demonstrating hydrogen for heat

Department for Business, Energy & Industrial Strategy

WORK PACKAGE 7

Safety Assessment:

Experimental Testing – Commercial Pipework Leakage

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.

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

Project 204
Hy4Heat WP7 – Lot 1 Variation
Plant room testing

Final Report

Version	Notes	Date
V1.0	Draft, issued for review.	31 Jan 2020
V1.1	Formal issue for comment	14 Feb 2020
V1.2	First response to comments	11 May 2020
V1.3	Steer comment response	10 Jul 2020
V2.0	Issued as final	11 Aug 2020

Client: BEIS

Ref: TRN: 1819/02/2019 Lot 1

Project: 204 – H4H WP7 Lot1 Variation: Phase 1

Authors: S. Roberts / N. Morris / N. Ryan

Table of Contents

Executive summary

This report covers variation work carried out by Steer Energy to measure comparable hydrogen and methane leak rates on a commercial gas pipework system. The system in question was the gas meter and equipment contained in the Plant Room, known as Building 41 in the MOD Worthy Down site. The plant room is due for demolition as part of site development works and this provided a small window of opportunity to test the equipment ‘as found’ in the undisturbed plant room prior to demolition.

A site visit was undertaken on 10 December 2019 and a programme of work proposed to test the system in the plant room. The system was broken down into five sections which could be tested individually to provide more than just a single date point.

Testing was carried out during two site visits. The system was tested first in air on 9 January 2020 to trial the equipment, procedures and review the risk assessments. This provided an opportunity to overcome any potential challenges and unknowns such as powering the isolation valve in the plant room. The main methane and hydrogen tests were carried out on 16/17 January 2020 and then the system was made safe by purging all flammable gases and handed over to the demolition team.

The work was undertaken as the installation was of a suitable scale to be comparable with a commercial installation which might be converted with minimal changes. It is particularly important to note that the installation was not disturbed in undertaking the tests (except where noted) and is therefore representative of an installation that has been commissioned with natural gas for an extended period being converted to hydrogen (and a comparatively large one).

The findings of the Worthy Down tests were that the system was a good system that would be classed as gas tight. A number of lock-off tests were carried out and all of the calculated leak rates were very low, indicating a good overall system.

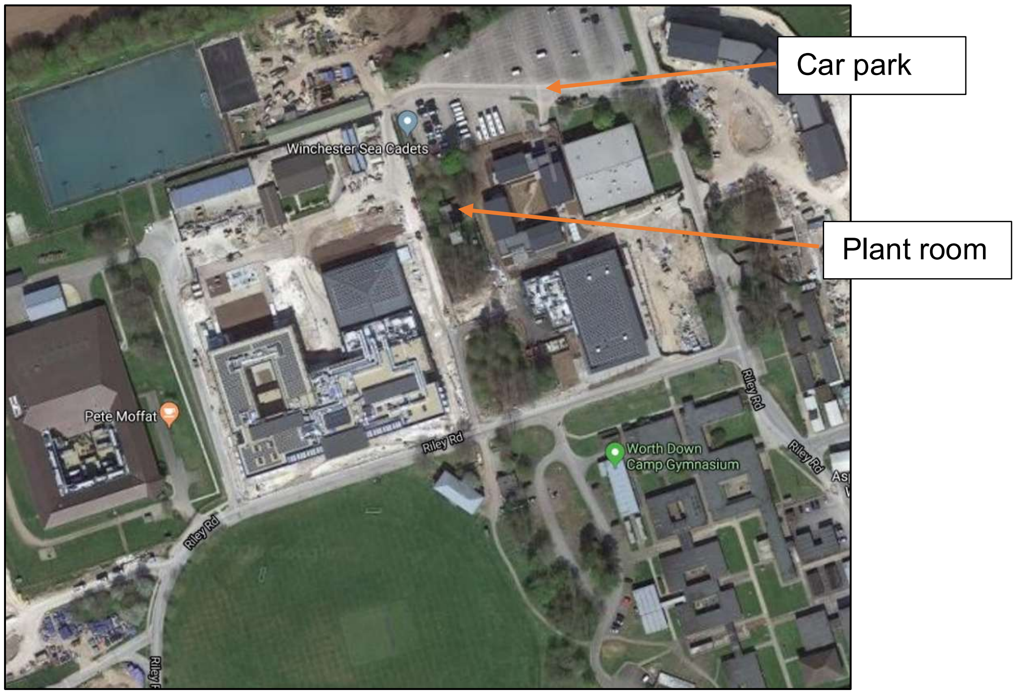
The system performed in a very similar manner in both methane and hydrogen. Small leaks were measured in all of the test gases, but these leaks were well below what is deemed as leak tight for the system. Leakage in hydrogen was slightly greater than that seen in methane but not to a particularly large extent. It further demonstrates the narrative that a property which is leak tight on methane will be leak tight on hydrogen.

These conclusions match those from the extensive testing carried out by Steer Energy Solutions as part of the main WP7 Lot 1 work of the Hy4Heat programme of tests on fixtures and fittings.

One of the conclusions from the leak report was that for the scale tested, a system which is tight for methane will be tight for hydrogen, with no theoretical reason why a larger more complex system would not be tight. This work has gathered primary evidence from a real-world installation to further support that conclusion on a larger scale. This should provide additional confidence that installations which are currently leak tight will continue to be so if the supply is switched to hydrogen. Note that this does not imply that pressure testing on properties which are to be converted should not be carried out.

1 Background

Worthy Down is the location of the Defence College of Logistics, Policing and Administration (DCLPA). It is owned by the Ministry of Defence, which maintains its infrastructure via the Defence Infrastructure Organisation (DIO). DIO's agent on site is AECOM and the main contractor is Amey. DCLPA is currently undergoing a major expansion and refurbishment programme known as Project Wellesley, who's main contractor is Skanska. Building 41, referred to as the plant room in this document. It is situated near to the car park, as shown in Figure 1.



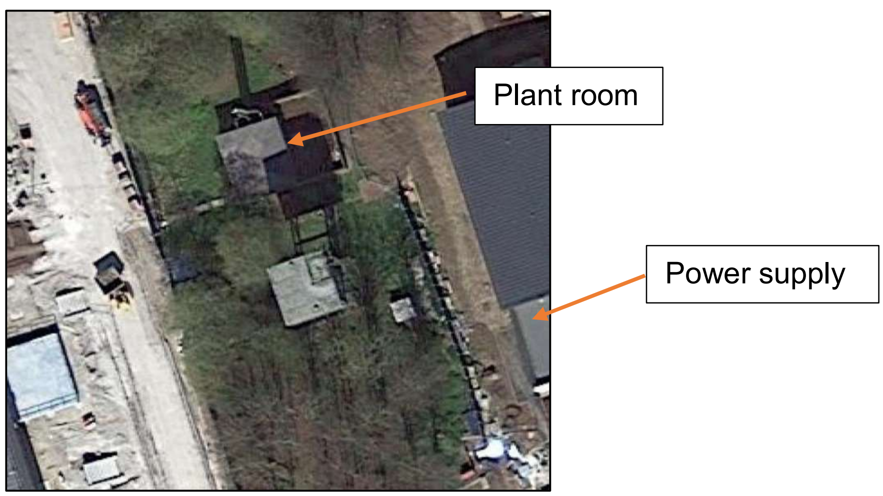


Figure 1: General location of the plant room under test

This plant room has three boilers inside and gas pipework to supply the boilers. This is fed from a single meter outside the building. As part of the Project Wellesley programme, the building is due to be demolished at the end of January 2020, giving Steer Energy a limited amount of time to investigate 'as found' pipework leakage and test in hydrogen and methane. To enable DIO to permit the test work, the building was handed back to DIO (via AECOM) by Skanska and from DIO to Steer Energy for the duration of the testing period. After the tests, Steer handed the building back to DIO (via AECOM) for immediate handover back to Skanska.

2 Site survey 9 January 2020

A number of photos were taken during the first site visit. These include the outside of the plant room, inside the building, the meter cabinet, the 4-inch supply pipe and one of the boiler feed pipes.

2.1 Outside the building

Figure 2: Looking north towards the plant room, building 41

Figure 3: Looking east towards the plant room

Key features outside of the building were the location of the meter cabinet, the incoming gas supply and the vented windows and doors to prevent build-up of gas in the building.

2.2 Meter cabinet

The meter cabinet was situated on the south wall of the plant room to the left of the door. At the time of testing, the meter, shown in Figure 4, has since been confirmed as a U160 size meter with an installed volume of 0.304 m^3. This figure is included in the overall system volumes used for the leak rate calculations.

Figure 4: Meter cabinet with blue ECV and test point used for gas injection

The test point shown on the right of Figure 4 was used as the gas injection point for all of the tests. The blue butterfly valve to the left was the manual isolation ECV (emergency control valve) for the meter and the plant room.

2.3 Four-inch pipe

The supply line to the building from the meter was a four-inch nominal bore steel gas line, shown in Figure 5.

Figure 5: Four-inch pipe from meter cabinet into the plant room

The four-inch pipe passed through the south wall of the plant room and connected to a 230 VAC electrically operated solenoid valve (SOV), shown in Figure 6. It then extended into the building above the boilers as shown in Figure 7.

Figure 6: Electrically operated solenoid valve (SOV)

Figure 7: 4-inch gas pipework showing end plate and 2-inch boiler feed pipes

Three separate 2-inch boiler lines ran down from the 4-inch suspended manifold pipe. The route of one of these 2-inch pipes is shown in Figure 8 and Figure 9. Each of the 2-inch lines included ball valves, purge and test points and a series of welded and threaded fittings and elbows.

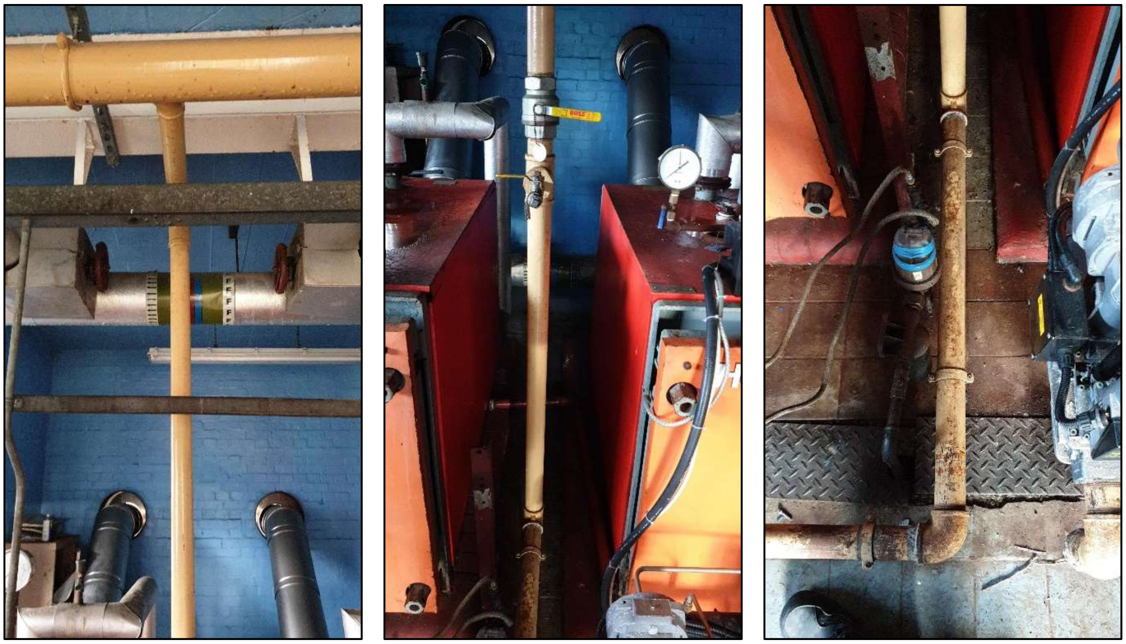


Figure 8: 2-inch gas pipework to the boiler inlets.

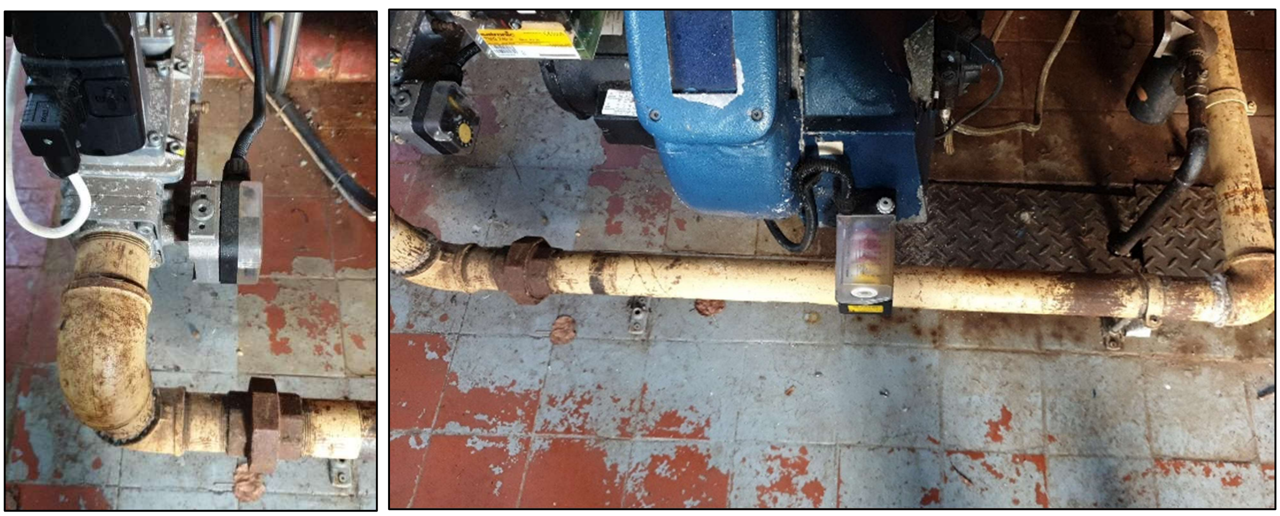


Figure 9: Continuation of 2-inch gas pipework to boiler 1 inlet

Detail of one of the boiler isolation valves and the purge points used for purging the gas through the pipework is shown in Figure 10.

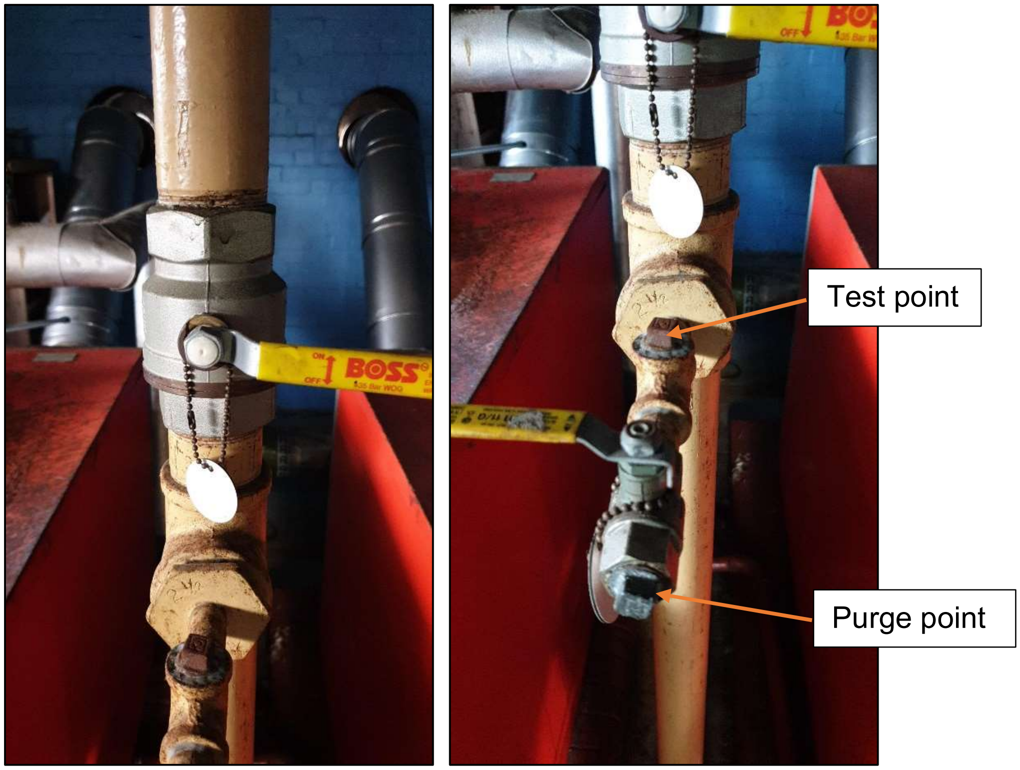


Figure 10: Boiler isolation valve and ½" purge and test ports

The horizontal end point on the right of Figure 10 was the gas purging point. The plug sitting vertically was the test point used for the manometer test. There was one of each purge and test point just downstream of each boiler isolation valve. These were all sealed with blanking plugs.

