APPROACHES AND METHODS TO DEMONSTRATE REPURPOSING OF THE UK'S LOCAL TRANSMISSION SYSTEM (LTS) PIPELINES FOR TRANSPORTATION OF HYDROGEN

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ABSTRACT

Hydrogen has the potential as an energy solution to contribute to decarbonisation targets as it has the capability to deliver low-carbon energy at the scale required. For this to be realised, the suitability of the existing natural gas pipeline networks for transporting hydrogen must be established. The current paper describes a feasibility study that was undertaken to assess the potential for repurposing the UK's Local Transmission System (LTS) natural gas pipelines for hydrogen service. The analysis focused on SGN's network, which includes 3000 km of LTS pipelines in Scotland and the south of England.

The characteristics of the LTS pipelines in terms of materials of construction and operation were first evaluated. This analysis showed that a significant percentage of SGN's LTS network consists of lower strength grades of steel pipeline that operate at low stresses, which are factors conducive to a pipeline's suitability for hydrogen service. An assessment was also made of where existing approaches in pipeline operation may require modifications for hydrogen. The effects of changes in mechanical properties of steel pipelines on integrity and lifetime as a result of potential hydrogen degradation were demonstrated using fitness-for-purpose analysis.

A review of pipeline risk assessment and Land-Use Planning (LUP) zone calculations for hydrogen was undertaken to identify any required changes. Case studies on selected sections of the LTS pipeline were then carried out to illustrate the potential changes to LUP zones. The work concluded with a summary of identified gaps that require addressing to ensure safe pipeline repurposing for hydrogen, which cover materials performance, inspection, risk assessment, land use planning and procedures.

1.0 INTRODUCTION

Heat policy decisions due by the UK Government in the mid-2020s will determine how heat will be decarbonised. The supply of energy for heat demand is currently dominated by natural gas delivered through the UK's gas infrastructure. All future energy modelling identifies a role for hydrogen in providing decarbonised energy for heat, transport, industry and power generation. There are currently a number of projects within the gas industry looking at the use of hydrogen and carbon capture methods. These projects have included investigating the feasibility of using hydrogen as a fuel, both in a domestic setting and for industrial use. As part of the evidence base it is also important to understand the feasibility of repurposing existing gas transmission and distribution networks to transport either hydrogen or carbon dioxide.

SGN's LTS Futures programme[1] is a national programme investigating the suitability of the above 7 barg (8 bar absolute) LTS for conversion to hydrogen. The programme is aimed at the development of safety, technical and practical evidence to support the use of hydrogen in the LTS. This includes development of a blueprint for repurposing LTS pipelines for hydrogen and live hydrogen trials.

As a first step on the route to developing this evidence base, SGN worked with HSE Science Division on a desk-based study looking at the feasibility of repurposing some of their pipelines within the LTS to transport or store hydrogen, hydrogen blends or carbon dioxide. The aim of the first phase of the LTS programme was to assess the scientific and regulatory feasibility of this repurposing, including both the materials aspects and the risks posed to people by pipeline failure. The current paper describes the hydrogen repurposing aspects of this study.

2.0 AIM AND APPROACH

The aim of this study was to demonstrate a route for repurposing existing LTS pipeline to transport or store hydrogen or hydrogen blends and to develop a scope for testing the assumptions made in the assessment.

Case studies, such as the Granton-to-Grangemouth pipeline, have been used to test the assessment methods and to aid in the identification of any gaps in existing knowledge. The approach detailed below was adopted as, although standards exist for hydrogen applications, a formalised approach or standard for re-purposing conversion of natural gas pipelines to hydrogen currently does not exist. The approach adopted was as follows:

- Review of existing experience in hydrogen pipelines and the latest standards applicable to carrier pipelines for natural gas and hydrogen.
- An evaluation of the materials effects of hydrogen on pipeline integrity.
- Identification of any additional operational aspects that need to be considered.
- Possible changes to consequence distances and regulatory risk assessment.
- Identification of the key areas of risk if hydrogen was to be transported in the LTS.
- Assessment of the safety regulatory processes needed for repurposing for use with hydrogen.
- Case study on a section of the LTS demonstrating how some of these methods could be applied

3.0 HYDROGEN PIPELINE EXPERIENCE

Hydrogen is significantly less dense than natural gas and it has wider flammability limits. As a consequence, leaks from pipelines and associated infrastructure will tend to produce larger flammable clouds for hydrogen. It was shown in [1] that for high-pressure leaks, where the dispersion behaviour is jet dominated, the flammable cloud is likely to extend around three times further for hydrogen than for the equivalent methane release. This has implications for the size of zones needed for hazardous area classification. SGN and the other Gas Distribution networks (GDNs) and National Grid Gas Transmission have partnered with IGEM (Institution of Gas Engineers and Managers) to complete the second phase of the LTS Futures programme, Hytechnical[2], which is currently coordinating an update to their relevant standard [2], to address this issue.

Unlike natural gas, hydrogen does not contain carbon atoms that produce soot or carbon dioxide when the gas is burned, which means that hydrogen flames tend to emit less radiation within the visible

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[1] IGEM LTS Futures, available at https://www.sgn.co.uk/about-us/future-of-gas/hydrogen/lts-futures, accessed 12 April 2021

[2] 'HyTechnical- literature, science review and subsequent revision technical standards for hydrogen pipelines' available at: https://www.smarternetworks.org/project/nia_sgn_0165/print, accessed 12 April 2021

spectrum than natural gas flames – at least for small to medium scale releases [3]. Larger scale releases have been found to produce visible, luminous flames, e.g. the tests reported in [4] involving rupture of a buried 6-inch diameter pipeline with an initial pressure of 60 bar. This difference in behaviour with scale may be partly attributable to the entrainment of soil and dust in the hydrogen flame [4]. However, other above-ground, large-scale jet fire tests also produced bright yellow and orange coloured flames, despite care being taken to ensure no particles were entrained into the flame [5].

