J07 V06 T01	-5.15E-07	-9.76E-07	Lock Off	22.5	1.89	Negligible Flow
J07 V06 T02	-4.26E-07	-6.29E-07	Lock Off	22.2	1.48	Negligible Flow
J07 V06 T03	1.27E-05	7.33E-06	Lock Off	21.8	0.58	Negligible Flow
J07 V06 T04	-2.50E-07	-1.50E-06	Lock Off	21.2	5.99	Negligible Flow
J07 V06 T05	3.65E-05	6.40E-04	Lock Off	20.1	17.53	Negligible Flow
J07 V06 T06	6.48E-05	1.02E-04	Lock Off	20.0	1.57	Transition Flow

Table 15: Valves 04, 05 and 06 results table

3.9.3 Valves 07 – 10

The final set of valves were valves 07 – 10. Valve 07 is a 1 inch emergency control valve (ECV). This is a taper plug valve lubricated with a bespoke gas valve grease. Valves 08 – 10 are all conventional ball valves with elastomer seats that have been subjected to different types of damage. Valve 08 has had iron oxide grit applied to the valve seat and then the valve stoked 100 times. This has scored the ball and the valve seals. Valve 09 has had a blowtorch applied to the valve whilst in the open position and then tested for leakage into the atmosphere through the stem seals. Valve 10 has had a blowtorch applied whilst the valve is in the closed position. The ability of the valve to block the flow of gas was then tested.

Figure 67: Valve 07 and Valve 10

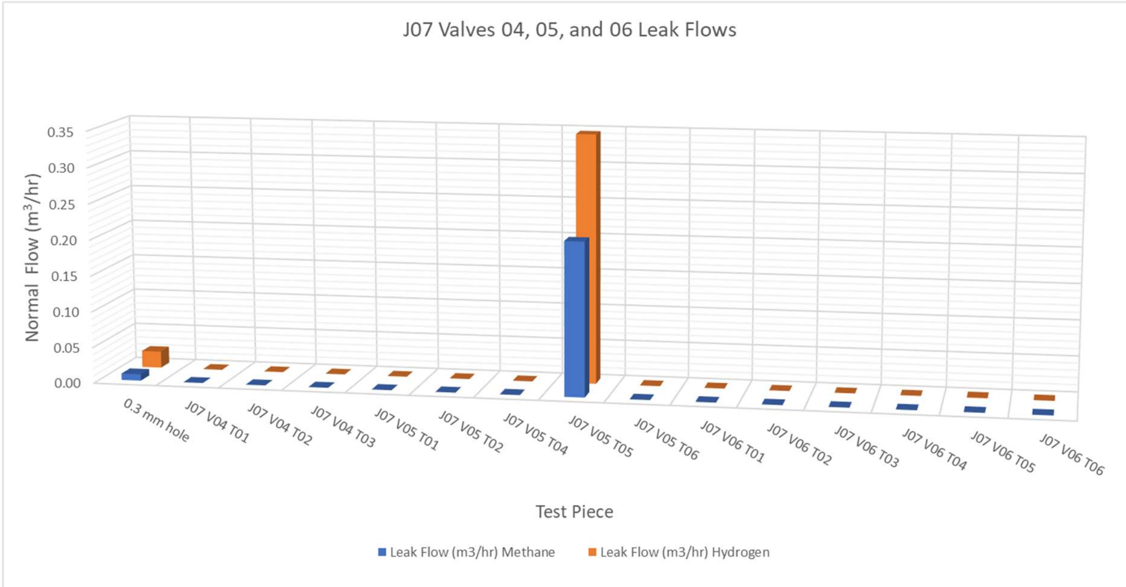


Figure 68: Valves 07 – 10 comparison chart

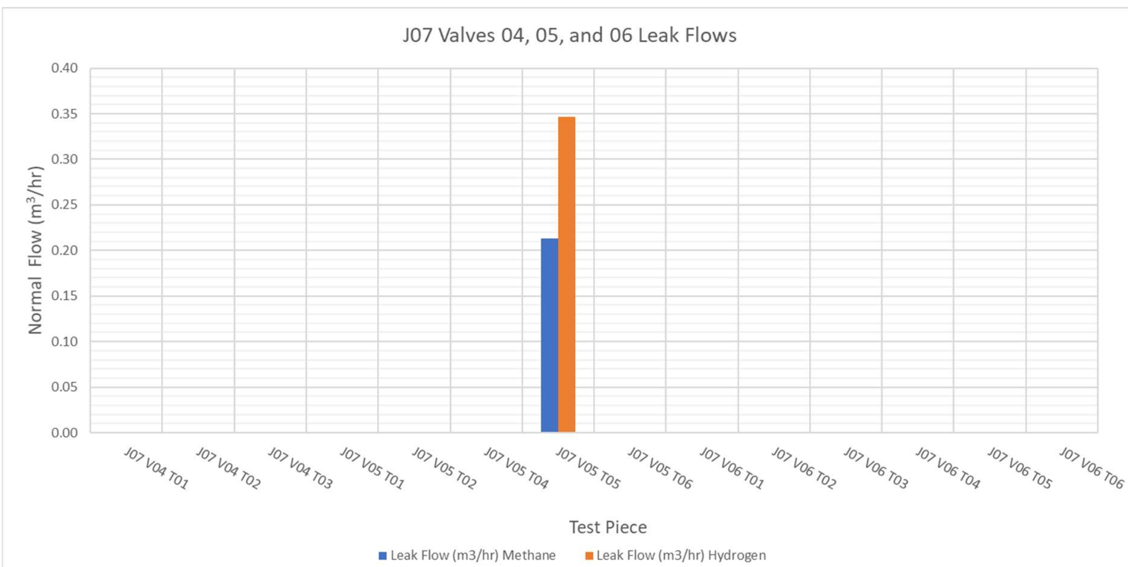


Figure 69: Valves 07 – 10 leak rates

Test Piece	Leak Flow (m^3/hr)		Test Type	Nominal Pressure (mbar)	Leak Flow Ratio	Flow Type
	Methane	Hydrogen				
J07 V07 T01	1.78E-06	-2.05E-06	Lock Off	22.6	-1.15	Negligible Flow
J07 V07 T02	-3.33E-07	-2.64E-07	Lock Off	21.6	0.79	Negligible Flow
J07 V07 T03	5.14E-08	-2.45E-06	Lock Off	22.2	-47.66	Negligible Flow
J07 V07 T04	4.17E-07	3.26E-07	Lock Off	22.0	0.78	Negligible Flow
J07 V07 T05	3.45E-06	4.56E-07	Lock Off	22.2	0.13	Negligible Flow
J07 V07 T06	9.28E-08	-7.01E-07	Lock Off	22.2	-7.56	Negligible Flow
J07 V07 T07	1.19E-05	1.51E-05	Lock Off	20.5	1.28	Negligible Flow
J07 V07 T08	6.29E-09	-1.93E-06	Lock Off	22.6	-307.32	Negligible Flow
J07 V07 T09	0.013	0.016	Flow	20.0	1.25	Laminar Flow
J07 V08 T01	1.21E-04	1.16E-04	Lock Off	20.0	0.96	Negligible Flow
J07 V08 T02	5.23E-05	3.10E-05	Lock Off	20.0	0.59	Negligible Flow
J07 V09 T01	5.00E-06	1.92E-06	Lock Off	21.5	0.38	Negligible Flow
J07 V10 T01	1.38E-01	3.80E-01	Flow	20.0	2.76	Turbulent Flow

Table 16: Valves 07 – 10 results table

3.10 J08: Damage results

The damage tests aimed to simulate DIY accidents and other damage situations that could occur on the domestic gas network. The results of the tests generally mimic those for holes with a leak ratio approaching 2.8:1. The majority of the nail and screw punctures resulted in an equivalent hole size less than 1 mm diameter, except for the NT5 which is a large helical shaft roofing nail, shown in Figure 70.

