The Development of Supplements to IGEM/TD/1 Edition 6 and IGEM/TD/13 Edition 2 for Hydrogen Service

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The safe and economic development of a hydrogen economy in the United Kingdom will require a suite of standards for the design, construction, inspection, testing, operation and maintenance of pipelines and associated installations for hydrogen service.

The Institution of Gas Engineers and Managers (IGEM) is responsible for the suite of standards used in the natural gas industry in the United Kingdom. At the request of the gas industry, IGEM has developed supplements to its existing suite of standards, to enable the design, construction, etc. of new and the re-purposing of existing pipelines and associated installations from transporting natural gas to transporting either hydrogen or a blend of hydrogen and natural gas.

IGEM/TD/1 Edition 6 *Steel pipelines for high pressure gas transmission* addresses the design, construction, inspection, testing, operation and maintenance of steel pipelines and certain associated installations for the transmission of dry natural gas (predominantly methane) at a maximum operating pressure (MOP) exceeding 7 barg. IGEM/TD/13 Edition 2 *Pressure regulating installations for natural gas, liquefied petroleum gas and liquefied petroleum gas/air* addresses the same for pressure regulating installations.

IGEM/TD/1 Edition 6 Supplement 2 *High Pressure Hydrogen Pipelines* and IGEM/TD/13 Edition 2 Supplement 1 *Pressure regulating installations for hydrogen at pressures exceeding 7 bar* have been developed to give additional requirements and qualifications for steel pipelines in hydrogen service, and guidance on repurposing existing natural gas pipelines for hydrogen service. The term hydrogen service is used to indicate a pipeline transporting hydrogen or a blend of natural gas and hydrogen. The development of the supplements has taken into account the requirements in ASME B31.12 *Hydrogen Piping and Pipelines* and the work reported in the published literature or conducted by the gas industry, and tailored that to be consistent within the framework of the existing requirements in the United Kingdom.

The development of and the content in the new supplements is presented and discussed. The gaps in the supplements are highlighted, in order to show where more research and development work is required.

Introduction

The Paris Agreement, 2015 set the goal of limiting the increase in the global average temperature to 1.5 ºC above pre-industrial levels to significantly reduce the risks of climate change [1].

The Climate Change Act 2008 (2050 Target Amendment) Order 2019 [2,3] committed the UK Government to "ensure that the net UK carbon account for the year 2050 is at least 100% lower than the 1990 baseline", i.e. 'net zero' by 2050. The UK Hydrogen Strategy states that: "Low carbon hydrogen will be critical for meeting the UK's legally binding commitment to achieve net zero by 2050" [4].

The Institution of Gas Engineers and Managers (IGEM) is responsible for the suite of standards used in the natural gas industry in the United Kingdom. IGEM/TD/1 Edition 6 *Steel pipelines for high pressure gas transmission* [5] addresses the design, construction, inspection, testing, operation and maintenance of steel pipelines and certain associated installations for the transmission of dry natural gas (predominantly methane) at a maximum operating pressure (MOP) exceeding 7 barg. IGEM/TD/13 Edition 2 *Pressure regulating installations for natural gas, liquefied petroleum gas and liquefied petroleum gas/air* [6] addresses the same for pressure regulating installations in transmission pipelines, distribution mains and service pipework containing natural gas, and distribution mains and service pipework containing liquefied petroleum gas and liquefied petroleum gas/air.

IGEM/TD/1 Edition 6 Supplement 2 *High Pressure Hydrogen Pipelines* [7] has been developed to give additional requirements and qualifications for steel pipelines in hydrogen service, and guidance on repurposing existing steel pipelines in natural gas service for hydrogen service. It addresses the design, construction, etc, in hydrogen service at an MOP exceeding 7 barg and not exceeding 137.9 barg. IGEM/TD/13 Edition 2 Supplement 1 *Pressure regulating installations for hydrogen at pressures exceeding 7 bar* [8] addresses the same for pressure regulating installations in transmission pipelines. The term hydrogen service is used to indicate a pipeline transporting hydrogen or a blend of natural gas and hydrogen.

ASME B31.8 and B31.12

The first edition of a standard for gas transmission and distribution piping systems was published in 1952, as ASA B31.1.8-1952 *Gas Transmission and Distribution Piping Systems*. Section 8 of American Standard Code for Pressure Piping (ASA B31.1-1951), albeit it was largely based on ASA B31.1-1951 [9]. The second edition, ASA B31.1.8-1955, was a general revision of the standard and considerably expanded its scope; elements of that standard are still evident in the current edition of (what is now) ASME B31.8. Gas, as used in the code, is defined as any gas or mixture of gases suitable for domestic or industrial fuel and transmitted or distributed to the user through a piping system.

ASME B31.12-2008 *Hydrogen Piping and Pipelines*, the first edition, was published in 2008. The current (fourth) edition is ASME B31.12-2019 [10]. The B31 Standards Committee had determined that the existing piping and pipeline codes and standards were not sufficient for hydrogen applications, and that a new standard was required [10-12]. The B31.12 Code Committee used ASME B31.1, B31.3, B31.8 and B31.8S as model codes. It further determined that:

1. Carbon steel materials used in piping and pipeline systems in hydrogen service are generally lower strength steels, with a specified minimum yield and tensile strengths less than 52,000 and 80,000 psi (359 and 552 $N.mm^{-2}$), respectively[1]; and the systems are operated at low stress levels, sometimes 30-50% SMYS.
2. The resistance of carbon steel to hydrogen embrittlement in a gaseous hydrogen environment decreases with increasing tensile strength, pressure and stress level.
3. Additional design conservatism to account for the effects of hydrogen embrittlement is required in the absence of comprehensive base and weld material test data.

A material performance factor, H_f, was introduced to account for the adverse effects of hydrogen gas on the mechanical properties of carbon and low alloy steels operating within the range where hydrogen embrittlement might occur. The factor is equal to 1.0 for material grades of carbon steel with a specified minimum yield strength (SMYS) not exceeding 52,000 psi, and for a system design pressure not exceeding 1,000 psig (68.95 barg) in piping materials and 2,000 psig (137.9 barg) in pipeline materials (see Tables IX-5A-C in Mandatory Appendix IX of ASME B31.12).

ASME B31.12 is split into three parts: Part GR General, Part IP Industrial Piping (piping in plant and refineries) and Part PL Pipelines.

PL-3.7.1 Steel Piping Systems Design Requirements defines an Option A (Prescriptive Design Method) and an Option B (Performance-Based Design Method). Option A limits the design factor in Location Class 1, Division 2 and Location Class 2 to 0.5 (down from 0.72 and 0.6, respectively). It also applies a material performance factor.

IGE(M)/TD/1 and Supplement 2

The (then) Institution of Gas Engineers (IGE) published IGE Communication 674, *Recommendations Concerning the Installation of Steel Pipelines for High-Pressure Gas Transmission*, in 1965 [13-17]. The design of pipelines in the United Kingdom was then based on the American B31 Codes. IGE Communication 674 was informed by ASA B31.8, etc. The (then) Gas Council had reviewed the American B31 Codes. It identified two principal requirements: i) assess the infrastructure along the route of a proposed pipeline; and, ii) reduce the operating stress in areas of higher levels of infrastructure. The United Kingdom had (and has) a higher population density than the United States, and that, and the higher level and different characteristics of land development along the routes of proposed pipelines, informed the need to adapt and develop the American B31 Codes. A minimum distance between the pipeline and normally occupied buildings, based on the diameter and pressure of the pipeline, and within which future developments must be constrained, was defined (the Building Proximity Distance). The operating stress was reduced in areas of higher population density. It defined three area types: Types R, S and T[2] (IGEM/TD/1 Edition 6 introduced a fourth area type, Type H, between Types S and T), similar to the Location Classes 1-4 in ASME B31.8 (a simple comparison is given in Figure 1). IGE Communications 674A-D, adding to and extending the requirements in the Communication 674 were then published in the period from 1970 through to 1977, with the consolidation document published as IGE/TD/1: Edition 1: 1977 [14]. That was then followed by IGE/TD/1: Edition 2: 1977 Section 5 Design [18], IGE/TD/1: Complete Edition 2: 1984 [19], and subsequently IGE(M)/TD/1 Editions 3-6 [5,20-22].

