



HYDROGEN PIPELINE SYSTEMS

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Asia Industrial Gases Association

3 HarbourFront Place, #09-04 HarbourFront Tower 2, Singapore 099254
Tel : +65 62760160 Fax : +65 62749379
Internet : <http://www.asiaiga.org>



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1 Introduction

This publication has been prepared by a group of specialists in pipeline systems, representing major industrial gases producers in various countries of Europe and North America and is based on the technical information and experience currently available to the authors.

This publication has been prepared by member associations of the International Harmonization Council, IHC, under the lead of EIGA and is intended for the worldwide use and application by all members of the International Harmonization Council. The International Harmonisation Council is composed of members from the Asia Industrial Gases Association (AIGA), Compressed Gas Association, (CGA), European Industrial Gases Association, (EIGA), and the Japanese Industrial and Medical Gases Association (JIMGA). Regional editions may use non SI units and refer to national, and or regional legislation.

It shall be recognized, however, that pipeline systems, developed over 50 years in the various countries of Europe and North America have shown good and comparable safety records, although national practices show many differences in design and operations. Some national authorities have also introduced legislation, which is mandatory for the operators in those countries.

Thus, the information contained in this document applies only to future installations and not to existing installations or those in the project phase, as of the date of this publication. Furthermore, to the extent that they exist, national laws supersede the suggested practices listed in this publication. It should not be assumed that every local standard, test, safety procedure or method is contained in these recommendations or that abnormal or unusual circumstances may not warrant additional requirements or procedures. The authors make no representations or warranties on the information in or the completeness of this document and disclaim all warranties, express or implied including, but not limited to, the warranty of merchantability and the warranty of fitness for a particular use or purpose.

ISO units and corresponding Imperial units in brackets are used in this document. Corresponding values may be approximate.

Those involved in the safe design, operation, and maintenance of gaseous transmission and distribution systems should be aware of various documents, guidance, publications, and standards prepared by various multinational organizations which may be pertinent to such systems. These are listed in Appendix K. In addition to these documents, there are a number of pertinent publications, technical papers, bulletins which provide useful information on materials of construction, metallurgy, environmental degradation mechanisms found also in Appendix K. While the cited references provide valuable background, it cannot be stated that these are all of the standards documents or technical papers published by international organizations that could be pertinent to the subject of this publication.

2 Scope and purpose

The scope of this document is for metallic transmission and distribution piping systems carrying pure hydrogen and hydrogen mixtures, as shown in Diagram 1 of Appendix A.

It is limited to gaseous products:

- with a temperature range between -40°C (-40°F) and 175°C (347°F),
- total pressures from 1MPa (150 psig) up to 21 MPa (3000 psig) or for stainless steels only partial H₂ pressure higher than 0,2 MPa
- concentration criteria defined in Appendix G.

Concerning Ultra High Purity (UHP) hydrogen, specific guidance is provided in Appendix I.

This document does not apply to the following processes:

- cylinder filling plants
- producing plants
- compressor units

- Bulk facilities (liquid or high pressure gas) at the customer's site up to the point where gas enters the distribution systems
- Piping on specialized equipment and machines.

The purpose of this publication is to further the understanding of those engaged in the safe design operation and maintenance of transmission and distribution systems. It is not intended to be a mandatory standard or code. It contains a summary of the current industrial practices. It is based upon the combined knowledge, experience, and practices of the major producers in Europe and North America as represented by their members on the IHC Ad-Hoc group on pipeline transportation systems.

Some of the practices represent conservative compromises and not all situations are described. The designer is cautioned that this document is not a complete design handbook and does not negate the need for competent engineering judgment and interpretation. It is suggested that the user reviews any special problems or concerns with his hydrogen supplier who should be able to provide advice and guidance.

3 Definitions

3.1 Terminology

Shall is used only when procedure is mandatory. Used wherever criterion for conformance to specific recommendation allows no deviation.

Should is used only when a procedure is recommended.

May and Need Not are used only when procedure is optional.

Will is used only to indicate the future, not a degree of requirement.

Can: Indicates a possibility or ability.

3.2 Distribution piping

Piping contained on the property (generally owned by the customer) at the use point such as mains, feeders, station connections, and valves.

3.3 Plant piping

Piping within the production facility

3.4 Transmission piping

Piping between the production plant boundary and distribution piping boundary, including that which passes over public land and third party property.