The fraction of heat released as radiation was found to be 29% in experiments [4], which was similar to the value found previously for equivalent releases of natural gas alone and blends of hydrogen and natural gas [6]. In tests reported in [5] the radiative fraction was found to scale with the size of the release, increasing from 15 – 22% for a small orifice (20.9 mm in diameter) to 22 – 32% for a larger orifice (52.5 mm in diameter). The release pressure was 60 bar in both cases.

The laminar burning velocity for hydrogen is roughly an order of magnitude higher for hydrogen than methane (3.2 m/s versus 0.37 m/s), meaning that hydrogen explosions will tend to be more severe than natural gas explosions. There is some evidence that delayed ignition of hydrogen releases from pipelines could lead to appreciable explosion overpressures [7][8]. Current risk assessment methods for natural gas transmission pipelines do not account for delayed ignition leading to a vapour cloud explosion. Further work may be needed in this area and will be incorporated in the LTS Futures programme.

Hydrogen pipelines are currently in operation at several locations around the world. Information kindly provided to HSE by the US Pipelines and Hazardous Materials Safety Administration (PHMSA) showed that there are currently 3,500 km of hydrogen pipelines operating in the US, concentrated mainly around the Gulf of Mexico coast in Texas and Louisiana. These are regulated by PHMSA under the Code of Federal Regulations (CFR) 49, Part 192 on “Transportation of natural and other gas by pipeline: minimum federal safety standards”[3]. The design and operation of US hydrogen pipelines, including issues related to repurposing of natural gas pipelines, are discussed in [9][10]. Recommendations for equations of state for use in design calculations and criteria for avoiding problems with hydrogen embrittlement were also presented, including in the latter case a limitation on allowable upper yield strength of 414 MPa, limiting the design factor to 0.6 and limiting the number and magnitude of pressure cycles.

The European Roads2HyCom project[4] produced an index of the hydrogen pipelines in Europe, which identified 15 large hydrogen pipeline networks, with a total length of nearly 1,600 km. The largest lengths of hydrogen pipelines are in Belgium, the Netherlands, Germany and France. Gasunie Waterstof Services (GWS) in the Zeeland province of Netherlands has recently started operating a 12 km hydrogen pipeline from the plastics and chemical company Dow Benelux to a nearby fertilizer producing company (Yara). The pipeline was repurposed from an existing natural gas pipeline and started operation in November 2018. In the UK, Air Products operates a 2 km, 45 barg, 50 mm diameter hydrogen pipeline in Hull, and BOC operates two hydrogen pipelines: an 8 km, 45 barg, 33 mm diameter pipeline on Teesside and a 1 km, 46 barg, 114 mm diameter long pipeline in Port Talbot, South Wales. In comparison, the majority of the LTS operates at 39 bar or below. A key difference is that these examples are above-ground while the LTS is below-ground, which affects the relative importance of the hazards independent of the transported gas, e.g corrosion from being surrounded by damp earth below ground or vehicle/machinery strikes above ground.

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[3] https://www.phmsa.dot.gov/pipeline/annotated-regulations/49-cfr-192 , accessed 25 March 2021.
[4] https://cordis.europa.eu/project/id/19733/reporting, accessed 25 March 2021.

4.0 APPLICATIONS AND LIMITATIONS OF CURRENT STANDARDS IN CONTEXT OF PIPELINE REPURPOSING

4.1 Pipeline Safety Regulations (PSR)

The Pipelines Safety Regulations (PSR) provide a risk-based goal-setting approach to regulating pipelines throughout Great Britain. They apply to most pipelines but there are additional requirements for pipelines categorised as major accident hazard (MAH) pipelines. MAH pipelines are those that carry a dangerous fluid that has the potential to cause a major accident. Schedule 2 of PSR provides a definition of a dangerous fluid, which includes flammable fluids conveyed at pressures of 7 bar and above. Hydrogen, like natural gas, is therefore classed as a dangerous fluid under PSR and pipelines transporting it at pressures of 7 bar and above are classed as MAH pipelines.

PSR requires the calculation of risk for the routing of all pipelines. For MAH pipelines, as defined in the regulations, additional calculations, outside of PSR, are undertaken by the Regulator to calculate land-use planning zones around the pipeline. These zones are based on the risk to people associated with the pipeline and used to provide advice to land-use planning decision makers.

4.2 BS PD 8010

Part 1 of PD 8010 ‘Pipeline Systems: steel pipelines on land; code of practice’ (BSI, 2016)[11] covers the design, construction, operation, maintenance and abandonment of onshore steel pipeline systems. The design section also considers pipeline safety. The substances that can be carried in the pipeline are divided into Categories A to E. Hydrogen falls into Category E and natural gas falls into Category D, with both categories requiring a safety evaluation under the standard. Details of what is required for the safety evaluation are given in Annex E of Part 1 of PD 8010, which is a summary of the information contained in Part 3 of PD 8010 (BSI, 2013)[12]. It covers each of the steps required in a risk assessment and provides typical examples of protection measures that can be applied to pipelines to lower the risk.

