AN INVESTIGATION INTO THE CHANGE IN LEAKAGE WHEN SWITCHING FROM NATURAL GAS TO HYDROGEN IN THE UK GAS DISTRIBUTION NETWORK

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ABSTRACT

The H21 National Innovation Competition project is examining the feasibility of repurposing the existing GB natural gas distribution network for transporting 100% hydrogen. It aims to undertake an experimental testing programme that will provide the necessary data to quantify the comparative risk between a 100% hydrogen network and the natural gas network. The first phase of the project focuses on leakage testing of a strategic set of assets that have been removed from service, which provide a representative sample of assets across the network. This paper presents the work undertaken for Phase 1A (background testing), where HSE and industry partners have tested a range of natural gas pipework assets of varying size, material, age and pressure-rating in a new bespoke open-air testing facility at the HSE Science and Research Centre, Buxton. The assets have been pressurised with hydrogen and then methane, and the leakage rate from the assets measured in both cases. The main finding of this work is that the assets tested which leak hydrogen also leak methane. None of the assets were found to leak hydrogen, but not methane. In addition, repair techniques that were effective at stopping methane leaks were also effective at stopping hydrogen leaks. The data from the experiments have been interpreted to obtain a range of leakage ratios between the two gases for releases under different conditions. This has been compared to the predicted ratio of hydrogen to methane volumetric leak rates for laminar (1.2:1) and turbulent (2.9:1) releases and good agreement was observed.

1.0 INTRODUCTION

The aim of the H21 National Innovation Competition (NIC) project is to undertake an experimental testing programme that will provide the necessary data to quantify the comparative risk between a 100% hydrogen network and the natural gas network[1]. The project focuses on assets that will be in service in 2032, when it is estimated that around 90% of the gas distribution network will be polyethylene (PE). However, there will still be some retained iron and steel mains in service at that time. Furthermore, there will be a range of PE pipe types of differing strengths, ages, transition fittings (between PE, iron, steel, different diameters etc.), services, service connections, buried valves, repairs, service governors and district governors. The H21 NIC project aims to provide the quantitative safety-based evidence across a strategically-selected range of these assets through a comprehensive three-phase testing programme. The first two Phases 1A and 1B were completed in 2020 and the third Phase 2 is currently ongoing. The scope of work in the three phases includes:

Phase 1A – Background testing: A strategic set of tests were undertaken on a range of assets and pipe configurations that are representative of the GB gas distribution network. The assets were removed from the network and transported to the HSE Science and Research Centre at Buxton where they underwent controlled testing with methane and 100% hydrogen.

Phase 1B – Consequence testing: A range of tests were undertaken to help quantify the risk associated with background leakage as determined in Phase 1A, failure leakage (for example mains fracture, third-party damage) and operational response, i.e. response by the emergency supplier and customer to a leak at a property. The aim was to establish the consequences of hydrogen leaks for various scenarios with different potential sources of ignition, and to compare these consequences to those for natural gas. These tests were undertaken at the DNV site at Spadeadam.

[1] https://www.ofgem.gov.uk/publications-and-updates/gas-nic-submission-northern-gas-networks-h21, accessed 26 February 2018.

Phase 2 – Field trials: A series of tests are currently being planned on in-situ mains, the purpose of which is to corroborate the results gathered in Phases 1A and 1B. It is important to note these tests will not be undertaken downstream of the meter and will not affect customers' gas supply. The work involves extensive liaison with local authorities and a comprehensive customer engagement plan.

This paper discusses the findings from the H21 Phase 1A experiments, and does not go into Phase 1B and Phase 2. The Phase 1A tests involved measurements of the leakage rates of gas network assets at a range of pressures with both hydrogen and methane to assess whether certain assets leak hydrogen, but not methane, and to quantify the difference in leakage rates of the two gases. Methane was used in the experiments to represent natural gas. The tests were all conducted above ground, in the open air, and soap tests and gas detection equipment were used to identify leak sources.

2.0 TEST PLAN

The scope of the Phase 1A experiments encompassed Low Pressure (LP, 19–75 mbarg), Medium Pressure (MP, 75–2000 mbarg) and Intermediate Pressure (IP, 2000–7000 mbarg) assets from Tiers 1 (≤ 8"), 2 (9" – 17") and 3 (≥ 18") in the UK natural gas network. It was unclear before undertaking the tests whether the leakage behaviour of one material (e.g. cast iron pipe) could be extrapolated to the other types of material (e.g. spun and ductile iron). The project therefore included tests on the following materials: PE, cast iron, spun iron, ductile iron and steel. A matrix was developed to help guide the selection of assets for testing, which comprised 270 assets covering different combinations of pressure rating, size tier, material of construction and fitting type.

The project focused on retrieving assets from the existing network and assessing any existing leaks, rather than engineering holes in new assets. This approach was taken so that the leaks were representative of those that might occur on the network. None of the IP assets retrieved for testing were found to be leak, and so in this one instance, it was deemed prudent to engineer a leak to see how it compared to those found on LP and MP assets. This was done by drilling a 0.7 mm diameter hole in a retrieved IP asset (Asset 12345).

