PIPELINE SYSTEMS FOR THE HYDROGEN ERA

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ABSTRACT

There are many advantages to introducing hydrogen into the gas grid, especially for industry, domestic heat and heavy-duty transport applications. On site, small scale hydrogen production is costly and transporting hydrogen in tankers to fuel filling stations is highly inefficient. Hydrogen as a key element of achieving net zero is now being taken very seriously with major projects in the UK and around the world. The use of hydrogen in converted natural gas pipelines, especially at high percentage levels is relatively untried from the perspective of long-term pipeline integrity. There is a risk of pipeline life being adversely affected by hydrogen embrittlement. The extent of this risk requires quantification before repurposing can be implemented.

The work presented includes pressure cycling trials with 30% hydrogen rich methane gas mixes using full scale 300mm diameter pipe in a 6m loop configuration. The pressure cycling regime of 45-70bar was derived from historical records of pressure fluctuations in the UK gas transmission grid managed by National Grid and attempted to accelerate 50 years of pressure cycles in a six-month test period. Two types of pipeline were included in the trial consisting of X52 carbon steel pipe with girth welds and MASiP, a new type of polymer lined pipe reinforced with high strength steel strip.

This paper presents project objectives, challenges, results and data after six months exposure, with recommendations for future trials. The results showed no significant changes in the performance of the pipes tested but did show significant changes to the elongation, Charpy and hardness properties of x52 steel test coupons stored within the pipe- but not tensile strength. These results support the view that risk mitigation should include quantitative fatigue life evaluations with a new hydrogen specific materials data base as an evidential basis for risk evaluations, especially under cyclic stress conditions.

1. INTRODUCTION

National Grid (NG) needs to understand the implications that a hydrogen rich gas mix may have on the existing pipeline network. The primary network is the National Transmission System (NTS) which comprises ~7600km of welded pipeline in a range of material grades between X42 and X80. Different welding specifications have been used in the past 40 years and girth welds with different specifications may behave differently when encountering hydrogen gas.

There are differences in chemical and physical behaviour between methane and hydrogen gas. The suitability of the current network to transport hydrogen needs to be assessed across a multitude of aspects, including: general operation of the overall network; compatibility with hydrogen of the materials in the network (e.g. pipeline steels, welds and gaskets); functionality of components (e.g. valves, meters and compressors); and safety zones and procedures. The use of hydrogen-methane blends offers a compromise between decarbonisation and maintaining functionality of the current network and a useful step to potential 100% conversion to hydrogenAdditionally asessing the impact of various blend concentrations helps to understand the limits of the current network and determine the scale of retrofit required.

Hydrogen embrittlement (HE) in steel is a process by which the ingress of hydrogen atoms can lead to a degradation of mechanical properties caused by the exposure of a material to a hydrogen containing environment. The literature [1,3,5,7] evidence is that exposure of steel materials in the range x42 to x70 to hydrogen at gas pressures above 20bar can lead to a reduction in elongation (ie a reduction in ductility) and order of magnitude increases in fatigue crack growth rate. However tensile strength does not appear to be similarly affected. Most literature studies were performed in the laboratory and not with full scale pipe trials and so although the literature clearly does show an effect, the interpretation of this effect in real life pipeline operational conditions needs to be carefully interpreted before being translated into a risk assessment for pipelines. The literature indicates that severity and mechanisms of HE in steel depend on several factors, hydrogen concentration and availability of atomic hydrogen (H^+) (as opposed to molecular hydrogen), mechanical stress - especially cyclic loading and the composition and microstructure of the steel.

Regarding the effect of hydrogen on polymers, 10 year pipe trials of polymer pipes with hydrogen transport [2] report no evidence of any effect on polymer mechanical properties. This is the expected result because, unlike steel, there is no clear molecular mechanism for complex formations that could cause embrittlement. However, the permeation rate of hydrogen through polymer pipe walls will be faster than that of methane because it is a smaller molecule. This needs to be considered in pipeline system design- especially the design of end fittings.