IGEM/TD/1 Edition 6 Supplement 2 *High Pressure Hydrogen Pipelines* is similarly informed by ASME B31.12, but adapted to be compatible with IGEM/TD/1 Edition 6.

Supplement 2 is a supplement; it is intended to be read and used in conjunction with Edition 6. IGEM/TD/1 Edition 6 was reviewed in order to identify what would need to be revised to address the implications of hydrogen service. The clause numbers in Supplement 2 are as in Edition 6 (preceded by 'S'), and specify the requirements and qualifications which are in addition to those in the main document. Where there is no numbered clause in the supplement, the requirements of the main document apply in full.

Supplement 2 is primarily informed by ASME B31.12-2019 [10]. Secondary sources included: CGA G-5.5–2021, EIGA IGC Doc 121/14, HSG253, IGE/SR/22 and PD ISO/TR 15916:2015 [23-27]. The primary source for the published literature is the review reported in *Hydrogen in the NTS* [28].

Supplement 2 will be updated as and when significant new information becomes available.

Table 1, below, lists the main clauses in Supplement 2 that specify additional requirements and qualifications (although this list is not intended to be exhaustive)[3]. Section 13, on repurposing an existing natural gas pipeline, is a wholly new section.

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[1] The specified minimum yield and tensile strengths of Grade L360 (X52) are 360 and 460 $N.mm^{-2}$, respectively.
[2] Types R, S and T stand for rural, suburban and town.
[3] Huising & Krom, 2020 [29] describe the repurposing of an existing pipeline in The Netherlands from natural gas to hydrogen service. It is of interest to note that this repurposing is, at a high level, broadly consistent with the requirements in Supplement

Table 1 summarises the additional requirements and qualifications, and gives a short commentary, by way of explanation, in italics. Then additional commentary is given.

Hydrogen embrittlement is a broad term; ASME B31.12 defines it as the "loss of ductility of a metal resulting from absorption of hydrogen." Supplement 2 (informed by ASME B31.12) implicitly assumes that, within the limits, the effects of hydrogen embrittlement, as hydrogen environment-assisted cracking, will (might) manifest as a reduction in the fracture toughness and an increase in the rate of fatigue crack growth; the likelihood of hydrogen cracking mechanisms associated with sour conditions or cold cracking is assumed to be very low.

IGE(M)/TD/13 and Supplement 1

The (then) Institution of Gas Engineers (IGE) published IGE Communication 1672, *Pressure regulating installations*, in 2001 [30]. IGE/TD/13 replaced IGE/TD/9 *Offtakes and pressure regulating installations for inlet pressures between 7 and 100 bar* [31] and IGE/TD/10 *Pressure regulating installations for inlet pressures between 75 mbar and 7 bar* [32]. IGEM/TD/13 Edition 2 was published in 2011[4] [6].

IGEM/TD/13 Edition 2 Supplement 1 *Pressure regulating installations for hydrogen at pressures exceeding 7 bar* is informed by ASME B31.12, as above, but adapted to be compatible with IGEM/TD/13 Edition 2. Additional secondary sources included: CGA G-5.5–2021, EIGA IGC Doc 121/14, EIGA IGC Doc 211/17, IGE/SR/22, IGE/SR/23, IGEM/SR/25, Model Code of Practice Part 15, NSS 1740.16 and PD ISO/TR 15916:2015 [23-27,33-38].

Supplement 1 addresses the practical implications of: the increase in the flammable range, the increase in the probability of ignition, and the increase in the flame speed (with the potential for unconfined vapour cloud explosions with significant overpressure, as compared to flash fires with negligible overpressure for natural gas) and the reduction in flame visibility.

Supplement 1 will be updated as and when significant new information becomes available, and it will be extended to cover distribution mains and service pipework.

IGE/SR/23 *Venting of Natural Gas* [36] and IGEM/SR/25 Edition 2 *Hazardous area classification of Natural Gas installations* [37] are also being updated to also consider hydrogen service. IGE/SR/23 covers venting natural gas through vent stacks with an internal diameter greater than or equal to 25 mm. IGEM/SR/25 presents a procedure for classifying hazardous areas around installations that then enables the correct selection and location of fixed electrical equipment.

Table 2, below, lists the main clauses in Supplement 1 that specify additional requirements and qualifications (although this list is not intended to be exhaustive). Section 16, on repurposing an existing natural gas installation, is a wholly new section. Table 2 summarises the additional requirements and qualifications, and gives a short commentary, by way of explanation, in italics. Then additional commentary is given.

2, specifically (with reference to Huising & Krom, 2020): 3.2 Wall thickness, steel type, pipe type, 3.3 Design factor and 3.4 Girth welds.

[4] IGEM/TD/13 Edition 3 is in the final stages of development.

Table 1 Commentary on the clauses in IGEM/TD/1 Edition 6 Supplement 2

S5.3 LINEPIPE	
S5.3.1 Specification	If the linepipe specification states the carbon equivalent is "as agreed" then the carbon equivalent shall not exceed 0.43. [*BS EN ISO 3183:2019, Table A.1 limits CE_{IIW} to 0.43 (and CE_{Pcm} to 0.25) in Grades L360NE, L415QE-485QE and L450ME-L485ME, but that for L415NE and L555QE is "As agreed" (the limits in API Spec 5L, Table 5 are identical). The supplement replaces "As agreed" with CE_{IIW} equal to 0.43 (and, by inference, although not explicitly stated, with CE_{Pcm} equal to 0.25). EIGA IGC Doc 121/14 informed the extension of the limit on carbon equivalent (the limits for what it described as microalloyed steels were not adopted). [24,39,40]*] The hardness of linepipe intended for hydrogen service shall be limited to 250 HV10. [*ASME B31.12, Table GR-3.10-1 Hardness Testing Acceptance Criteria specifies a maximum hardness of 235 HV10; PL-3.19.8 specifies a maximum hardness of 237 BHN (equivalent to 248 HV [41]). EIGA IGC Doc 121/14 states that the maximum hardness of steels in hydrogen service should be approximately 22 HRC (equivalent to 248 HV [41]). API Spec 5L Annex H PSL 2 Pipe Ordered for Sour Service specifies a maximum hardness of 250 HV10 (cf. 9.10.6 Hard Spots that defines a hard spot as a defect if the hardness exceeds 345 HV10). BS 4515-1:2009, Table 4 specifies a maximum hardness in sour service of 250 HV10 for the root (weld and heat affected zone). A limit for sour service should be conservative for hydrogen service. [10,24,39,42]*] [*IGEM/TD/1 Edition 6 cites API Spec 5L and BS EN ISO 3183. Supplement 2 implicitly assumes that Annex A PSL 2 pipe ordered for European onshore natural gas transmission pipelines is specified for hydrogen pipelines. [5]*]
S5.3.3 Strength grades	Grades higher than L485 (X70) shall not be used unless the pipe and weld material is qualified for the intended service (see clause S5.8). [*ASME B31.12, PL-3.7.1(b)(1)(-e) [Option A] specifies a maximum minimum specified yield strength (SMYS) of 70 ksi, i.e. Grade L485 or X70[5]. [10]*] The maximum tensile strength of the pipe shall not exceed 690 N.mm^{-2}. [*ASME B31.12, PL-3.7.1(b)(1)(-c) [Option A] [10]*] The maximum tensile strength of the weld metal shall not exceed 690 N.mm^{-2}. [*ASME B31.12, PL-3.7.1(b)(1)(-d) [Option A] [10]*]
S5.3.4 Testing S5.3.4.11	Fracture toughness testing shall be conducted to determine the fracture toughness in hydrogen service (see clause S5.8). [*see additional commentary*]
S5.4 Fatigue	The rate of fatigue crack growth in steels in environments that contain hydrogen is higher than that in air. The impact of higher fatigue crack growth shall be taken into consideration in design. [*see additional commentary*]
S5.5 FITTINGS S5.5.1	The hardness of fittings intended for hydrogen service shall be limited to 250 HV10. [*see S5.3.1*]
S5.6 COMPONENT SELECTION S5.6.1	Metallic and non-metallic components shall be qualified for hydrogen service or otherwise demonstrated to be acceptable for hydrogen service (see clause S5.8). [*PD 8010-1:2015, 8 Design – Materials and coatings states that the suitability of a material for a particular application should be determined. [43]*]
S5.8 MATERIAL QUALIFICATION S5.8.1	… The materials used should be qualified for hydrogen service … Linepipe specified to Annex M PSL 2 pipe ordered for European onshore natural gas transmission pipelines in BS EN ISO 3183:201[2][†], or equivalent, is acceptable for hydrogen service provided that the design complies with all of the requirements in