The rate at which gas leaks from assets in the network is controlled by four main factors: gas properties, pressure, leak path characteristics and the effect of the back fill (for buried assets). The Phase 1A experiments examined the first three factors but did not examine the effect of the back fill, since all of the assets were tested above ground. Tests on buried assets were undertaken in Phase 1B and further tests are planned in Phase 2 to assess the resistance to penetration of hydrogen and natural gas through the ground.

To undertake the leakage tests in Phase 1A, a purpose-built test facility was constructed, as shown in Figure 1. The method of measuring leakage on the H21 test rig was to measure the flow required to maintain the asset at a constant pressure. When a leak was detected by the measurement equipment, a hydrogen detector and leak detection fluid were utilized to check that the asset was not leaking from fittings which were not associated with the asset (i.e. the end caps and emid plugs installed following asset extraction). If a leak was in the measurable range of the test equipment, i.e. 100 - 20,000 cm^3/min, the leakage rate was recorded at various pressures for both hydrogen and methane. This then allowed for the leakage flow rates for hydrogen and methane to be compared and a ratio obtained.

Figure 1 – Aerial view of the test facility (right) and Asset Ready for Testing (left)

4.0 PREDICTIONS

Prior to conducting the tests, the hydrogen to methane leakage ratio was predicted by first considering the different flow regimes in which the leak could occur. In order of decreasing pressure these are:

- Turbulent, Sonic flow (compressible)
- Turbulent Subsonic flow (compressible)
- Turbulent flow (incompressible)
- Laminar flow
- Diffusion (permeation)

By analysing equations for flow through a hole, ratios for the flow rate of hydrogen compared to methane can be obtained for each of these flow regimes. As this project was looking at leaks greater than 100 cm^3/min, the diffusion flow regime was not analysed. The ratios for the other four flow regimes are discussed below.

4.1 Sonic Flow

The sonic (choked) flow regime is a limiting condition that is reached when the pressure is above a certain critical pressure, P_c. The velocity of the gas at the orifice in this case is sonic (i.e. a Mach number of one). If the pressure is increased still higher, above P_c, the velocity of gas remains bounded by the speed of sound in the gas at the given pressure and temperature, and the mass flow rate increases due to an increase in the density of the gas (which is compressed). The critical pressure, P_c, is 0.84 barg for methane and 0.90 barg for hydrogen.

An equation for the mass flow rate of gas ($\dot{m}$) from a choked release is presented in BS EN 60079-10-1. The ratio of the volumetric flow rate of hydrogen to methane $\left(\dot{V}_{H2}/\dot{V}_{CH4}\right)$ for choked releases is found from the ratio of the mass flow rate of hydrogen and methane multiplied by the molecular weights, as follows:

$$\frac{\dot{V}_{H2}}{\dot{V}_{CH4}} = \frac{\dot{m}_{H2}}{\dot{m}_{CH4}}\frac{M_{CH4}}{M_{H2}} = 0.36\frac{16.043}{2.016} = 2.9 \qquad (1)$$

In the above equation, the gas properties for hydrogen and methane and been substituted into the equations and it has been assumed that the hole size and pressure is the same for the two gases. The results show that the volumetric flow rate of hydrogen is **2.9 times** the equivalent volumetric flow rate of methane. In terms of mass flow rates, the hydrogen mass flow rate is approximately one third of the methane mass flow rate.

4.2 Subsonic flow

A similar approach can be taken to that described above using the subsonic mass flow rate equations contained within BS EN 60079-10-1. These equations are applicable at gas pressures below the critical pressure of around 0.9 barg. The ratio of the hydrogen to methane release rates is approximately **2.8 – 2.9** in terms of volume flux and 0.35 – 0.36 in terms of mass flux.

4.3 Turbulent leaks

Swain and Swain (1992) analysed the ratio of hydrogen to methane leak rates for turbulent, laminar and diffusion-controlled flows. In their analysis, they neglected the effects due to compressibility of the gas (which are accounted for in the above analysis of sonic and subsonic flow). Their assumption is appropriate for the low pressure gas distribution network (i.e. pressures up to 75 mbarg).

For the case of turbulent incompressible flow, Swain and Swain (1992) modelled the volumetric flow rate for gas leaks using Darcy's equation. Using this equation, the ratio of hydrogen to methane volumetric flow rates is equal to the inverse of the square-root of the gas densities. Assuming that hydrogen and methane behave as ideal gases, the ratio of gas densities can be expressed in terms of the molecular masses as follows:

$$\frac{\dot{V}_{H2}}{\dot{V}_{CH4}} = \frac{\sqrt{\rho_{CH4}}}{\sqrt{\rho_{H2}}} = \frac{\sqrt{M_{CH4}}}{\sqrt{M_{H2}}} = \frac{\sqrt{16.043}}{\sqrt{2.016}} = \mathbf{2.8} \tag{2}$$