2. PROJECT OBJECTIVES

The overall objective was to evaluate the durability of pipeline materials using realistic full scale pipe tests and a gas mix with a high percentage of hydrogen. A pipe loop was designed using 300mm diameter pipe sections and an ability to provide an extended period of gas pressure cycling. The use of realistic pressure cycling conditions is intended to help qualify the pipeline systems tested for service in gas pipelines where high percentages of hydrogen gas are to be used.

One specific objective was to investigate the resistance to hydrogen embrittlement of a conventional steel (X52) with commonly used girth welds. The primary concern is that the phenomenon of hydrogen embrittlement may cause unexpected or early failure mechanisms especially in older pipe sections with less stringent girth weld specifications.

Published literature suggests that if hydrogen ions can penetrate into steel then embrittlement can operate as a form of stress corrosion cracking causing a reduction in fatigue life. Under wet conditions, especially with cathodic protection there is a mechanism for hydrogen embrittlement and this is clearly a risk – especially for directly exposed welds between steel sections when the weld specifications may have been of a less developed nature than current specifications. Any sort of weld defect would be expected to be especially vulnerable.

The project objectives aimed at conducting realistic but accelerated pressure cycling to provide an element of fatigue but also realistic conditions with hydrogen gas present under pressure.

Two different pipeline systems were included in the trials (a) standard X52 sections with girth welds and (b) a new pipeline system with a polymer liner pipe that prevents direct contact between hydrogen and steel.

The flow loop design was developed to resemble a real-life scenario as much as possible. Pressure cycling was designed to simulate pressure cycles likely in service with an acceleration factor based on National Grid data of the past 5 years of pressure fluctuations in the UK gas transmission grid with the aim of simulating many years of service in a short test period.

The project that is reported on in this paper performed pressure cycling trials with hydrogen rich methane gas mixes and 100% hydrogen in two systems.

3. CHALLENGES WITH HYDROGEN GAS

Generic effects of Hydrogen

The propensity to hydrogen degradation in pipelines depends on a complex interaction of mechanical, material and environmental factors such as:

- The steel grade and microstructure
- The steel’s strength
- Applied and residual stress levels
- Loading conditions (slow rate, high rate, cyclic)
- The occurrence of plastic strain
- The presence of crack-like defects and other stress concentrating features

- The source of hydrogen (gaseous or ionic)
- Gas pressure
- Temperature
- Other gaseous elements which may enhance (e.g. H2S) or impede (e.g. O, CO) hydrogen pickup

One of the challenges with hydrogen gas is that it has a wider combustion range than natural gas therefore any potential leakage could be significant. However, the gas will disperse more readily than methane as it is lighter and so the risk is reduced. A better understanding of fatigue mechanisms is therefore a key challenge so that pipeline life cycle predictions can be better quantified than in the past. In the past there has been a tendency to overdesign to meet internal pressure requirements and safety margins driven by codes and standards based on long established practice. The sensitivity to the risks of hydrogen make this engineering philosophy less tenable. Using pipelines for hydrogen may change the primary failure mode as existing pipelines were not designed specifically for hydrogen gas. The key challenge in that context is now crack growth in existing welds under hydrogen pressure cycling, its possible acceleration and impact on long term fatigue life.

A challenge with testing a mix of hydrogen and methane was that the partial pressures are different which complicates the adjustments needed to the volume of gas in the pipe loop to always maintain the pressure range and the gas mix.