4.3 IGEM/TD/1

The scope of IGEM/TD/1, ‘Steel pipelines and associated installations for high pressure gas transmission’ [13] is the design, construction, inspection, testing, operation and maintenance of steel pipelines and associated installations such as block valves, metering stations and pig traps in the UK. The standard applies to dry natural gas at pressures between 16 and 100 bar and American Petroleum Institute (API) pipeline grades between B (SMYS 245 MPa) and X80 (SMYS 555 MPa), where SMYS= specified minimum yield stress. It is noted that the standard can be applied to other gases, as long as the characteristics of the gas and its consequential effects on design, material, operations and maintenance are taken into account.

Integrity management is described in the standard as the strength, quality and condition which provide resistance to the applied loads and tolerance to damage such that the product is contained at an adequate level of safety considering the principal threats. These include material and construction defects, ground movement, external interference and fatigue. Some of these threats, such as ground movement and external interference, may remain unaffected by the presence of hydrogen in the pipeline, but the material response may differ significantly. A hydrogen supplement of this standard is part of the second phase of the LTS Futures Hytechnical programme.

4.4 ASME B31.12

ASME B31.12-2019 [14] is a standard specific to the case of hydrogen piping and pipelines, with emphasis on new-build rather than re-purposing. It covers hydrogen blends from 10% to 100% and pressures up to 210 bar. The standard is structured in five sections covering general requirements, industrial piping, pipelines, mandatory appendices and non-mandatory appendices. Materials issues are covered in the non-mandatory Appendix A, ‘Precautionary Considerations’. The key trend observed for structural materials such as pipeline steels is that susceptibility to hydrogen embrittlement increases with increasing strength. Effects on yield strength and toughness are observed in the presence of hydrogen.

It is noted that carbon steels have been used for hydrogen piping in welded constructions for many decades and such steels are listed as ‘acceptable for gaseous hydrogen service’ in the standard. Examples of steels that have been proven for hydrogen service are quoted as ASTM A106 and ASTM A53 Grade B, API 5L X42 and X52. Minimisation of the hydrogen embrittlement issues can be achieved by ensuring that operating stresses are maintained at below 30-50% of SMYS. A significant percentage of SGN’s LTS network consists of grade X52 and below, operating at low stresses.

4.5 ISO TR 15916

PD ISO/TR 15916: 2015 [15] has as its aim the promotion of acceptance of hydrogen technologies by providing key information to regulators and education of those involved with hydrogen safety issues. The five principal sections cover hydrogen applications, properties of hydrogen, safety considerations for use of gaseous and liquid hydrogen, mitigation and control of hazards and risks and a series of appendices.

The appendix on materials compatibility emphasises the need for careful evaluation for the design, operating and emergency conditions to which a material will be exposed. Compatibility issues with hydrogen include embrittlement and permeation, while the nature of the failure mode such as rapid rupture should also be considered. Material compatibility is given firstly in terms of degree of embrittlement (negligible, slight, severe and extreme), with the caveat that although a material may be subject to hydrogen embrittlement the material may still be used in hydrogen service if the service conditions (such as low stress) allow. A material suitability table for gaseous and liquid hydrogen service is also included. API or ISO 3183 pipeline steels are not specifically listed, but carbon steels are stated as being in need of evaluation due to their susceptibility to hydrogen embrittlement.

5.0 CHARACTERISTICS OF THE LOCAL TRANSMISSION SYSTEM

SGN operate and maintain 3100 km of steel pipeline, with 44% of this in Scotland and 56 % in the south of England. 75% of the combined lengths of the pipelines operate at 39 bar or below. Key differences between these two sectors are that the south of England sector tends towards higher proportions of high-strength grades, larger diameters and lower operating pressures. Nevertheless, 86% of the total length of SGN’s LTS is grade X52 or lower strength and 80% of it operates at a stress factor at MOP (Maximum operating Pressure) of 0.3 or below. Lower strength steels tend towards reduced sensitivity to hydrogen embrittlement, while lower stress factors place less demand on the material in terms of fracture propensity; both these features of the LTS are conducive to repurposing.

The SGN LTS network was designed and constructed to operate with natural gas. Parts of the GB’s LTS network date from 1960s and over the years pipelines have been manufactured to varying quality standards. Therefore, existing assets may not be manufactured and welded to the same quality as equivalent pipe today. To understand if these pipelines can be repurposed for hydrogen transportation, material testing and further analysis is required. Similarly, while the likelihood of third party activity (TPA) such as impact from earth-moving equipment, is independent of the gas being transported, the subsequent remnant properties in cold worked areas such as dents and gouges may be affected by hydrogen; testing of pre-strained pipe is hence of interest. In order to develop a blueprint for repurposing LTS pipelines, it is proposed that a trial and demonstration incorporating SGN’s Granton-to-Grangemouth LTS pipeline is undertaken. Preliminary work on this is given later in this paper.

6.0 EFFECTS OF HYDROGEN ON THE PROPERTIES OF PIPELINE STEELS

6.1 Required Properties for steel pipelines for gas transportation

In the context of steel pipelines used for natural gas transport, the fundamental mechanical properties necessary for maintaining pipeline integrity are strength, ductility, toughness and fatigue resistance. The effect of hydrogen on the tensile properties of pipeline steels has been extensively reported on. While the effect on yield strength (YS) and ultimate tensile strength (UTS) is usually quite limited, hydrogen universally reduces the ductility (measured as % elongation to failure) of metals such as carbon-steels.