4.4 Laminar leaks

Laminar flow occurs at low speeds through small holes, producing smooth flow paths and little or no mixing within the flow. Swain and Swain (1992) showed that the volumetric flow rate for a laminar flow is proportional to the pressure inside the pipe, and inversely proportional to the dynamic viscosity of the gas, μ. For the same supply pressure and hole size, the relative volumetric leak rate of hydrogen as compared to methane is given by the ratio of the viscosities of the two gases:

$$\frac{\dot{V}_{H2}}{\dot{V}_{NG}} = \frac{\mu_{NG}}{\mu_{H2}} = \frac{1.1 \times 10^{-5}}{8.7 \times 10^{-6}} = \mathbf{1.23} \tag{3}$$

4.5 Summary

The results presented above are summarised in Table 1, which shows that choked, subsonic and turbulent leaks behave very similarly in terms of the change in behaviour of hydrogen relative to methane. In all three of these cases, the hydrogen mass flow rate is approximately a third of the methane flow rate for the same leak geometry and pressure. Methane is eight times denser than hydrogen, so in volumetric terms, the hydrogen flow rate is approximately three times greater than methane.

Laminar leaks behave differently, with less hydrogen being released (relative to methane) than for the turbulent, subsonic or choked releases. In the laminar case, the hydrogen mass flow is around six times smaller than the mass flow rate of methane and the volumetric flow rate is around 20% higher for hydrogen than methane.

Table 1 Ratio of hydrogen to methane flow rates for the same leak geometry and pressure

Flow Regime	**Ratio of volumetric flow rates**	**Ratio of mass flow rates**	**Equation Analysed**
Turbulent Sonic Flow (compressible)*	2.9	0.36	BS EN 60079-10-1, Equation B.4
Turbulent Subsonic Flow (compressible)†	2.8 - 2.9	0.35 - 0.36	BS EN 60079-10-1, Equation B.3
Turbulent (incompressible)‡	2.8	0.35	Swain & Swain analysis of Darcy's Equation assuming a constant friction factor
Laminar‡	1.2	0.16	Swain & Swain analysis of Darcy's Equation assuming a friction factor which varies with velocity.

* Applies for leak pressures above the critical pressure, i.e. $P > 0.9$ barg
† Applies for leak pressures below the critical pressure, i.e. $P < 0.9$ barg
‡ Applies to leak pressures up to around 75 mbarg

The calculations presented above all assume that the pressure is maintained at a constant value over time. If there is a large leak in a pipeline, the pressure at the leak point will decay over time as the pipeline unpacks, which could potentially cause a leak to transition from choked to subsonic, turbulent (incompressible) and finally to laminar.

The above analysis shows that the ratio of the hydrogen to methane volumetric flow rates should lie between the lower and upper bounding values of 1.2 and 2.9. The effect of these leak rates on the size of flammable clouds has been studied by Gant *et al*. (2021).

5.0 RESULTS

For the H21 Phase 1A testing, 239 assets were recovered to the Buxton facility. Of these, 215 assets were suitable for testing on the experimental rig and, of these, 174 of these assets did not leak (or leaked less than 100 cm^3/min). Of the remaining 41 assets that leaked, all of them leaked on both hydrogen and methane and 19 of those 41 assets provided suitable data to allow the ratio of hydrogen to methane leak rates to be compared. The other 22 assets which leaked were not suitable for calculating this ratio due to the leaks not being within the measurable range of the rig (100-20,000 cm^3/min) or the leaks not being stable.

When the assets were tested, flow rates were measured at each set pressure for hydrogen and methane. To show how the final ratios were determined, the data collation for Asset 97 is presented below. The measured flow over time in Figure 2 shows that the leakage rate was steady for the duration of the test.