2.4 Inside the building

The building contained three oil / gas fired boilers, associated water systems and control systems. These are shown in Figure 11 and Figure 12.

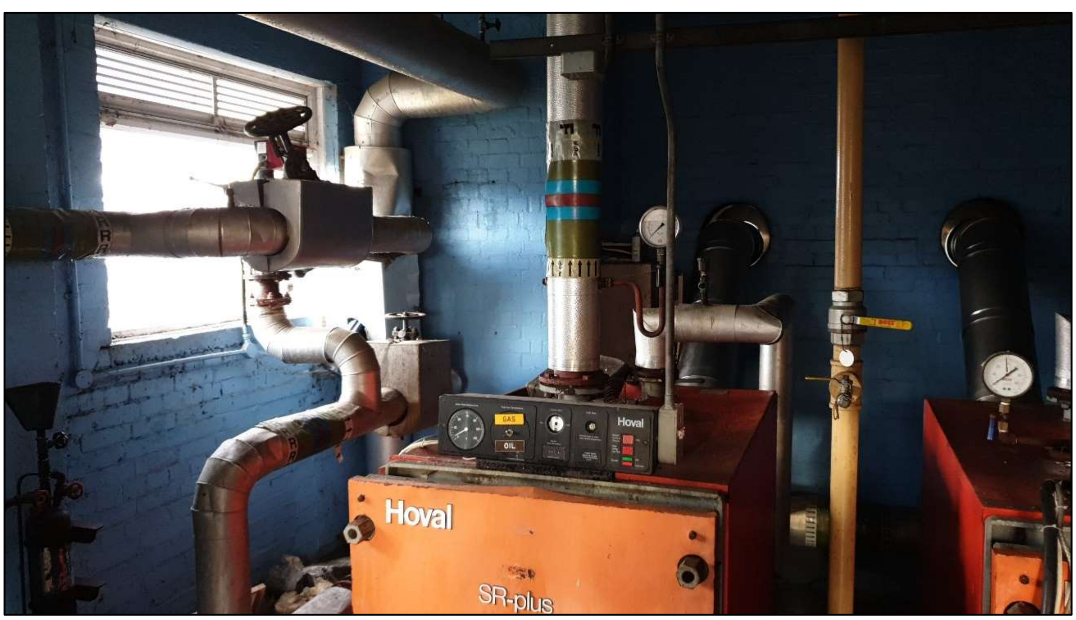


Figure 11: First boiler

Figure 12: Second and third boilers

3 Set up

This chapter examines the experimental and site setup as used during the second site visit, 16 and 17 January. Learning was taken from the first site visit on 9 January resulting in improved site access, shelter and floor covering to manage mud. The second visit also including venting flammable gases so a purge stack was used along with a perimeter fence and warning signage.

3.1 Site safety

Ensuring a safe working environment is a priority for good working practices. A full risk assessment was carried out prior to both site visits. This was reviewed during both visits and toolbox talks were held prior to carrying out any work.

Required PPE for site was high visibility clothing and safety boots mandatory at all times. Other PPE such as ear defenders, safety glasses and gloves were deemed suitable to be used as appropriately during the activities.

Flammable gas was the main risk to personnel during the operations. The site was appropriately labelled with warning signs and bunting put up to restrict access to the site. Slips, trips and falls were highlighted as a risk on the 9 January 2020 site visit. This risk was minimised by cutting back undergrowth and overhanging branches. A path was cleared to the car park for transport of equipment to and from the plant room. A tent and a gazebo provided a dry and sheltered working environment for the equipment and personnel. Ground sheeting was used to stop the ground churning into mud. It was pegged along the edges to minimise the trip hazard.

Figure 13: South side of the plant room with shelter and warning perimeter

The gas was taken to site in a number of gas bottles. Care was taken with handling and storing the gas bottles. Two people were required for lifting of the nitrogen cylinder due to the weight. All cylinders were secured vertically in the plant room, shown in Figure 14. A Crowcon T4 Type 2 gas monitor was tied to the gas bottles to detect either presence of methane or a drop in oxygen levels. This would alert personnel to potentially unsafe conditions.

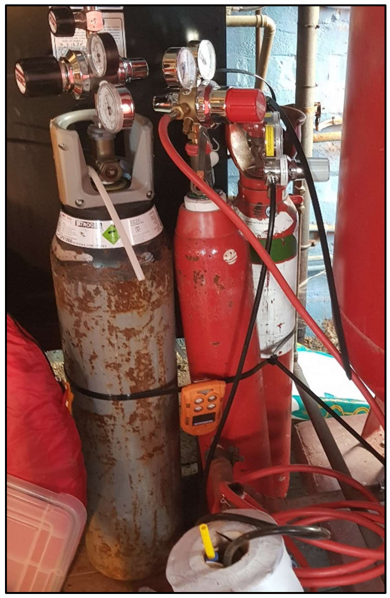


Figure 14: Secured gas canisters

The pipes in the plant room were purged of any oxygen using nitrogen before any flammable gases were injected.

The purge gas was connected into the system via the injection point, shown in Figure 4. All valves were opened and the plugs in the purge lines were removed. Three exhaust lines were connected from the purge points to a purging stack, shown in Figure 15. The stack was then placed downwind and away from the working space. Finally, a gas meter was used to record the volume of gas passing through the stack.

Figure 15: Purge stack with flow volume meter in operation

A calculation of the required purge volume was provided by Kiwa Gastec, using standard practices. The required volume was determined as 0.46 m^3 of gas to purge from one gas to another.

Calculations based on the room volume and the volume of gas in each cylinder indicate that even a full evacuation of either the hydrogen or methane would not reach the lower explosive limits for the gas in a room with no venting. The room was well ventilated with slatted doors and windows, further mitigating any risk. Any leaks within the system during testing would be detected by the measurement equipment and the maximum flow through the system was controlled by the test equipment. The work station was set up outside the plant room further reducing risks.

After completion of testing, responsibility for the site was returned to Skanska via AECOM on behalf of DIO. To make this safe a final purge was carried out to remove the flammable test gases. Nitrogen was used for this to avoid mixing oxygen (air) and flammable gas. Following the purge, the pressure of Nitrogen in the pipes was checked and recorded as atmospheric pressure.

3.2 Site equipment

The site visit on 9 January 2020 visit highlighted challenges of the working situation during a rain storm. In the enclosed space of the plant room. There was a clear risk of catching cables and hoses, posing a trip hazard and a risk to test equipment. During the second site visit, a walkway was established with loose cables and hoses tied down to minimise the risk of tripping while crossing the walkway.

Figure 16: Hose management from test equipment through to gas injection point

Additional lighting was placed inside the plant room and the tent to assist with visibility. The SOV, labelled 5 in Figure 20, is sprung closed and required external power to open. This was done by re-routing the original supply cable, wiring it to a standard three-pin plug and plugging into a switched RCD extension cable. Power was also required for the flow controllers, pressure gauge and laptop chargers. This was supplied by running an extension lead from a nearby boiler room. Two tables and a set of chairs provided comfortable working conditions and a stable platform for the sensitive test equipment. The test equipment layout is shown in Figure 17.

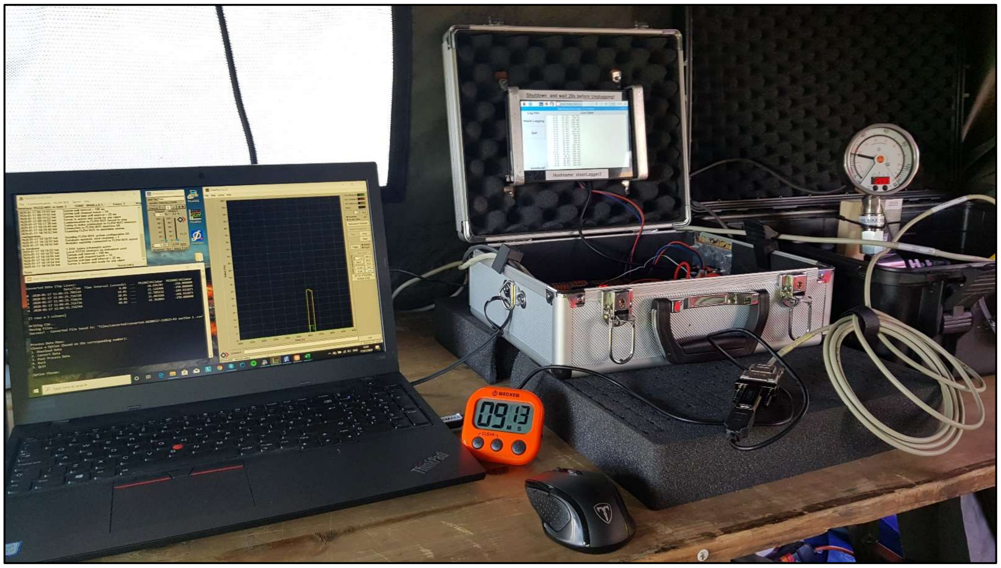


Figure 17: Electronic equipment set up

3.3 Test equipment and accuracy

3.3.1 Pressure Sensor

An ifm PG2489 pressure gauge was used for these tests.

- Resolution 0.25%
- Measuring range: -5 to 100 mbar

Accuracy / deviations	
Accuracy / deviations (in % of the span) Turn down 1:1	
Switch point accuracy	< ± 0.6
Characteristics deviation *)	< ± 0.35 (BFSL) / < ± 0.6 (LS)
Hysteresis	< ± 0.5
Repeatability **)	< ± 0.1
Long-term stability ***)	< ± 0.1
Temperature coefficients (TEMPCO) in the temperature range 0...70° C (in % of the span per 10 K)	
Greatest TEMPCO of the zero point	< ± 0.3
Greatest TEMPCO of the span	< ± 0.3

Figure 18: Accuracy of ifm PG2489 pressure gauge

The stated accuracy of the pressure gauge used is shown in Figure 18. The datasheet is included as Appendix E - ifm pressure gauge datasheet

3.3.2 Timing

While tests were timed with a stopwatch, the logged data contains a timestamp. This was used to calculate pressure drop over time / flow.

3.3.3 Volume

The volume of the system was based on the measured pipe lengths and internal diameters, as well as the advised meter installed volume. The volume was an estimation, however it is the same for both gases and as the relevant result is a comparison between the two, the volume is not critical. More detail is given on volume calculations in section 4.1.

4 Test plan

This chapter outlines the test plan actually used during the second site visit during which the methane and hydrogen tests were carried out. This was informed by the tests in air during the first site visit.

4.1 Test overview

The tests aimed to obtain a representative data point, or set of data for an ‘as found’ commercial gas system. The test plan was to fill the various pipe sections of the plant room with the given test gas, hydrogen or methane, and then pressure up to approximately 20 mbar and then measure the leak flow for each section in each gas.

This work builds on the WP7 Lot 1 work of testing on fixtures and fittings and uses some of the same test equipment. A Bronkhörst F-201CV-10K flow controller, rated and calibrated to 5 l/m in air, 8 l/m in methane and 10 l/m in hydrogen was available for flow control. An IFM PG2489 pressure gauge rated to 100 mbar was used for pressure measurement. Data was captured using a Steer Energy bespoke data logger. The results were then used to identify the level of leakage from the system in air, methane and hydrogen.

Figure 19 and Figure 20 show the pipework layout and the sections which were tested.

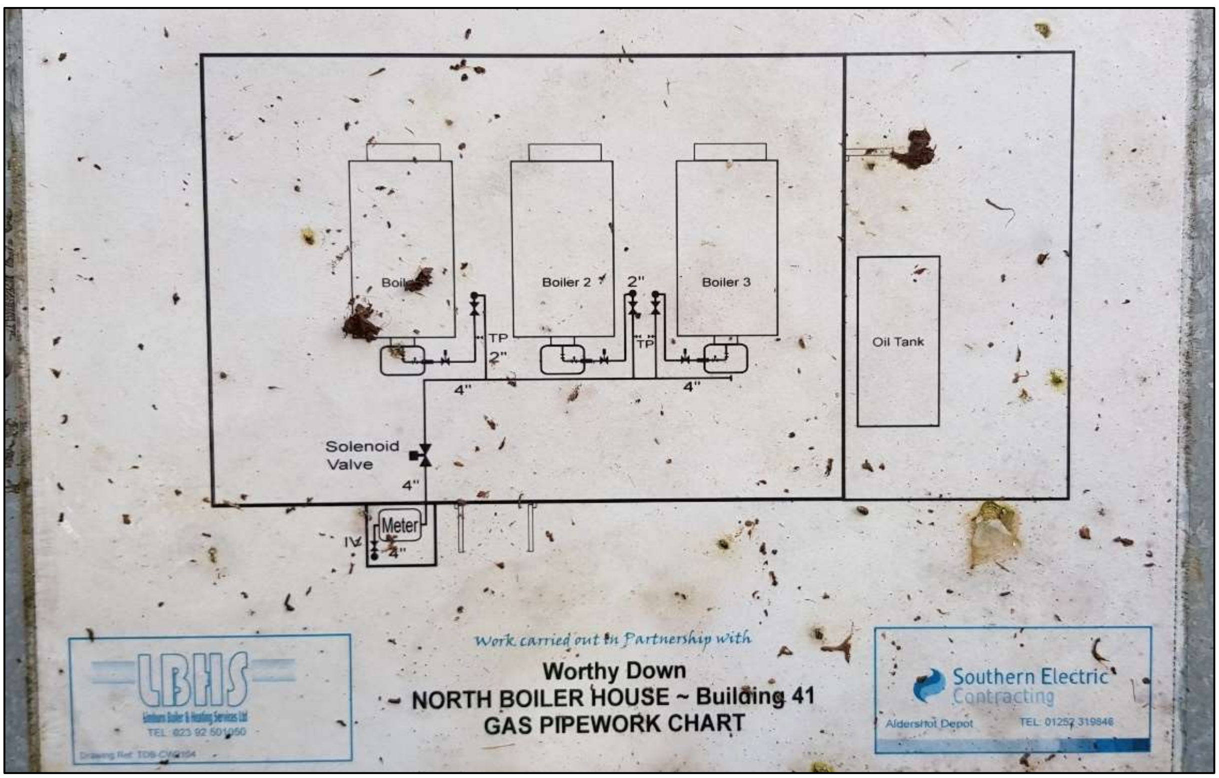


Figure 19: Building 41 gas pipework chart

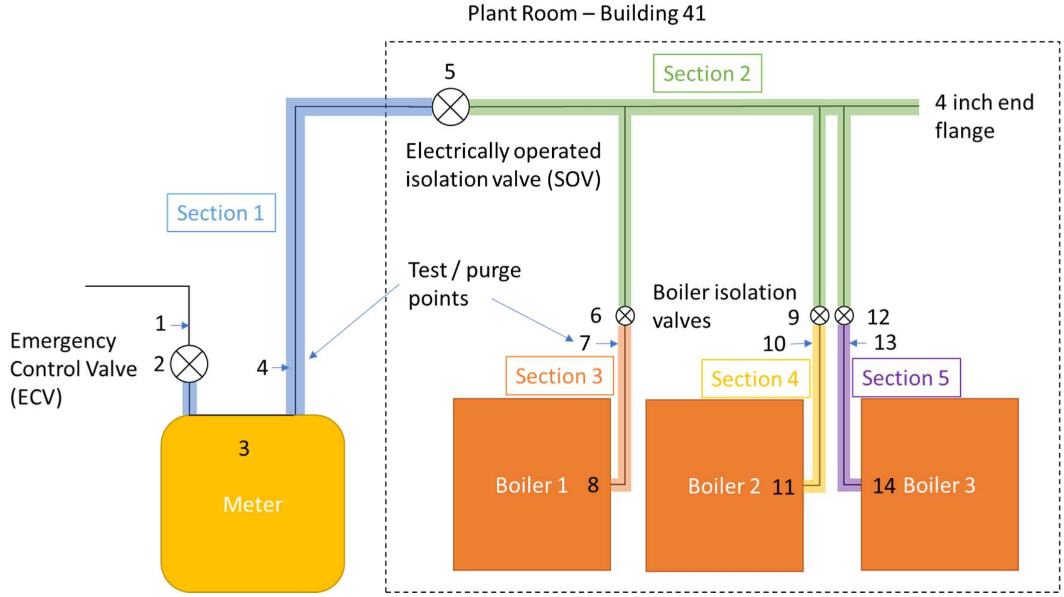


Figure 20: Plant room system layout

The calculated system volumes are shown in Table 1. These volumes were calculated directly from the measured pipe lengths and internal diameters, as well as the advised meter installed volume. These system volumes differ from the complete installation volume used for the purge volume due to purge safety factors and other considerations.