Figure 70: J08 NT05 Roofing Nail

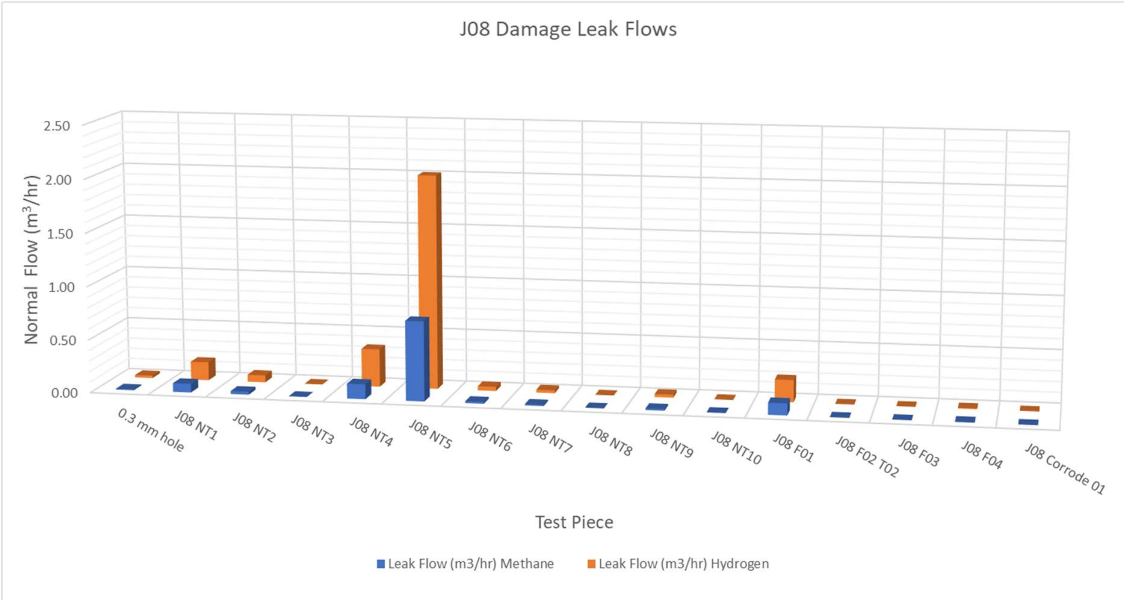


Figure 71: Damage Tests Combined Data

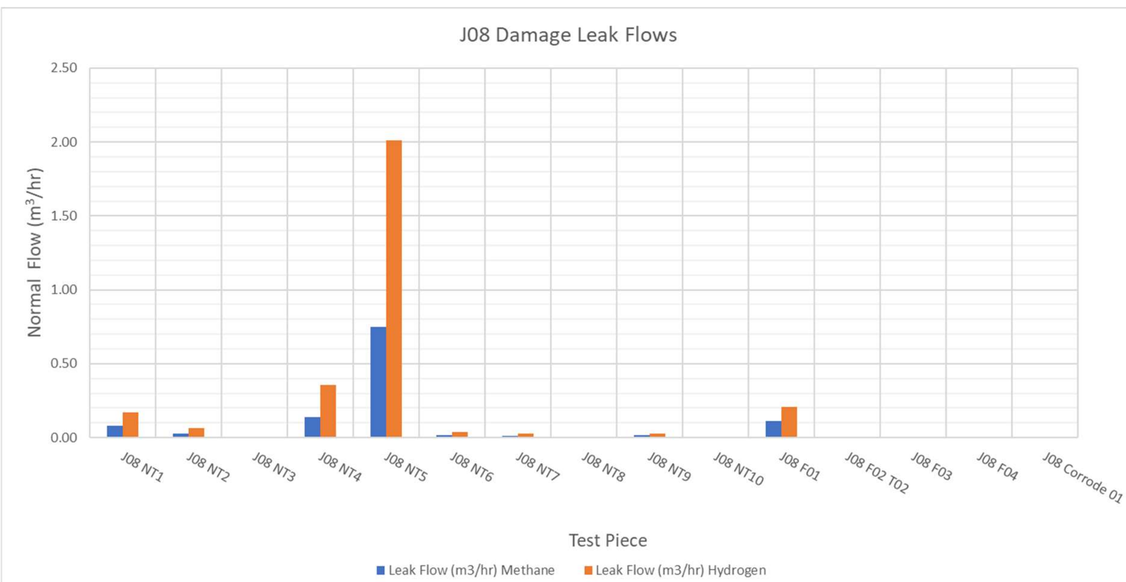


Figure 72: Damage leak rates

Test Piece	Leak Flow (m³/hr)		Test Type	Nominal Pressure (mbar)	Leak Flow Ratio	Flow Type
	Methane	Hydrogen				
J08 NT1	8.19E-02	1.72E-01	Flow	20.0	2.10	Turbulent Flow
J08 NT2	2.82E-02	6.61E-02	Flow	20.0	2.34	Turbulent Flow
J08 NT3	1.55E-04	1.37E-04	Lock Off	20.0	0.89	Laminar Flow
J08 NT4	1.40E-01	3.55E-01	Flow	20.0	2.54	Turbulent Flow
J08 NT5	7.47E-01	2.01E+00	Flow	20.0	2.69	Turbulent Flow
J08 NT6	1.69E-02	3.90E-02	Flow	20.0	2.30	Transition Flow
J08 NT7	1.16E-02	2.73E-02	Flow	20.0	2.35	Transition Flow
J08 NT8	1.61E-04	1.94E-04	Lock Off	20.0	1.20	Laminar Flow
J08 NT9	1.50E-02	2.78E-02	Flow	20.0	1.85	Transition Flow
J08 NT10	5.56E-05	6.01E-05	Lock Off	14.6	1.08	Laminar Flow
J08 F01	1.12E-01	2.08E-01	Flow	20.0	1.86	Transition Flow
J08 F02 T02	4.86E-05	7.29E-05	Lock Off	20.0	1.50	Laminar Flow
J08 F03	6.75E-05	8.07E-05	Lock Off	20.0	1.20	Laminar Flow
J08 F04	4.52E-03	6.25E-03	Flow	20.0	1.38	Laminar Flow
J08 Corrode 01	-1.63E-06	-8.90E-07	Lock Off	22.2	0.55	Negligible Flow

Table 17: Damage results table

Four test pieces have been used for the fold tests. The first, *F01* of this is a cut end of pipe which was crimped in a vice to crush the ends together, shown in Figure 73. This test was a flow through test; it is a measurement of how much gas passes through the defect.

Figure 73: J08 F01 Test Piece

The second, third and fourth were tubes which had been folded to see if they would leak at the fold. These were lock in tests and the leak path under investigation was out of the tube at the fold. The second test, *F02* piece was a single fold at 90° shown in Figure 74. The third test piece, *F03* had the tube folded in half beyond 90°. After the initial test this test piece had the fold opened and closed five times to fatigue the metal to form a definite leak. For *F04* the leak was greater when the fold was opened out and then reduced when the fold was re-made. The leak was therefore on the inner pipe wall where the bend radius was tighter. Continued fatiguing of the metal would result in a steady increase in leak size and eventual failure of the tube.

Figure 74: J08 F02 Test Piece

Figure 75: F03/F04 Test Piece

3.11 J09: Flow investigations

A number of separate tests were carried out to investigate comparative flow of the two gas types in pipe networks. The aim of these was to see if the flow of hydrogen was in some way significantly different to methane. All of the flow tests involved measuring the pressure loss seen on either side of the test piece when a given flow was applied to the test piece. The results were then compared to manufacturers' data. The three sets of flow investigation were:

- Straight Lengths: 15 mm and 22 mm pipe runs have been investigated
- Elbows: multiple tests on 22 mm elbows have been investigated
- Tees: a single set of tests carried out on a 22 mm tee in straight through and branch configurations.

The data has then been compared to published data to provide a pressure loss per meter for the straight pipes vs. a given flow speed. The elbow and tee results are presented in terms of equivalent pipe lengths as per manufacturers data.

Due to the large flows used for these tests, the 100 l/m and 300 l/m rotameters were used for these tests.

3.11.1 Straight lengths

Flow tests were carried out for 22 mm and 15 mm pipe runs. The results can be compared to manufacturers data sheets for methane which is included for 2nd family gas in Figure 76.

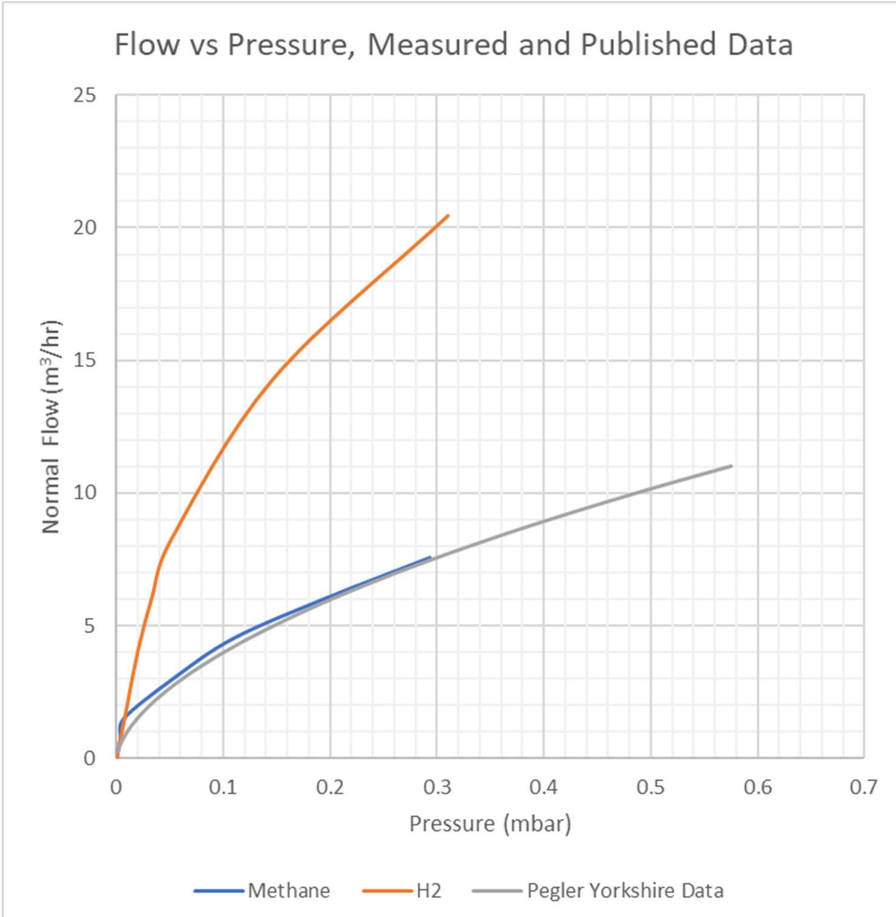
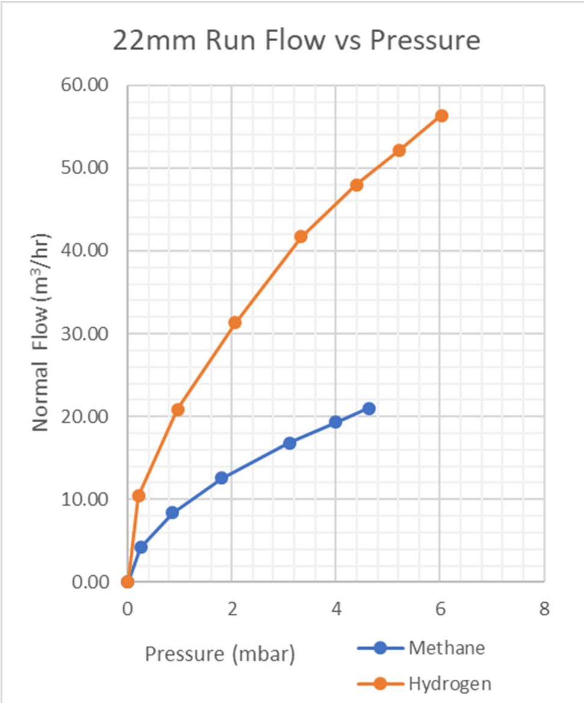