4. PIPE SYSTEMS UNDER TEST

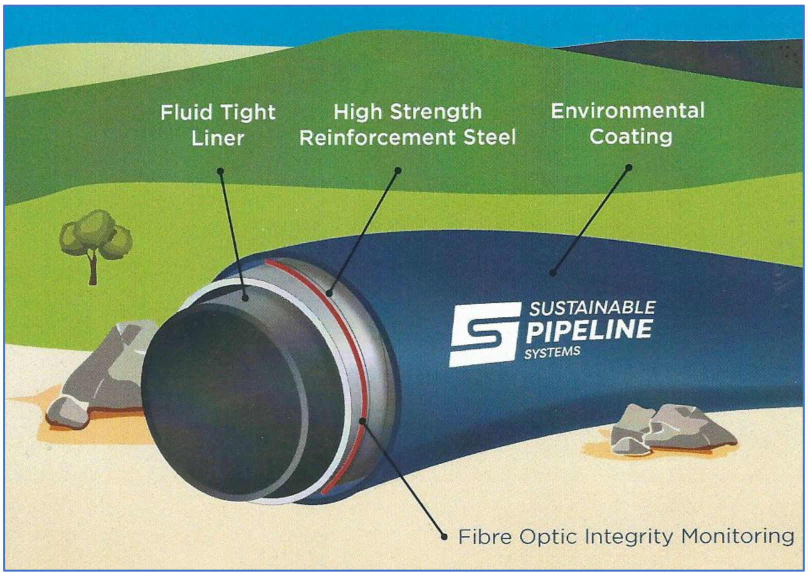
4.1 X52 Pipe

This was standard 12-inch diameter 12.7mm wall thickness pipe manufactured in 2010. Prior to the test 2 girth welds were inserted to BS 4515 the girth welds were NDT tested and then the pipe section with girth welds was hydrotested to 120bar and recertified. In a standard pipe the steel wall of the pipe provides both the mechanical and chemical resistance to the transported fluid.

4.2 MASIP pipe

This is a continuous pipe system which removes the need for girth welds between pipe sections. The mechanical and chemical resistance functions are separated by means of a layered structure with a polymer liner. Transported gas is prevented from direct contact with the steel mechanical reinforcement layer by means of a 15mm thick polymer liner pipe of HDPE. Two layers of high strength steel strip reinforcement strip with a patented interlock that are spirally wound around the liner pipe. Outside of the reinforcement are 2 layers of corrosion coating protection. Thus, the mechanical resistance of the high strength steel is separated from the chemical resistance of the polymer line pipe. The pipe wall structure also incorporates a helically wound fibre optic cable embedded in the pipe wall with the steel reinforcement. Incorporating the optical fibre into the wall of the pipe means that data on pipe wall strain, pipe movement and external threats is available on a continuous real time basis with a high level of sensitivity. The pipe is manufactured using an automated mobile pipe factory on site leading to large schedule, cost and environmental savings.

Figure 4-1 Structure of MASiP pipe



This is a new category of pipe which is undergoing a range of trials in 2021 for introduction into service in 2022 which is described in more detail in reference [3]. The incorporation of fibre optics into the wall of the pipe means that continuous fatigue life assessments are possible in real time in a relatively automated fashion – using strain monitoring.