[5] ASME B31.12, PL-3.7.1(b)(2)(-h) [Option B] specifies a maximum minimum specified yield strength (SMYS) of 80 ksi (552 N.mm^{-2}). (-f) and (-g) specify a maximum tensile strength of 110 ksi (825 N.mm^{-2}).
[†] IGEM/TD/1 Edition 6 Supplement 2 quotes BS EN ISO 3183:2019. This is a typographical error.

	clauses S5 and S6. … Note 4: … the most relevant contemporaneous line pipe specification is BS EN ISO 3183:2012 … *[see additional commentary]*
S6.4 WALL THICKNESS OF LINEPIPE S6.4.2	The minimum wall thickness of linepipe shall be equal to or greater than the design thickness as determined from: t = PD(20fs)$^{-1}$ … f = design factor (see Table S1 … Maximum Design Factor) … limits the hoop stress to 180 N.mm^{-2}. *[ASME B31.12, PL-3.7.1(a) & Table PL-3.7.1-1 [Option A] [10]] [see additional commentary]*
S6.5 ADDITIONAL LOADS S6.5.3.6	The maximum tensile longitudinal stress … should meet: … 180 N.mm^{-2}. *[see additional commentary]*
S6.6 FATIGUE S6.6.2.1	The simplified and detailed fracture mechanics approaches for defining the fatigue life of a pipeline in hydrogen service are as specified in IGEM/TD/1 Ed 6 clause 6.6.2, but modified as follows: … Table S2 … Figure S4a …. S4b … *[see additional commentary]*
S6.7 AREA TYPES AND DESIGN CRITERIA	*[The minimum proximity of pipelines to normally-occupied buildings is as defined in Figures 5 and 6 in IGEM/TD/1 Edition 6.] [see additional commentary]*
S6.7.4 Design of pipelines in Type R areas S6.7.4.1	Pipelines should be designed in accordance with the design factors specified in Table S1, clause S6.4, unless the material is qualified for hydrogen service in accordance with S5.8. *[see additional commentary]*
S6.7.5 Design of pipelines in Type S areas S6.7.5.1	Pipelines shall be designed to a maximum design factor of: 0.3 or Table S 1, clause S6.4 (but not exceeding 0.5) for pipelines constructed using pipe having a nominal wall thickness of not less than 19.1 mm. *[see additional commentary]*
S7.12 WELDING S7.12.1	Low hydrogen consumables shall be used. *[EIGA IGC Doc 121/14, 7.4.5 [24]]* The hardness of the weld and heat affected zone shall not exceed 250 HV10 … *[see S5.3.1]* The maximum tensile strength of the weld metal shall not exceed 690 N.mm^{-2}. *[ASME B31.12, PL-3.7.1(b)(1)(-d) [10]]*
S9.4 DRYING, PURGING AND GASSING UP	Only indirect purging operations using an inert gas such as nitrogen shall be used on pipelines for operation in hydrogen service. … *[EIGA IGC Doc 121/14 states that nitrogen or other inert gas shall be used to purge hydrogen. [24]]*
S12.2.3.9 Venting gas	… Guidance on venting for pipelines in hydrogen service is given in CGA G5.5. *[CGA G-5.5–2021 Standard for Hydrogen Vent Systems [23]]*
S12.10.5 Under-pressure connections, hot taps and stoppling	Under-pressure (i.e. "hot tap") operations shall not be carried out on pipelines operating in hydrogen service unless proven to be suitable. *[HSG253, Appendix 5 states that hot tapping and stoppling is not appropriate for systems containing hydrogen. [25]]*
SECTION 13: REPURPOSING AN EXISTING NATURAL GAS PIPELINE	REQUIREMENTS FOR REPURPOSING … FIGURE 1 – PROCESS OVERVIEW FOR REPURPOSING A NATURAL GAS PIPELINE
APPENDIX 3: RISK ASSESSMENT TECHNIQUES - REPURPOSING AN EXISTING NATURAL GAS PIPELINE	… Apply IGEM/TD/1 Ed 6 clause 6.8 and Appendix SA3 (note to be developed), taking full account of additional hazards posed by and probability of failure of pipelines transporting hydrogen or natural gas/hydrogen blends … full account of additional hazards posed by and probability of failure … is to be addressed.

Table 2 Commentary on the clauses in IGEM/TD/13 Edition 2 Supplement 1

SECTION 5: PLANNING, LOCATION, LAYOUT AND SECURITY	
S5.1	Where possible all PRIs and installations … should be located outside to allow good ventilation throughout the PRI and ensuring there is no congested pipework which would allow gas to accumulate. [*Model Code of Practice Part 15 [33]*]
S5.2	Where the main pipework … is to be installed inside a housing … in areas where natural ventilation is not possible, consideration shall be given for the installation of permanent atmosphere analysis equipment at suitably located point (s) and/or forced ventilation … explosion relief shall be designed so that if an explosion occurs the pressure will be relieved without generating dangerous missiles.
S5.3	PRI and installation layout shall consider the hazardous areas generated by all equipment, with careful consideration given to the location of vent or relief systems and the hazardous area generated. [*Natural gas is Fluid category G(i), but hydrogen is Fluid category G(ii), so the hazardous area is larger [33].*] [*HSG253 [25]; Model Code of Practice Part 15 [33,34]*]
SECTION 7: DESIGN OF A PRI	
S7.1	… Specific consideration shall be given to: calculation of gas velocity, design of venting systems, hazardous areas generated. … [*Model Code of Practice Part 15 [33]*]
S7.2 PIPEWORK SIZING	PRI pipework shall be sized such that the gas velocity shall not exceed the erosional velocity at peak conditions. High hydrogen gas velocities in piping increases turbulence and pressure drop, contributes to excessive sound pressure levels (aerodynamic noise) and can cause internal piping erosion and acoustically induced vibration. … [*Control and relief valves typically operate at sonic or near sonic velocities. The speed of sound in hydrogen is higher, so the velocities in hydrogen service will be higher than in natural gas service. Higher velocities increase turbulence and pressure drop. IGEM/TD/13 Edition 2 states that pipework should be sized such that the (natural) gas velocity will not exceed 20 $m.s^{-1}$ for unfiltered gas and 40 $m.s^{-1}$ for filtered gas.*] [*EIGA IGC Doc 121/14, 5.2 [24]*]
S7.3 DESIGN PRESSURE BOUNDARIES	The design of regulator streams shall take into consideration the flowrate and pressure differential to ensure the erosional velocity (see clause S7.2) is not exceeded … Regulator impulse lines shall be located so that they are not affected by pressure variations due to turbulence and flow instabilities (vortex shedding). …
S7.4.4 Selection of valves	A key consideration for hydrogen is to prevent leakage both across the valve and to atmosphere. …, the following shall be specified: double block and bleed … soft seats in a metal retainer for in-line automatic valves and automatic vents … metal to metal seat or soft seats in a retainer for in-line manual valves … minimise through bolting, body flanges or threaded connections in assembly of the body of the valve unless gaskets are suitable for hydrogen service … [*CGA G-5.5–2021 Standard for Hydrogen Vent Systems [23]; EIGA IGC Doc 121/14, 4.5.2, 5.4.2, 5.4.3, 5.5 [24]*]
S7.4.4.1	Valves … made of cast or ductile iron shall not be used. … components made from martensitic steels, cast iron, copper and nickel alloys shall be qualified for hydrogen service. Non-metallic materials present in seals shall be qualified for hydrogen service. … [*PD 8010-1:2015, 8 Design – Materials and coatings states that the suitability of a material for a particular application should be determined. [43]*] [*ASME B31.12, GR-2.1.4 states that the use of cast, ductile, malleable and high silicon irons*