Flaws in real structures, such as corrosion features or weld defects, will have higher local stresses than in the uniform pipe, described by the stress intensity factor K. In order to prevent fracture from such regions of elevated stress intensity, the material must also possess sufficient fracture toughness. Similar properties are also required in welded joints in the pipeline.

In the context of toughness, many empirical approaches for fracture resistance of natural gas pipelines have been developed based on the Charpy impact energy. This is a relatively low cost test and is used to qualify pipeline steels in place of the more complex and expensive fracture toughness test. The Drop Weight Tear Test (DWTT) is also used for pipeline steel characterisation, based on a notched full wall-thickness sample subject to impact load, and quantifies the ability of the steel to arrest a running fracture. These properties are also required in the case of category E substances to PD 8010.

Fatigue crack growth can occur in pipeline steels subject to cyclic stresses well below yield stress. The growth rate of a fatigue crack is given by da/dN as a function of ΔK, where ΔK is derived from the crack size at a given stage of its growth and the stress range and the slope of the line is the crack growth rate. Steels also exhibit a threshold value of ΔK, ΔK_{th}, below which fatigue crack growth cannot occur. Fatigue crack growth rate depends on the steel grade, the environment (e.g. air, hydrogen) and the cyclic loading frequency. Fatigue constants for steels describing the linear portion of fatigue crack growth are available in the literature and recommended values are also given for different classes of steels and environments, excluding hydrogen, in standards such as BS7910 [16].

6.2 Measurement of the effects of hydrogen on steels

Hydrogen embrittlement (HE) is the degradation of mechanical properties caused by the exposure of a material to a hydrogen-containing environment. This can lead to failures at applied loads below the material’s yield strength and can cause usually ductile metals to fail in a brittle manner. The field of hydrogen embrittlement is a broad one, which has been progressed by a range of industries, each with a different focus. The oil and gas sector has been the predominant driving force in understanding the degradation of materials in hydrogen environments. Since this sector is largely interested in highly engineered alloys that operate in extreme conditions, such as high temperature, high pressure, H_2S containing environments, most of the testing has been conducted using aggressive cathodic charging conditions that may not be directly applicable to the milder hydrogen gas environments found in gas transmission pipelines. As 75% of the SGN LTS operates below 39 bar, materials test data under representative conditions is limited in the literature. As a consequence, the applicability of much of the data presented and reviewed will be highly conservative when applied to gas pipelines. Studies are underway to correlate cathodic charging conditions to partial pressures of hydrogen.

Comparison between data sets acquired from different testing parameters should be made with caution. Even a difference in one test parameter (e.g. loading frequency in a fatigue test, or surface condition) can have a very significant effect on the results. By extension, large variations in test procedures can lead to differing observations for the same material. The breadth of potential variations in a test is illustrated in Fig.1.

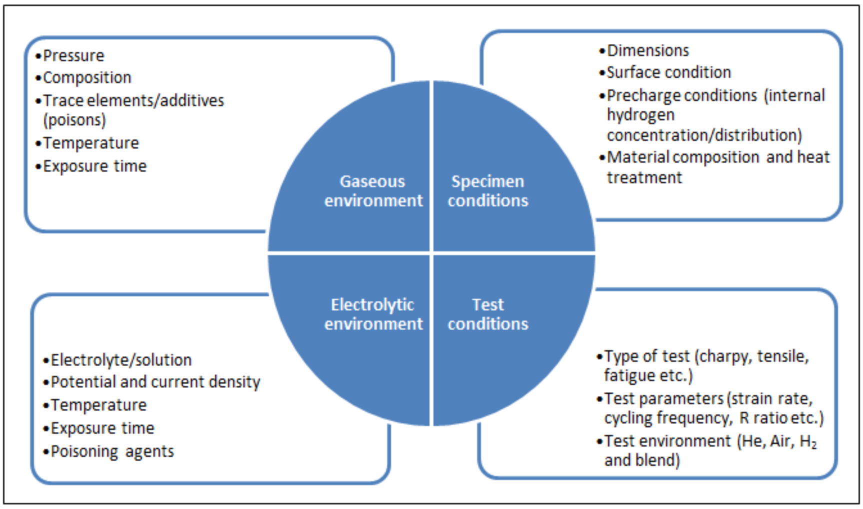
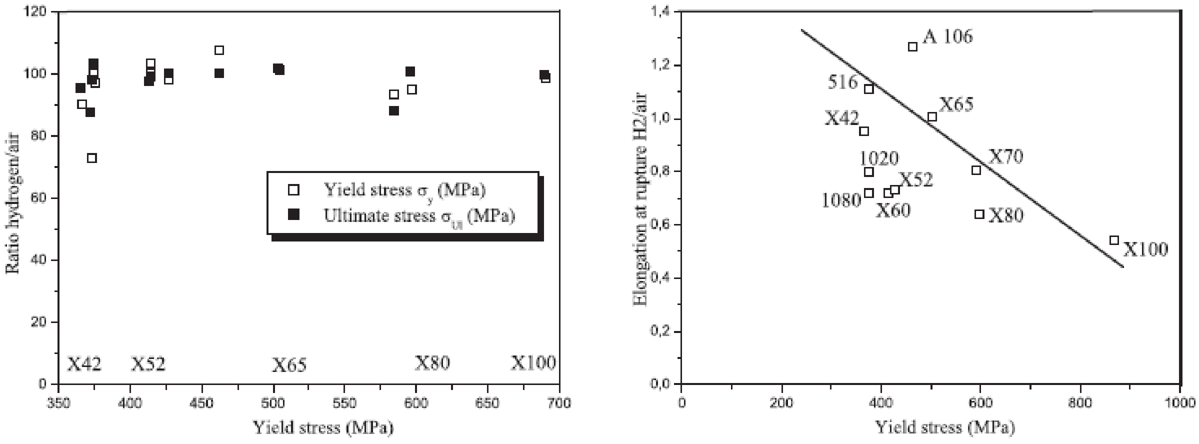