Figure 76: Flow and Pressure Comparison with Pegler Yorkshire Published Data for 22 mm Copper Pipe

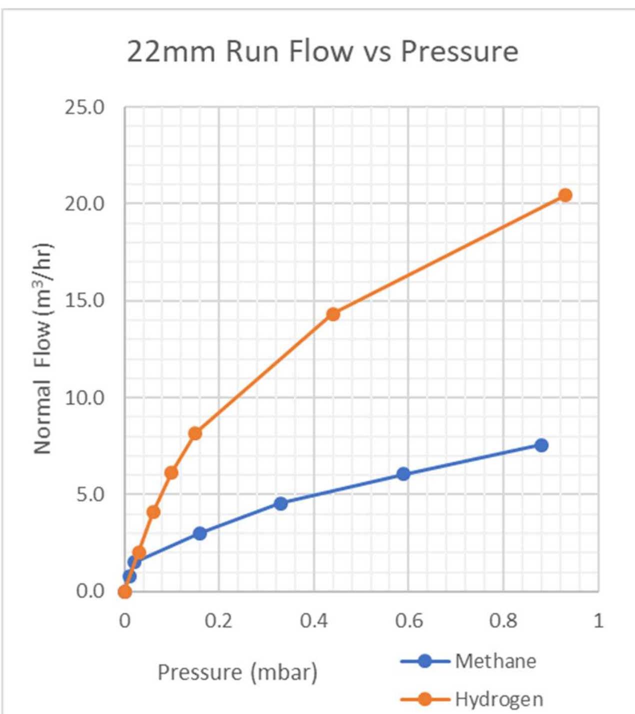
22 mm Pipe Run

Two sets of data were taken, one with the 300 l/m rotameter and one with the 100 l/m rotameter. Flow was driven through a single 3 m length of 22 mm tube and the pressure measured at either end. The 300 l/m data is presented in Figure 77 and the 100 l/m data is presented in Figure 78.



Normal flow m3/hr	Pressure loss per metre CH4	Pressure loss per metre H2
0.00	0.000	
4.20	0.083	
8.39	0.287	
12.59	0.603	
16.79	1.037	
19.31	1.333	
20.99	1.543	
0.00		0.000
10.43		0.070
20.87		0.320
31.30		0.690
41.74		1.110
48.00		1.467
52.17		1.740

Figure 77: 22mm tube flow vs pressure using the 300 l/m rotameter

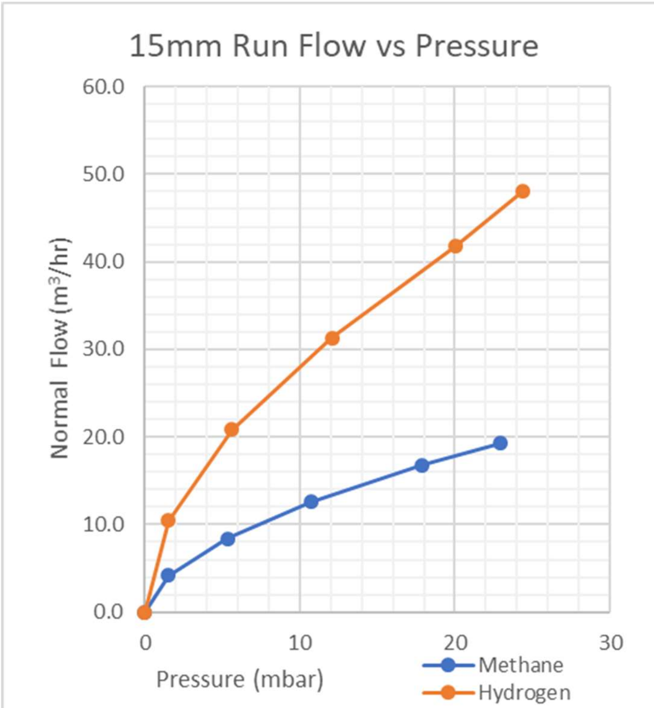


Normal flow m3/hr	Pressure loss per metre CH4	Pressure loss per metre H2
0.00	0.000	
0.76	0.003	
1.51	0.007	
3.03	0.053	
4.54	0.110	
6.06	0.197	
7.57	0.293	
0.00		0.000
2.04		0.010
4.09		0.020
6.13		0.033
8.18		0.050
14.31		0.147
20.45		0.310

Figure 78: 22 mm tube flow vs pressure using the 100 l/m rotameter

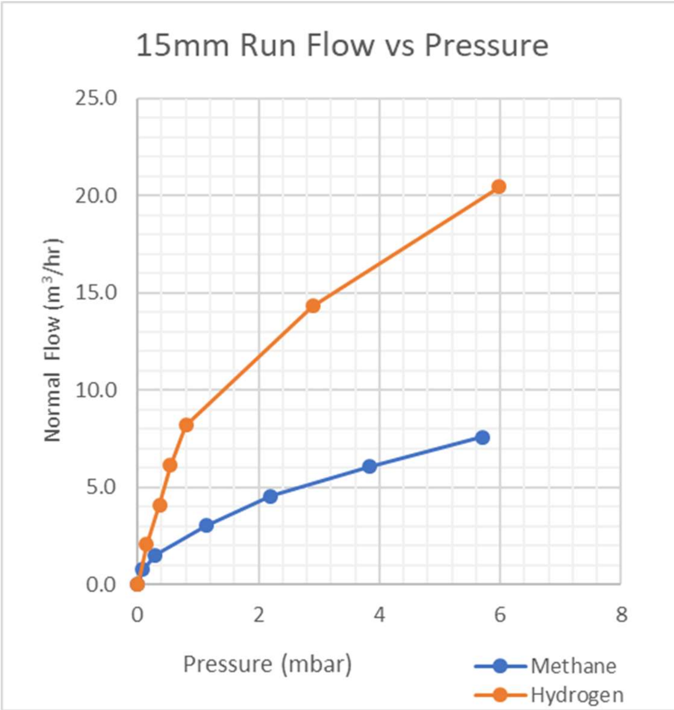
15 mm Pipe Run

Two sets of data were taken using the 300 l/m and 100 l/m rotameters. The flow was driven through a single length of 15 mm tube and the pressure measured at either end. 300 l/m data is presented in Figure 79 and the 100 l/m data is presented in Figure 80.



Normal flow m3/hr	Pressure loss per metre	
	CH4	H2
0.00	0.000	
4.20	0.510	
8.39	1.780	
12.59	3.570	
16.79	5.967	
19.31	7.633	
0.00		0.000
10.43		0.507
20.87		1.870
31.30		4.030
41.74		6.680
48.00		8.113

Figure 79: 15mm tube flow vs pressure using the 300 l/m rotameter



Normal flow m3/hr	Pressure loss per metre	
	CH4	H2
0.00	0.000	
0.76	0.027	
1.51	0.097	
3.03	0.377	
4.54	0.733	
6.06	1.277	
7.57	1.900	
0.00		0.000
2.04		0.050
4.09		0.120
6.13		0.180
8.18		0.267
14.31		0.967
20.45		1.993

Figure 80: 15 mm tube flow vs pressure using the 100 l/m rotameter

The frictional losses for the straight pipe runs are given for methane and hydrogen. As expected, the flow / pressure relationship indicates turbulent flow in the pipes.

3.11.2 Elbows

The flow measurement was carried out using the 100 l/m rotameter and pressure measurement was carried out using the Extec HD350 Differential Manometer.

The elbow test set-up is designed to have one or more elbows in the system with each feature separated by (a minimum of) 440 mm of pipe. A rule of thumb of 20x pipe diameter's equivalent length is used for flow conditions to settle to uniform conditions (laminar or turbulent). The internal pipe diameter is 20 mm but a value of 22 mm was used to give the 440 mm pipe lengths. The pressure loss due to the 0.44 mm pipe sections is then subtracted from the measured test result to give the pressure loss due to the elbows only. Tests were carried out for combinations of up to 6 elbows and the results collated. The test setup is shown in Figure 81. The collated results for methane are given in Figure 82 and those for hydrogen are given in Figure 83.

The pressure drop per elbow can be expressed for each flow rate, shown in Figure 84 and Figure 85. The results indicate a nominally linear relationship between pressure drop and number of elbows for each flow rate.