	is prohibited due to their lack of ductility and their sensitivity to thermal and mechanical shock; PL-2.2.2(a)(2) states that valves having shell (body, bonnet, cover, and/or end flange) components made of cast or ductile iron shall not be used in hydrogen service. [10]]
S7.6 HEATING GAS S7.6.1	The requirement for pre-heating in hydrogen service shall be considered. [*Pre-heating might be required in natural gas service to avoid unacceptably low temperatures on the outlet of pressure regulating equipment. The Joule-Thomson coefficient of hydrogen is negative (the maximum inversion temperature is approximately -73 ºC [44]), so pre-heating would not be required, but the coefficient for blends is positive, so pre-heating might be required.]*
S7.7 NOISE AND VIBRATION	
S7.7.1	Velocities for hydrogen … will exceed the velocities in natural gas pipelines. … erosion and abrasion shall be considered. Specific attention should be given to control valves and relief valves which usually have sonic or near sonic velocities. The high sonic velocity may result in problems at lower differential pressures than acceptable for other gases … [*see 7.2*]
S7.7.2.1	High velocities … can increase turbulence and pressure drop, contributing to excessive sound pressure levels (aerodynamic noise) … Acoustically induced vibration shall be avoided …
S7.7.2.2	Consideration of fatigue shall take account of the higher rate of fatigue crack growth and degradation of endurance limits in hydrogen service. [*see additional commentary*]
S7.7.2.3	The design of pipework systems shall consider the higher flow rates and velocities. Pipework systems that had not previously experienced vibration issues with natural gas might be affected by significant vibration in a high-speed hydrogen flow.
S7.8.3 Manual vent lines S7.8.4 Relief vent lines	… For hydrogen there is a possibility of deflagration or detonation of the hydrogen-air mixture inside the vent stack … The L/d ratio of the vent pipe shall be below 60:1. The number of turns and connections to the vent stack shall be limited … and it shall be designed to withstand an overpressure event. [*CGA G-5.5 states that deflagration is possible when the length to diameter ratio of any section is greater than 60:1 [23]. Deflagration is the propagation of flame at subsonic speeds through a flammable mixture (in contrast to detonation where the front propagates at supersonic speeds).*]
S7.9 PIPE AND FITTINGS	
S7.9.1.1	Welded joints should be used where possible. … Threaded connections shall be used only where welded (including seal welded threaded connections) and flanged connections are not practical. … Erosion, abrasion and excessive noise shall be addressed in the design. … [*EIGA IGC Doc 121/14, 5.4.3, 5.5.2.3 [24]*]
S7.9.2 Steel pipe for main PRI pipework	Grades higher than L485 (X70) shall not be used … Table S1 … Maximum Design Factor … [*ASME B31.12, PL-3.7.1(a) & Table PL-3.7.1-1 [Option A] [10]*] [*see additional commentary*]
S7.9.3 Fittings	… hardness shall not exceed 250 HV10. [*see S5.3.1*]
S7.10 WELDING	Low hydrogen consumables shall be used. [*EIGA IGC Doc 121/14, 7.4.5 [24]*]
	The hardness of the weld and heat affected zone shall not exceed 250 HV10 … [*see S5.3.1*]
	The maximum tensile strength of the weld metal shall not exceed 690 $N.mm^{-2}$. [*ASME B31.12, PL-3.7.1(b)(1)(-d) [10]*]
S7.11 STRESS ANALYSIS	

S7.11.1.1	The tensile hoop and longitudinal stresses shall be limited to 180 N.mm^{-2}. *[see additional commentary]*
S7.11.1.2	Fatigue analysis shall take into account the higher rate of fatigue crack growth in hydrogen service. A reduction factor of 50 on predicted life (N) should be applied to S-N curves applied in IGEM/TD/12. … *[see additional commentary]*
S7.11.3	… The analysis of high stressed locations in thick components shall take into account the risk of hydrogen stress cracking. *[Hydrogen stress cracking is associated with high stress triaxiality.] [EIGA IGC Doc 121/14, B2.1.1 [24]]*
SECTION 8: PRESSURE AND FLOW CONTROL	
S8.2.1	The effect of the high sonic velocity of hydrogen should be taken into account when the pressure drop through the regulator is greater than 10%. Hardened seats and plugs should be used. Special attention should be given to the stability of the regulators … *[EIGA IGC Doc 121/14, 5.5.2.3 [24]]*
SECTION 10: ELECTRICAL INSTALLATION AND INSTRUMENTATION	
S10.1.2 Hazardous areas	… are defined in defined in EI IP-MCSP-P15 and the Research Report: Dispersion Modelling in support of EI IP-MCSP-P15. *[see 5.3]*
S10.2.4 Selection of equipment	Special attention shall be made to ensure all electrical and instrumentation equipment is suitable for the gas to be conveyed. *[Hydrogen has a low minimum ignition energy. Natural gas is classified as Equipment Group IIA, but hydrogen is Equipment Group IIC [45].]*
SECTION 13: COMMISSIONING, DE-COMMISSIONING AND DISPOSAL	
S13.1.4 Purging	Only indirect purging operations … shall be permitted … in hydrogen service. *[EIGA IGC Doc 121/14 states that nitrogen or other inert gas shall be used to purge hydrogen. [24]]*
SECTION 14: OPERATION AND MAINTENANCE	
S14.2.3 Systems of work S14.2.3.1	The systems of work shall be suitable for the different hazards … : increased flammable range … increased probability of ignition … poor visibility in daylight … higher volume leakage rate … increased flame speed … requirement for ATEX equipment rated for Equipment Group IIC rather than IIA … increased noise from venting … *[BS EN ISO 80079-20-1:2019 [45]; CGA G-5.5–2021 Standard for Hydrogen Vent Systems [23]; Model Code of Practice Part 15 [33,34]]*
S14.2.4 Emergency arrangements S14.2.4.1	… Clear signage shall be installed so that PRIs and installations … can be clearly identified by the emergency services.
S14.8 PURGING	Only indirect purging operations … shall be permitted … in hydrogen service. *[see S13.1.4]*
S14.9 LEAKAGE TESTING S14.9.1	Special attention shall be paid to the final leak check to take account of the increased leakage rate associated with hydrogen and … blends.
SECTION 16: REPURPOSING AN EXISTING NATURAL GAS INSTALLATION	… REPURPOSING PROCEDURE … FIGURE 1 – PROCESS OVERVIEW FOR REPURPOSING OF AN INSTALLATION … TABLE 2 – DESIGN ASSESSMENT CHECKLIST

Additional Commentary

The Design Factor and the Material Performance Factor, and Options A and B in ASME B31.12 [S6.4 Wall Thickness of Linepipe, S6.5 Additional Loads, S6.7 Area Types and Design Criteria; S7.9.2 Steel pipe for main PRI pipework]

Supplements 1 and 2 limit the maximum design factor of pipelines in hydrogen service to 0.5 (see Table 3 and Figure 1). IGEM/TD/1 Edition 6 generally limits the design factor to 0.72, but, in some circumstances, to 0.8. Supplements 1 and 2 also apply a material performance factor to Grade L415 (X60) and above, which further reduces the design factor. It also specifies limits on the yield and tensile strength, and hardness, as summarised in Table 1, above.

Supplement 2 states that these requirements (specifically, S5.3 Linepipe, S6.4 Wall Thickness of Linepipe (Table S1 Maximum Design Factor), S6.5 Additional Loads and S7.12 Welding) may be relaxed if the materials are qualified for hydrogen service. Laboratory-scale testing is required (see below).

Supplements 1 and 2 are informed by ASME B31.12-2019:

PL-3.7.1 Steel Piping Systems Design Requirements in ASME B31.12 defines (in the terminology of the standard) two fracture control options: Option A (Prescriptive Design Method); and Option B (Performance-Based Design Method). Option B requires that the pipe and weld material are qualified for adequate resistance to fracture in hydrogen gas at or above the design pressure and at ambient temperature using a slightly modified form of the rules in Article KD-10 of ASME BPVC, Section VIII, Division 3. PL-3.7.1(b)(2)(-a)(-6) further specifies that K_{IH}, the threshold stress intensity factor in hydrogen gas, shall not be less than 50 ksi.in$^{-0.5}$ (1737 N.mm$^{-3/2}$)[6]. Table PL-3.7.1-2 Basic Design Factor, *F* (Used With Option B) specifies design factors for Location Class 1, Division 2 through Location Class 4 that are identical to those in ASME B31.8 [9]. Location Class 1, Division 1 is not applicable to hydrogen service.