Named Test	Sections	Volume (m^3)
A	1	0.324
B	1 and 2	0.378
C	1, 2 and 3	0.382
D	1, 2, 3 and 4	0.387
E	1, 2, 3, 4 and 5	0.389

Table 1: System section volumes used for leak rate calculations

Tests in air on January 9 showed very low levels of leakage. Instead of carrying out flow tests, 'leak-off' tightness tests were used to determine leak rates. The leak rates for methane and hydrogen were also expected to be low; therefore, the test plan assumed tightness testing to determine leak rates.

The tightness test process requires 'stabilisation time' to allow thermal effects from the compression of the gas to settle and allow accurate pressure readings. Following standard practice, Kiwa Gastec suggested a 13 minute stabilisation time followed by a 13 minute lock off test to measure leak rates from the system. The tightness test was extended to 15 minutes to ensure 13 minutes of useable data was generated.

The testing was arranged such that the pressure in the system was kept as close to 20 mbar during each complete run of tests. This reduced the need for a settling period; examining the pressure over time showed stabilisation took less than 2 minutes. The stabilisation period was therefore subsequently shortened to three minutes.

4.2 Test programme for 16/17 January 2020 trials

The test programme for the second visit refers to the system layout shown in Figure 20 and detailed in Table 1. The programme of tests was followed for each gas with purges being carried out between tests to fill the system with the gas under test. The system was purged to nitrogen before and after tests on flammable gases to ensure no mixing of oxygen and flammable gases.

The final test programme comprised five tests, A-E, with regular equipment tests to confirm the leak rates measured were genuine system leaks.

The test sequence carried out was:

- Equipment test 1
- Test A: Section 1
- Test B: Sections 1 and 2
- Equipment test 2
- Test C: Sections 1, 2 and 3
- Test D: Sections 1, 2, 3 and 4
- Test E: Sections 1, 2, 3, 4 and 5
- Equipment test 3

4.2.1 Equipment tightness tests

These tests gave a baseline leakage figure for the test equipment. The measured volume was from the outlet of the Bronkhörst flow meter up to the ball valve at the gas injection point (4) on the schematic. This test was carried out to ensure any seepage from the equipment connections did not unduly affect formal measurements. Note: This first test was not done during the first field visit, testing in air on January 9.

4.2.2 Test A equipment

The SOV (5) was closed for this test. This tested combined leakage from: the manual ECV (2), the meter (3), the SOV (5) and the pipework running from the ECV to the SOV. The extent of this test is illustrated in Figure 21. The most likely source of leakage in this test is the SOV (5).

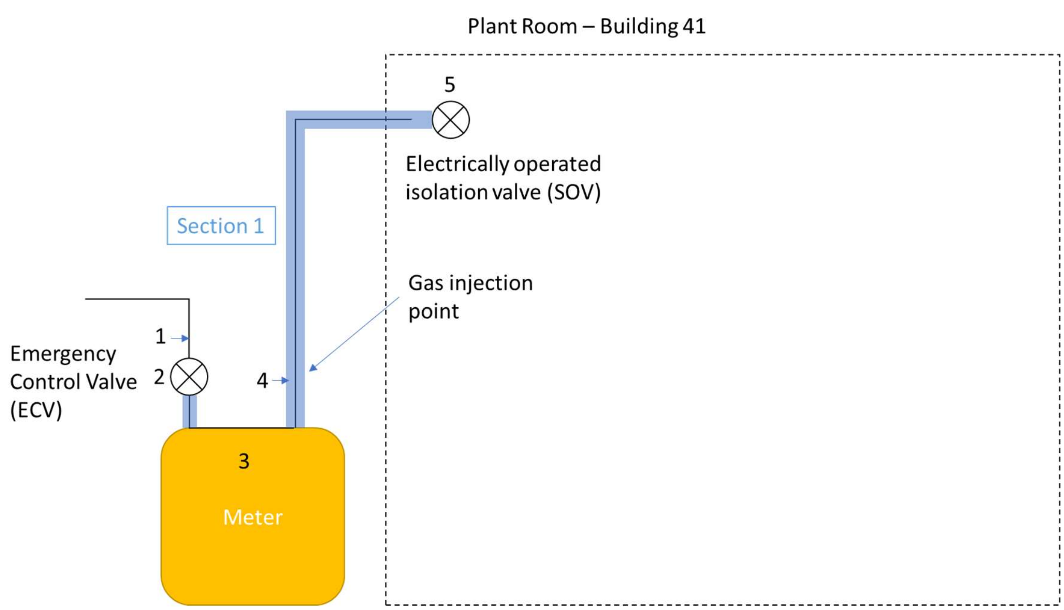


Figure 21: Test A equipment

4.2.3 Test B equipment

The SOV (5) was opened, adding all three of the boiler isolation valves (6, 9 and 12) and all of the pipework from the electric isolation valve to the three boiler isolation valves. This equipment is illustrated in Figure 22. The most likely sources of leakage here are the three boiler isolation valves.

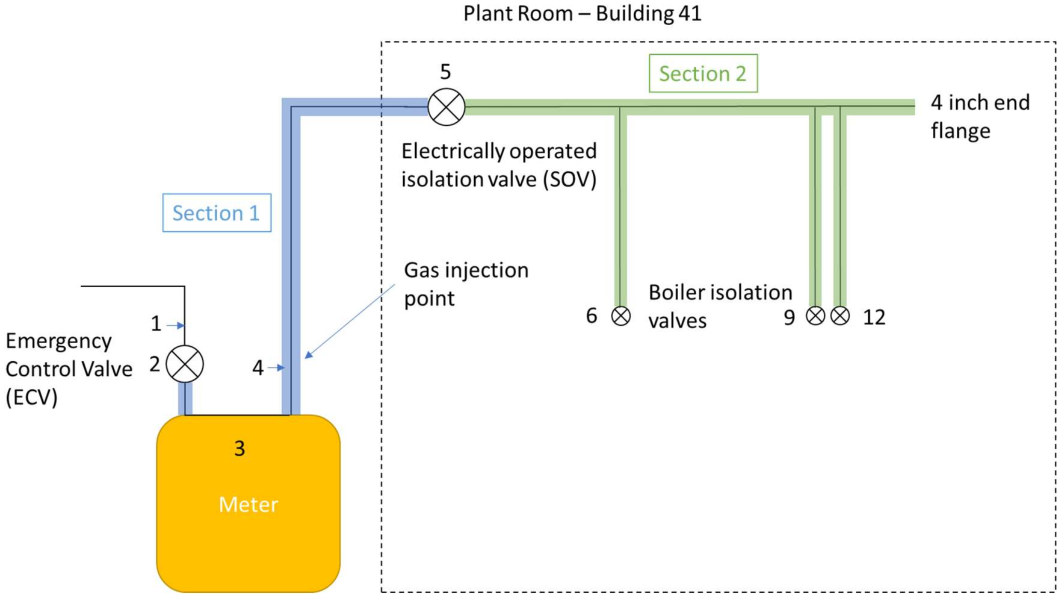


Figure 22: Test B equipment

4.2.4 Test C equipment

The isolation valve for boiler 1 (6) was opened, adding the purge plug, ball valve and fittings, the boiler inlet, and the pipework from the boiler 1 isolation valve to the boiler inlet. The equipment is illustrated in Figure 23, changes to the system are the opening of valve 6 and the purge and test points (7).

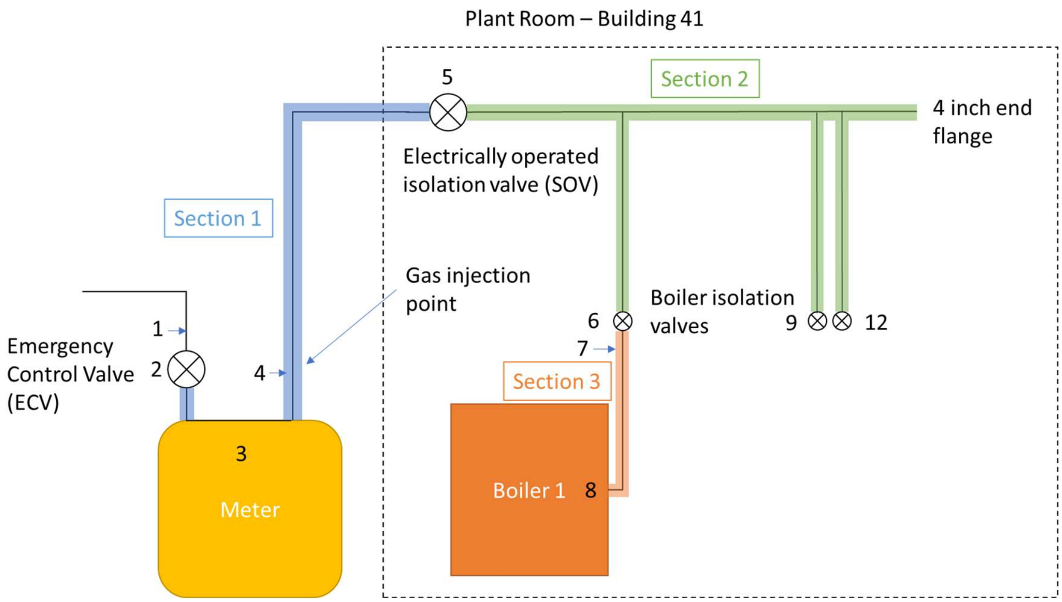


Figure 23: Test C equipment

4.2.5 Test D equipment

The isolation valve for boiler 2 (9) was opened, adding the purge plug, ball valve and fittings, the boiler inlet, and the pipework from the boiler 2 isolation valve to the boiler inlet.

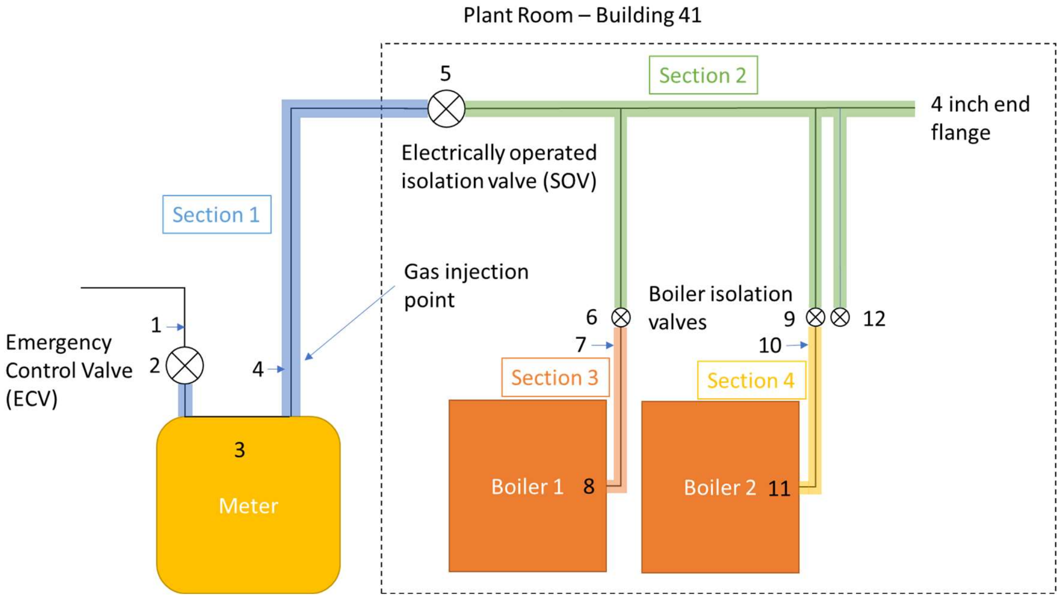


Figure 24: Test D equipment

4.2.6 Test E equipment

Finally, the isolation valve for boiler 3 (12) was opened adding the purge plug, ball valve and fittings, the boiler inlet, and the pipework from the boiler 3 isolation valve to the boiler inlet. The test equipment is illustrated in Figure 25.

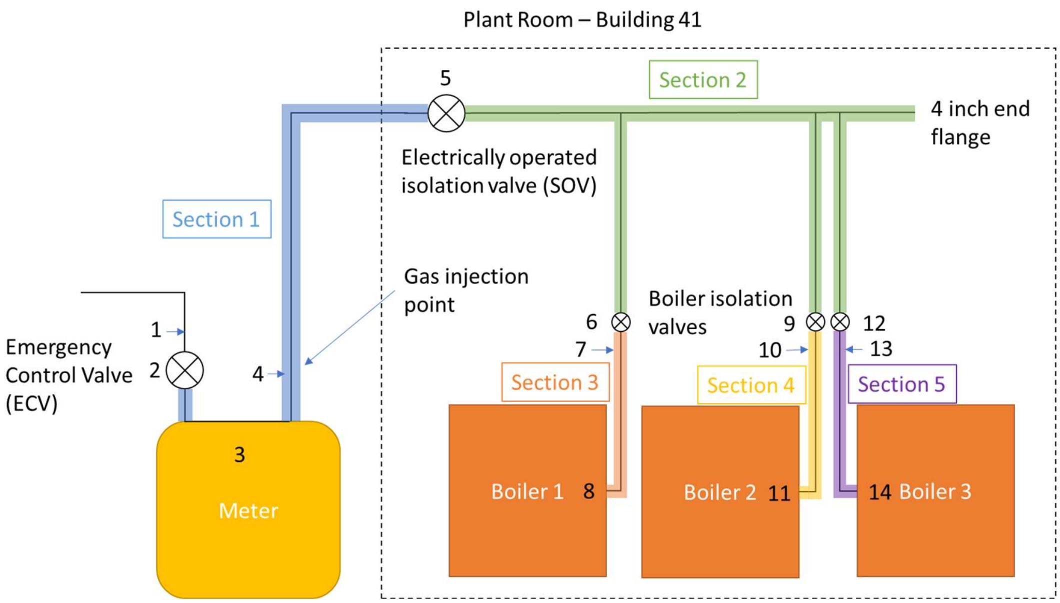


Figure 25: Test E equipment

This method of testing sections together minimises valve operations, thereby reducing changes made to the system. It should be recognised, however, that the system is fundamentally changed between gases as valves are moved and the purge plugs are removed and replaced. This changes the potential leak paths making direct comparisons between the different gases challenging.

5 Results

Results for each test are presented as a graph between 17 mbar and 22 mbar along with a table of results showing air, methane and hydrogen. It should be noted that the leakage rates for all of the tests were extremely small and each of the test sections would be approved as gas tight by a Gas Safe fitter.

Tests were performed using compressed air on 9 January 2020, methane on 16 January 2020 and hydrogen 17 January 2020.

The pressure fall-off graphs below represent the tightness tests. The data is shown from the point where the system is pressurised until the pressure is relieved. Calculated results use selected data and remove the initial drop off of pressure. Due to test equipment leaks the data in air for tests A and B are not valid. These data are therefore not included in the results.

5.1 Equipment tightness tests

The equipment tests were designed to ensure no significant leakage was coming from the measuring kit. During the tests on 9 January 2020, we identified a leak in the test equipment and this led to false results for early tests. Equipment tightness tests were introduced after test B in air. For this reason, tests A and B in air are not valid. The equipment only system has a small volume so any leakage has a large effect on a pressure fall off test.

Equipment tightness tests were carried out in methane before test A, after test B, and after test E. The test was repeated on the morning of 17 January in methane to give a comparison to the previous day.

	Air	Methane	Hydrogen
Leak rate E1 (m^3/hr)		6.22 $\times10^{-07}$	1.38 $\times10^{-06}$
Leak rate E2 (m^3/hr)	2.97 $\times10^{-06}$	2.62 $\times10^{-06}$	6.92 $\times10^{-06}$
Leak rate E3 (m^3/hr)	3.82 $\times10^{-06}$	2.81 $\times10^{-06}$	8.42 $\times10^{-06}$
Leak rate E4 (m^3/hr)		2.38 $\times10^{-06}$	

Table 2: Equipment tightness test data

The largest equipment leak seen was 8.24 $\times10^{-6}$ m^3/hr in hydrogen. This is two orders of magnitude less than the plant room leak tests.