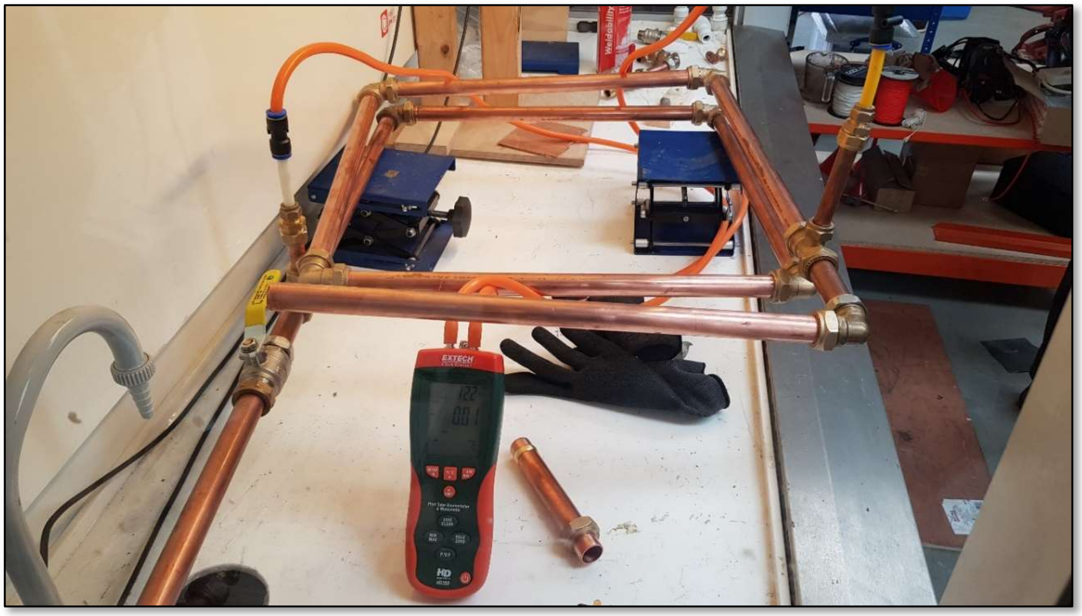


Figure 81: Experimental set-up for elbow tests

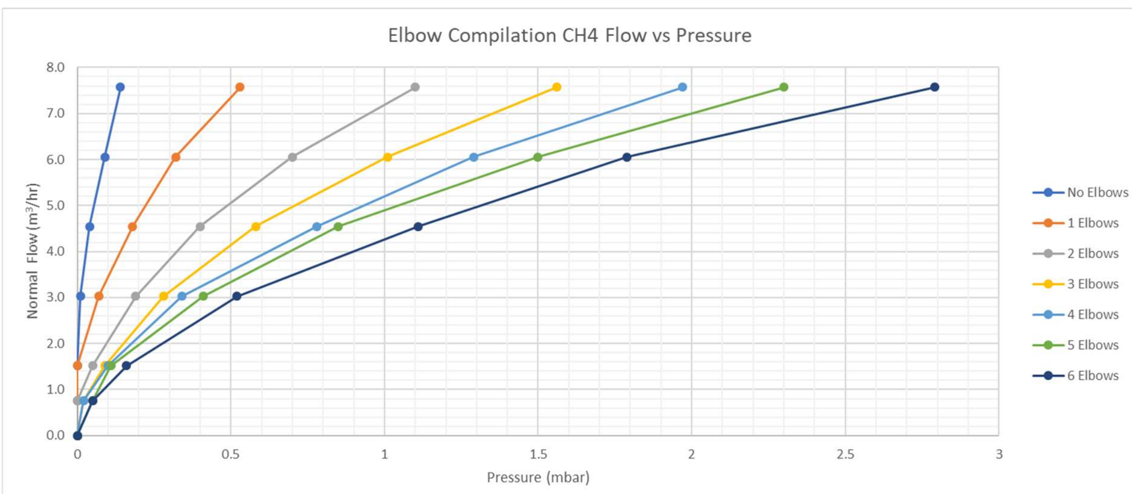


Figure 82: Methane flow vs. pressure by number of elbows

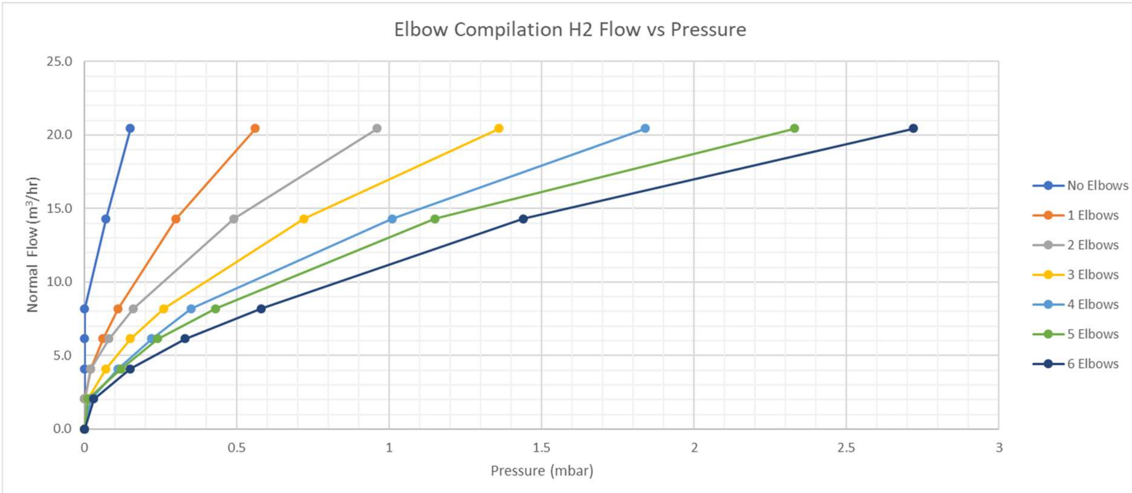


Figure 83: Hydrogen flow vs. pressure by number of elbows

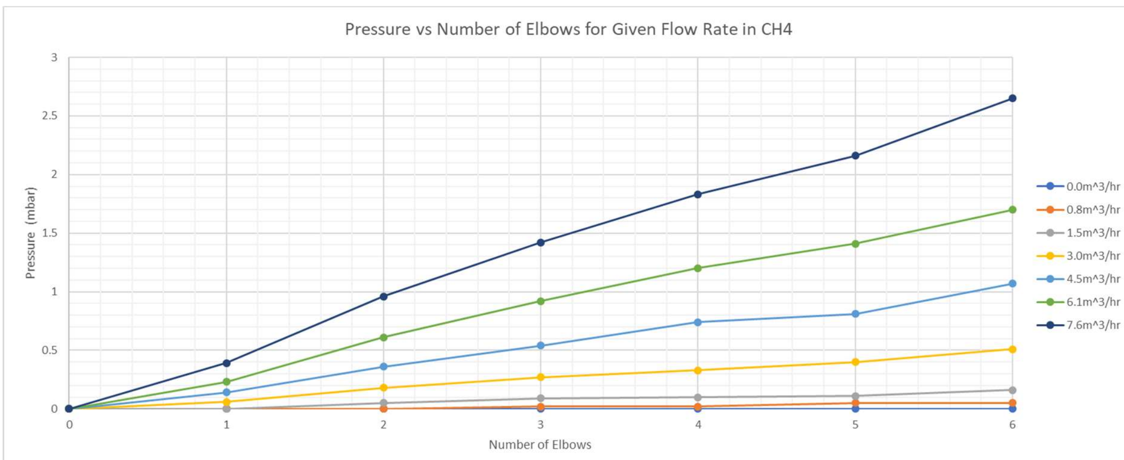


Figure 84: Pressure vs number of elbows for methane

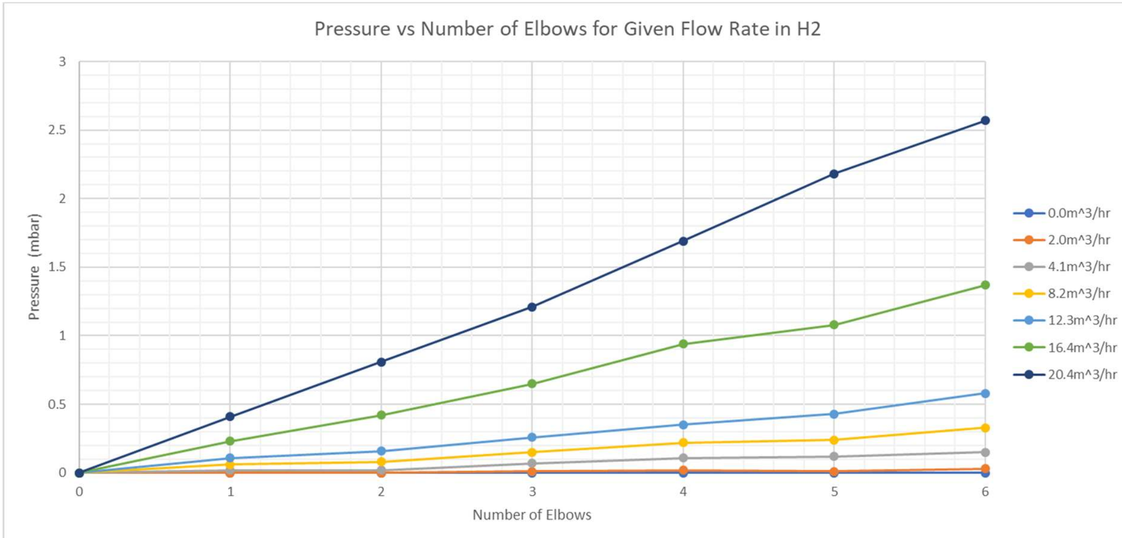


Figure 85: Pressure vs number of elbows hydrogen

Finally, it is possible to express the pressure loss per elbow in terms of an equivalent pipe length. These values calculate out as: 1.04 m for methane and 1.03 m for hydrogen. Essentially the data shows that the equivalent length method appears to hold for hydrogen as well as methane. This can be compared with the manufacturer's data for equivalent length as it follows closely the published data as shown in Figure 86. The change in gas does not appear to change the equivalent length of elbows.