Fig.1. Potential variables in hydrogen embrittlement testing

6.3 Tensile Properties

An extensive and comprehensive compilation of mechanical property data under various hydrogen environments is presented in [17]. A series of API 5L pipe grades between X42 and X65, including weld metals, is included in this study and were tested in gaseous hydrogen at slow strain rates. The results compilation showed that in general there is little effect of gaseous hydrogen at a pressure of 69 bar on yield stress and UTS. The effect on elongation to failure is more marked, with mean elongation in hydrogen being 0.82 times that in air, with a range between 0.61 and 1.00

A review of the effect of hydrogen embrittlement on tensile properties [18] suggests that for a wide range of API pipe grades, the reduction in yield stress and UTS is quite small in most cases, Fig.2a, but the reduction in failure elongation can be up to 40%, Fig.2b. The slight reduction in strength occurs across all grades, while the loss of tensile elongation in hydrogen shows a dependence on strength grade.



a. Effect of hydrogen on yield stress and UTS as function of pipe grade

b. Effect of hydrogen on elongation at rupture as function of pipe grade

Fig. 2. Sensitivity of tensile properties in hydrogen as a function of pipe strength [18]

6.4 Fracture Toughness

A comprehensive compilation of mechanical property data under various hydrogen environments is presented in [17] and a series of API 5L pipe grades are included in this study. It is noted that while hydrogen gas at a pressure of 6.9 MPa (69 bar) degrades fracture toughness by as much as 50%, the absolute toughness remained relatively high, with K_I near to 100 MPa $m^{0.5}$. It is noted however that the pressures in the LTS are lower than this. Hydrogen has a more pronounced effect on ductile crack propagation resistance as measured in the R-curve since the tearing mode provides a continuously renewed active zone for hydrogen to enter. Generalisation is therefore difficult, but the slope of the R-curve has been observed to reduce by many times that of the value in inert atmospheres.

A range of effects observed in fracture toughness testing of pipeline steels after hydrogen exposure have been identified in[18]; the hydrogen/air fracture toughness ratio shows that for pipe grades X42 to X70, the fracture toughness after hydrogen charging, both gaseous and charged (electrolytic), averages 67% of the value in air, Fig. 3. No systematic effect of strength grades is observed up to grade X70, although the lowest value obtained was in an X80 grade.

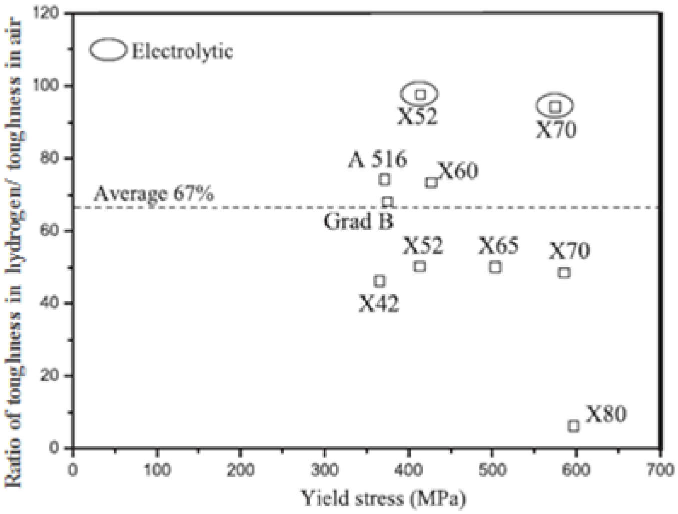


Fig.3. Ratio of retained toughness in hydrogen/ toughness in air for pipeline steels [18]

Values for fracture toughness measured on pipeline steels in both ambient and hydrogen atmospheres were collated from the literature in the current study for both gaseous and cathodically charged conditions. The ratio of toughness in hydrogen to that in ambient atmosphere (usually air or nitrogen) was then determined. The results, summarised in Table 1, show the wide variation of retained toughness, with an overall average across pipe grades X42 to X65 of 0.54, based on 45 datasets. The potential reduction in this parameter due to the presence of hydrogen does not necessarily render a steel unfit for its purpose, it is the remnant toughness in the presence of hydrogen that is important rather than the relative loss.

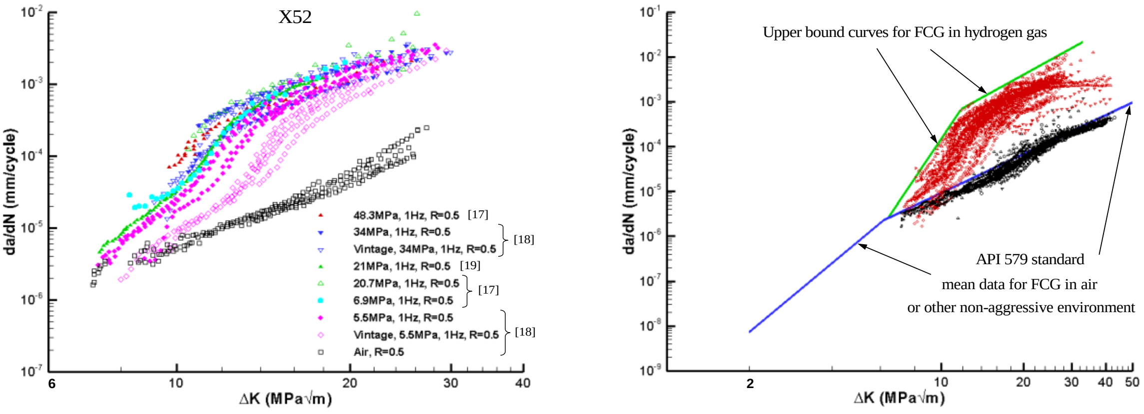
Table 1: Compilation of retained toughness for pipeline steels in cathodically charged and hydrogen gas test environments combined, for pipe grades relevant to the LTS.