3.5 Copper based alloys

Copper based alloys used in components for the transmission of industrial gases via pipeline generally contain at least 55 weight % copper. Included within this group are the coppers, brasses (copper alloyed primarily with zinc), bronzes (copper alloyed with aluminium, silicon, manganese, tin, lead) and copper nickels (copper alloyed with nickel).

3.6 Nickel base alloys

Nickel based alloys used in components for gas transmission pipeline systems contain at least 50 weight % nickel and nickel contents up to 99+ weight % have been used. However, some tabulations of nickel alloys may list alloys with nickel contents as low as 30 weight %.

Some of the major nickel alloy families and examples of each are as follows:

- nickel (nickel 200);
- nickel-copper (Monel® 400 and Monel® 500);
- nickel-chromium (Inconel® 600 and Inconel® X-750); and
- nickel-chromium-molybdenum (Hastelloy® C-276 and Inconel® 625).

For hydrogen gas transmission applications, the potential for hydrogen embrittlement, which is affected by metal strength and hydrogen partial pressure, should be considered.

3.7 Stainless steel alloys

Ferrous alloys become stainless when they contain a minimum chromium content of at least 10-13 weight %. There are a number of stainless steel classifications, which are dependent upon the alloy content, crystalline lattice, strengthening mechanisms and the ratio of ferrite stabilizers to austenitic stabilizers.

Stainless steel classifications, with examples of each type, are as follows:

- Austenitic (304, 304L, 316, 316L, 321, 347);
- Ferritic (430);
- Martensitic (410);
- Precipitation hardening (17-4 PH);
- Duplex (329, SAF 2205).

The preceding alloy designations were for wrought products but there are alloys such as CF-8, CF-3, CF-8M, CF-3M which are the cast analogs of 304, 304L, 316 and 316 L respectively.

Of the various stainless steels, the 300 series stainless steels and their cast analogs are the most commonly used in gas transmission piping systems and have excellent toughness even in high pressure hydrogen.

3.8 Cobalt alloys

The commercial listings of cobalt alloys generally start with a minimum cobalt content of at least 40 weight %. Wear resistant alloys such as Stellite 6 or Stellite 6B are sometimes used as coatings on valve trims to minimise erosion damage and improve valve life.

3.9 Non-ferrous alloys

When the term nonferrous alloy is used in this document, it includes only copper, nickel and cobalt alloys. It does not include aluminium or reactive materials such as titanium or zirconium.

3.10 Ferrous alloys

Included in this category are carbon-steel, low-alloy steel and all stainless steels irrespective of whether these alloy families are in cast or wrought form.

3.11 Microalloyed steels

The broadest description of microalloying is the use of small additions of alloying elements which achieve improvements of steel properties which seem to be out of proportion to the amount of alloying elements which are added. The steel characteristics which may be improved include strength, toughness, weldability and formability. Reactive metals, rare earths, boron and sulfide shape control additives would be included in the inventory of microalloying agents in the broadest definition.

A more restricted definition of microalloying is the use of small amounts of alloying additions of elements such as vanadium, niobium and titanium which are strong carbide and nitride formers to achieve improvements in strength, toughness and weldability through specific thermomechanical processing steps.

3.12 Carbon equivalent and the composition parameter

Carbon equivalent (C.E.) is a parameter used to assess the weldability of carbon and low alloy steels and their susceptibility to cracking during welding. Steels with low carbon equivalents generally do not require any preheating or post heating treatment. Those with intermediate carbon equivalents may require preheating and those with high carbon equivalents require both preheating and post heating.

Generally carbon equivalents of 0.55 and above are considered to be high and carbon equivalents less than 0.35 are considered to be low. However, thickness, weld heat input and other factors enter the overall assessment.

It should be noted that various carbon equivalent relationships have been developed and published over the years. One of the earliest carbon equivalent relationships is the following:

$$\text{C.E.} = \%C + \%Mn/6$$

The most common carbon equivalent relationship currently in use is :

$$\text{C.E.} = \%C + \%Mn/6 + (\%Mo + \%Cr + \%V)/5 + (\%Ni + \%Cu)/15$$

A major benefit of microalloyed steels is that low carbon equivalents may be achieved and the alloys are more resistant to weld cracking. For steels with lower carbon contents or carbon equivalents, the composition parameter P_{cm} has been used as an indicator of cracking susceptibility. An acceptable limit is 0.2% maximum for the following:

$$P_{cm} = \%C + (\%Mn + \%Si + \%Cu + \%Co)/20 + \%Ni/60 + \%Mo/15 + \%V/10 + 5\%B$$

3.13 Base metal

The material which is to be welded, brazed or soldered

3.14 Heat affected zone (HAZ)

That portion of a weld, braze or solder joint that has not melted but where mechanical properties or microstructure have been altered by the heat of welding, brazing or soldering. It should be noted that certain cutting processes may also result in a discernible heat affected zone.