5.2 Test A

Test A examines leakage from section 1.

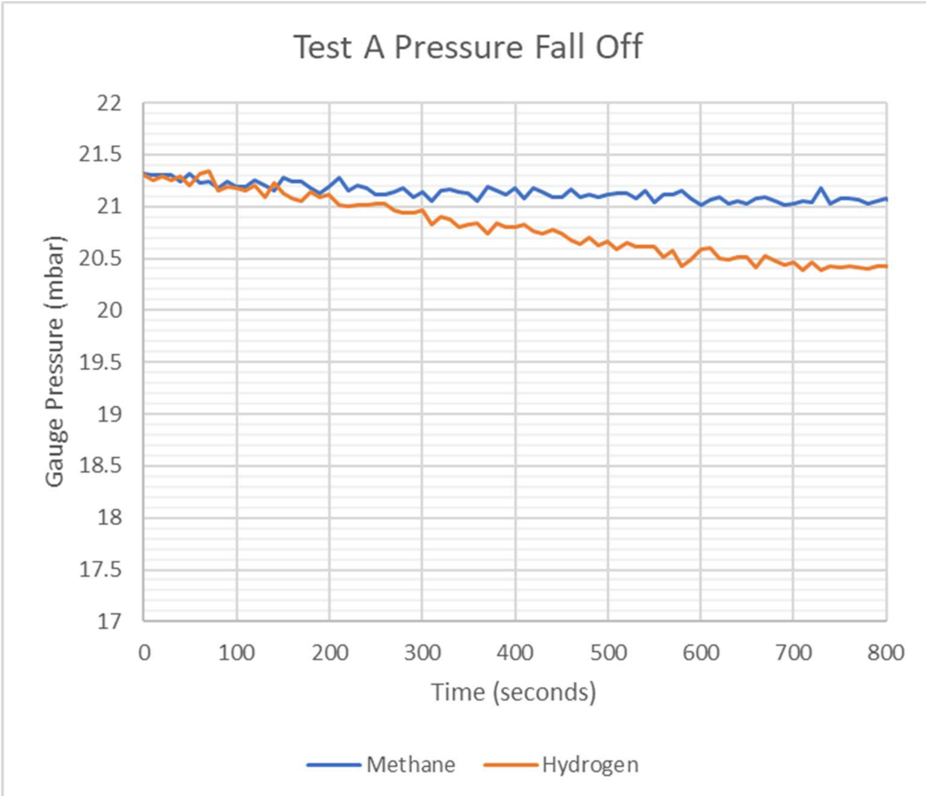


Figure 26: Test A pressure fall off graph

Test A results show very low levels of leakage from the system. Comparison of the two gases indicates that the hydrogen leakage was significantly more than methane leakage. A leak of this magnitude at 20 mbar is likely to be in laminar flow, and can be expected to produce a hydrogen to methane ratio of 1.2:1. One possible cause for this discrepancy is the possibility that there was unvented pressure in the system when tested in methane, so the pressure drop over the SOV was not fully 20 mbar. If this is the case it would indicate a leak passing through the SOV, which is not seen in methane due to pressure both sides of the valve. Alternative theories are that stroking the SOV changed the system between the two sets of test runs. It was also stroked before the input of methane however so any major changes would be expected to be already present. Other possibilities include temperature and pressure weather effects, wind affecting the measuring equipment and insufficient gas stabilisation time. The leakage rates are very small in both methane and hydrogen, so external factors such as sunlight on external pipes could have a noticeable effect.

	Methane	Hydrogen
System volume (m^3)	0.324	0.324
Pressure loss (mbar)	0.28	0.91
Time (mins)	13	13
Leak rate (m^3/hr)	4.1 $\times10^{-4}$	1.3 $\times10^{-3}$
Leak rate (ml/hr)	411	1,327
H_2 : CH_4 ratio	3.22	

Table 3: Test A pressure fall off data

5.3 Test B

Test B examined leak rates from sections 1 and 2.

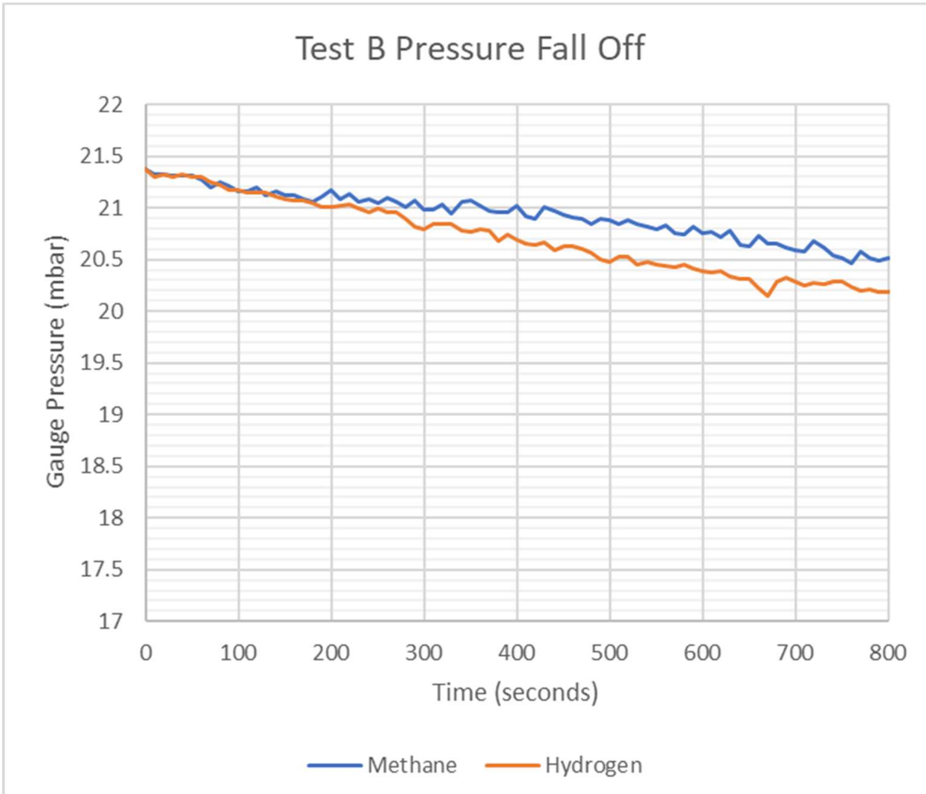


Figure 27: Test B pressure fall off graph

The leakage seen in test B is as expected. A leak of this magnitude at 20 mbar is likely to be in laminar flow, and can be expected to produce a hydrogen to methane ratio of 1.2:1.

Test B only includes sections 1 and 2, and appears to be the leakiest test in all gases. This is addressed in section 0. A passing boiler isolation valve is the most likely cause of this leak flow.

	Methane	Hydrogen
System volume (m^3)	0.378	0.378
Pressure loss (mbar)	0.86	1.16
Time (mins)	13	13
Leak rate (m^3/hr)	1.47 x10^{-3}	1.98 x10^{-3}
Leak rate (ml/hr)	1,470	1,978
H_2 : CH_4 ratio	1.35	

Table 4: Test B pressure fall off data

5.4 Test C

Test C measured leak rates from sections 1, 2 and 3. Section 3 is added to the system which removes leakage measured across boiler 1 isolation valve but adds leakage from boiler 1 and the associated purge and test plugs.

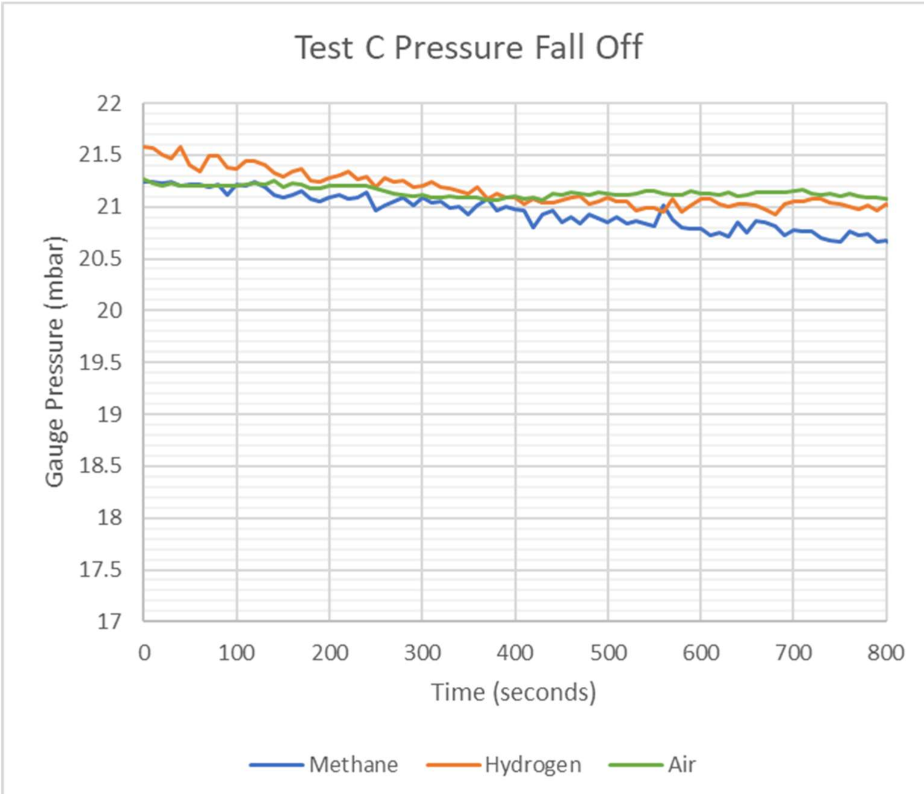


Figure 28: Test C pressure fall off graph

Test C provided the best sealing rate despite including sections 1, 2 and 3 in the test. This may indicate a leak through boiler 1 isolation valve. The leak rate in hydrogen measured higher than in methane for the first 7 minutes, then the hydrogen leak rate decreased. The methane leak rate is quite steady throughout. Averaged over the 13 minute test period, using suitable starting points, the leak rates are very similar with a ratio of 1.16 hydrogen to methane.

This result was most likely caused by a change in system set up between the two gases. The boiler isolation valves have all been stroked to enable the purge to methane and then to hydrogen, which changes the system. The purge plugs were also removed and replaced between the different gasses. Finally, the weather also varied significantly between the days of testing. The leakage rates are so small that differences are likely to be due to system variables rather than gas behaviour differences.

	Methane	Hydrogen	Air
System volume (m^3)	0.382	0.382	0.382
Pressure loss (mbar)	0.49	0.57	0.18
Time (mins)	13	13	13
Leak rate (m^3/hr)	8.51×10^{-4}	9.86×10^{-4}	3.05×10^{-4}
Leak rate (ml/hr)	851	986	305
H_2 : CH_4 ratio	1.16		N/A

Table 5: Test C pressure fall off data

5.5 Test D

Test D measured the leak rates from sections 1, 2, 3 and 4. Section 4 is added to the system which removes leakage measured across boiler 2 isolation valve but adds leakage from boiler 2 and the associated purge and test plugs.

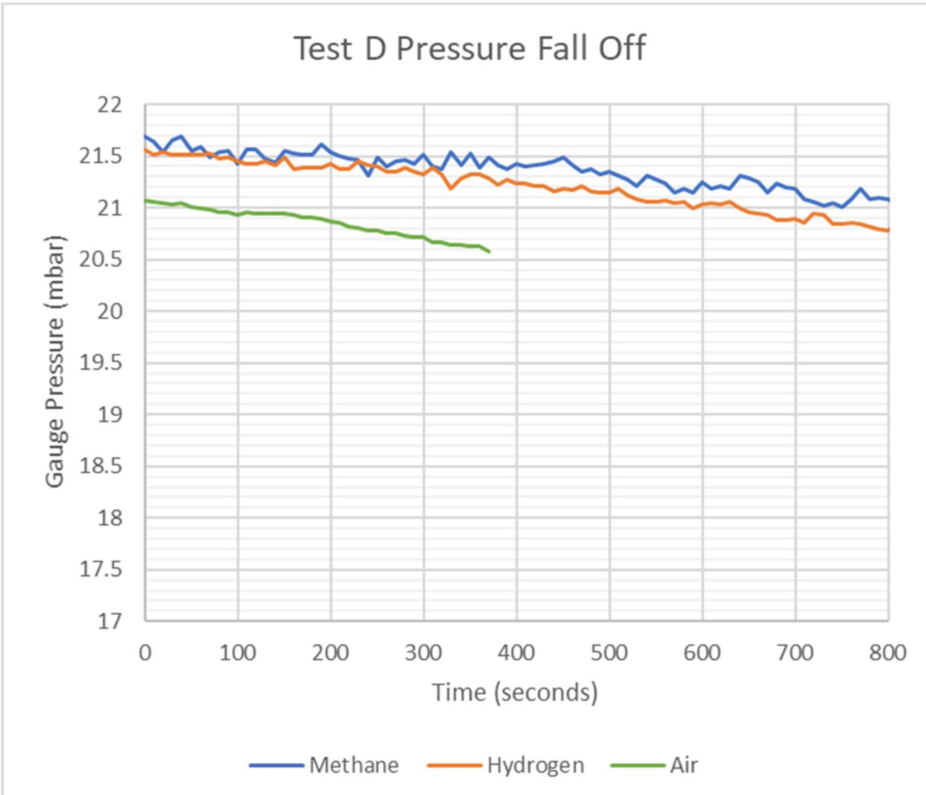


Figure 29: Test D pressure fall off graph

The hydrogen to methane ratio in test D matches the expected leak ratio. The air leakage rate is higher than either methane or hydrogen for test D, which would be unexpected for a constant system. This may be explained by the gas fitter removing and re-fitting the purge plugs properly after each gas purge, effectively changing the system between tests. For the test using air, the purge plugs were tested as found. This may indicate an initial leak from boiler 2 purge port which was sealed after the purge to methane and then hydrogen.

Test D leaks more than test C. This implies that the leakage from boiler 2 inlet, pipework, fittings and purge port were greater than the leakage through boiler 2 isolation valve.

	Methane	Hydrogen	Air
System volume (m^3)	0.387	0.387	0.387
Pressure loss (mbar)	0.61	0.74	0.43
Time (mins)	13	13	6
Leak rate (m^3/hr)	1.07 x10^{-3}	1.30 x10^{-3}	1.63 x10^{-3}
Leak rate (ml/hr)	1,065	1,298	1,634
H_2 : CH_4 ratio	1.22		N/A

Table 6: Test D pressure fall off data

5.6 Test E

Test E measured leak rates from all five sections of the system. Section 5 is added to the system which removes leakage measured across boiler 3 isolation valve but adds leakage from boiler 3 and the associated purge and test plugs.

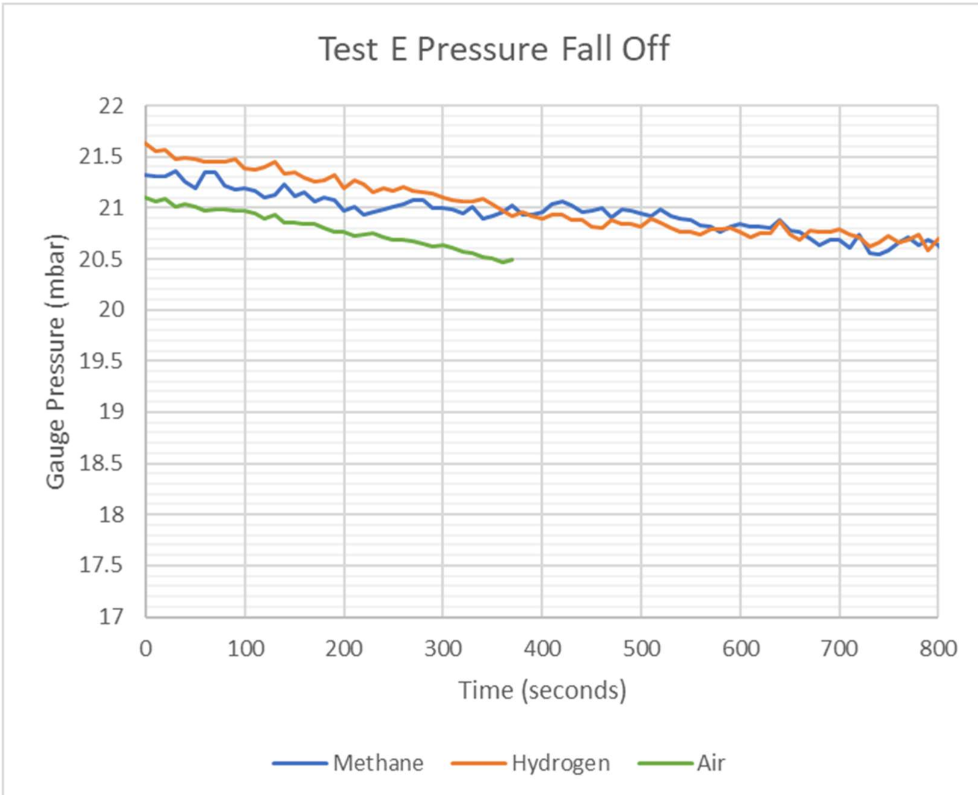


Figure 30: Test E pressure fall off graph

Test E leaks more than test C or D in all three gases. This implies that the leakage from boiler 3 inlet, pipework, fittings and purge port was greater than the leakage through boiler 3 isolation valve. Hydrogen leaks more than methane with a ratio of 1.31:1. This ratio ties in with expected laminar flow conditions. The tests in air measured greater leakage than hydrogen or methane. As with test D this is most likely due to the purge ports being properly fitted after the purge between each gas.