Option B, in effect, defaults to the requirements for a natural gas pipeline.

Option A is more conservative and restrictive. Option A is based on a cautious interpretation of operational experience, rather than clearly defined technical requirements. Table PL-3.7.1-1 Basic Design Factor, F (Used With Option A) specifies a design factor of 0.5 for Location Class 1, Division 2 and Location Class 2 (down from 0.72 and 0.6, respectively), and for Location Class 3 and 4 it specifies values identical to those in ASME B31.8 [9] (see Figure 1). The maximum value of the design factor is 0.5. Option A also specifies a material performance factor, H_f, to account for the adverse effects of hydrogen gas on the mechanical properties of carbon steels used in the construction of pipelines. Table IX-5A Carbon Steel Pipeline Materials Performance Factor tabulates the material performance factor with respect to the system design pressure, and the specified minimum yield and tensile strengths. H_f is equal to 1.0 for a system design pressure not exceeding 2,000 psig (137.9 barg), and specified minimum yield and tensile strengths less than or equal to 52 and 66 ksi, respectively (i.e. Grade L360 (X52)). Option A also specifies limits on the yield and tensile strength of line pipe and welds. Option B specifies higher limits on the yield and tensile strength.

Hayden & Ulucakli, 2007 [12], 9.1 Design Factor Table Population Methodology gives the background to the material performance factors given in Table IX-5A Carbon Steel Pipeline Materials Performance Factor. It is semi-empirical.

Hydrogen embrittlement increases as the yield and tensile strength increase, and it increases as the pressure increases. The concentration of hydrogen in the steel lattice is directly proportional to the square root of the (partial) pressure of the hydrogen gas. Carbon steel materials used in piping and pipeline systems in hydrogen service are generally lower strength steels, with a specified minimum yield and tensile strengths less than 52,000 and 80,000 psi (359 and 552 N.mm^{-2}), respectively; and the systems are operated at low stress levels, sometimes 30-50% SMYS. A pipeline system constructed using Grade X52 and designed to operate at 50% SMYS was assumed to be least affected by hydrogen embrittlement. That then defined the point for H_f equal to 1.0. It was then assumed that “the design stress is ... the average value of tensile stress and yield stress”, and then the design factors for higher strength steels were calculated, recalculated as material performance factors in Table IX-5A in ASME B31.12, e.g. 0.5x(52+66)/(60+75)/0.5 = 0.437/0.5 = 0.874, etc. [12].

The design factors in IGEM/TD/1 (and in ASME B31.8, and in Part PL of ASME B31.12) are calculated with respect to the specified minimum yield strength, not the average of the yield and tensile strengths. Table IX-5A did not recalculate the factors with respect to the yield strength.

Table S1 Maximum Design Factor (reproduced in Table 3) in Supplements 1 and 2 is based on the material performance factors given in Table IX-5A. It only considers the factors for a system design pressure not exceeding 2,000 psig (137.9 barg)[7]; the effect of pressure is included in the factors for a higher system design pressure. The design factors and material performance factors were calculated using the harmonised values of the specified minimum yield strength, as in API Specification 5L Forty Forth and subsequent editions (and also in Table 4 of IGEM/TD/1), e.g. 0.5x360/415/0.5 = 0.433/0.5 = 0.867, etc. The design factors in Table S1 are equal to 0.5x*h*, where *h* is the material performance factor. The maximum design factor is then grade dependent, as illustrated in Figure 2. Note that the values in Table S1 were rounded to two decimal places.

[6] The conversion from stress intensity factor to crack tip opening displacement is dependent on the assumed tensile properties, see Equations (7.16) and (7.17) in BS 7910:2019 [46]. 50 ksi.in$^{-0.5}$ equates to approximately 0.015-0.023 mm, based on the specified minimum and maximum yield and tensile strength of Grade L360 (X52).

[7] Consequently, Supplement 2 is limited to a maximum operating pressure (MOP) not exceeding 137.9 barg.

The Steel Pipe Design Formula in ASME B31.8 (and ASME B31.12) uses the nominal wall thickness. The equivalent formula in IGEM/TD/1 Edition 6 uses the specified minimum wall thickness, acknowledging the wall thickness under-tolerance in line pipe specifications. The material performance factors were not adjusted to correct for this difference (introducing a slight additional conservatism).

Table S1 limits the hoop stress to 180 $N.mm^{-2}$ (=0.5x360) (see Figure 2), as do Tables PL-3.7.1-1 and IX-5A in ASME B31.12 (expect that the limit is lower in Location Class 4, see below).

The hoop stress is a tensile stress. A limit on the hoop stress is then (or it can be interpreted as) a limit on the maximum tensile stress. Accordingly, Supplements 1 and 2 also limits the tensile longitudinal stress to 180 $N.mm^{-2}$.

Supplements 1 and 2, and ASME B31.12 differ slightly in their interpretation of the material performance factor. Supplements and 2 interpret it as defining a limit on the hoop stress, whereas ASME B31.12 interprets it as a limit on the design factor. A limit on hoop stress is arguably closer to the underlying physics.

IGEM/TD/1 Edition 6 limits the design factor of 0.72 in Type R areas and to 0.3 in Type S areas (or 0.5 if line pipe with a nominal wall thickness greater than or equal to 19.1 mm is used), as summarised in Figure 1. Table S1 specifies the maximum design factor. The design factor includes the material performance factor. Supplement 2 supersedes the limits in IGEM/TD/1 only if the limits in Table S1 are lower than the limits in IGEM/TD/1. Supplement 2 will then limit the design factor in Type R areas, but not necessarily in Type S areas.

Table PL-3.7.1-1 specifies the design factor by location class. It does not include the material performance factor (that is in Table IX-5A). The effective design factor is then the product of the design factor and the material performance factor. The effective design factor (for a system design pressures not exceeding 2,000 psig) in Location Class 3 is 0.388-0.5, and in Location Class 4 it is 0.3104-0.4 (see Figure 1).

Material Qualification [S5.6 Component Selection and S5.8 Material Qualification; S7.9.2 Steel pipe for main PRI pipework]

Supplements 1 and 2 require that all materials are qualified for hydrogen service. Supplement 1 refers to Supplement 2. Qualification requires that acceptance criteria are defined and then that testing is conducted to demonstrate that the materials meet these acceptance criteria. A material may be qualified by laboratory or demonstration-scale testing, or operational (field) experience.

Supplement 2 is not prescriptive with respect to how a material is qualified for hydrogen service. A material could be qualified for hydrogen service by conducting laboratory-scale tests using smooth test specimens in a hydrogen-charged environment, and tests using pre-cracked test specimens in an inert environment and in a hydrogen-charged environment. The hydrogen-charged environment should be representative of the partial pressure of hydrogen in the pipeline under design conditions. A test using a smooth specimen could be used to establish a threshold stress for cracking. A test using a pre-cracked test specimen could (depending on the specific details of the test) be used to establish the threshold stress intensity factor for hydrogen-assisted cracking, or the initiation toughness and the tearing resistance in a hydrogen-charged environment.

The qualification of a material for hydrogen service does not necessarily mean that the material is not susceptible to hydrogen embrittlement, but rather that the degree of hydrogen embrittlement is acceptable.

Line pipe specified to Annex M PSL 2 pipe ordered for European onshore natural gas transmission pipelines in BS EN ISO 3183:2012, or equivalent, is, by default, taken to be qualified for hydrogen service. The citation of a dated standard is intentional.

Option A in ASME B31.12-2008 (and subsequent editions) permits grades up to and including Grade X70 at a design factor up to 0.5, with a material performance factor applied to grades above Grade X52. Option A does not require additional material qualification. Therefore, it follows that line pipe specified to ANSI/API Spec. 5L Forty-Fourth Edition, 2007 (the then contemporaneous specification), or subsequent editions, is acceptable for (qualified for) hydrogen service within the limits implied by Option A. The equivalent contemporaneous line pipe specification is then BS EN ISO 3183:2012, there being no equivalent of Annex M in ISO 3813:2007 (there was no BS EN ISO 3813:2007) and BS EN 10208-2:2009 having been withdrawn on publication of BS EN ISO 3183:2012. BS EN ISO 3183:2019 is equivalent to BS EN ISO 3183:2012. BS EN 10208-2:2009 could be argued as being broadly equivalent to Annex M in BS EN ISO 3183:2012.