Direct analytical method (ζ) / equivalent length (m)

OD	DN	ζ	(m)	ζ	(m)	ζ	(m)	ζ	(m)	ζ	(m)	ζ	(m)	ζ	(m)
15	12	1,02	0,49	0,69	0,33	0,40	0,19	1,13	0,55	0,36	0,17	0,52	0,25	0,64	0,31
18	15	0,93	0,58	0,77	0,48	0,50	0,32	1,41	0,89	0,46	0,29	1,06	0,67	0,96	0,60
22	20	0,44	0,35	0,38	0,30	0,15	0,12	1,05	0,84	0,11	0,08	0,73	0,59	1,29	1,04
28	25	0,35	0,38	0,28	0,32	0,13	0,28	0,93	1,01	0,05	0,06	0,65	0,72	0,82	0,92
35	32	0,31	0,43	0,29	0,40	0,08	0,11	0,93	1,34	0,03	0,04	0,53	0,79	1,47	2,19
42	40	0,25	0,48	0,22	0,42	0,11	0,20	1,20	2,27	0,06	0,11	0,46	0,85	-	-
54	50	0,30	0,79	0,19	0,49	0,09	0,24	1,15	3,06	0,06	0,14	0,36	1,43	-	-
76,1	65	0,25	1,04	0,15	0,62	0,08	0,31	1,07	4,42	0,04	0,17	0,32	1,68	-	-
88,9	80	0,24	1,22	0,13	0,66	0,07	0,36	1,06	5,38	0,04	0,20	0,27	2,10	-	-
108	100	0,23	1,51	0,12	0,76	0,07	0,43	1,05	6,90	0,03	0,20	-	-	-	-

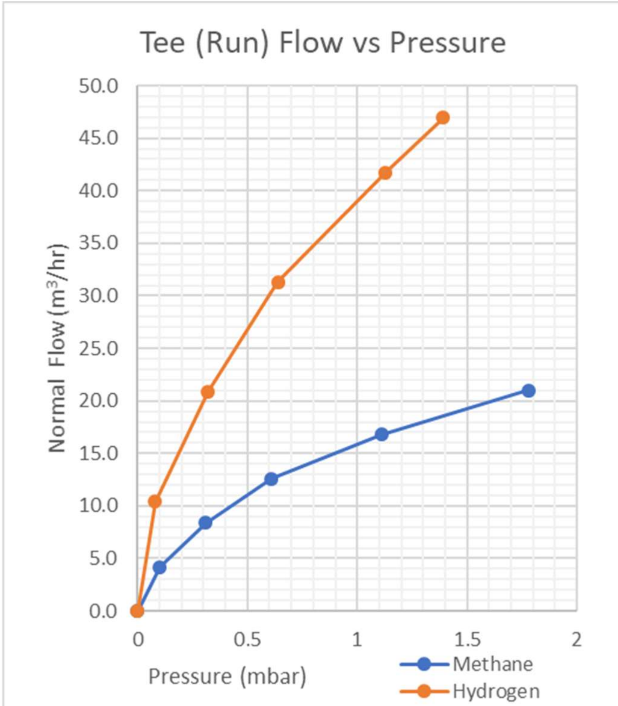
TABLE OF LOCALIZED FLOW LOSS VALUES AND EQUIVALENT METERS

Figure 86: Equivalent lengths for bends, elbows and tees by Pegler Yorkshire

3.11.3 Tees

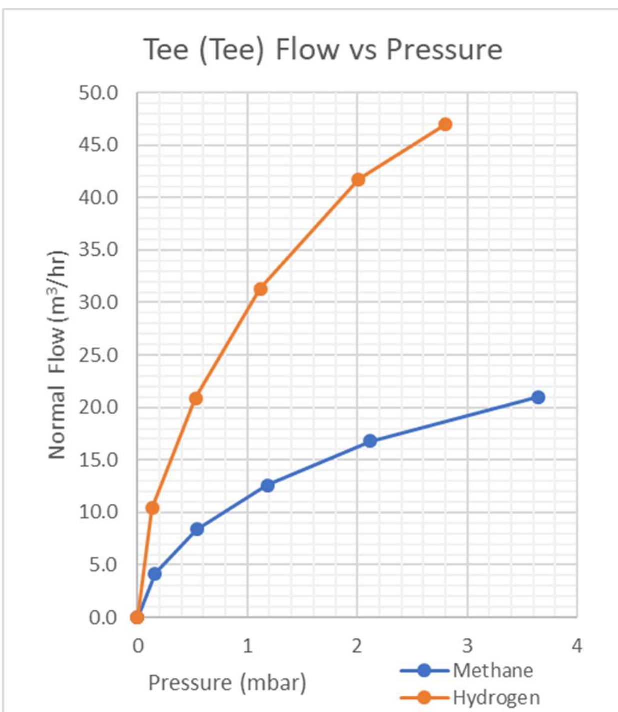
A simplified version of the elbow tests was carried out for two configurations of tee: a straight through configuration and a branch configuration. The 440 mm straight pipe sections were used again to allow for flow stabilisation. These tests were carried out using the 300 l/m rotameter since only one tee was used and the higher flows enable a higher pressure differential to be measured.

The results have been processed to compensate for the 440 mm pipe lengths and calculate the equivalent length result for each flow rate. The overall results are then averaged.



	Equivalent Length (metres)	
Normal flow m3/hr	CH4	H2
0.00		
4.20	0.32	
8.39	0.20	
12.59	0.13	
16.79	0.19	
20.99	0.27	
Average	0.22	
0.00		
10.43		0.26
20.87		0.12
31.30		0.05
41.74		0.14
Average		0.14

Figure 87: Losses in straight through tee



	Equivalent Length (metres)	
Normal flow m3/hr	CH4	H2
0.00		
4.20	1.04	
8.39	1.00	
12.59	1.08	
16.79	1.17	
20.99	1.49	
Average	1.07	
0.00		
10.43		0.98
20.87		0.78
31.30		0.74
41.74		0.93
Average		0.86

Figure 88: Losses in tee (branch configuration)

Comparing the results with published data for the tees, the equivalent lengths for methane are greater than the published figures whilst those for hydrogen are closer to the published data. This is believed to be due to the fact only one tee was used for the measurement. To develop a measurable pressure difference across the fitting a very large flow was used. In methane this will have generated a significantly turbulent flow regime and as such may well have influenced the data when compared to manufacturer's data which is derived from lower flow rates. The less turbulent hydrogen flow would then produce a result closer to published data.

3.11.4 Flow test conclusions

Tests were carried out at flows up to 56 m^3/hr in hydrogen and 21 m^3/hr in methane. The flow in the pipes was in general turbulent during the tests due to these large flows. Most of these flows were therefore large compared to the expected 6.4m^3 maximum flow for a domestic network.

The pressure drops for a given flow rate are smaller for hydrogen than for methane. The lower viscosity means transition to turbulent flow occurs at faster speeds and higher flow rates whilst much lower density means lower frictional loss in turbulent conditions. This was borne out in the results of the flow tests.

The effect of this will be that hydrogen will flow more freely in any pipe system, so larger volumes of gas can be transported in a given network when fed by hydrogen compared to methane.

3.12 J10: Regulator investigations

Three domestic regulators have been tested, a Mesura A6N, a Sperryn G940 and a Jeavons J42. An additional test has been carried out using the highest flow regulator (the Sperryn G940) and a Schlumberger U6 gas meter.

These regulator tests build on the tests carried out on the Jeavons J78R ½ inch commercial regulator reported in the *50 Test* report. The early tests on Jeavons J78R did not have the benefit of the high flow rotameters and the 15 mm pipe connections to the regulator are likely to have imposed a greater flow restriction on the system under test than the regulator itself.

All of the tests are high-flow tests that used the 300 l/m rotameter to control and measure flow. The ifm pressure sensors were used to monitor and log the pressure immediately upstream of the regulator. The flow was increased over a number of set points up to the maximum flow achievable through the 300 l/m rotameter. The regulator was unconnected downstream, venting to atmosphere to provide maximum flow.

3.12.1 Mesura A6N regulator

Figure 89: Mesura A6N regulator

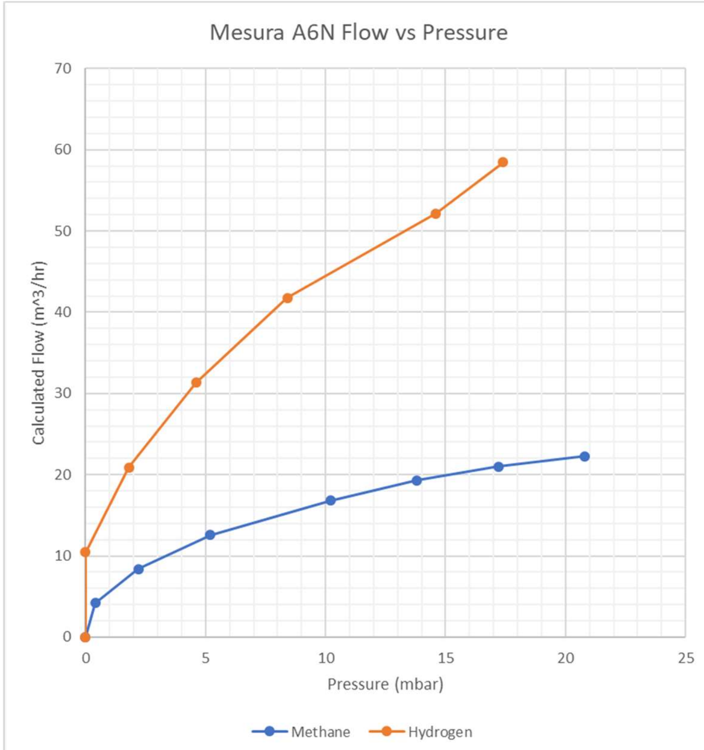


Figure 90: Mesura A6N Flow vs Pressure Graph

It is possible the highest point of the hydrogen curve is anomalous. This data point is near the extremity of the rotameter and therefore could be inaccurate especially as the flow conversion rates have been extrapolated from much lower flow figures. At 17 mbar the approximate ratio of hydrogen to methane is 2.71. This ratio is indicative of turbulent flow.