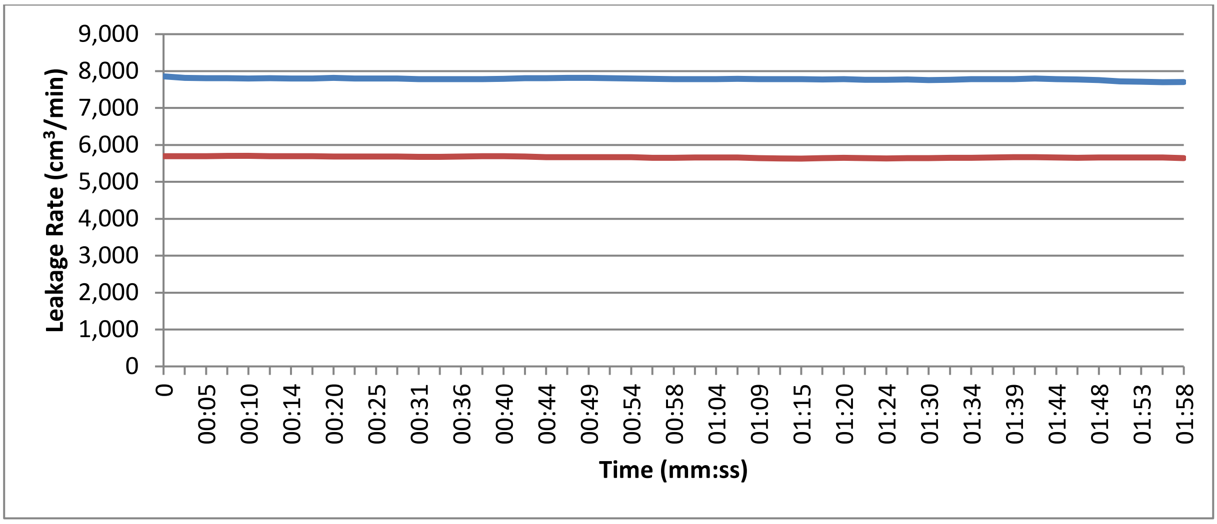

Figure 2 – Asset 97 measured leakage rates over time on hydrogen (blue line) and methane (red line).

The set pressures in the LP range were 20, 30, 45, 60 and 75 mbarg. For each set pressure, an average flow rate for the two minute test period was obtained for hydrogen and methane (Figure 3). It is noted that the 75 mbarg hydrogen recording for Asset 97 is above the calibrated range of the flow measurement equipment. The ratio of the hydrogen to methane volumetric leak rates showed a general trend towards a higher ratio at higher pressures (see Figure 4).

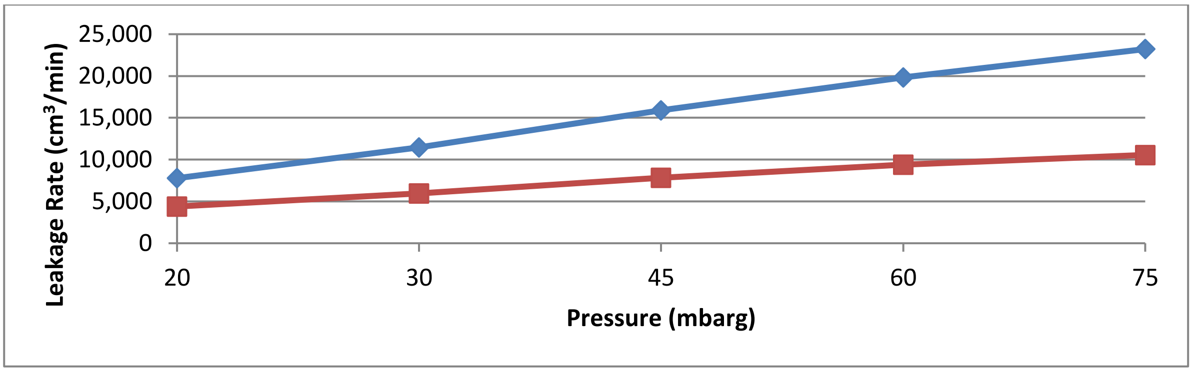

Figure 3 – Asset 97 Average leakage rates for hydrogen (blue line) and methane (red line).

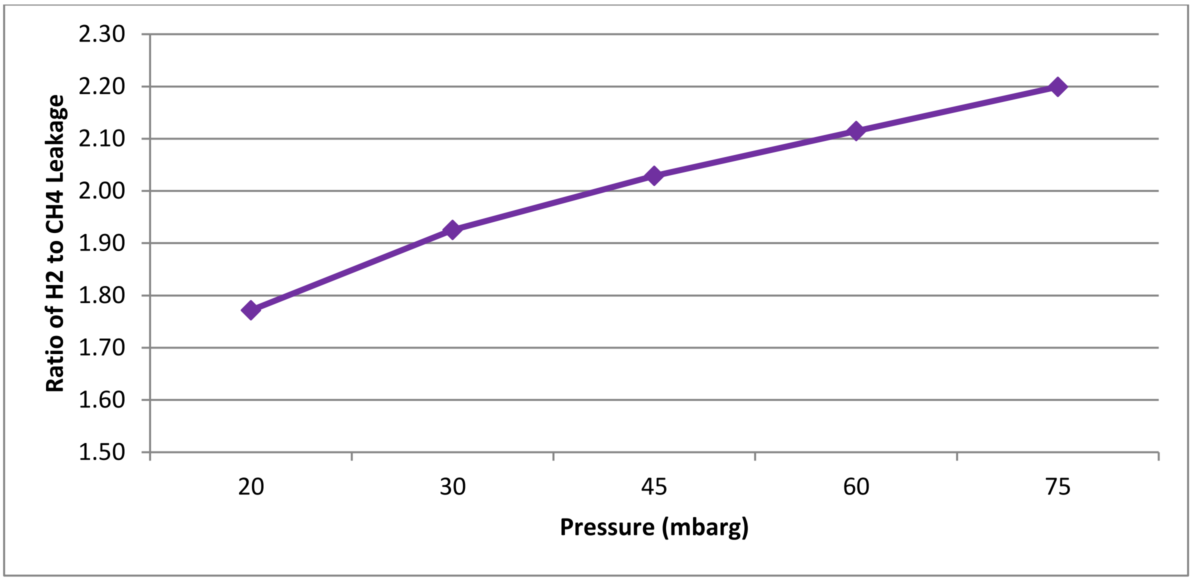

Figure 4 – Asset 97 Ratios of hydrogen to methane volumetric leakage rates.