Grade	Mean ratio [Toughness H_2/ Toughness air]	Range of ratios [Toughness H_2/ Toughness air]	Number of test data
X42	0.48	0.22-0.90	17
X52	0.68	0.49-0.90	11
X60	0.62	0.35-0.96	7
X65	0.38	0.13-1.25	10
All grades	0.54	-	45

6.5 Fatigue Crack Growth

The effect of hydrogen environments on the fatigue crack growth parameters of the Paris Law is quite complex, with different sensitivity to hydrogen observed in different ΔK regions of the curve, coupled with effects of R-ratio, loading frequency and presence of gaseous impurities. The threshold stress intensity range appears to be relatively insensitive to the presence of hydrogen. At low ΔK values the crack growth behaviour of pipeline steels in hydrogen gas and inert gas are similar, but a sharp increase in crack growth is noted at ΔK in the region of 6 MPa $m^{0.5}$ to 10 MPa $m^{0.5}$, depending on grade and test conditions. This is attributed to the hydrogen diffusion rate exceeding the crack growth rate such that the hydrogen is continuously active at the crack tip. Above a ΔK of approximately 15 MPa $m^{0.5}$, the crack growth curves in air and hydrogen become parallel as the relative speeds of crack growth and hydrogen diffusion are reversed.

Various 'Master Curves' for defining these observed effects have been proposed such as in [19] based on extensive compilations of fatigue crack growth curves for different pipelines steels. An example is given in Fig.4a for X52 pipeline steel of different vintages, tested at hydrogen pressures between 20 and 69 bar. A compilation of data was also carried out by the same authors covering grades B to X70, tested at 69 bar hydrogen pressure, and leading to the concept of a fatigue master-curve, Fig. 4b.



a. X52 steels in air (black symbols) and 20-69 bar hydrogen (colour symbols) at 1Hz

b. Collated data for grades B, X52, X60, X65 and X70, red symbols in hydrogen, black symbols in air

Fig.4. Fatigue crack growth curves for pipeline steels in gaseous hydrogen [19]

A compilation of available data for grades X42 and X52 pipe material, weld metal and heat affected zones was made in the current study and showed that the fatigue crack growth rate in hydrogen can range from 5 times to 67 times the rate in air, with a mean increase of 29. However, the observed increases also need to be considered in the context of pipeline operation and sources of cyclic pressure such as the use of 'line packing'. The generally very low number of daily pressure cycles, coupled with the stress conditions and flaw size necessary for the conditions to exceed the fatigue threshold, are both factors which may mitigate the significance of fatigue crack growth in hydrogen. Understanding the cyclic pressure loading in future operation is an important part of any pipeline repurposing plan.

7.0 DEMONSTRATION OF APPROACHES FOR PIPELINE REPURPOSING

7.1 Risk Assessment in Context of PSR and Determination of Land Use Planning Zones

When assessing the risk around the pipeline there are two aspects that need to be considered. The first is to provide evidence to the regulator that the pipeline has been constructed to the necessary standards and will be operated safely, following the requirements under PSR. The second is to generate the LUP zones around the pipeline.

To satisfy the first of these aspects, evidence is required that a suitable standard, such as PD 8010 [11], has been followed. PD 8010 requires the identification of average populations along the pipeline and to certain distances away from the pipeline. It also requires the calculation of the Minimum Distance to Occupied Buildings (MDOB). There should be no occupied buildings within this distance from the pipeline.

The three LUP zones (Inner (IZ), Middle (MZ) and Outer (OZ)) equate to the distances to risks of 10 cpm (chances per million per year), 1 cpm and 0.3 cpm respectively, or to the MDOB, whichever is the greater (for natural gas, the Building Proximity Distance (BPD) is used instead of the MDOB). Work is ongoing within the HyTechnical project on the effects of hydrogen on BPD and the current rules for parallel pipelines.

7.2 Case study on a Selected LTS Pipeline: Granton-to-Grangemouth

Case studies were undertaken to demonstrate the effects on the risk and the LUP zones of moving from natural gas to hydrogen. A decommissioned pipeline, the 29.5 km Granton-to-Grangemouth line, was used for the study. The pipeline details are shown in Table 2.

Table 2: Granton-to -Grangemouth pipeline parameters

Description	Value
Diameter	457 mm
Wall thickness	6.35 mm spiral
	9.52 mm seamless
Maximum operating pressure (MOP)	17.5 bar[1]
Depth of cover	Generally 1.1 m
Material grade	Spiral – API5L X52 & GC/PS/LS1
	Seamless – API5L X52 & GC/PS/LX2

Building proximity distance (BPD)	3 m for 7 bar operation

[1] The MOP was reduced to 7 barg after decommissioning

Assumptions have had to be made when modelling the pipeline. For example, it is assumed that the pipeline would be able to operate at pressures up to 70 barg, and that the depth of cover is 1.1 m everywhere along its length.