3.12.2 Sperryn G940 regulator

Figure 91: Sperryn G940 regulator

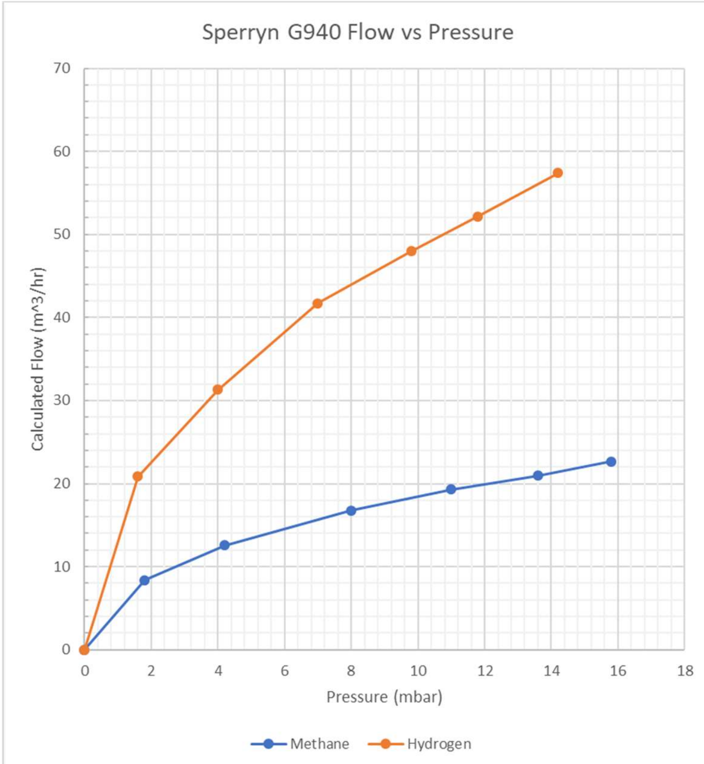


Figure 92: Sperryn G940 Flow vs Pressure

The ratio between hydrogen and methane at 14 mbar was approximately 2.71. This ratio is indicative of turbulent flow.

3.12.3 Jeavons J42 regulator

Figure 93: Jeavons J42 regulator

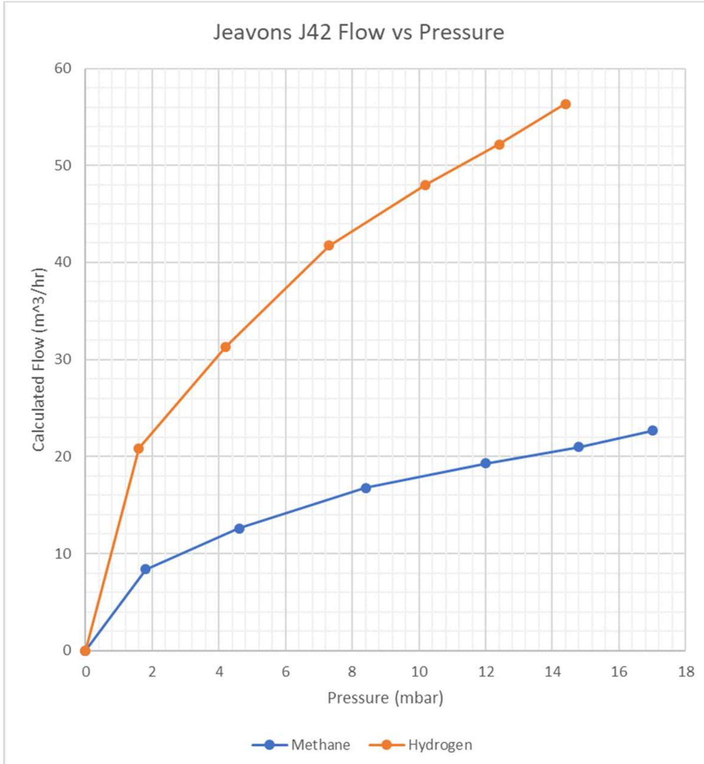


Figure 94: Jeavons J42 Flow vs Pressure

The ratio of hydrogen to methane at 14 mbar was approximately 2.62. This ratio is indicative of turbulent flow.

3.12.4 Sperryn G940 and meter

The Sperryn G940 regulator permitted greatest flow. This was therefore selected for testing in series with a Schlumberger U6 gas meter.

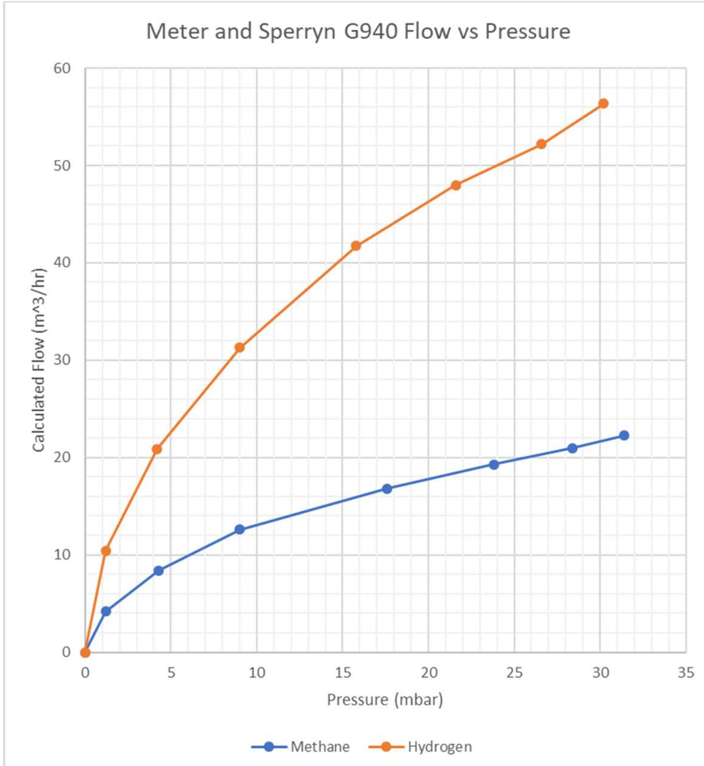


Figure 95: Meter and Sperryn G940 Flow vs Pressure

The ratio of hydrogen to methane at 30 mbar was approximately 2.55. This ratio is indicative of transition / turbulent flow.

Once the meter was in place, the back pressure in the system is greater than 20 mbar for the upper ranges of the test flows. This test therefore gives a likely upper limit to the volume of gas which could be released into a domestic situation in an extreme case. This would require complete full bore venting of the system downstream of the regulator and meter coupled with a stiff 20 mbar supply to the regulator.

3.13 J11: Other

In addition to the tests carried out on domestic fixtures and fittings, Steer was able to carry out tests on representative 6 inch cast iron pipe sections being used for a parallel project. Steer have the permission to include a brief overview of those findings here.

Two cast iron joint types commonly found in the UK gas network have been tested. Lead-yarn joints based on BS1211 and mechanical joints based on Stanlock type fixtures. Test fixtures have been designed to replicate these joints and enable detailed analysis of the joint sealing performance when subjected to movement expected in service. These fixtures are being used to test new sealants against a range of tests specified in relevant GIS standards.

Design drawings are shown in Figure 96; the left-hand image is a lead-yarn joint type and the right-hand image is a mechanical joint type. Figure 97 shows one of the lead-yarn test fixtures under test with hydraulics and end caps. The end caps allow the system to be pressured up and the hydraulics are used to manipulate the joint whilst leakage measurements are made.