3.15 Metastable austenitic alloys

These are austenitic alloys which have a chemistry which renders the austenitic microstructure susceptible to transformation to martensite when subjected to thermomechanical processes involving various combinations of strain and reduced temperatures. The relative ratio of austenite stabilizer to ferrite stabilizer is significant in the transformation process.

3.16 Stable austenitic alloys

These are alloys which have a high ratio of austenite stabilizers or formers to ferrite formers or stabilizers. When subjected to high strain and reduced temperature, the austenitic alloy will not transform to martensite.

3.17 Austenite stabilizers or formers

These are elements which promote austenitic formation and stabilize austenite when stressed at reduced temperatures. They include: nickel, carbon, manganese, nitrogen, cobalt and copper. There are various empirical relationships which quantify the strength of various alloying elements as austenite stabilizer or formers.

3.18 Ferrite stabilizer or formers

These are elements which promote the formation of ferrite and stabilize it. These include: chromium, molybdenum, silicon and niobium. Empirical relationships which quantify the strength of the alloying elements in this capacity have been developed.

3.19 Austenite stability factor (Δ)

Austenite stability factors have been developed to determine when an austenite stainless steel would be likely to transform to martensite at cold reductions as high as 80%. Shown below are the Griffith and Wright Stability Factor Relationship:

$$\Delta = \text{Ni} - [(\text{Cr} + 1.5\text{Mo} - 20)^2 / 12 - 0.5\text{Mn} - 35\text{C} - \text{Cu} - 27\text{N} + 15]$$

and the « modified Post and Eberly » formula (see reference Hydrogen and Materials)

$$\Delta = \text{Ni} + 0,5\text{Mn} + 35 \text{ C} - 0,0833(\text{Cr} + 1,5\text{Mo} - 20)^2 - 12$$

Negative numbers indicate a high tendency for austenite to martensite transformations when severely strained.

If Ni content is greater than 10.5% in a 300 series stainless steel, Δ is usually positive and the steel is stable.

3.20 Austenite to martensite transition temperatures

M_s is the temperature at which metastable austenite transformation to martensite occurs on cooling. The Eichelman and Hull Relationship is as follows:

$$M_s (^\circ\text{F}) = 75(14,6 - \text{Cr}) + 110(8,9 - \text{Ni}) + 60(1,33 - \text{Mn}) + 50(0,47 - \text{Si}) + 3000[0,068 - (\text{C} + \text{N})]$$

M_{d30} is the temperature at which 50% austenite will transform to martensite at 30% strain. Shown below is the relationship developed by Angel:

$$M_{d30} (^\circ\text{F}) = 413 - 462(\text{C} + \text{N}) - 9,2\text{Si} - 8,1\text{Mn} - 13,7\text{Cr} - 9,5\text{Ni} - 18,5\text{Mo}$$

3.21 Chromium and nickel equivalents

The most common relationship for the calculation for the chromium equivalent is as follows:

$$\text{Cr eq} = \% \text{Cr} + \% \text{Mo} + 1,5 \% \text{Si} + 0,5 \% \text{Nb}$$

The most common relationship for the calculation of the nickel equivalent is as follows:

$$\text{Ni eq} = \% \text{Ni} + 30 \% \text{C} + 0,5 \% \text{Mn}$$

In conjunction with a "Shaeffler Diagram", chromium and nickel equivalents can be used to predict the ferrite and austenite forming tendencies of austenitic stainless steels in weld metals and cast metals. It should be noted that newer relationships which include the effects of other elements which affect austenite and ferrite formation or stability do exist.

3.22 Velocity

The volumetric flowrate at the actual pressure and temperature divided by the pipe inside cross-sectional area

3.23 Gas pressure

The operating pressure of the piping system

4 Design philosophy

4.1 General criteria

The safe operation of a transmission piping system depends on various factors which can influence each other. This chapter describes the principal risks and hazards associated with Hydrogen systems and the manner in which the hazards can be minimized by good engineering design.