If this system were being tested with natural gas in commercial use, the maximum permitted leak rate (MPLR) is 3.8 mbar per 13 minute test period.

	Methane	Hydrogen	Air
System volume (m^3)	0.389	0.389	0.389
Pressure loss (mbar)	0.68	0.89	0.64
Time (mins)	13	13	6
Leak rate (m^3/hr)	1.20 x10^{-3}	1.57 x10^{-3}	2.45 x10^{-3}
Leak rate (mL/hr)	1,196	1,567	2,449
H_2 : CH_4 ratio	1.31		N/A

Table 7: Test E pressure fall off data

5.7 Test E methane repeat test

This repeat was performed on 17 January 2020 to ensure the leak rate of the system was similar to the previous day. This test repeat was done before purging to hydrogen.

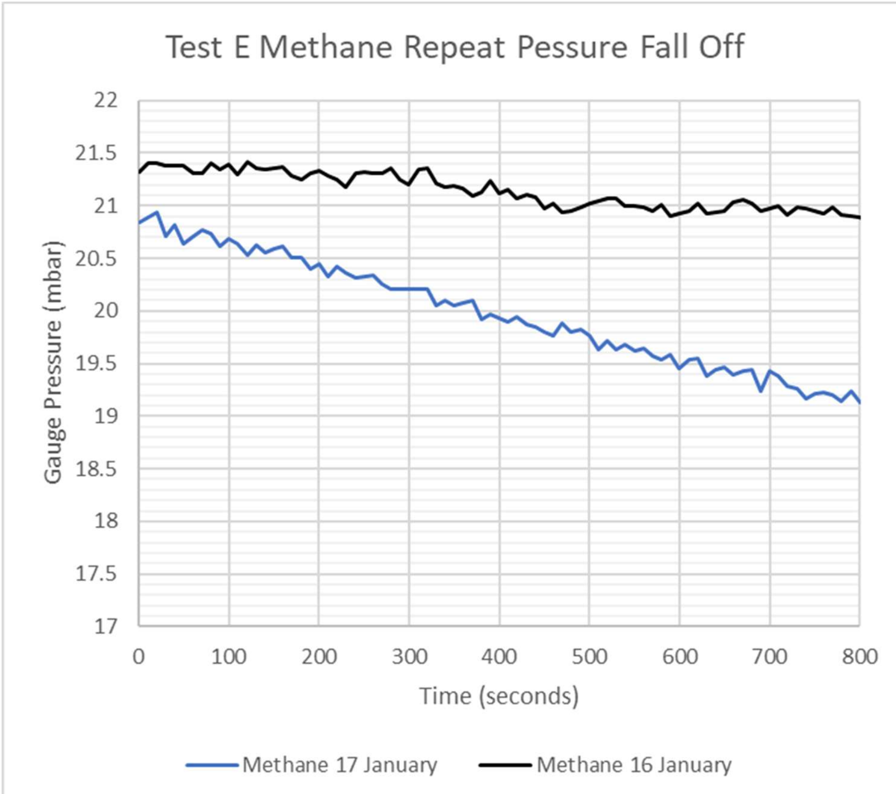


Figure 31: Test E methane repeat pressure fall off graph

The methane leak rate for test E was four times higher on the second day of testing. There was a possible change to the system with the removal of a test port for the water gauge tests. This test port plug may not have been re-sealed properly until after the hydrogen purge. This would explain the temporary increase in leakage.

There was also a weather change between the two days, but the leakage seen here in methane was not repeated in the subsequent hydrogen tests.

	Methane 16 January	Methane 17 January
System volume (m^3)	0.389	0.389
Starting Pressure (mbar)	21.32	20.84
Pressure loss (mbar)	0.41	1.70
Time (mins)	13	13
Leak rate (m^3/hr)	7.15×10^{-04}	2.99×10^{-03}
Leak rate (ml/hr)	715	2,988
Ratio 17/16 January	4.18	

Table 8: Test E methane repeat pressure fall off data

5.8 Flexible manometer tests

The standard equipment to test a gaseous system pressure drop is a flexible manometer, colloquially called a water gauge. Similar to a weather glass, a U-shape transparent plastic tube is half filled with water. One point at the top of the U is then attached to the pressurised system and the other point is left exposed to atmospheric pressure. The manometer is held vertically. The pressure displaces the water and the meniscus on the opposite side correlates to a pre-measured pressure value. The minimum pressure drop readable is 0.25 mbar.

The flexible manometer was used by a gas safe consultant (Kiwa's representative 'competent person'), to conduct a comparison test in methane and hydrogen on test E. The test equipment was not included; however, the input ball valve was closed.

These tests were performed immediately after the conclusion of both methane and hydrogen tests (test E).

The result was a drop of approximately 0.5 mbar in methane and a drop of 1.0 mbar in hydrogen over a 13 minute period. These results have an error of ±0.25 mbar. With a system of this volume a pressure drop up to 3.8 mbar is acceptable and would pass a tightness test. The system therefore passes as leak tight to a competent fitter and is at the low end of a readable pressure drop using current approved test equipment.

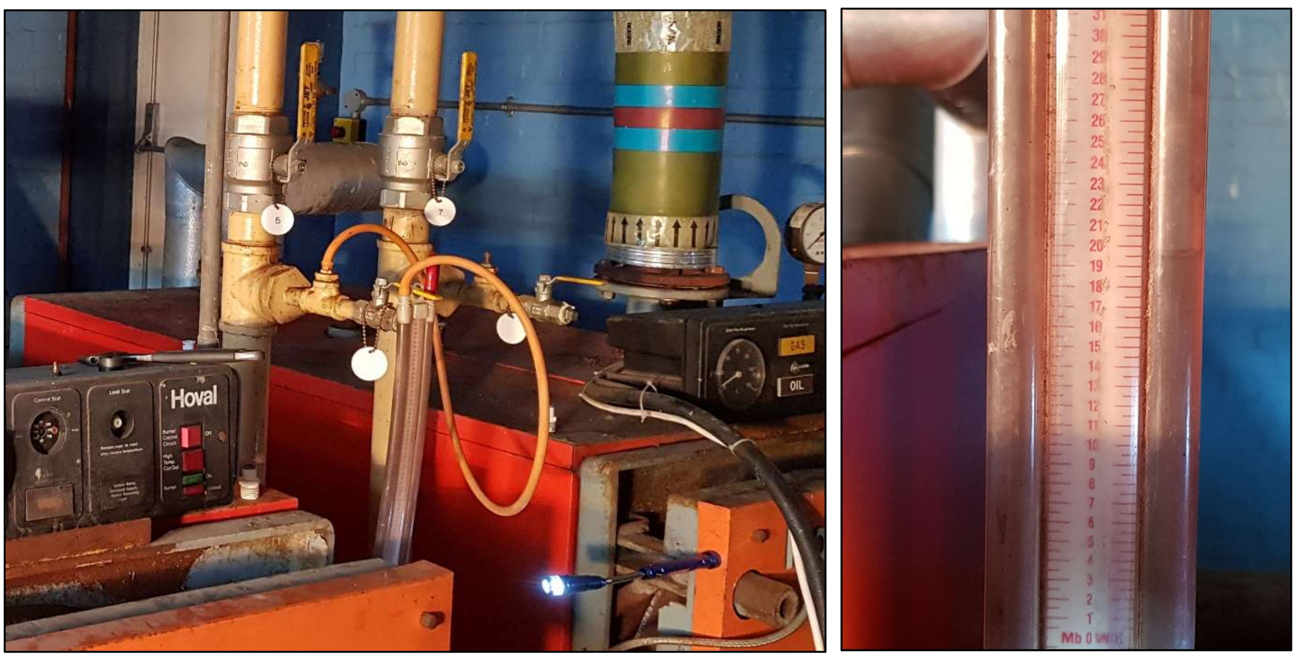


Figure 32: Flexible manometer (water gauge) readings

5.9 Discussion of results

These tests were set up to start with the smallest element of the system and then add each section of the plant room equipment to the test setup incrementally. Test E examines the largest system and encompasses the largest range of possible leaks to the external environment, while test A is the smallest system. A simplistic view is that as the system is extended for each test there are components added that may give additional paths for leakage. One would therefore expect the leak rates to increase as additional sections are added. This simplistic view does not, however, take account for leakage from one section to another via passing valves. A further complication when examining the effects of passing valves is that the system downstream of individual valves may not be at a consistent pressure between the two test runs. The valves themselves have been stroked during the test runs so there is no guarantee that a seeping valve seat will leak the same amount each time it is operated. Finally, the purge plugs had to be removed to facilitate the change of test gases. Any leakage seen at these plugs would be changed by a removal and refitting of the plug further changing the system between test runs. Figure 33 gives an overview of all of the tests and this indicates that there was not this incremental trend of increased leakage throughout the tests.

The only time that the system did exhibit increasing leakage as the tests progressed was during the tests in air. Tests C, D and E show an increase in leakage from section to section. Prior to their operation, the valves were 'as found' and likely to have not been moved since the plant room had been decommissioned. The valve seats are likely to have relaxed and be most likely to seal well. The purge and test plugs were not touched at this point, therefore any leakage from these points would be 'as found' and not have fresh seals. Once the first set of tests was carried out and the purge points were removed to facilitate a change of gases the system would be fundamentally changed.

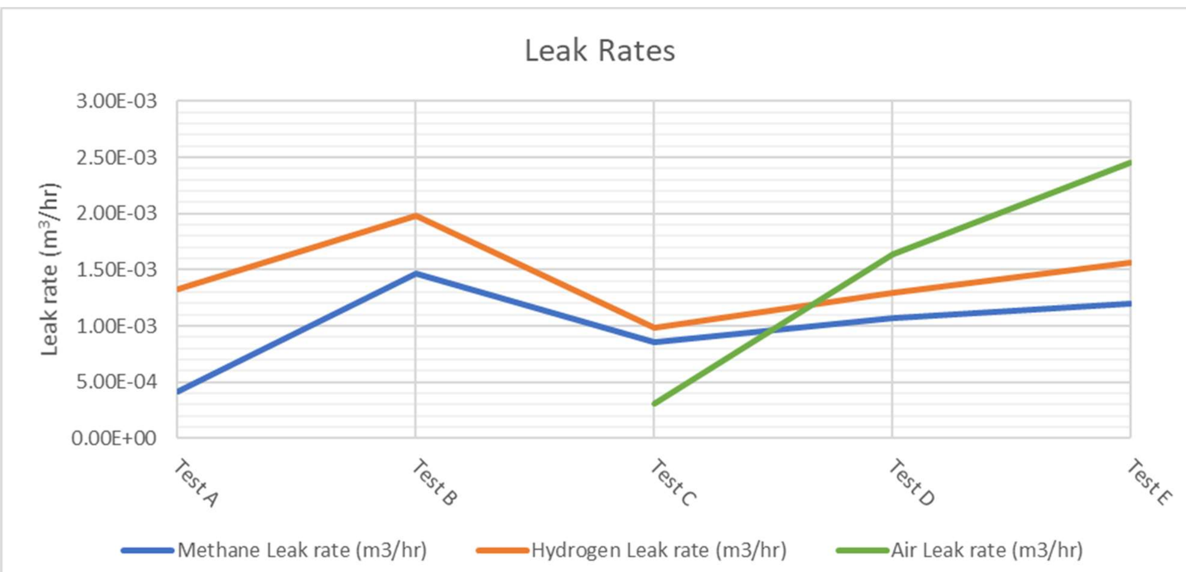


Figure 33: Graphical representation of all leak rates

Test	Methane Leak rate (m^3/hr)	Hydrogen Leak rate (m^3/hr)	Air Leak rate (m^3/hr)
Test A	4.11×10^{-04}	1.33×10^{-03}	
Test B	1.47×10^{-03}	1.98×10^{-03}	
Test C	8.51×10^{-04}	9.86×10^{-04}	3.05×10^{-04}
Test D	1.07×10^{-03}	1.30×10^{-03}	1.63×10^{-03}
Test E	1.20×10^{-03}	1.57×10^{-03}	2.45×10^{-03}

Table 9: Leak rate values

The leak rate decrease from test B to test C in both methane and hydrogen suggests that boiler 1 isolation valve could be responsible for a significant amount of the leakage present in test B in both gases.

The weather, in particular the wind was noticeably gusty on the morning of 17 January. The effects of this were seen in fluctuations on the pressure gauge. This led to discussions on external factors which could be affecting the tests. External factors that may affect results include:

- Atmospheric temperature changes
- Atmospheric pressure changes
- Gas temperature changes
- Wind moving equipment

The ambient pressure and temperature were logged on 17 January and shown in Figure 34, this indicates that although the weather was windy, there was not a significant swing of pressure or temperature over the test period. Periods of sunshine on external pipework may well have a greater effect on internal system pressure.

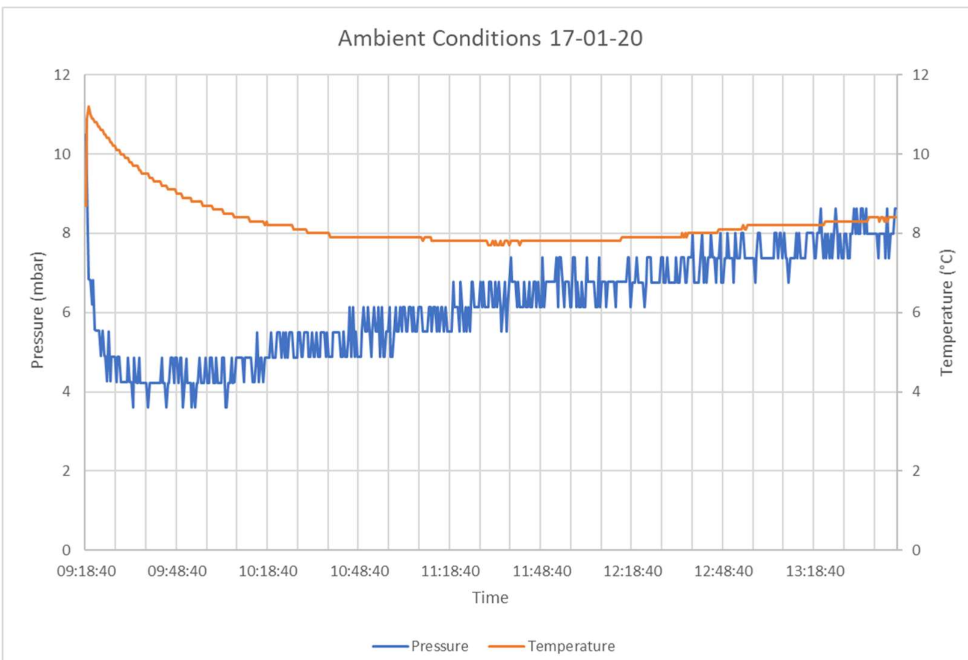


Figure 34: Ambient conditions 17 January 2020

Wind moving equipment would be likely to cause short periods of higher and lower pressure if it changed at all. The length of time the tightness test is carried out for should smooth these fluctuations. The wind could not have caused longer term damage to the test equipment as the equipment tests would have shown any degradation.