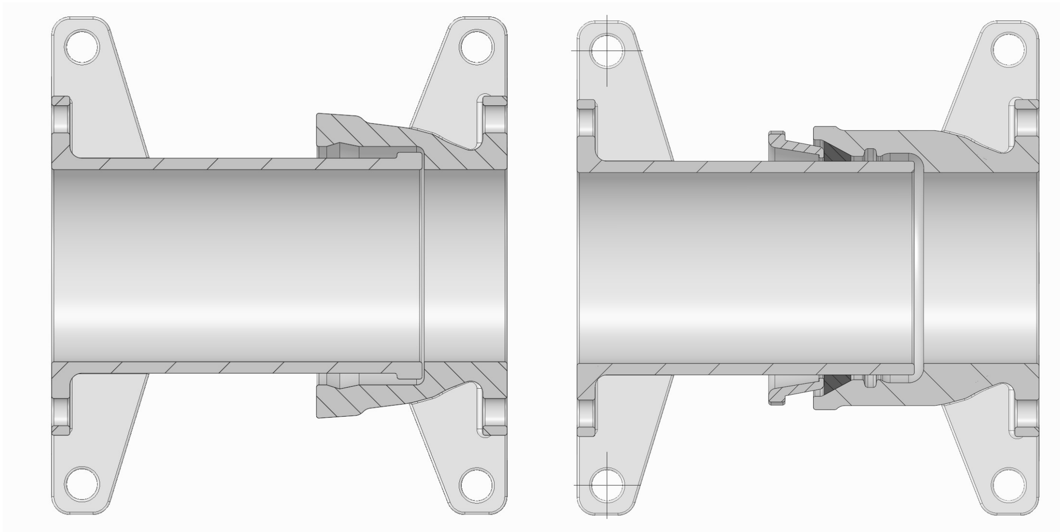


Figure 96: CAD files showing lead-yarn and mechanical test fixtures

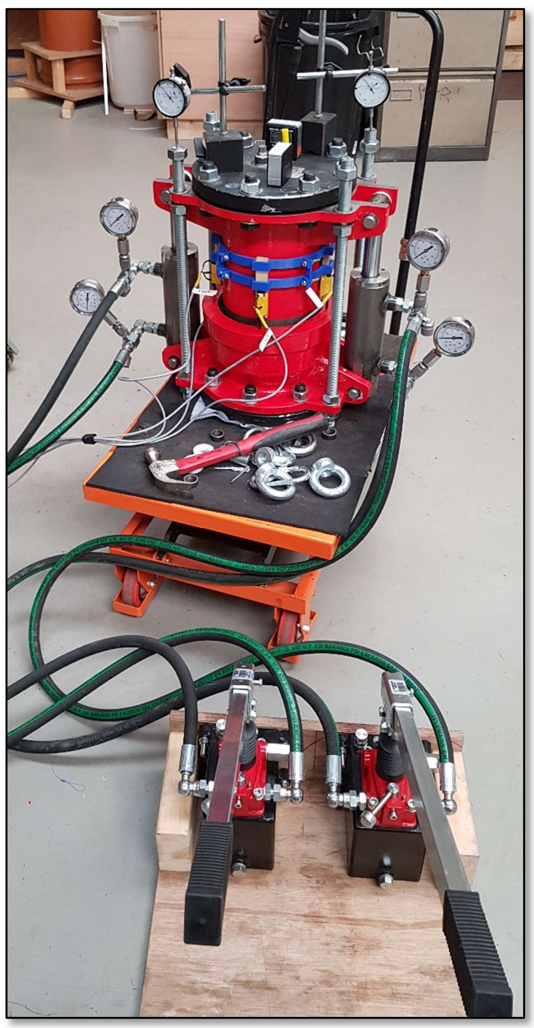


Figure 97: Complete lead-yarn test fixture with end caps and hydraulics

Leak flow tests have been carried out on the lead-yarn joints and on mechanical joints whilst subjected to the type of movement which would be expected from thermal expansion and contraction or from ground movement. Examples of leakage caused by movement are shown in Figure 98. The setup was not optimised for these tests as time was limited and these counted as additional tests for both the associated projects. However, the indication is that these leak types result in laminar flow leakage. These tests focused on low pressure network pressures. It is worth repeating these tests for medium pressure networks to assess under what conditions the leak type would transition to fully turbulent flow regimes.

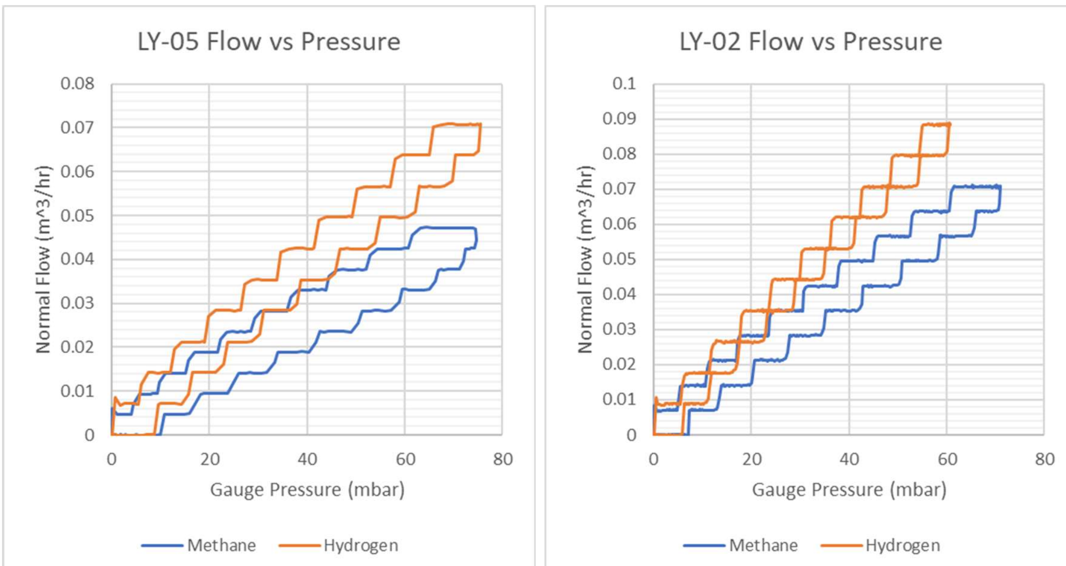


Figure 98: Leak rate measurements on 6 inch lead-yarn joints

The test fixtures have been used to set up known leak sizes, as per GIS standards and then are being used to assess the efficacy of PhotonFix™ a new sealant developed by Steer which is currently being accredited for the UK gas network.

As part of this work, after the leaks were set up using nitrogen. The leak rates were then measured in hydrogen and methane for one of each joint type, lead-yarn and mechanical at test pressures of 75 mbar and 2 bar.

Joint Type	Gas Type	Flow rate (l/hr)	
		75 mbar	2 bar
Lead-yarn LY-06	Methane	41.2	540
	Hydrogen	71.2	1209
	Ratio	1.73	2.24
Mechanical M5	Methane	35.2	752
	Hydrogen	66.1	2005
	Ratio	1.88	2.67

Table 18: Leak setup rates for PhotonFix™ leak seal testing

After the joints have been sealed with PhotonFix™ and allowed to cure a further pressure test has been carried out resulting in the following lock off tests.

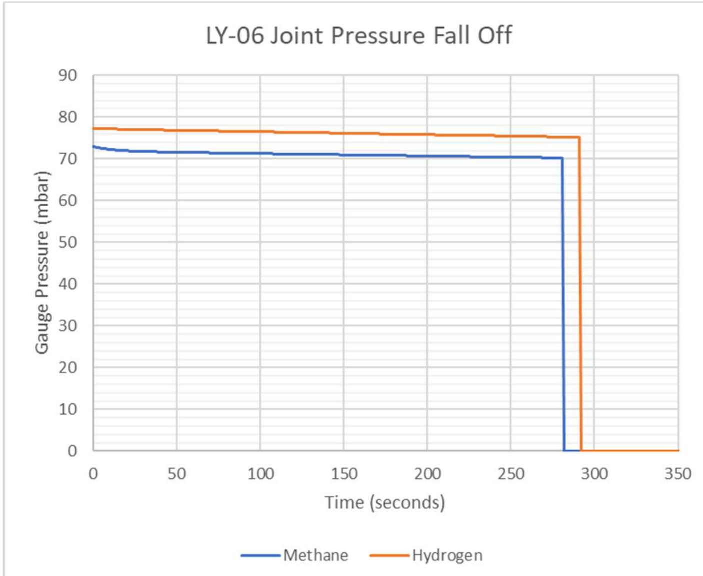


Figure 99: Leak off test of PhotonFix™ sealed joint

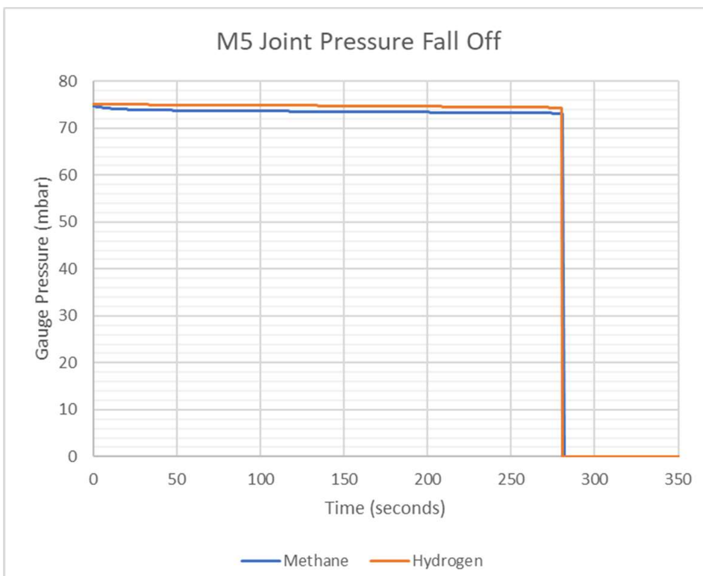


Figure 100: Leak off test of PhotonFix™ sealed mechanical joint

The formal accreditation test programme is just commencing so further opportunities will be taken to test in methane and hydrogen where possible. This can be added to the Hy4Heat data in due course.

4 Summary and discussion

A range of tests have been carried out investigating a large number of leakage and flow scenarios. The final list of the leakage tests has been collated into a single summary spreadsheet and sorted by methane leak flow. The output of this has then been presented in a single graph, see Figure 101, with logarithmic scales. This gives an indication of the wide range of leakage types. The x axis of the graph gives a nominal test number of the sorted tests. The x axis has been set to cross the y-axis at the $1x10^{-3}$ m^3/hr value. This is the calculated leak that would just pass a 2 minute leak-off test in a 0.035 m^3 domestic installation.

The sorting uses the methane value as the base for each test hence the methane data forms a contiguous set from small to large values. The change in leakage for hydrogen is then displayed by the deviation of the orange hydrogen data from the blue methane data. The values above the x axis have hydrogen greater than methane by an amount bounded by the 1.2 to 2.8 ratio discussed in the results.

To the left of the graph, below the x axis we start to see the more spurious data where the tests involved moveable fittings. A particular point of note is test point 54 on the graph which has a hydrogen value significantly larger than methane. This was the V06 plug valve which had the plug loose and was free to move between tests. It is very likely that the physical leak was different between the two test gases.