A line pipe steel that is qualified for hydrogen service, as per Option A in ASME B31.12, is presumed to have sufficient strength and ductility in hydrogen service, within the limits specified in Option A. Similarly, line pipe specified to BS EN ISO 3183:2012, or equivalent, is presumed to have sufficient strength and ductility in hydrogen service, within the limits specified in Supplement 2 (said limits having been based on the limits in Option A).

Laboratory-scale testing is required to waive the limits specified in Supplement 2 (specifically, S5.3 Linepipe, S6.4 Wall Thickness of Linepipe (Table S1 Maximum Design Factor), S6.5 Additional Loads and S7.12 Welding). Supplement 2 is, again, not prescriptive with respect to the details of the laboratory-scale testing.

Option A in ASME B31.12 does not quantify the fracture toughness of the material. Laboratory-scale tests demonstrate that (under laboratory conditions) the fracture toughness in hydrogen is lower than that in air.

Supplement 2 requires that fracture toughness testing is conducted to determine the fracture toughness in hydrogen. Additional experimental work is required to further investigate the effect of hydrogen on the fracture toughness of line pipe steels, and to investigate the implications of that effect on the integrity of the pipeline.

A code or standard, or equivalent, on the qualification of materials for hydrogen service is required[8].

Fatigue [S5.4 Fatigue, S6.6 Fatigue; S7.11 Stress Analysis]

IGEM/TD/1 Edition 6 requires that the consideration is given to the fatigue life of the pipeline. The fatigue life may be defined using a simplified approach, based on an *S-N* curve, or a detailed fracture mechanics based approach. The *S-N* curve in IGEM/TD/1 is rather conservative; it is lower than the class W1 curve (for an unclassified detail) in BS 7608:2014 [47]. The constant amplitude limit of 35 $N.mm^{-2}$ is identical to that for the class F2 curve. IGEM/TD/13 Edition 2 also requires that fatigue is considered, and refers to the guidance given in IGE/TD/12 Edition 2 [48,49].

Supplements 1 and 2 adopt identical approaches.

The rate of fatigue crack growth in hydrogen is higher than that in air (or natural gas). Fatigue crack growth rate test data indicates that the rate of crack growth in hydrogen is potentially at least 10-100 times higher than that in air, but that it tends to that in air as the stress intensity factor range decreases. It depends upon the stress ratio (the ratio of the minimum stress to the maximum stress), R. Endurance test data (of which there is very little) similarly indicates a shorter fatigue life; it is approximately ten (10) times shorter.

Figure S4a in Clause S6.6.2.3 of Supplement 2 (see Figure 3) defines the *S-N* curve. A factor of ten (10) has been applied to the *S-N* curve in IGEM/TD/1 Edition 6. The factor of ten (10) is based on the limited endurance test data. The constant amplitude limit of 35 $N.mm^{-2}$ is retained (informed by the trends in the rate of crack growth in hydrogen and in air). Clause S7.11.2 of Supplement 1 cites the *S-N* curves in IGEM/TD/12 Edition 3 [50]. The *S-N* curves in Table 26 in Appendix 5 of IGEM/TD/12 Edition 3[9] are as in Annex C of PD 5500:2015 [51]. A factor of fifty (50) has been applied to the *S-N* curves in Table 26, see Figure 3. The factor of fifty (50) is based on the limited endurance test data. The *S-N* curve in IGEM/TD/1 Edition 6 is more conservative than the *S-N* curves in Table 26. The *S-N* curves in Table 26 are based on statistical analysis of a large set of fatigue tests on welded joints. The *S-N* curve in IGEM/TD/1 Edition 6 is based on the fatigue life of a part-through-wall, crack-like flaw equal to the limiting flaw size in a high-level hydrostatic test. It was determined using fracture mechanics based calculations and full-scale fatigue tests. It incorporates a factor of safety on the number of cycles approximately equal to ten (10). The factor to account for the effect of hydrogen on the rate of fatigue crack growth that has been applied in Supplement 2 is smaller than that in Supplement 1 because the *S-N* curve in IGEM/TD/1 Edition 6 is more conservative than the *S-N* curves in IGEM/TD/12 Edition 3, see Figure 3. There is a need for additional endurance tests in hydrogen for the base metal and welded details.

Table S2 and Figure S4b in Clause S6.6.2.3 of Supplement 2 (see Table 4 and Figure 4) define the recommended fatigue crack growth law for steels in hydrogen service.

The fatigue crack growth law is based on fatigue crack growth rate test data reported in Dadfarnia et al., 2019 [53] and the fatigue crack growth law in San Marchi et al., 2019 [54]. It differs from that in ASME B31.12-2019. The crack growth law in Table S2 and Figure S4b for $R < 0.5$ is based on test data. That for $R \geq 0.5$ is an extrapolation, because there is (currently) a lack of test data for $R > 0.5$. There is a need for additional fatigue crack growth rate tests in hydrogen for $R \geq 0.5$.

Dadfarnia et al., 2019 complied fatigue crack growth rate data for line pipe steels from a number of different sources (as summarised in Figure 4) and proposed an approximate upper bound curve. Note that the upper bound curve is not a statistical upper bound.

The test data indicates that the rate of fatigue crack growth in hydrogen is similar to (the same as) that in air at lower ΔK and higher at higher ΔK (see Figure 4).

The stress ratio of the test data in Dadfarnia et al., 2019 is, with one exception, less than or equal to 0.5. A fatigue crack growth law is required for $R < 0.5$ and $R \geq 0.5$, to be consistent with Table 8.3 Recommended fatigue crack growth laws for steels in air in BS 7910:2019 [46]. That for $R \geq 0.5$ is required for welded joints.

The fatigue crack growth law given in ASME B31.12-2019 is non-conservative with respect to the test data presented in Dadfarnia et al., 2019, see Figure 4. It is not used.

The crack growth law in Table S2 (see Table 4) for $R < 0.5$ follows the mean plus two standard deviations in air curve for $R < 0.5$ in Table 8.3 in BS 7910 at lower ΔK, and then the approximate upper bound curve in Dadfarnia et al., 2019 (because it is based on tests for R less than or equal to 0.5). The approximate upper bound curve in Dadfarnia et al., 2019 follows the mean in air curve for $R \geq 0.5$ at lower ΔK.

The crack growth law in Table S2 (see Table 4) for $R \geq 0.5$ follows the mean plus two standard deviations in air curve for $R \geq 0.5$ in Table 8.3 in BS 7910 at lower ΔK, and is then parallel to, but higher than, the approximate upper bound curve in Dadfarnia et al., 2019. San Marchi et al., 2019 defines a master curve for the rate of fatigue crack growth in hydrogen. It

[8] Option B in ASME B31.12 and Article KD-10 of ASME BPVC are noted. A threshold stress intensity factor of 50 $ksi.in^{-0.5}$ is a relatively low value of fracture toughness.
[9] The *S-N* curves in IGE(M)/TD/12 Editions 2 and 3 are identical.

describes the effect of the stress ratio. The crack growth law for $R \geq 0.5$ is higher than that for $R < 0.5$ by a factor of 3.25 (=4.81/1.48), the difference between the predicted curves for $R = 0.5$ and $R = 0.8$ using the master curve. The difference is slightly larger than that between the parallel region of the corresponding curves for steels in air in BS 7910, where the difference is a factor of approximately 1.9 (=1.29/0.677).

The one set of test data in Dadfarnia et al., 2019 for $R > 0.5$, is for $R = 0.8$ (and is on line pipe steel of Grade X42). That data shows a rate of fatigue crack growth that is significantly higher than that implied by Table S2 and Figure S4b (see Figure 4). It is, however, notable that the growth rate in nitrogen (notionally in-air) for $R = 0.8$ is also significantly higher than either the simplified or the mean plus two standard deviations curves for steels in air in BS 7910, so there is an unresolved question mark over that set of data. It has not been used.