Measurements taken for the 19 suitable assets are compared in Figure 5 for LP assets and Figure 6 for MP and IP Assets.

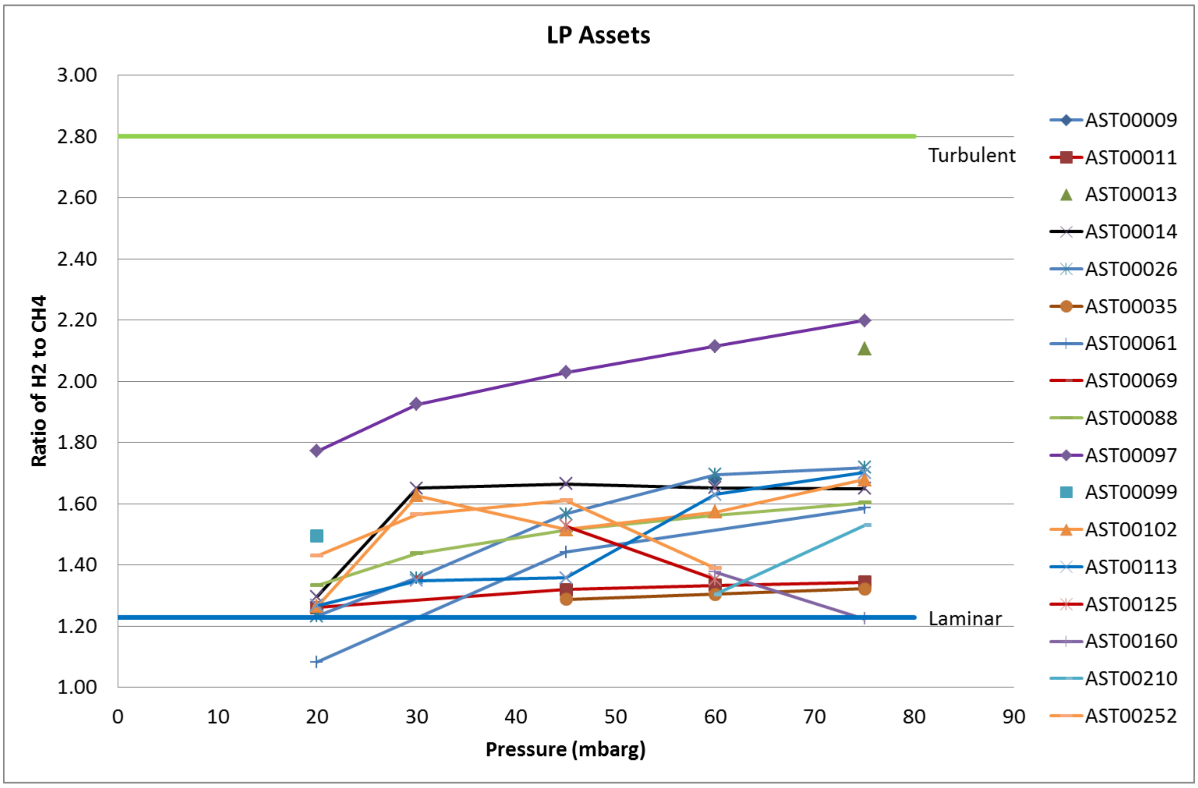

Figure 5 – Results of the measured ratio of volumetric flow rate of hydrogen and methane for LP assets