5. TEST SETUP AND TRIAL METHODOLOLOGY

The physical test set up is shown below

Figure 5.1 Diagram of Test Loop set-up

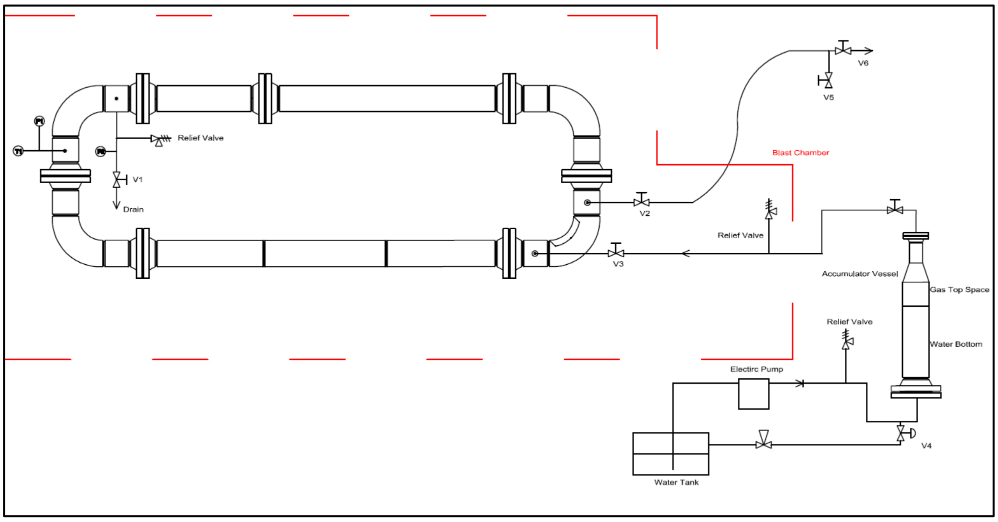


Figure 5.2 Photograph of 12 inch test pipes in test loop

(a) standard X52 on the right and (b) MASiP on the left

The test pipes are shown in Figure 4.2 with the front section removed. This shows of one 4.5m length of x52 pipe on the right with two girth welds and on the left two sections of MASIP pipe one of 1.5m length and one of 3m length. They were connected with standard flanges and elbows of x42 steel.

The trial methodology was based on statistical data from pressure fluctuations in the UK gas grid as shown in Figure 4-3 and summarised in Table 4-1.

Figure 5-3 Pressure fluctuations at 5 locations of UK gas grid over 5 years

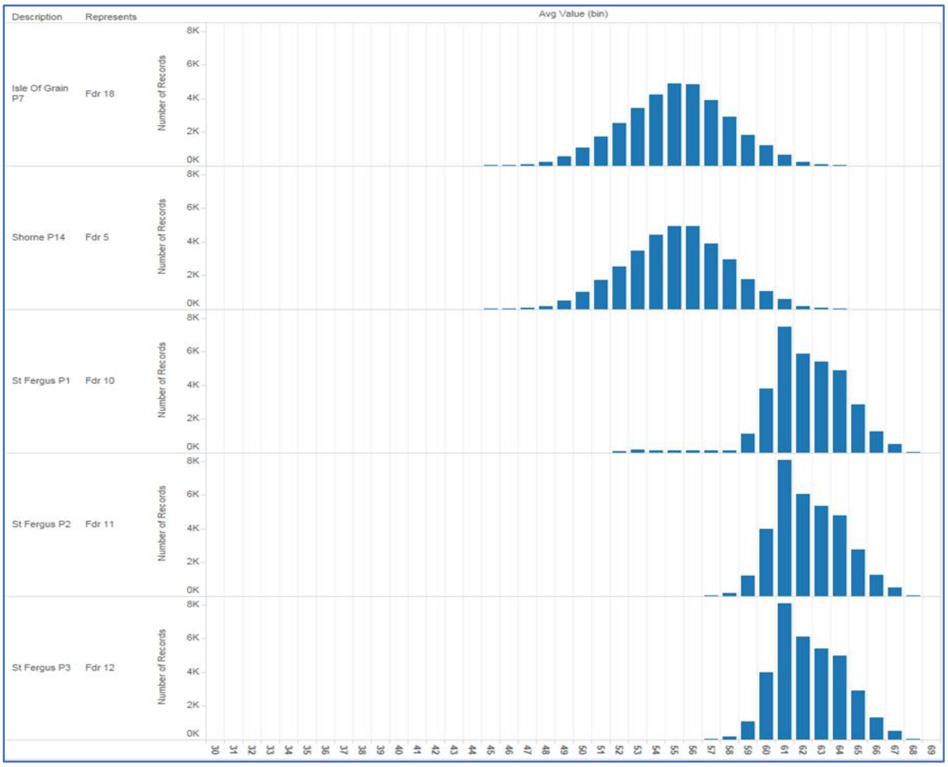


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Table 5-1 Summary of the statistical survey results used in the trials design

Location	Range of Gas Pressure Variations Between July 2015 and July 2019 (barg)		
	Extreme Low	Average	Extreme High
Isle of Grain	45	55	64
Shorne	45	55	64
St Fergus P1	52	61	68
St Fergus P2	57	61	68
St Fergus P3	57	61	68
Overall	**45**	**58.6**	**68**

The statistical study of pressure fluctuations found that over a 5 year period across all of the locations the minimum pressure was 45bar, the maximum pressure was 68 bar and the overall mean pressure was 59bar. The pressure cycling regime for the pipe loop trials was based on this analysis. The gas mix chosen was 30% hydrogen and 70% methane. A set of standard metallurgical coupons was installed on a tray inside the pipe and Figure 4-3 shows the tray inside the pipe after the conclusion of the trial period. There was evidence of some water inside the pipe.