A safe hydrogen piping transmission or distribution system, including all its components, is one that is designed taking into account:

- local conditions e.g. seismic zone, soil characteristics;
- applicable piping codes for mechanical design (including pressure rating and wall thickness) and installation;
- conditions of service with respect to fluid composition, gas velocity, pressure, temperature and dew point;
- selection of metallic materials;
- selection of non-metallic materials;
- national laws and regulations which apply to gas transmission pipelines generally and hydrogen systems specifically;
- standards of cleanliness for service;
- industry codes of practice relating to hydrogen systems; and
- hazard considerations such as flammability of hydrogen systems.

Piping fabricated from non-metallic material, such as plastic or composite material is outside the scope of this document.

4.2 Properties of hydrogen

4.2.1 Flammability

Hydrogen is lighter than air, highly flammable, easily ignited, heats up when reduced in pressure, does not support breathing and one of the most difficult gases to prevent from leaking. In the pure state, it presents some unique corrosion mechanisms and when combined with even small impurities (ppm), the corrosion concerns can multiply.

Hydrogen burns in air with a pale blue, almost invisible flame which increases the risk of injury in case of fire.

The lower and upper flammability limits in air are:

LFL : 4%
UFL : 75%

The minimum ignition temperature of hydrogen-air mixtures is 500°C (932°F).

Hydrogen-air mixtures are extremely easy to ignite requiring only 0.017 mJ ignition energy compared to 0.25 mJ for hydrocarbons.

The maximum flame propagation rate is up to 3 m/sec in air

Although auto-ignition of leaks and atmospheric vents is always a possibility with any flammable gas, hydrogen is especially prone to this phenomenon. This is due to hydrogen's low ignition energy and the fact that, unlike most gases, hydrogen increases in temperature when it expands from a higher to a lower pressure. This tendency towards auto-ignition of leaks and atmospheric vents, combined with the difficulty in seeing the flame make small leaks a serious potential personnel injury risk.

In order to mitigate fire risks, fire prevention practice and operator training shall be considered (see Sections 9 and 10).

4.2.2 Brittle fracture and environmental damage mechanisms

There are a number of brittle fracture mechanisms or degradation effects; some of which are attributed to hydrogen. These are all described in Appendix B. However, not all of these are pertinent to dry hydrogen gas. Those that are pertinent to the transmission of hydrogen via pipelines are:

- For internal corrosion
 - o Hydrogen gas embrittlement (HGE) at ambient temperature
- For external corrosion
 - o Stress corrosion cracking (SCC) of line pipe materials in underground environments

HGE covers a number of different effects which are described in detail in Appendix B. SCC of line pipe materials in underground environments is a phenomenon which may be linked to a number of factors such as defective coatings, improper cathodic protection and poor soil conditions. See Appendix B for more details.

The two phenomena mentioned above could lead to catastrophic failures. Approaches by which the risks associated with these mechanisms can be minimised include reductions on global or local stress levels and careful materials selection as described in 4.3

Note: The term “hydrogen attack” is sometimes improperly used when hydrogen pipelines are considered. Hydrogen attack only occurs at temperatures of 200°C (392°F) or more and consequently is not relevant to hydrogen pipelines (see Appendix B for more information about high temperature degradation modes).

4.3 Metallic materials

4.3.1 Generalities

4.3.1.1 Strength, hardness and microstructure

Many metallic materials can suffer embrittlement in hydrogen gas environments. These include steels (especially high strength steels), stainless steel, and nickel alloys.

Steels used in hydrogen pipeline service should have a maximum hardness of approximately 22 HRC (Hardness Rockwell C) or 250 HB (Hardness Brinell). This hardness limit is approximately equivalent to a tensile strength limit of about 116 ksi (800 MPa). Welds should also have a maximum hardness of 22 HRC or 250 HB. It shall be noted that the welded zone is often harder and therefore more susceptible to embrittlement than the base metal

To achieve an acceptable weld zone hardness, it may be necessary to use lower strength steels than indicated above (500 MPa). Special welding procedures and pre or post welding thermal treatments may be another approach.

In the pipeline systems, there may be a need for buffers which are usually seamless pressure vessels. Steels used for seamless vessels may have a UTS (Ultimate Tensile Strength) up to 950 MPa (ISO 9809 and ISO 11120).

The engineering alloys used in critical locations should have high toughness levels in the fabricated condition and be relatively insensitive to welding problems, e.g., hard/brittle areas, microcracks, fissures etc.