The Building Proximity Distance (BPD) [S6.7 Area Types and Design Criteria]

IGEM/TD/1 Edition 6 categorizes the location adjacent to a pipeline according to density of the population (number of persons per unit area) and/or the nature of the immediate surrounding area. It defines four area types: Types R, S, H and T (see Figure 1). It also defines a minimum distance between the pipeline and normally occupied buildings (the Building Proximity Distance). The population density is the average within a 1.6 km long strip centred on the pipeline of a width eight times the minimum distance to normally occupied buildings for a Type R area.

Supplement 2 adopts an identical approach.

A building proximity distance is required for a hydrogen pipeline:

The BPDs in Figures 5 and 6 in IGEM/TD/1 Edition 6 (reproduced in Figure 5) were first introduced in their current form in Figures 1 and 2 in IGE/TD/1: Edition 2: 1977 Section 5 Design [18]. Edition 2 revised the BPDs in IGE Communication 674A, 1970 [14]. The BPDs in Edition 6 (and 2-5) are based on the calculated distance to a thermal radiation level of 31.5 $kW.m^{-2}$ (10,000 $BTU.ft^{-2}.h^{-1}$) emitted from a (pseudo) steady-state fire [16,17]. The dose is approximately equivalent to 1 percent lethality after direct exposure for 10 seconds. Cotton fabrics would ignite in approximately 10 seconds and wood in approximately 60 seconds. The thermal radiation calculations were conducted using a phenomenological gas outflow model and an empirical model for a natural gas fire[10].

An equivalent calculation can be conducted for hydrogen based on evidence from large-scale pipeline rupture experiments performed under similar conditions for natural gas, hydrogen and natural gas/hydrogen blends [57,58]. These large fires exhibited similar radiative characteristics. A comparison of the thermal radiation field at times of equivalent power (where the power is the product of the mass release rate and the net calorific value of the gas) indicated that the thermal radiation levels were similar for the different gases, at times when the power of the release was similar. The fraction of energy released as thermal radiation was found to be approximately 0.29 for hydrogen, similar to the values obtained for natural gas and natural gas/hydrogen blends. The steady-state volume flow rate for hydrogen is approximately 2.8 times higher than that for natural gas (the square root of the ratio of the molecular weights). The net calorific values for hydrogen and natural gas are 10.8 $MJ.m^{-3}$ and (approximately) 36.6 $MJ.m^{-3}$, respectively. The ratio of the heat radiated from a hydrogen fire to that from an otherwise identical natural gas fire is then 0.83 (=2.8x10.8/36.6). The decay of the far-field thermal radiation follows the inverse square law. Therefore, the distance for hydrogen is approximately 90 percent of the distance for natural gas.

The BPDs in IGEM/TD/1 Edition 6 only consider the thermal radiation of the natural gas fire. The hazard associated with the overpressure associated with the delayed ignition of a release of natural gas is negligible compared to the thermal radiation (as has been demonstrated in experimental work and incidents). The delayed ignition of a release of hydrogen has the potential to generate greater overpressures, because of its higher flame speed and wider flammable limits. The minimum ignition energy of hydrogen is an order of magnitude lower than that for natural gas. That, and the wider flammable limits, indicates that delayed ignition of hydrogen might be less likely.

Supplement 2 adopts the BPDs in Figures 5 and 6 in IGEM/TD/1 Edition 6. These are conservative with respect to the thermal radiation effects of a hydrogen fire, but do not consider the effect of overpressure or the relative risk. Additional experimental work is required to further investigate the effect of the overpressure associated with the delayed ignition of a large-scale release of hydrogen.

The analysis of the effect of hydrogen on the BPDs in IGEM/TD/1 Edition 6 does not explicitly address the relative risks of hydrogen and the equivalent natural gas pipelines. The original method of calculating the BPDs reflects the techniques available at the time, approximately 40 years ago. Since then, the understanding of the hazards resulting from a pipeline failure, and the ability to model the consequences and to predict the associated risks to people in the surrounding area have advanced considerably, facilitated by improved models and documented in standards such as IGEM/TD/2 Edition 2 [59]. Considerations that will affect the relative risk for pipelines transporting hydrogen or natural gas/hydrogen blends include: the failure frequency of a pipeline in hydrogen service as compared to natural gas service; and the probability of immediate and delayed ignition of a release of hydrogen. The overpressure from the delayed ignition of a release of hydrogen might also contribute to the relative risk, but the likelihood of the delayed ignition of a large, turbulent release of high pressure hydrogen from a rupture might be very low, due to the wider flammability limits and lower minimum ignition energy for hydrogen compared with natural gas.

[10] The original models, PBREAK and FRACTURE, are included in TRANSPIPE and PIPESAFE [55,56].

Additional research is currently ongoing or is planned to address these gaps in knowledge, which should then allow for a more robust comparison of the relative risks to be made in the future.

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Table 3 … after Table S1 - Maximum design factor in IGEM/TD/1 Edition 6 Supplement 2

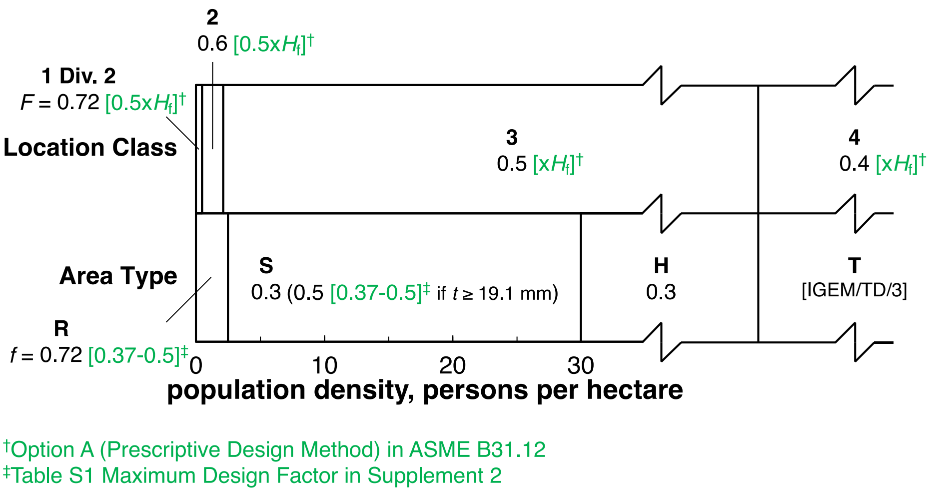
Material Grade	Design factor f	Material Performance Factor h
L360 / X52 and below	0.50	1.00
L415 / X60	0.43	0.87
L450 / X65	0.40	0.80
L485 / X70	0.37	0.74

Table 4 … after Table S2 - Recommended fatigue crack growth laws for steels in hydrogen service in IGEM/TD/1 Edition 6 Supplement 2

R	**Stage A**		**Stage B**		**Stage C**		**Stage D**		**Stage A/ Stage B transition point Δ*K*, N.mm$^{-3/2}$**	**Stage B/ Stage C transition point Δ*K*, N.mm$^{-3/2}$**	**Stage C/ Stage D transition point Δ*K*, N.mm$^{-3/2}$**
	A	*m*	*A*	*m*	*A*	*m*	*A*	*m*			
<0.5	$4.37x10^{-26}$	8.16			$5.18x10^{-24}$	7.82	$1.48x10^{-12}$	3.37	203	203	375
≥0.5	$2.10x10^{-17}$	5.10	$1.29x10^{-12}$	2.88	$1.68x10^{-23}$	7.82	$4.81x10^{-12}$	3.37	144	203	375

Note:

1. $R \geq 0.5$ values recommended for assessing welded joints.



Notes:

1. Area Type in IGEM/TD/1 Edition 6 is defined in terms of population density. Location Class in ASME B31.8 is defined in terms of the number of buildings intended for human occupancy in a ¼ mile wide and 1 mile long strip, centred on the pipeline. Location Class 1 is 10 or fewer buildings; Class 2 is more than 10, but fewer than 46 buildings; and Class 3 is more than 46 buildings for human occupancy. The population density is calculated assuming that the occupancy is 3 persons per dwelling, as per clause 6.7.2.3 in IGEM/TD/1 Edition 6.
2. The Steel Pipe Design Formula in ASME B31.8 (and ASME B31.12) uses the nominal wall thickness. The equivalent formula in IGEM/TD/1 Edition 6 uses the specified minimum wall thickness. A pipeline designed to IGEM/TD/1 Edition 6 is then slightly thicker than one designed to ASME B31.8, given the same numerical value of the design factor.