One of the calculations within PD 8010 requires knowledge of the distance to a risk of 0.3 cpm (note that PD 8010 is the most generally used and accepted standard, but others could also be suitable). As HSE's pipeline risk assessment model, MISHAP [20] calculates this as part of determining the LUP zones around pipelines the values from MISHAP have been used as part of the PD 8010 calculations. It should be noted, however, that additional modifications may be required for the modelling of hydrogen pipelines within MISHAP e.g. explosions may need to be considered but are not currently, and the natural gas failure rates have been assumed to be applicable for hydrogen. Failure rates for hydrogen could be developed on historical data although the population is small, whereas fracture-mechanics based failure rate models for TPA would need to consider material behaviour under hydrogen conditions.

Two pressures have been modelled, 24 barg and 70 barg at the two quoted wall thicknesses. The LUP zones, assuming 24 barg, are shown in Table 3 together with the zones for an equivalent natural gas pipeline, each zone being the distance measured from the pipeline itself. From Table 3 it can be seen that, when the zones are based on the risk, they are smaller for hydrogen than for natural gas, noting the caveats around how suitable the models are for hydrogen. The hydrogen zones are larger when the risk levels are not reached and hence the MDOB is used. This is because the MDOB for hydrogen is generally, although not always, larger than the equivalent BPD for natural gas. The results for the 70 barg pipeline show similar trends and are not illustrated here.

Table 3: LUP zones for 24 barg pressure around the Granton-to-Grangemouth pipeline

Zone	Distance (m) to zone assuming 6.35 mm wall thickness		Distance (m) to zone assuming 9.52 mm wall thickness	
	Natural gas	Hydrogen	Natural gas	Hydrogen
IZ	15[1]	20[2]	7[1]	20[2]
MZ	85	21	7[3]	20[4]
OZ	90	31	50	20[5]

[1] This is the BPD. The risk is always lower than 10 cpm for this pipeline.
[2] This is the MDOB. The risk is always lower than 10 cpm for this pipeline.
[3] This is the BPD. The risk is always lower than 1 cpm for this pipeline.
[4] This is the MDOB. The risk is always lower than 1 cpm for this pipeline.
[5] This is the MDOB. The risk is always lower than 0.3 cpm for this pipeline.

7.3 Sensitivity study on Maximum Distance to Occupied Buildings (MDOB)

Sensitivity tests were also undertaken assuming that the failure rates were either doubled or an order of magnitude larger. This was to reflect the uncertainty in the appropriateness of using natural gas failure rates for hydrogen. Little difference was seen when doubling the failure rates with larger differences seen when the failure rates are an order of magnitude larger, as would be expected. The risk-based zones, however, were generally still smaller than those for the equivalent natural gas pipeline.

One of the requirements in PD 8010 Part 1 [11] is to calculate the population density along the pipeline and assign it to one of three location classes. The population density is expressed in terms of the number of persons per hectare. Two methods are quoted for calculating the population density; the first takes the average population within the 0.3 cpm risk contour and the second assumes a strip, centred on the pipeline, of width eight times the MDOB for any 1.6 km of pipeline.

For both the 24 barg and 70 barg scenarios, the population density has been calculated using the National Population Database [21]. In both cases the population densities imply that the pipeline is location class 2 at the Granton end of the pipeline, and class 1 elsewhere.

The location classes are used to define the required degree of protection for the pipeline [13], with greater protection being required for class 2 (suburban) pipelines than for class 1 (rural). The design factor for the Granton-to-Grangemouth pipeline, using either of the two specified wall thicknesses and assuming a pressure of 24 barg, is less than 0.3, implying that it has been designed to a class 2 standard. Additional modifications to the pipeline are therefore not required. If a MOP of 70 barg is assumed, however, the design factor would imply that it has been designed to a class 1 standard and modifications would be required to the pipeline at the Granton end.

For both the 24 barg and 70 barg scenarios, occupied buildings were found within the MDOB. The pipeline would therefore potentially need upgrading within the vicinity of these buildings to reduce the MDOB. There are also some vulnerable populations within the eight times MDOB strip, which would require additional consideration.

7.4 Fitness-for-Service Case study on a selected pipeline: Granton-to-Grangemouth

A number of pipeline integrity models exist for assessing the acceptability of different types of flaws from a pressure limit perspective, such as BS 7910 [16] Failure Assessment Diagram (FAD) method. Application of these methods in a hydrogen context is beneficial in that the effect of changes in mechanical properties such as toughness can be assessed simultaneously together with the pipe dimensions, postulated flaw sizes and operating pressures. The toughness in hydrogen should be factored from that in an ambient atmosphere based, for example, on the type of information shown in section 6.4. The fatigue life of a pipeline subject to cyclic loading can also be determined using BS7910. In this latter case, the fatigue properties for the material would be factored for the effect of hydrogen using data such as that described in section 6.6.

The Granton-to-Grangemouth pipeline was used as a demonstration for this approach, and has characteristics as given in table 2. The spiral-welded section with nominal wall thickness of 6.35 mm was evaluated. The tensile properties were taken as the minima for the grade (X52) and the fracture toughness was determined by correlation given in BS7910 from Charpy impact specification for the grade. The determined fracture toughness of 110MPam $^{0.5}$ was taken as being applicable to actual gas service and was also assessed at 0.50 and 0.65 times this value, based on the mean reduction factors collated from the literature. Pressure (P) of 24 and 35 bar were assessed and the cases of without and with residual stress (RS) were included to represent a flaw in the pipe body and in the weld metal respectively. The flaw was taken as an axial flaw on the inside face of the pipe with length 100 mm. The TWI software ‘Crackwise’ [22] was used for the calculations to determine critical flaw sizes. The output of the analysis is shown in Fig.5.