The flexible manometer tests showed that all of the leaks found were very small and would be below the rate required to fail a standard tightness test when being commissioned by a gas safe fitter. All investigations in this discussion are therefore below a meaningful level when examining a leaking system.

6 Conclusions

These tests were successful at testing ‘as found’ pipework for leakiness in different gases.

The overall conclusion of the tests is that the system was essentially leak free, and would pass an existing gas tightness test. The data collected indicates that a leak tight system in methane is also leak tight in hydrogen.

It is currently believed that in a standard gas tightness test for this system (as for test E), a test failure would be more than 3.8 mbar pressure drop over 13 minutes. All of the systems tested would have passed a current gas tightness test.

The highly accurate and sensitive recording equipment used for these tests were useful and enabled a detailed investigation into the variation of leaks between different sections. The flexible manometer, however, was able to measure the pressure drop and therefore leak rate of the entire system adequately. There is nothing to indicate that current measuring equipment used by gas fitters in the field require adapting.

The purge between methane and hydrogen did not show a difference on the Gasco seeker used by the gas safe consultant. It remained at 100% flammable gas throughout. This suggests that existing gas detection devices (‘sniffers’) could be used with hydrogen when investigating for leaks. When purging back to nitrogen from hydrogen the gas detection device successfully monitored hydrogen down to safe levels.

7 Return to safe condition

After the tests, the system was returned to a safe condition prior to handing over the site to DIO. This was witnessed by their agent (AECOM), their main contractor (Amey), the Project Wellesley representative and their main contractor, Skanska.

The system was purged of flammable gas in two sections: section 1 and sections 1-5. Section 1 contained the meter and a section of pipe upstream to the ECV. To successfully purge this volume, the SOV was closed and section 1 was pressurised with nitrogen to approximately 100 mbar. The feed was then connected to the purge stack to allow the diluted gas mixture to exhaust. The flammable gas (hydrogen) reading fell to 40% on the first attempt. This process was repeated a total of 6 times until the hydrogen reading did not reduce further than 11%.

Following the purge of section 1, the SOV was opened and the full system purged through the three boiler purge ports. A volume of 0.46 m^3 of nitrogen was used. This is 1.7 times the installation volume, more than the required 1.5 times.

This stage was witnessed amongst others by the SHE Co-ordinator for Worthy Down, Kiwa's representative competent person, and a representative from AECOM as DIO's agent) prior to their immediate handover to Project Wellesley's main contractor Skanska.

The system was then vented to atmospheric pressure and plugged. The automated isolation valve was electrically disconnected. The plant room was then returned to its original state as requested by Skanska.

Figure 36 and Figure 37 are the signed handover of the site, confirming a safe environment remains.

8 Appendix A - risk assessments

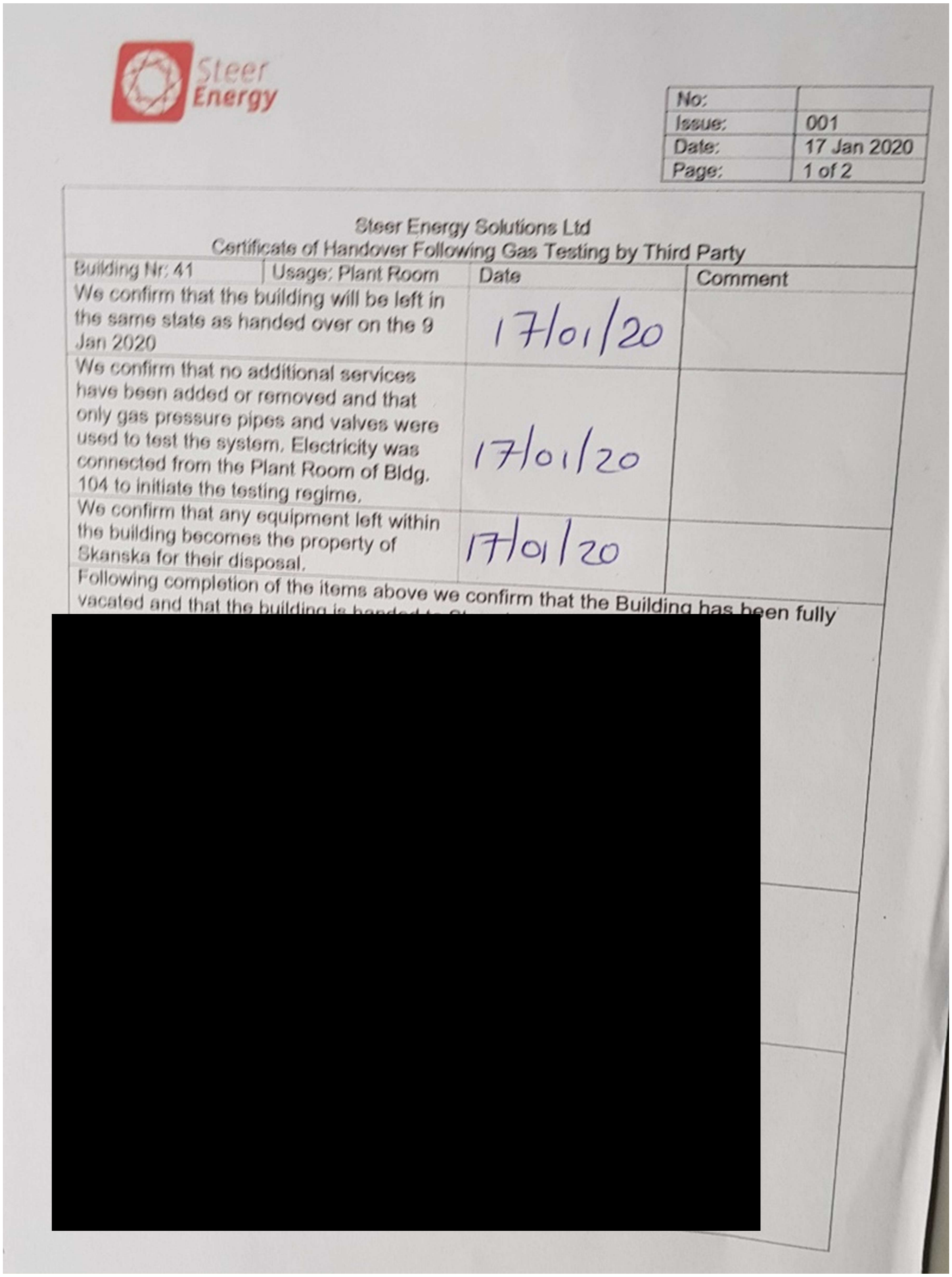
Project / Sale	Hy4Heat
Scope	These are tests involving nitrogen, methane and hydrogen leaks. There will be flammable gases leaking within an enclosed space. Small volumes of gas are used, and with appropriate ventilation of the room, this should not be an issue.
Date for assessment	13/12/2019
Author of assessment	NM
Peer reviewed by	SR

RISK		Likelihood				
		Very Low	Low	Medium	High	Very High
Severity	Very High	5	10	15	20	25
	High	4	8	12	16	20
	Medium	3	6	9	12	15
	Low	2	4	6	8	10
	Very Low	1	2	3	4	5

	Hazard progresses to ...					Risk			Barrier			Risk		
ID	Activity	Energy Source	Event	Consequence	Type	Unmitigated Severity	Unmitigated likelihood	Level	Description	Passive /Active	Initiation / Escalation	Mitigated Severity	Mitigated likelihood	Level
1	Use of experimental rigs	Chemical	Inhalation of gases	Asphyxia	Personnel	Very High	Very Low	5	Listen & smell for any leaks. **Note that gases may not be odourised.** Be aware of the possiblity of leaks	Active	Escalation	Very High	None	0
									Conduct an investigation upon setup of the rig to establish that the system does not leak significantly	Passive	Initiation			
									Monitor flow meters					
									Turn gas off	Passive	Escalation			
									Ensure ventilation of room	Passive	Initiation			
2	Storage of gas cylinders	Pressure	Cylinder falling over, knocking off regulator	Discharge of cylinder	Environment	Medium	Very Low	3	Canisters strapped in at all times (unless moving)	Passive	Initiation	Very Low	Very Low	1
									Use smaller gas bottles	Passive	Initiation			
									Regulators turned off overnight	Passive	Initiation			
									Canisters stored outside during testing	Passive	Initiation			
3	Equipment condition	Electrical	Exposed, faulty wiring causing ignition	Ignition	Personnel	High	Low	8	Ensure equipment is in good condition	Active	Initiation	High	Very Low	4
									No sparking equipment in area of test	Passive	Initiation			
									Installed by competent person	Passive	Initiation			
									Ensure no build up of gas	Active	Initiation			
4	Area management	Kinetic	Slips, trips and falls	injury	Personnel	Very Low	Low	2	Ensure clear working environment	Active	Initiation	Very Low	Very Low	1
									Care with supply and purge hoses/electrical wires	Active	Initiation			
5	Making up test equipment	Kinetic	Splinters of metal, cuts from sharp edges	Cuts	Personnel	Very Low	High	4	Be aware & take care	Active	Initiation	Very Low	Very Low	1
									PPE as appropriate	Passive	Initiation			
6	Unfamiliarity with site		Unknown	Unknown		Medium	Medium	9	Be aware of potential hazards	Active	Initiation	Low	Low	4
									Everyone can stop the tests	Active	Initiation			
7	Speed of planning		Unknown	Unknown		Medium	Medium	9	Be aware of potential hazards	Active	Initiation	Low	Low	4
									Everyone can stop the tests	Active	Initiation			
8	Gas leak	Chemical	Gas Leak	Build up of gas in confined space	Environment	Medium	Medium	9	Ensure ventilation of room	Passive	Initiation	Medium	Very Low	3
									Look at options for detection systems in place	Passive	Initiation			
									Be aware of volume of gas vented	Active	Initiation			
9	Gas leak	Chemical	Build up of gas	Explosion	Personnel	High	Low	8	Ensure ventilation of room	Passive	Initiation	High	Very Low	4
									Look at options for detection systems in place	Passive	Initiation			
									Use smaller gas bottles	Passive	Initiation			
									Be aware of volume of gas vented	Active	Initiation			
10	Purge	Chemical	Gas release	Build up of gas	Environment	Medium	Medium	9	Use purge stack to purge to atmosphere out of building	Passive	Initiation	Low	Very Low	2
									Purge in order of nitrogen then methane then hydrogen	Active	Initiation			
									Don't impede the stack with a 'hat'	Passive	Initiation			
11	Infrastrcture	Electrical	Ignition source	Explosion	Personnel	High	Low	8	Ensure all boiler room infrastructure is electrically disconnected prior to tests	Passive	Initiation	High	Very Low	4
									Ensure no build up of flammable gases	Active	Initiation			
12	Steer equipment	Electrical	Damage to Steer equipment	Stopping of tests	Equipment	Low	High	8	Keep Steer equipment sheltered from weather	Passive	Initiation	Low	Very Low	2
									Sensible cable management	Passive	Initiation			
									Take care when moving around site	Active	Initiation			
13	Interference	Kinetic	Interference by external parties	Damage to tests or equipment	Valid Result	Low	Low	4	Working area enclosed by bunting	Passive	Initiation	Very Low	Very Low	1
									Warning signs in place around the perimeter	Passive	Initiation			
									Only one entrance to the site	Passive	Initiation			

Figure 35: Risk assessment

9 Appendix B - site handover



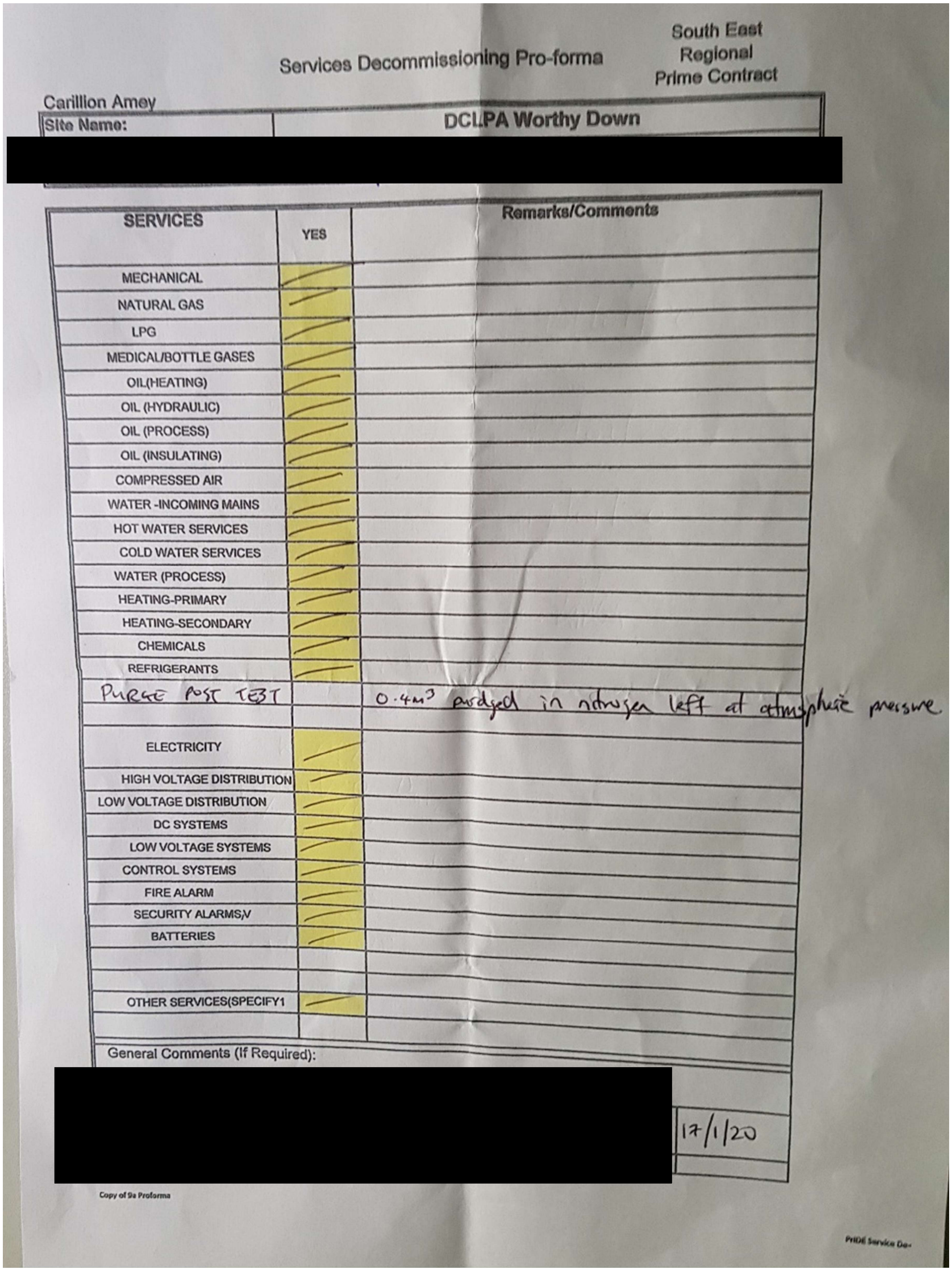
No:	
Issue:	001
Date:	17 Jan 2020
Page:	1 of 2

Steer Energy Solutions Ltd
Certificate of Handover Following Gas Testing by Third Party

Building Nr: 41	Usage: Plant Room	Date	Comment
We confirm that the building will be left in the same state as handed over on the 9 Jan 2020		17/01/20	
We confirm that no additional services have been added or removed and that only gas pressure pipes and valves were used to test the system. Electricity was connected from the Plant Room of Bldg. 104 to initiate the testing regime.		17/01/20	
We confirm that any equipment left within the building becomes the property of Skanska for their disposal.		17/01/20	

Following completion of the items above we confirm that the Building has been fully vacated and that the building [redacted]

Figure 36: Hand over sheet 1



Services Decommissioning Pro-forma

South East Regional Prime Contract

Carillion Amey

Site Name:	DCLPA Worthy Down

[redacted]

SERVICES	YES	Remarks/Comments
MECHANICAL	✓	
NATURAL GAS	✓	
LPG	✓	
MEDICAL/BOTTLE GASES	✓	
OIL(HEATING)	✓	
OIL (HYDRAULIC)	✓	
OIL (PROCESS)	✓	
OIL (INSULATING)	✓	
COMPRESSED AIR	✓	
WATER -INCOMING MAINS	✓	
HOT WATER SERVICES	✓	
COLD WATER SERVICES	✓	
WATER (PROCESS)	✓	
HEATING-PRIMARY	✓	
HEATING-SECONDARY	✓	
CHEMICALS	✓	
REFRIGERANTS	✓	
PURGE POST TEST		0.4m³ purged in nitrogen left at atmospheric pressure
ELECTRICITY	✓	
HIGH VOLTAGE DISTRIBUTION	✓	
LOW VOLTAGE DISTRIBUTION	✓	
DC SYSTEMS	✓	
LOW VOLTAGE SYSTEMS	✓	
CONTROL SYSTEMS	✓	
FIRE ALARM	✓	
SECURITY ALARMS,V	✓	
BATTERIES	✓	
OTHER SERVICES(SPECIFY1	✓	

General Comments (If Required):

[redacted] 17/1/20

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PRIDE Service De-

Figure 37: Hand over sheet 2

10 Appendix C – testing timeline

This chapter gives a brief overview of activities with approximate times.