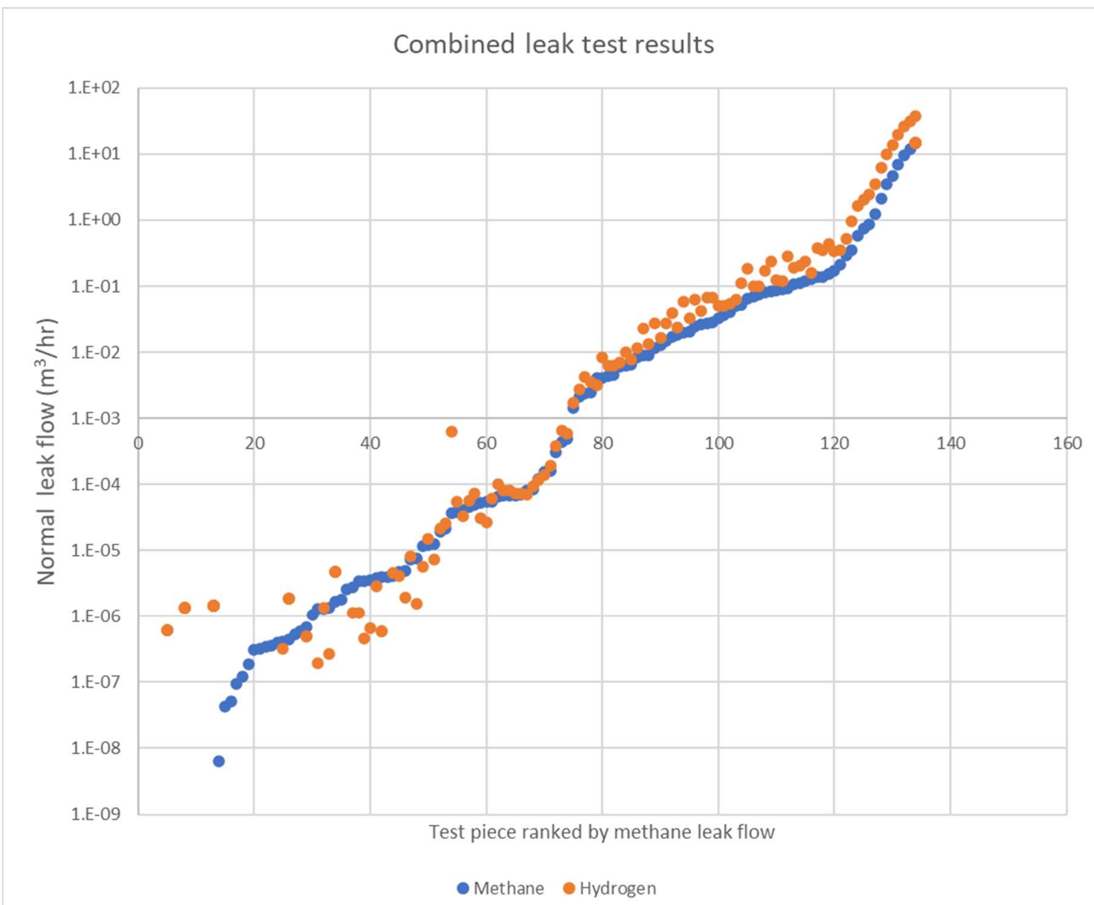


Figure 101: Combined leak test results

Further to the left of the graph we get to the very low levels of leakage where measurement limitations begin to become apparent. Areas where leakage levels are below $1x10^{-5}$ m^3/hr are two orders of magnitude lower than would be picked up on a domestic leak-off test.

A number of clear conclusions from the main body of work can be drawn and these are presented in terms of leakage, gas flow and leak types.

A summary of the key observations on leakage are:

- A non-leaking fitting in methane will be non-leaking in hydrogen.
- A leak in methane will result in a leak in hydrogen.
- The majority of tests resulted in leak rates between 1.2 and 2.8 times greater in hydrogen than in methane. Tests not holding to this were those where it was likely that movement had occurred during the purge between gases leading to a physical change in the leak.

A summary of the key observations on gas flow are:

- Laminar, transition and turbulent flow regimes have been observed in both gases.
- Laminar flow is characterised by a linear relationship between flow and pressure and a leak flow ratio of 1:1.2 between methane and hydrogen.
- Turbulent flow is characterised by a square root relationship between flow and pressure and a leak flow ratio of 1:2.8 between methane and hydrogen.
- For a given leak flow, transition from laminar to turbulent flow occurs at a lower pressure for methane than for hydrogen. Reynolds number is 6.43 times greater for methane than for hydrogen.

A summary of the key observations on leak types are:

- Damage and other large defects leading to holes showed the largest leakage in the investigation. These leaked with a turbulent flow regime and a leak flow ratio of 1:2.8 between methane and hydrogen.
- The majority of leaking fittings resulted in the lower flow leaks in the investigation. These tended to leak with a laminar flow regime and a leak flow ratio of 1:1.2 between methane and hydrogen.
- Fitting leaks leading to transition flow were the worst-case scenarios, such as a compression fitting with no olive or a steel thread, only hand tight with no jointing compound. These are occurrences that are possible but very unlikely.

During the course of the project we have been looking for a system that leaks in hydrogen but not in methane. We have been unable to find such a system, however this is not really unexpected if we compare the molecular kinetic diameter[17] of the two gases with the leaks. The molecular diameter for methane is 3.988 Angstroms and for hydrogen is 2.25 Angstroms. To devise a system which allows the passage of methane but not hydrogen would require a molecular sieve which could effectively filter out

[17] https://en.wikipedia.org/wiki/Kinetic_diameter

hydrogen from a mix of hydrogen and methane. The leaks under investigation in this work are all significantly larger in sizer than the two gas molecules.

As part of the study into fitting leaks, a range of different fitting types including different brands of fittings have been tested. The most common mixing of fitting components were olives and nuts on compression fittings. It was not possible to discern a particularly bad combination. All of the olives were compatible with the fittings used and only leaked when subjected to damage. Incorrect application of fittings was the most effective method of creating leaks followed by damage to fittings. Mixing olives from different manufacturers may have resulted in a less robust joint but did not appear to compromise the seal. Multiple opening and closing of compression joints did result in eventual leakage especially as this led to overtightening of the joints.

It has already been noted that fitting leaks tended to be laminar, this led to a leak flow rate 1.2 times greater in hydrogen than methane. Applying this to a standard pressure fall-off test, such as that currently employed for testing a gas installation, will result in a more stringent test for a system filled with hydrogen system than one filled with methane. If the current pressure test is adopted for hydrogen systems then the test will be more challenging to pass than for methane. This will not be prohibitively more difficult to pass but does result in a more stringent test.

This study has presented the findings from the comparative leak study for a range of fixtures and fittings when containing hydrogen and methane. This will contribute to an assessment of the relative safety of the two gases. Whilst the study does not assess the likelihood of different defect types occurring, accidental damage leading to holes will lead to turbulent flow with a 2.8:1 hydrogen to methane ratio. These leaks are most likely to be due to an action such as drilling holes or hammering in nails. Smaller fitting leaks due to poor installation or movement of pipes are much more likely to result in lower flow leaks with smaller hydrogen to methane ratios closer to 1.2:1.

The development of the theory presented in chapter 2 has been borne out by the test results. The measured leak ratio of methane to hydrogen matches the theoretical ratios for laminar and turbulent flow regimes. The flow in hydrogen tended to produce lower frictional losses in all systems tested and the flow was quieter. This was particularly noticeable when purging between gases during the 2 bar leak set up tests in the 6 inch joints. Methane flow was turbulent and gave an audible hiss which stopped as the hydrogen reached the leaking joint. This may warrant further investigation for safety considerations during management of high-volume gas escapes.

5 Appendix List

Appendix 1: J05 - Holes in pipes

- Holes drilled in 15 mm copper tube. 0.3 mm up to 10 mm
- Small diameter holes drilled in 32 mm MPDE pipe. 0.3 mm up to 1.0 mm

Appendix 2: J06 - Joints and Fittings - Cold crimp fittings (press fit)

Appendix 3: J06 - Joints and Fittings - Compression Fittings

Appendix 4: J06 - Joints and Fittings - Screwed and Threaded

Appendix 5: J06 - Joints and Fittings - Solder Joints

Appendix 6: J06 - Joints and Fittings - Miscellaneous Fittings

- Sweated joints
- Cooker hose to bayonet fitting
- MDPE compression fittings
- MDPE pipe squeezed off
- Corrugated semi-flexible steel pipe

Appendix 7: J07 - Valves

- Valve 01 - Gas Ball Valve with Test Port
- Valve 02 - Domestic Meter Control Valve (ECV
- Valve 03 - Disc on Seat Valve
- Valve 04 - Domestic Meter Control Valve (ECV)
- Valve 05 - Disc on Seat Cooker Bayonet
- Valve 06 - Self Lubricating Taper Plug Valve
- Valve 07 - Meter Control Cock - Taper Plug (ECV)
- Valve 08 - Conventional Ball Valve
- Valve 09 - Conventional Ball Valve Melted Seats Open
- Valve 10 - Conventional Ball Valve Melted Seats Closed

Appendix 8: J08 - Damaged Pipe

Appendix 9: J09 - Flow Investigations

Appendix 10: J10 - Regulators

6 Glossary and Abbreviations

BSP	British Standard Pipe - standard for pipe thread types
BSPT	BSP tapered thread
BSPP	BSP parallel thread
BSPF	BSP female thread
BSPM	BSP male thread
CH_4	Methane
CSV	Comma separated values - file format used for raw data
H_2	Hydrogen
MDPE:	Medium density polyethylene pipe
NPT:	National Pipe Thread - North American standard for pipe thread types
PE:	Polyethylene pipe
Choked flow	Fluid dynamic phenomenon limiting the flow of a fluid through a restriction. See section 2.2.3
Emergency control valve (ECV):	Valve used to isolate gas supply in an emergency
Laminar flow:	Flow is dominated by friction. Reynolds number lower than 2100. See section 2.2
Turbulent flow:	Flow is determined by momentum. Reynolds number greater than 4000. See section 2.2
Transition flow:	Flow is between laminar and turbulent. Reynolds number between 2100 and 4000. See section 2.2
Reynolds number:	Ratio of inertial forces (momentum) to viscous forces (friction) in fluid flow within a pipe