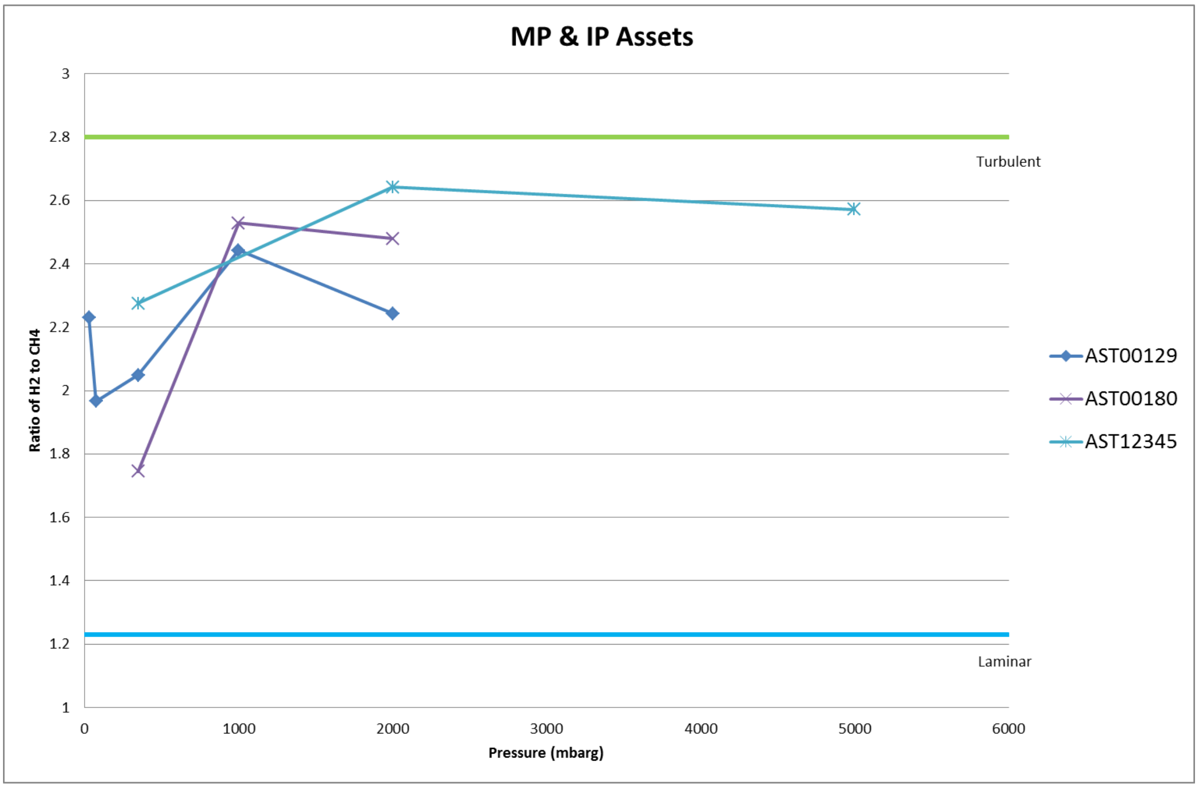

Figure 6 – Results of the measured ratio of volumetric flow rate of hydrogen and methane for MP and IP assets

6.0 RESULTS ANALYSIS

The results showed that the majority of the recorded hydrogen to methane volumetric leak ratios were between 1.2 and 2.9. The one outlier was a 20 mbar measurement with Asset 61, which was a LP 4-inch cast-iron main with a hook-bolt joint. Upon further analysis of the Asset 61 measurements at 20 mbar, it was found that the flows were not steady over time and this could have been a contributing factor to the reduced ratio.

Results from the asset tests were grouped together in terms of common materials, diameters, ages etc. to see if there were any clear trends in leakage rates. It was difficult to draw definitive conclusions, due to the limited number of assets that were found to leak. Asset diameter and age did not appear to have a strong effect on leakage ratio. In terms of asset material, none of the PE assets leaked; cast, ductile and spun iron leaked to a similar degree (around a quarter of all iron assets tested leaked) and the proportion of leaking steel assets was slightly less (14%). Within the limited sample set, four types of joints appeared to be responsible for most of the leaking joints. These were: screwed, lead yarn, bolted gland and hook bolts. Other types of joints were less likely to leak (flanged, welded and mechanical). None of the PE joints leaked (butt welded, hot iron or electrofusion). Two of the valves leaked, both from the valve stem. One of these also had a let-by leak. It was not possible to quantify the ratio of hydrogen to methane leak rate for these valves, since it depended on the position of the spindle.

Figure 5 shows that there was a general trend for the ratio of hydrogen to methane leak rates to increase with pressure for the LP assets. A similar trend was present in the MP and IP assets (Figure 6), although there were only three MP/IP assets tested, so the data was limited. Further analysis of this trend was undertaken using a methodology developed by Ann Halford (DNV), who had developed the methodology to analyse the gas leakage data collected in the H21 Phase 1B experiments. The methodology assumes that the total pressure drop through the leak is composed of two parts, one from entrance/exit effects and the other from frictional losses through the leak pathway. The entrance and exit losses are assumed to be inertial losses, meaning that they depend on the momentum of the fluid and therefore the pressure drop is proportional to the volumetric flow rate squared:

$$\Delta P_{entrance\ and\ exit} = a\,\dot{V}^2 \tag{1}$$

where a is a constant that depends on the gas properties and shape of the leak inlet and outlet. This inertial loss has the same relationship between pressure and velocity as the "turbulent" flow condition analysed earlier in Section 4.

Once the flow has entered the leak pathway, frictional losses are likely to be dominant. For the relatively small leaks assessed in the Phase 1A tests (with flow rates up to 20,000 cm^3/min) the flow is assumed to be in the laminar regime, in which case the pressure drop (ΔP) through the leak is proportional to the volumetric flow rate ($\dot{V}$):

$$\Delta P_{leak} = b\,\dot{V} \tag{2}$$

where b is a constant that depends upon the properties of the gas and the geometry of the leakage path and its roughness.

The contributions from the frictional loss and the inlet/outlet losses are summed to give the following expression for the total pressure drop through the leakage path:

$$\Delta P_{total} = a\,\dot{V}^2 + b\,\dot{V} \tag{3}$$

For a given gas, the values of constants a and b can be found from measurements of the flow rate at two or more different pressures. An example is presented below using the methane data for Asset 14 in the Phase 1A experiments. Flow rates were measured at five pressures from 16 mbar to 74 mbar, which are plotted in Figure 7.