Figure 5-4 Standard test coupon tray inside pipe

Table 5-2 Pressure Cycles used in Pipe trials with 30% hydrogen 70% methane

Cumulative Cycles	Pressure Range (barg)
134	45-55
256	55-70
632	55-70
7261	60-65

The aim in conducting the pressure cycles was to use different stress ranges that were reasonably realistic compared to the ranges from service. The test arrangement was such that the smaller the amplitude of the pressure range the faster the cycle rate that could be achieved. In service it is considered that variations as large as 55 to 70bar will be rare and certainly not more frequent than about 20 per year. Thus 888 cycles at 55-70bar can be said to reasonably represent 50 years life.

6. RESULTS AFTER SIX MONTHS EXPOSURE

The total elapsed time of the pressure cycling programme was 8 months, with pressure cycling gathered for six months. There was no measurable deterioration of any of the pipe sections themselves as measured by strain gauge outputs. Fatigue assessment of the girth welds was carried out and the damage factors were calculated.

Table 6-1 – X52 and X42 Pipe Strain Gauge Values

		Pipe Strain Gauge Locations			
No. of Cycles	**Pressure Range (barg)**	**SG01 (X52) Next to Girth Weld**		**SG02 (X42) - Elbows Extrados of Bend (Centre)**	
		Max Strain (µs)	Min Strain (µs)	Max Strain (µs)	Min Strain (µs)
134	45-55bar				
	Hoop Strain	300	250	500	400
498	55-70bar				
	Hoop Strain	336	257	526	380
6629	60-65				
	Hoop Strain	364	327	507	457

Table 6-2 – SG01 – Girth Weld Fatigue Assessment

Pressure Range (barg)	**No. Of Cycles**	**Cumulative Cycles**	**VM Stress Range (Max-Min) MPa**	**No. of Cycles Allowed at Stress Range**	**Damage Factor**	**Cumulative Damage Factor (<1.0)**
45-55	134	134	19	4176694	3.208E-5	
55-70	498	632	36	627810	7.932E-5	0.001
60-65	6629	7261	55	179209	3.700E-5	0.038

Two sets of mechanical tests were undertaken; the first before the trial and the second from a set of coupons retrieved from the flow loop at the end of the testing programme. Both sets of results are summarised in Table 5-3.

Table 6-3 – Mechanical Test Results for x52 steel samples

Test	Before Trial	After 8 Months Trial	% Change
Tensile (Parent)	471 MPa	466 MPa	-1.06
Tensile (Weld)	482 MPa	481 MPa	-0.21
Tensile (HAZ)	484 MPa	489 MPa	+1.03
Elongation (Parent)	32	29.5	-7.81
Elongation (Weld)	33	29	-12.12
Elongation (HAZ)	38	35.5	-6.58
Charpy Weld Centre Line (Av)	162 J	147 J	-9.26
Charpy Fusion Line (Av)	238 J	233 J	-2.10
Charpy HAZ + 5 mm (Av)	262 J	238 J	-9.16
Vickers Hardness Parent (Av)	157	148	-5.73
Vickers Hardness HAZ (Av)	188	179	-4.79
Vickers Hardness Weld (Av)	202	190	-5.94

From the mechanical testing undertaken, it is noticeable that the more localised measurements show a consistent reduction after the exposure period. Changes of this order of 10% are statistically significant for these types of tests and the detailed test data show less than 4% variation across multiple data points. Tensile strength changes are of the order of 1% but elongations reduce by up to 12% with this greatest change being at the weld. This is consistent with a reduction in ductility.