10.1 9 January 2020

- 09:00 arrived on site
- 09:45 safety briefing with SHE coordinator for Worthy Down and 4Cs induction. SHE coordinator noted that the procedures were missing emergency contact numbers / details. These were noted down and added to the procedures for the second site visit
- 10:30 arrived at building 41, unpacked equipment and set up site working with table, chairs and temporary shelter
- 10:45 Toolbox talk and worked through the risk assessment: Gas Safe consultant identified the need for continuous electrical bonding if we were to disconnect any of the pipework at the meter. This was noted on the risk assessment
- 11:00 Set up electrical supplies to the workspace for computers
- 11:15 Gas Safe consultant carried out a gas assessment of the site pipework:
  - Boiler room side of the meter isolation valve was 9% LEL
  - Mains supply side of the meter isolation valve was 18% LEL

A discussion was held and it was decided that since the system was well below LEL with only residual methane in the system we were safe to work with air for the initial tests.

All testing carried out on 9 January 2020 was therefore done using compressed air. No purging or exchange of gas was carried out at this stage.

- 11:45 Compressor was charged up and connections made to the test point immediately after the meter in the meter cabinet
- 12:15 Testing commenced

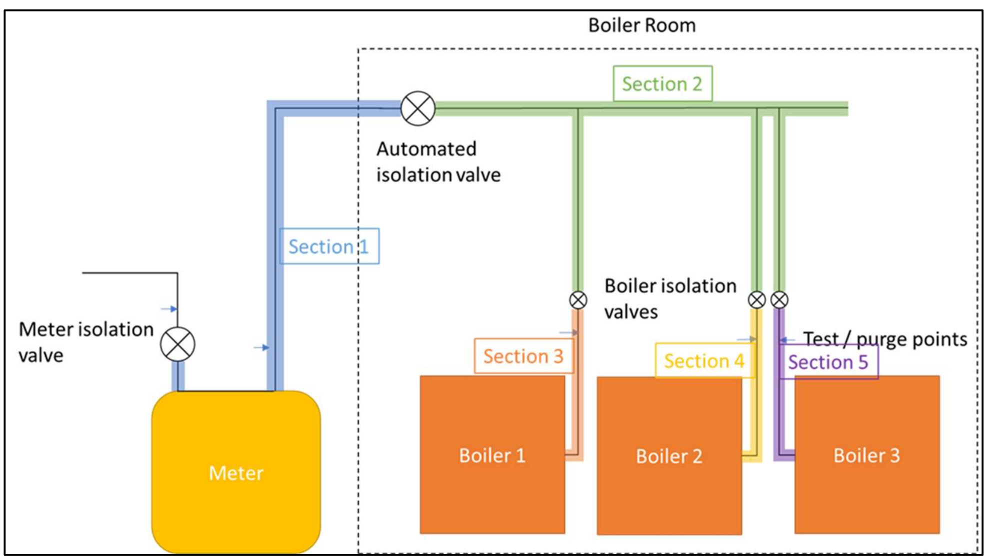

Figure 38: Boiler room schematic

- 12:25 **Test A** - section 1. From the meter isolation valve to electrically operated isolation valve. 20 mbar tightness test
- 13:15 Wiring to electric isolation valve completed and tested

- 13:38 **Test B** - section 1 and section 2. From the meter isolation valve to all three boiler isolation valves. 20 mbar tightness test
- 15:00 **Equipment test** - test on Steer logging equipment up to ball valve on injection point to eliminate small system leak. 70 mbar tightness test on logging equipment
- 15:13 **Test C** - sections 1, 2 and 3. From meter isolation valve to boiler 1. 20 mbar tightness test
- 15:42 **Test D** - sections 1, 2, 3 and 4. From meter isolation valve to boilers 1 and 2. 20 mbar tightness test
- 16:15 **Test E** - sections 1, 2, 3, 4 and 5. From meter isolation valve to all three boilers. 20 mbar tightness test
- 16:48 **Equipment test** - test on Steer logging equipment to confirm good test system. 70 mbar tightness test on logging equipment
- 17:00 Packed up and made site safe
- 17:30 Leave site

10.2 16 January 2020

Times are approximate. These tests closely followed the Test plan.

- 09:30 Arrive on site
- 09:45 Site safety talk
- 10:00 Equipment set up and site management (delay caused by connectivity issues)
- 13:00 All equipment set up. Site cleared and perimeter established
- 14:15 Nitrogen purge
- 14:30 Nitrogen equipment tightness test
- 14:35 Methane purge
- 14:45 Methane equipment tightness test E1
- 15:00 Methane **test A**
- 15:30 Methane **test B**
- 16:00 Methane equipment tightness test E2
- 16:05 Methane **test C**
- 16:25 Methane **test D**
- 16:50 Methane **test E**
- 17:15 Methane equipment tightness test E3
- 17:15 Methane system tightness test using water gauge (manometer)
- 17:30 Packed up, site made safe
- 18:00 Leave site

10.3 17 January 2020

- 08:45 Arrive on site
- 09:00 Equipment set up
- 09:15 Methane equipment tightness test E3 repeat
- 10:30 Methane **test E** repeat for continuity
- 10:50 Hydrogen purge
- 11:00 Hydrogen equipment tightness test E1

- 11:05 Hydrogen **test A**
- 11:40 Hydrogen **test B**
- 12:15 Hydrogen equipment tightness test E2
- 12:20 Hydrogen **test C**
- 12:45 Hydrogen **test D**
- 13:10 Hydrogen **test E**
- 13:25 Hydrogen equipment tightness test E3
- 13:30 Hydrogen system tightness test using water gauge (manometer)
- 14:00 Purge to nitrogen (witnessed)
- 14:20 Site handover to Defence Infrastructure Organisation and witnessed by their agent AECOM, the Project Wellesley representative and the main contractor, Skanska
- 14:30 Packed up
- 16:00 Leave site

11 Appendix D - Gas leak theory from Hy4Heat WP7-Lot1 Final Report

This appendix reproduces the gas leak theory section from the Hy4Heat WP7-Lot1 Final Report.

11.1 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

11.1.1 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[1]	1.4	1.32	1.41	-
Gas Density[2]	1.226	0.680	0.0852	kg/m^3
Absolute Dynamic Viscosity[3]	1.80×10^{-05}	1.08×10^{-05}	8.7×10^{-06}	Pa.s
Universal Gas Constant[4]	287	518	4124.2	J/kgK

Table 10: Specific gas properties

11.1.2 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 11, 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.

[1] 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.
[2] Calculated at 15 Deg C and 1 atm from https://www.engineeringtoolbox.com/gas-density-d_158.html
[3] Calculated at 15 Deg C and 1 atm from https://www.engineeringtoolbox.com/gases-absolute-dynamic-viscosity-d_1888.html
[4] https://www.engineeringtoolbox.com/individual-universal-gas-constant-d_588.html

			H_2	Ratio	CH_4
Model			$\mu = 0.870 \times 10^{-5}$ Pa.s	1 : 1.24	$\mu = 1.08 \times 10^{-5}$ Pa.s
			$\rho = 0.0852$ kg/m^3	1 : 7.98	$\rho = 0.680$ 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 11: Ratios from flow models

Table 11 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.

11.1.3 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 γ= *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.

11.1.4 Leak flow

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

$$\dot{m} = C_d\, A_2 \sqrt{2\, \rho_1\, P_1 \left(\frac{\gamma}{\gamma - 1}\right) \left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{\gamma}} - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma+1}{\gamma}}\right]}$$ [5]

Where C_d, coefficient of discharge,

$$0.6 \leq C_d \leq 0.85$$ [6]

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:

$$\dot{m} = C_d\, A_2 \sqrt{\gamma\, \rho_1\, P_1 \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{\gamma-1}}}$$ [7]

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.

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

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

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

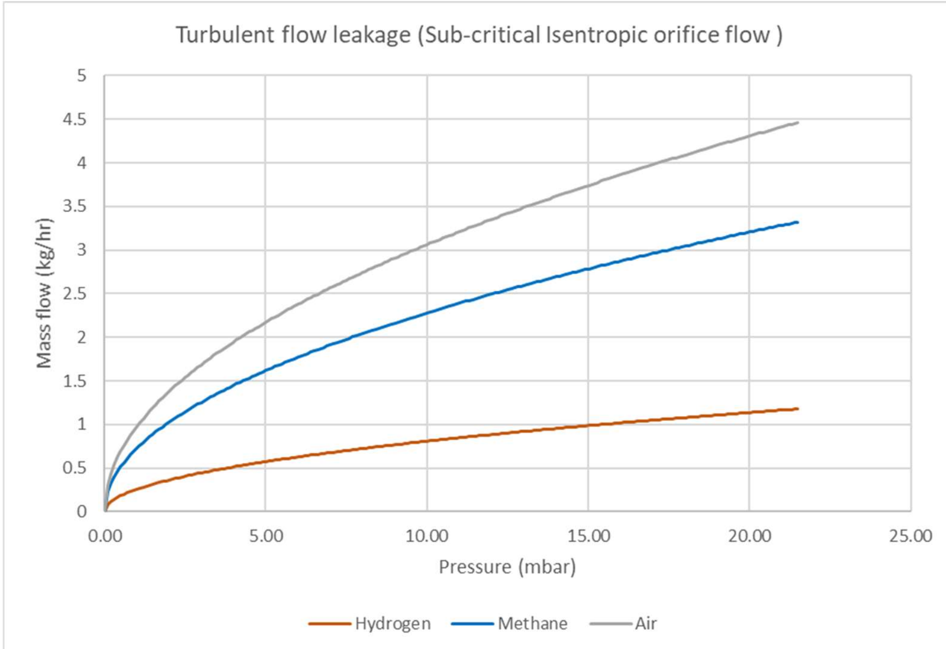

Figure 39: Mass flow vs pressure for turbulent flow regime

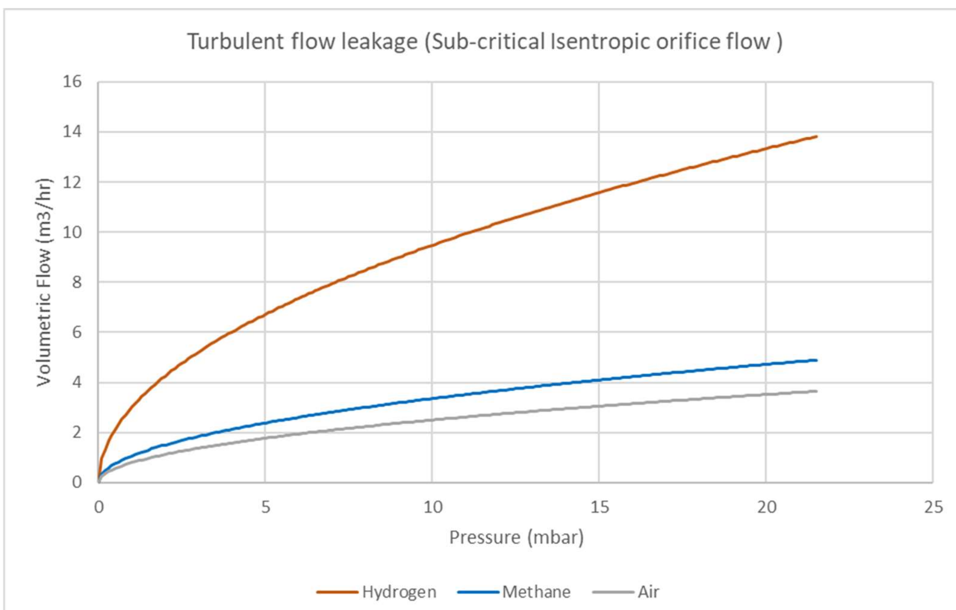

Figure 40: Volumetric flow vs pressure for turbulent flow regime

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.

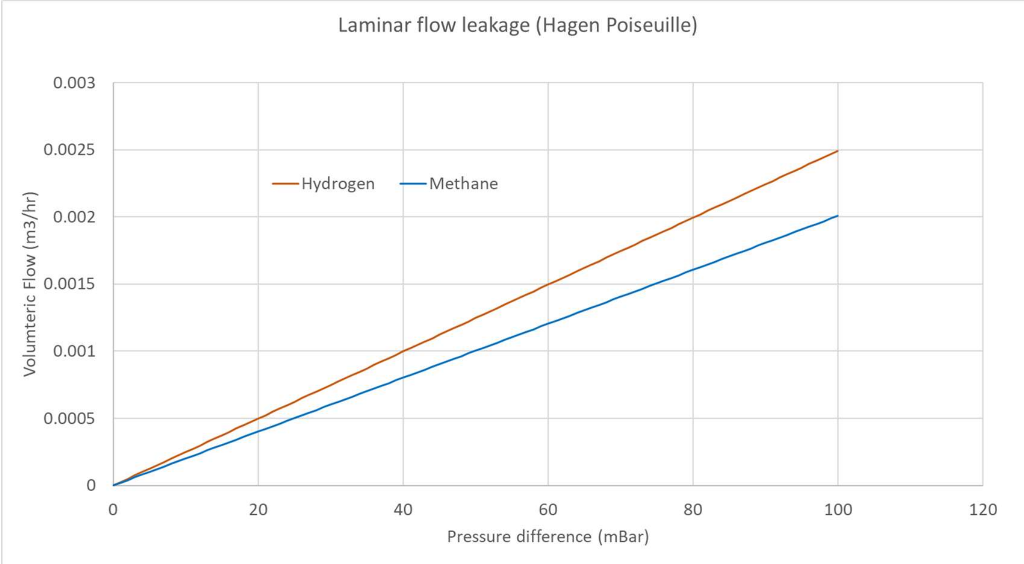

Figure 41: Volumetric flow vs pressure for laminar flow regime

An example of laminar flow calculations (using Hagen Poiseuille) has been shown in Figure 41 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 41 before moving towards the volumetric flow shapes given in Figure 40.

11.1.5 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 42 outlines how Reynolds number changes as the leak hole sizes increase for a range of flow rates in Hydrogen and Methane.

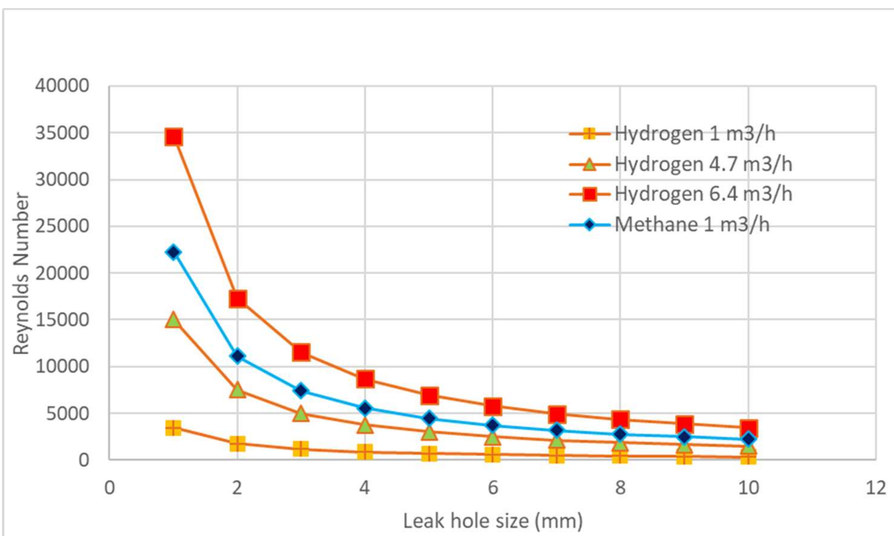

Figure 42: Demonstrating how Reynolds number changes with leak size

Finally, we can plot Reynolds number against velocity for a given pipeline diameter (20mm) as shown in Figure 43. This indicates that the transition for hydrogen is always later than for methane given the same flow conditions.