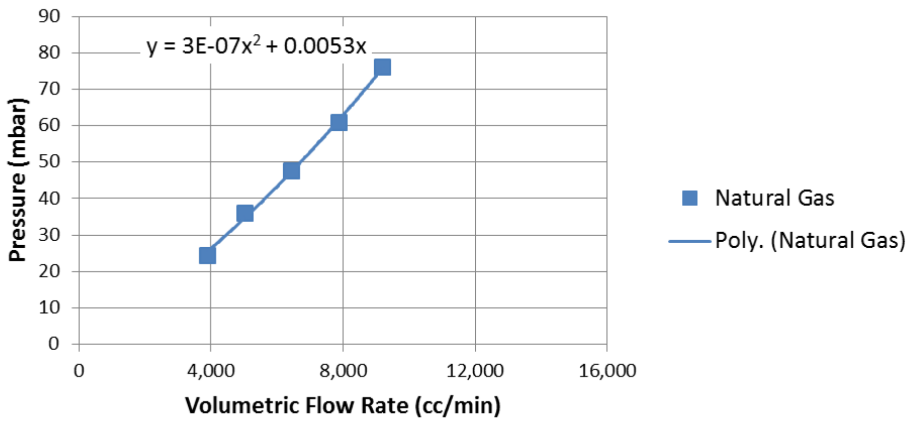

Figure 7 – Measured methane volumetric flow rates at five pressures for Asset 14. The line shown is a quadratic curve fit to the data points.

A curve of best fit is shown passing through the data, which has been calculated using Excel's in-built functionality for a polynomial "trendline" of order two. The constants a and b calculated by Excel in this case, are: $a_{CH4} = 3 \times 10^{-7}$ and $b_{CH4} = 0.0053$. In other words, the relationship between pressure and flow rate for methane in this case is:

$$\Delta P = 0.0000003\,\dot{V}_{CH4}^2 + 0.0053\,\dot{V}_{CH4} \tag{4}$$

The analysis presented earlier showed that for laminar leaks, the hydrogen volumetric flow rate is 1.23 times higher than the methane flow rate, for the same hole shape/size and pressure. For turbulent (incompressible) leaks, the hydrogen volumetric flow rate is 2.8 times higher than the methane value.

This means that the equivalent equation for the volumetric flow rate of hydrogen is:

$$\Delta P = \frac{0.0000003}{2.8^2}\,\dot{V}_{H2}^2 + \frac{0.0053}{1.23}\,\dot{V}_{H2} \tag{5}$$

Results from the above equation are presented in Figure 8 below as the red line, with the measured flow rates for hydrogen shown as red symbols. There is good agreement between the predicted and measured hydrogen flow rates.

The ratio of hydrogen to methane volumetric flow rates can then be found by dividing the predicted flow rates (the red line in Figure 8) by the measured methane flow rates (the blue line in Figure 8) which gives the "predicted" curve plotted in Figure 9. The predicted result shown in this graph (i.e. the black line) is solely based on methane measurements and does not rely on any hydrogen measurements. The measured results (i.e. the black symbols) are calculated from the hydrogen and methane measurements shown in Figure 8 (i.e. red and blue symbols). Since these measurements for hydrogen and methane were not at identical pressures, there is some scatter shown in the measurements. The results are compared to the theoretical values for laminar and turbulent flow (horizontal lines with ratios of 1.23 and 2.8, respectively). One notable feature of the predicted result is that the ratio tends to the laminar value of 1.23 as the pressure tends to zero, which is appropriate given that flows become more laminar as the flow speed decreases.

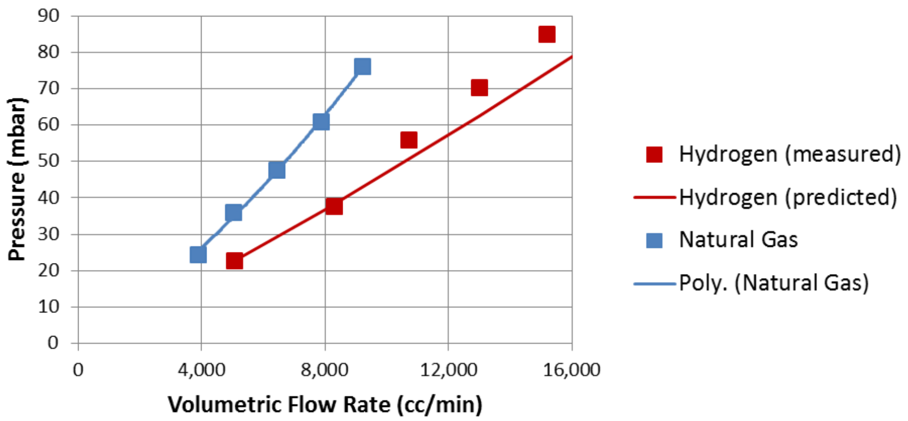

Figure 8 – Measured volumetric flow rates of hydrogen and methane for Asset 14 (symbols), predicted volumetric flow rates of hydrogen, based on the methane measurements (red line) and curve fit to the methane data (blue line)