The results do therefore show significant and consistent reductions in material coupon properties indicating a deterioration in elongation, hardness in weld areas. The changes are greater in weld areas

6.1 MASIP Pipe

For the MASiP pipe sections the above metallurgical tests are not really relevant as it is a composite structure where the steel is also protected from the hydrogen gas by the HDPE polymer liner pipe.

However, some high strength steel coupons of grade Ducol1000 were included in the sample tray and were tested. The results in fact showed no significant change in the high strength steel coupons even in elongation – which remained around 6% with tensile strengths remaining within the range 1050-1200 MPa.

Coupon tests were not performed on the PE100 material used in the polymer pipe but it is intended to cut material from the pipe at a later date.

7. CONCLUSIONS AND RECOMMENDATIONS

There were no pipe failures or deteriorations in pipe performance as measured by strain gauges during the pressure cycling trials which simulated 50 years of the highest stress range cycles experienced in the UK gas grid. From this it is concluded that the effects of hydrogen embrittlement are long term affecting fatigue life and not short term.

The tests showed that there was an observed deterioration in the elongation and other material properties of test coupons of X52 material and the largest effects were found close to the welds. It is concluded that the performance of welds is an important factor for further analysis and potential monitoring when using welded pipe for hydrogen service.

It should be noted that coupons from the flow loop experience much higher stress ranges than pipelines in service and so might be more sensitive to the effects of hydrogen embrittlement than strain gauge measurements of pipe performance.

The girth welds forming part of the wall of the pressurised pipe were not tested during this phase of the programme and so no results are yet available to show if they were more affected than the test coupons. They may be more affected because cyclic stress concentrations at a weld interface is more likely to be affected by hydrogen ingress than an unstressed test coupon.

Because water was observed inside the pipe, there is a potentially accelerated mechanism for hydrogen ions to migrate into the steel coupons and cause deterioration. However, there is a mismatch; the pipe test stress and fatigue damage factors and the stress imposed on test coupons. It can be concluded that deterioration of X52 standard gas transmission pipe is possible due to hydrogen gas at pressures between 45 and 70bar, but that deterioration will not be rapid or sudden but a fatigue phenomenon.

These results agree with available results reported in the literature for steel [1]. A study on X42 grade material HAZs using gaseous hydrogen and nitrogen at 1000 psi (69 bar) [5] showed a 50% decrease in the tearing resistance, and other studies show up to two orders of magnitude crack growth rate. A mechanism has been proposed whereby hydrogen is more likely to be adsorbed and dissolved in the region around a cyclic fatigue crack tip [7] and this seems plausible.

An extensive study of PE 80 and PE 100 polymer gas pipes in Sweden and Denmark after 10 years of hydrogen exposure under pressure has not shown any measurable effect on the polymer pipe [2]. It is concluded that there is no effect on polymeric gas pipes.

It is recommended that material from girth welds forming of x52 pipe under cyclic pressure be subjected to fatigue tests to characterise the effect of hydrogen on fatigue crack growth behaviour in x52 pipe. A good database of the fatigue behaviour of steel exposed to high pressure hydrogen to serve as the basis for pipeline live estimation calculations. This will place pipeline fatigue life on a similar basis to that of critical structures.

It is also recommended that material test pieces are cut from the wall of the MASiP pipe to verify the indication from the literature that there is no effect on the polymer liner pipe and also that permeated polymer molecules do not affect the embedded high strength steel reinforcement

It is generally recommended that pipelines for hydrogen service should be characterised in terms of fatigue life. There are well established procedures for analysing the fatigue lives of structures and this could be adapted for pipelines. This would enable the stress ranges in service to be accelerated in a test environment and fatigue tests could then characterise the rate of deterioration due to hydrogen embrittlement, and from this pipeline life calculations could be carried out.

8. REFERENCES

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