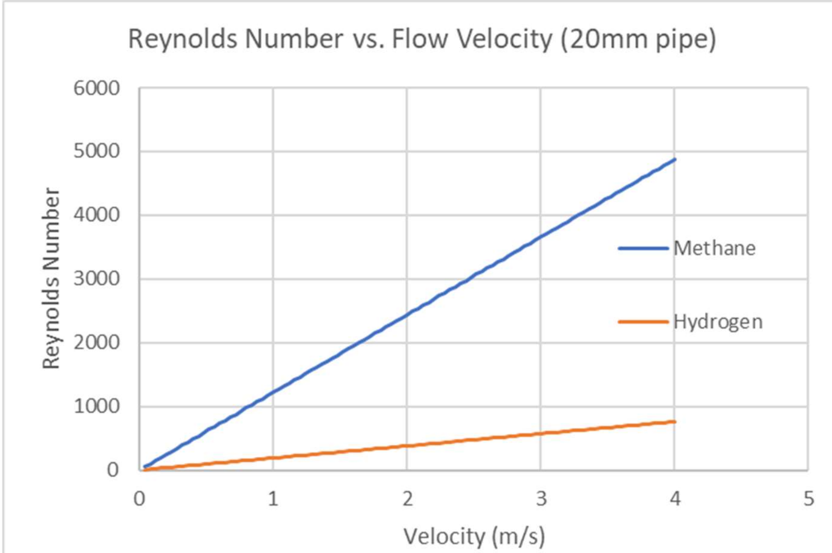

Figure 43: Reynolds Number against Velocity

11.2 Losses

Head losses are generally the result of two mechanisms:

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

11.2.1 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.

11.2.2 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[8]. 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.

11.3 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

11.3.1 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 44 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.

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

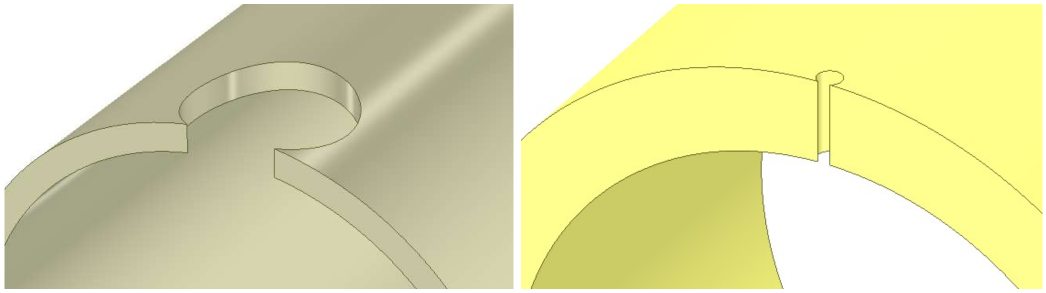

Figure 44: Thin wall hole in copper and thick wall hole in MDPE

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.

11.3.2 Circumferential and longitudinal cracks

Crack defects have width and length which are very different from each other, Figure 45. 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.

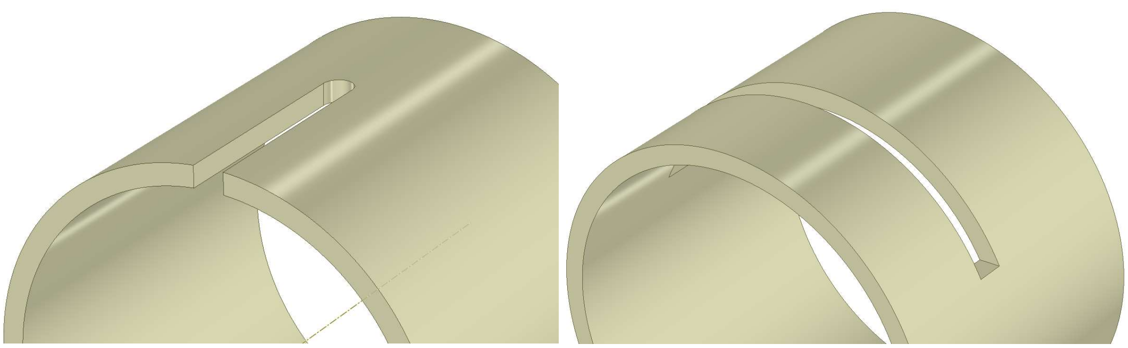

Figure 45: Longitudinal and circumferential cuts

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.

11.3.3 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 46 and will have a significantly restricted flow compared to the large damage hole and crack defects.

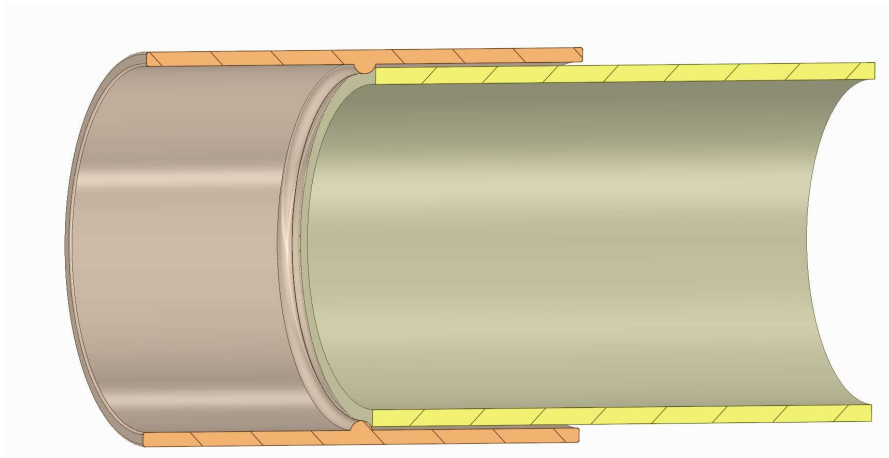

Figure 46: Annular gap leak

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.

11.3.4 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 47, and in greater detail in Figure 48. 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.

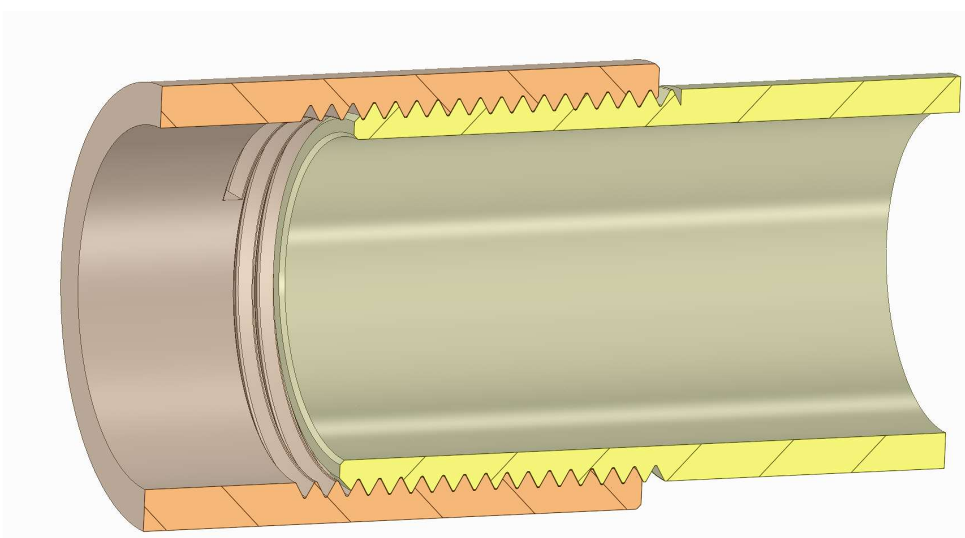

Figure 47: Helical Thread Leak

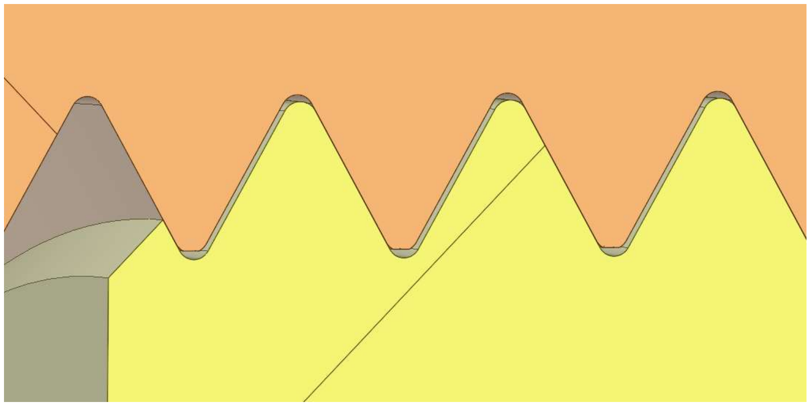

Figure 48: Detail of thread leak path

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.

11.3.5 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.

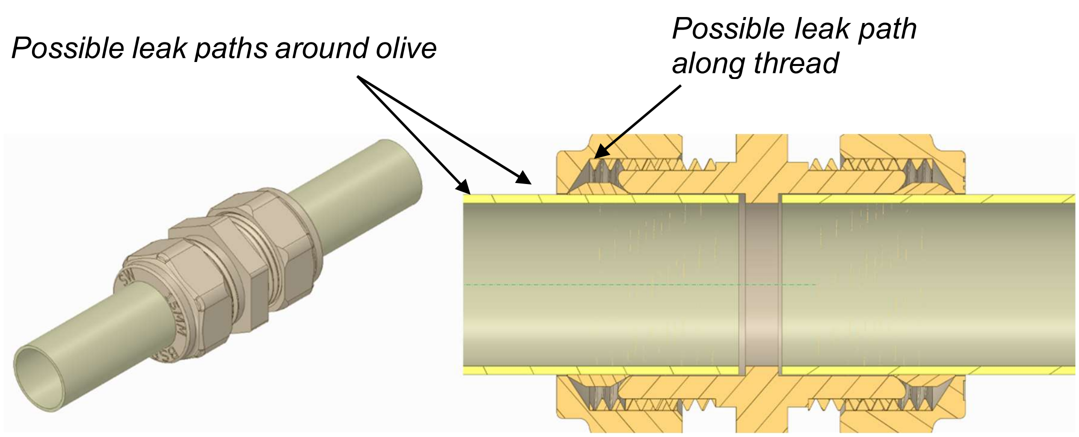

Figure 49: 15 mm compression joint and sectional view showing leak path

12 Appendix E - ifm pressure gauge datasheet

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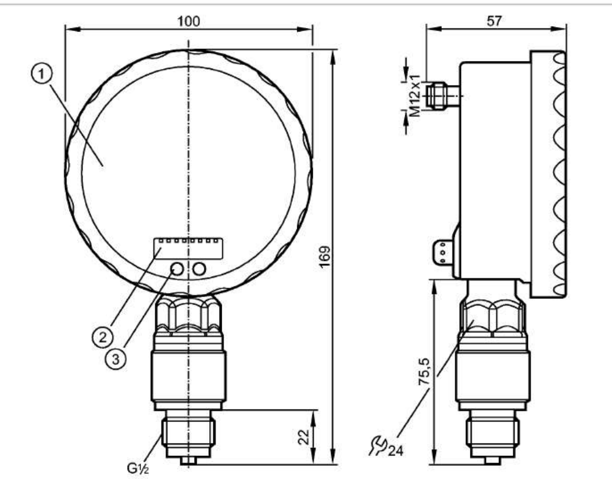
PG2489

PG-,10BREB12-MFRKG/US/ /P

Pressure sensors



1: Analogue display
2: 4-digit alphanumeric display
3: Touch button (programming button)

Made in Germany

Product characteristics
Electronic pressure sensor with analogue display
Connector
Analogue display 0...350° rotatable
Resolution 0.25%
Pointer not visible when unit disconnected
Process connection: G ½
2 outputs OUT1 = switching output OUT2 = analogue output
analogue display, 4-digit alphanumeric display
Measuring range: -5...100 mbar / -2.00...40.16 inH2O

Application			
Application		Type of pressure: relative pressure Liquids and gases	
Pressure rating		4000 mbar	1606 inH2O
Bursting pressure min.		30000 mbar	12044 inH2O
Medium temperature	[°C]	-25...80	

Electrical data		
Electrical design		DC PNP/NPN
Operating voltage	[V]	18...32 DC
Current consumption	[mA]	70; (24 V)
Insulation resistance	[MΩ]	> 100 (500 V DC)
Protection class		III
Reverse polarity protection		yes

Outputs

efectorsoo

PG2489

PG-,10BREB12-MFRKG/US/ /P

Pressure sensors

Output	2 outputs OUT1 = switching output OUT2 = analogue output	
Output function	1 x normally open / closed programmable + 1 x analogue (4...20 / 20...4 mA, scalable)	
Current rating [mA]	250	
Voltage drop [V]	< 2	
Short-circuit protection	pulsed	
Overload protection	yes	
Switching frequency [Hz]	75	
Analogue output	I: 4...20 mA (Ineg: 20...4 mA)	
Max. load [Ω]	I / Ineg: max. (Ub - 10 V) x 50	
Measuring / setting range		
Measuring range	-5...100 mbar	-2.00...40.16 inH2O
Setting range		
Set point, SP	-4.6...160.0 mbar	-1.84...64.24 inH2O
Reset point, rP	-5.0...159.6 mbar	-2.00...64.08 inH2O
Analogue start point, ASP	-5.0...135.0 mbar	-2.00...54.24 inH2O
Analogue end point, AEP	20.0...160.0 mbar	8.00...64.24 inH2O
in steps of	0.2 mbar	0.08 inH2O
Accuracy / deviations		
Accuracy / deviations (in % of the span) Turn down 1:1		
Switch point accuracy	< ± 0.6	
Characteristics deviation *)	< ± 0.35 (BFSL) / < ± 0.6 (LS)	
Hysteresis	< ± 0.5	
Repeatability **)	< ± 0.1	
Long-term stability ***)	< ± 0.1	
Temperature coefficients (TEMPCO) in the temperature range 0...70° C (in % of the span per 10 K)		
Greatest TEMPCO of the zero point	< ± 0.3	
Greatest TEMPCO of the span	< ± 0.3	
Reaction times		
Power-on delay time [s]	6	
Min. response time switching output [ms]	9	
Damping for the switching output (dAP) [s]	0.01...30	
Damping for the analogue output (dAA) [s]	0.01...30	
Step response time analogue output [ms]	28	
Integrated watchdog	yes	
Environment		
Ambient temperature [°C]	-20...80	
Storage temperature [°C]	-40...100	
Protection	IP 67 / IP 69K	
Tests / approvals		
EMC	EN 61000-4-2 ESD: 4 kV CD / 8 kV AD EN 61000-4-3 HF radiated: 10 V/m	

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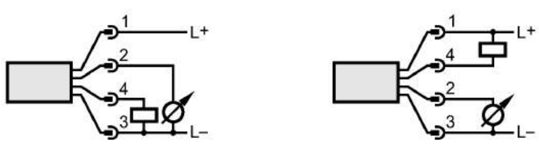
PG2489

PG-,10BREB12-MFRKG/US/ /P

Pressure sensors

	EN 61000-4-4 Burst: 2 kV EN 61000-4-5 Surge: 0.5/1 kV EN 61000-4-6 HF conducted: 10 V	
Shock resistance	DIN IEC 68-2-27: 50 g (11 ms)	
Vibration resistance	DIN IEC 68-2-6: 20 g (10...2000 Hz)	
MTTF [Years]	103	
Mechanical data		
Process connection	G ½	
Materials (wetted parts)	ceramics (Al2 O3); FPM; stainless steel 316L / 1.4404	
Housing materials	stainless steel 316L / 1.4404; PA; FPM (Viton); PTFE; viewing glass: laminated safety glass 4 mm	
Switching cycles min.	100 million	
Weight [kg]	0.609	
Displays / operating elements		
Display	Display unit 2 x LED green Switching status LED yellow Switch points LED ring Function display 4-digit alphanumeric display Measured values analogue display, 4-digit alphanumeric display	
Extended display range (max.)	160 mbar	64.24 inH2O
Electrical connection		
Connection	M12 connector; Gold-plated contacts	

Wiring



Remarks	
Remarks	*) BFSL = Best Fit Straight Line switch point accuracy in the extended display range: 1.5 % of the span **) with temperature fluctuations < 10 K ***) in% of the span / 6 months
Pack quantity [piece]	1

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