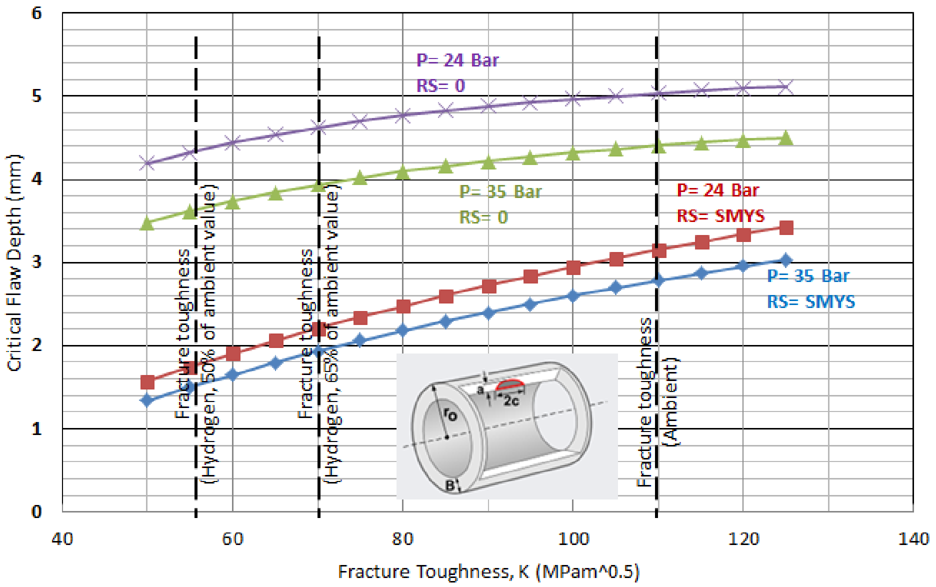


Fig.5: Critical flaw depths determined for Granton-to-Grangemouth pipeline

The upper two curves in Fig. 5 represent the case of a flaw in the pipe body at two pressures. In this case the difference between the calculated critical flaw depths in natural gas (intersection with vertical dashed line on the right) and hydrogen (intersection with vertical dashed lines on the left) is relatively minor, with values in hydrogen being 81-92% of the value in ambient (natural gas) conditions. The lower two curves represent the case of a flaw in the weld metal, where the presence of residual stress must be assumed. In this case, the residual stress acts together with the applied stress, such that the toughness reduction in hydrogen has a more significant effect on the critical flaw size at 54-71% of the value in ambient (natural gas) conditions.

The case of fatigue cycling due to line-packing was also assessed in a sensitivity study, taking a single daily pressure cycle with a range of 17.5-35 bar and an initial flaw depth of 10% wall thickness to represent, for example, a weld seam flaw. The time to grow the crack by fatigue to its final critical size in both natural gas and hydrogen was calculated. In this analysis, the effect of hydrogen was incorporated as a reduction of toughness to 50% and an increase of the fatigue crack growth exponent from 3 to 4. Given these severe assumptions, the predicted fatigue life of the pipe in hydrogen was reduced significantly from the case in natural gas, but the life was still predicted as being over 100 years.

The above approach has the advantage that sensitivity studies can be easily performed to determine the benefits of refining the quality of key data inputs. This might entail testing of actual exhumed pipeline materials under the relevant pressures and gas blend, detailed interrogation of records of as-installed materials to define mechanical properties and definition of characteristic flaw sizes from NDT records.

9.0 Conclusions

Key issues relevant to hydrogen transport have been evaluated in terms of the physical properties of the gas, energy density and combustion/explosion characteristics. Examples of hydrogen pipeline experience in the USA and Europe have been summarised and some key aspects of existing standards interpreted from a hydrogen perspective.

An understanding of the effects of hydrogen on pipeline steels with a focus on strength, ductility, toughness and fatigue was developed through a literature review. Potential reduction factors to account for the effects of hydrogen on toughness and fatigue properties of pipeline steels have been proposed.

A summary of the type of information required to re-purpose a pipeline for hydrogen service has been provided in terms of pipeline details, PD 8010 requirements, regulatory approvals, and additional modelling information and materials considerations.

Pipe integrity aspects to be considered when repurposing for hydrogen have also been described including: Material grade and strength; pipe age; level of weld inspection; maximum operating pressure; magnitude of daily pressure cycling; external loading arising from third-party action and; pipe straining arising from ground movement. A significant percentage of SGN’s LTS network consists of lower strength grades of pipeline that operate at low stresses, both of which are conducive to a pipeline’s suitability for hydrogen service.

For the Granton-to-Grangemouth pipeline a risk evaluation has been presented covering the changes to Land Use Planning (LUP) zones that would arise for hydrogen service. Calculations required under PD 8010 Part 1 have also been undertaken to assess the need for modifications prior to repurposing. A BS 7910 fitness-for-service evaluation was also carried out. Material properties were modified for the potential effect of hydrogen and the effect on critical flaw size and fatigue life demonstrated.

The subject of repurposing the LTS is being further developed within the LTS Futures programme focussed on 7 bar LTS suitability for conversion to hydrogen. The programme is designed to develop the safety, technical and practical evidence to support the use of hydrogen in the LTS and subsequently a route to provide the technical foundation for decarbonisation.

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