Figure 1 Area Type in IGEM/TD/1 Edition 6 and Location Class in ASME B31.8 and B31.12, and the design factor in the aforementioned, and in Supplement 2 and ASME B31.12

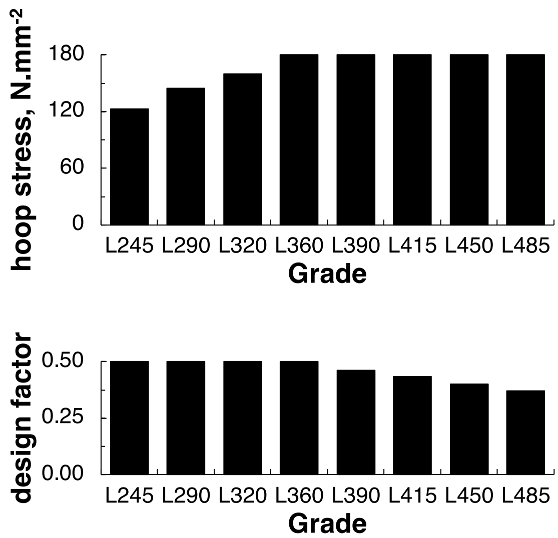
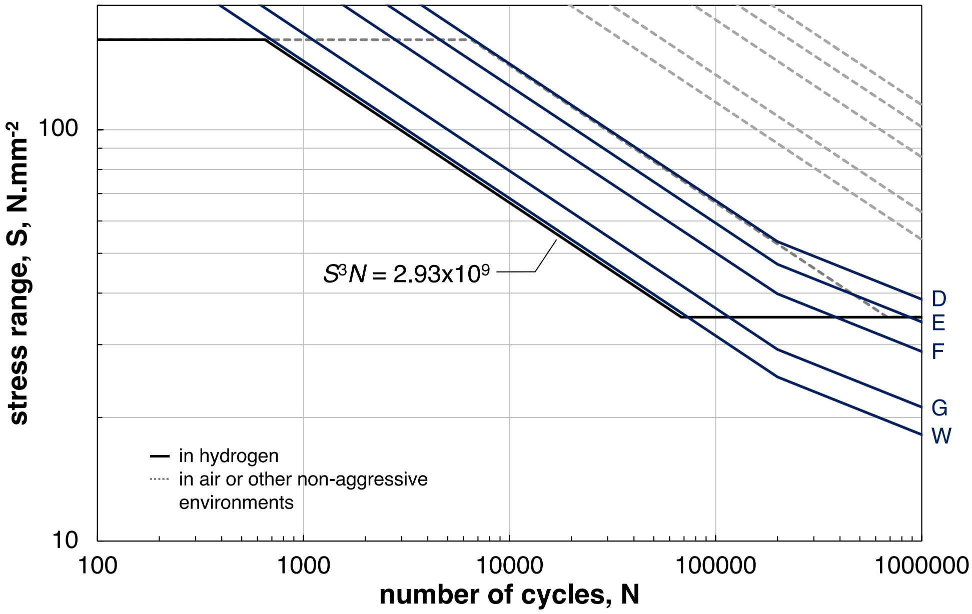


Figure 2 The maximum hoop stress and design factor in Supplement 2



Note:

1. Table 26 in Appendix 5 of IGEM/TD/12 is as in Annex C of PD 5500:2015 [51]. It differs slightly from Annex C of PD 5500:2021 [52], which is based on BS 7608:2014 [47]. Class W in Table 26 is class G2 in BS 7608. The slope transition point in Table 26 for calculations of the cumulative fatigue damage under variable amplitude fatigue loading is at 10^7 cycles, not $5x10^7$ cycles.

Figure 3 … after Figure S4a - Relationship between stress range and number of cycles for hydrogen and natural gas/hydrogen blend service in IGEM/TD/1 Edition 6 Supplement 2 and clause S7.11.2 in IGEM/TD/13 Edition 2 Supplement 1 (cf. Table 26 in Appendix 5 of IGEM/TD/12)

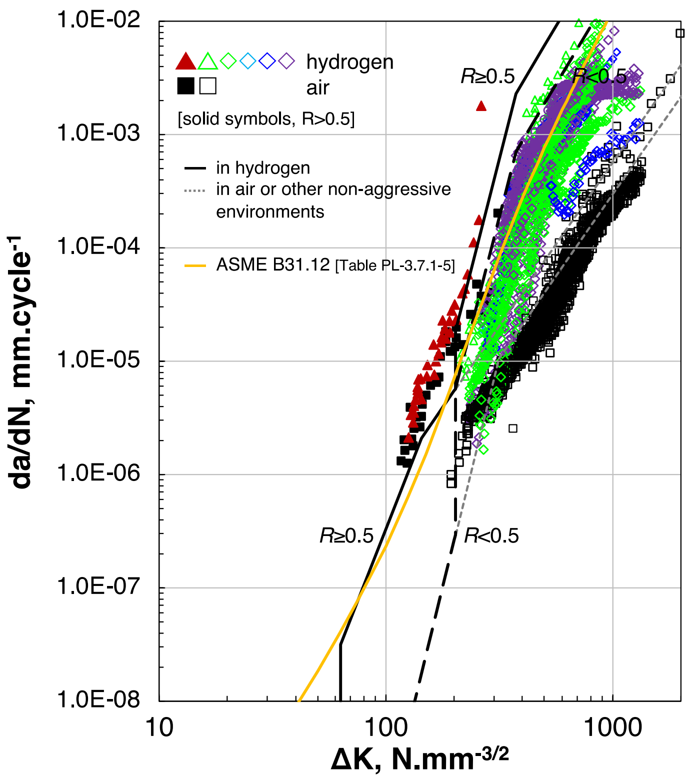
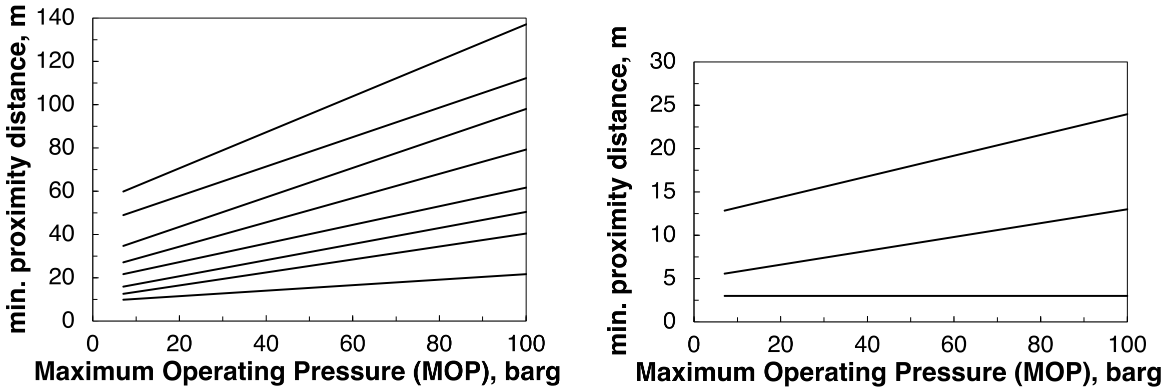


Figure 4 … after Figure S4b - Fatigue crack growth law for hydrogen and natural gas/hydrogen blend service in IGEM/TD/1 Edition 6 Supplement 2, and the fatigue crack growth rate test data reported in Dadfarnia et al., 2019



a) pipelines designed to operate in Type R areas b) pipelines designed to operate in Type S areas

Figure 5 … after Figure 5 - Minimum proximity distance to normally-occupied buildings of pipelines designed to operate in Type R areas and Figure 6 - Minimum proximity distance to normally-occupied buildings of pipelines designed to operate in Type S areas, in IGEM/TD/1 Edition 6