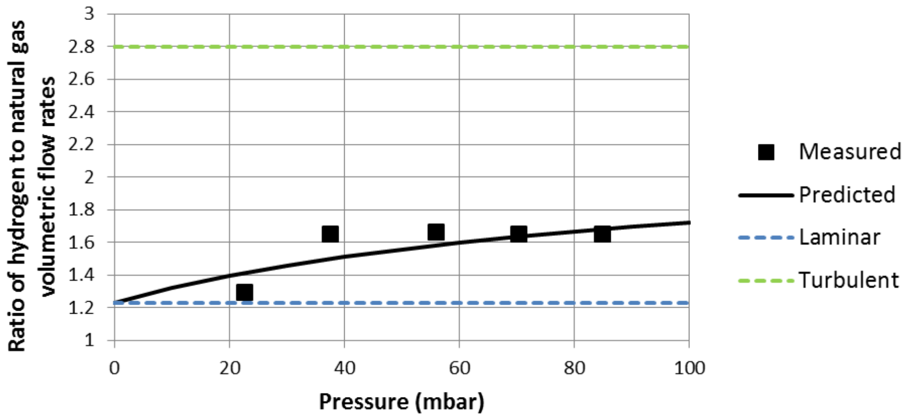

Figure 9 – Ratio of hydrogen to methane volumetric flow rates for Asset 14: comparison of measurements and predictions. Horizontal lines show theoretical values for laminar and turbulent leaks.

The calculation method described above provides a means of predicting the hydrogen leak rate from measured methane leak rate at a range of pressures. In the above example, the analysis uses methane data for five different pressures. In order to fit a polynomial curve through the measurements, a minimum of two measurements at different pressures is needed (assuming a third point is used to fit the curve, namely zero flow at zero pressure). In practice, it is useful to have more than two measurements to improve the accuracy of the curve fit and help to compensate for any scatter in the measurements.

The method described above to predict the hydrogen flow rates from the methane data was found to be in good agreement with the hydrogen measurements in most cases. Notable exceptions were Assets 129, 180 and 12345. In these three cases, MP or IP assets were tested and flow rates were measured at a higher range of pressures, up to 5 barg. As the pressure increased above 0.9 barg, the gas releases become choked and the variation of flow rate with pressure changes from being quadratic to linear. The method used to predict the hydrogen flow rates does not account for this change in behaviour, which may explain why the method performs poorly for these cases.

6.0 CONCLUSION

The results from Phase 1A of the H21 project indicate that:

- Gas network assets that leak hydrogen also leak methane. None of the assets tested were found to be gas-tight with methane but still leak hydrogen for the range of measured flow rates tested, i.e. for flow rates between 100 cm^3/min and 20,000 cm^3/min.

- The ratios of hydrogen to methane volumetric leak rates for LP, MP and IP leaks are between the lower and upper bounding values for laminar and turbulent flow, i.e. the ratios are between 1.2 and 2.9.

- There is a trend for the ratio of hydrogen to methane volumetric leak rates to increase with pressure for LP assets. A calculation method to predict this trend using methane data at two or more pressures was found to give good agreement with the measurements.

When assessing the impact of switching from natural gas to 100% hydrogen in the gas distribution network, the results suggest that it would be conservative to assume that the volumetric release rate of hydrogen will be 2.9 times greater than the current leakage rate with natural gas. Further work needs to be undertaken to understand how the backfill around buried assets affects the leak rate. Some work has been undertaken on this topic at DNV Spadeadam in Phase 1B of the H21 project and further work is planned in Phase 2.

The results presented here may be useful in assessing how shrinkage (i.e. the amount of gas lost in transmission) will be affected by the conversion from natural gas to hydrogen in the gas network. It is important when undertaking such analyses to use the correct metrics. The predicted maximum ratio of hydrogen to methane flow rates is 2.9 in volumetric terms. If this value is multiplied by the molecular weight ratio of hydrogen to methane (0.13), one obtains the mass flow rate ratio of 0.36. In other words, for every 1 kg of methane released, it is predicted that a maximum of 0.36 kg of hydrogen will be released. Scaling by the gross heats of combustion gives a ratio of 0.9, i.e. for every 1 J of energy released as methane, there will be a maximum of 0.9 J of energy released as hydrogen. This analysis assumes that natural gas is 100% methane and more precise values could be obtained for natural gas compositions. There remains some uncertainty over the behaviour of leaks smaller than those that could be detected on the H21 Phase 1A rig (which had a lower detection limit of 100 cm^3/min). Further measurements in the H21 Phase 2 trials and other shrinkage tests should help to clarify whether these smaller leaks when aggregated over the UK network could have a significant effect. A more sophisticated analysis of shrinkage could also be carried out, if required, particularly if the system pressures are increased for hydrogen.

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