There are a number of variables, which can affect the severity of the embrittlement mechanisms encountered such as purity, temperature and pressure. It is generally recognised that the tendency for embrittlement in hydrogen atmospheres increases with increasing pressure.

In general, the following are significant metallurgical considerations:

- use of alloys with homogenous fine-grained microstructures is preferred;
- avoidance of excessively hard or high strength alloys, see above;
- use of steels with enhanced cleanliness so non-metallic inclusions, which reduce toughness and hydrogen embrittlement resistance are minimized; and
- components free from significant surface and internal defects.

With respect to the above, there may be somewhat different positions on the degree to which the above are applied and at what pressures. Appendix D covers the preceding in great detail. Each user shall determine which of the above considerations should be applied to their specific applications.

If the above conditions cannot be fulfilled, it might be necessary to operate the equipment at a reduced stress/pressure (below 30% of the specified minimum yield strength SMYS or 20% of the specified minimum ultimate tensile strength SMUTS, whichever is the lowest).

4.3.1.2 Welding

4.3.1.2.1 Mechanical properties of welds

Welding processes and operators qualification should verify that weld sample meet the same strength and toughness requirement as the parent metal.

4.3.1.2.2 Weld and weld heat affected zone (HAZ)

The hardness level of welds and the weld HAZ should not exceed Rockwell C 22 which is equivalent to Vickers 248 or 250 HB. The hardness determination is to be made via microhardness traverses on mounted metallographic samples removed from process/operator weld qualification samples. Production hardness testing also should be considered (see 7.7.2.4).

4.3.1.3 Surface condition

Inside surface should be free of defects such as scratches, notches, carbon deposits, and corrosion.

4.3.1.4 Hydrostatic tests

Pipe shall be tested between 75 and 100% of the specified minimum yield strength (SMYS) with a holding time at pressure of at least 5-10 seconds depending on the diameter.

4.3.1.5 Inspection

The materials, source of materials manufacturing, all phases of testing, test specimens, results, etc. shall be available for inspection and approval.

4.3.2 Carbon steels

4.3.2.1 General

Carbon steel is the alloy family most commonly used in hydrogen gas transmission pipelines. Various carbon steel specifications for pipelines are listed in Appendix C. The choice of the specific grade will depend on many factors including the severity of the service, availability and relative cost.

In general, the common carbon steel piping grades such as API 5L X52 (and lower strength grades) and ASTM A 106 Grade B have been widely used in hydrogen gas service with few reported problems. This good service is attributed to the relatively low strength of these alloys, which imparts resistance to hydrogen embrittlement and the other brittle fracture mechanisms. API 5L pipe is available in two Product Specification Levels (PSL 1 and 2). PSL 2 incorporates desirable requirements, not included in PSL 1, including minimum notch toughness energy, maximums for tensile strength and carbon equivalent. These requirements help ensure base metal and weld hardness are maintained at acceptable values and hydrogen embrittlement concerns are minimized. Therefore, PSL 2 material is advantageous for hydrogen piping. Further, it is recommended that only lower strength API 5L grades (X52 or lower) be used. API 5L PSL 2 grades meet the requirements discussed below.

Further, some pipeline operators utilize design stress values lower than standard values, resulting in a heavier wall, lower stress pipeline than would be required by typical national codes. One approach is to limit the hoop stress at normal operating pressure to less than 30% of the minimum specified yield strength of the alloy or 20% of the specified minimum ultimate tensile strength SMUTS, with a 6.4 mm (0.250 inch) minimum wall thickness. This lower stress design is used primarily to mitigate third party damage to the pipeline, but the low stress also reduces the potential for hydrogen damage.

4.3.2.2 Heat treatment

It is acknowledged that as-worked mill forms (not normalized) can be successfully used in hydrogen applications. However, for pipe that is to be used at high stress levels, it is preferable to normalize carbon steel for hydrogen service. This assures the presence of fine grained homogenous microstructures. It should be noted that seam welded pipes shall be normalized locally in the seam weld (see also 7.2.3). Special attention also should be given to the surface condition of alloy mill forms during and after heat treatment.

4.3.2.3 Chemistry

4.3.2.3.1 General

All of the line pipe steels and products from Appendix C have specified compositional range for chemical elements. Chemical composition limits as practiced in conventional carbon steel metallurgy have generally been found to be suitable for hydrogen pipeline applications. With newer melting processes, reduced sulfur and phosphorous are possible. The use of lower sulfur and phosphorous levels is an approach which enhances steel toughness and therefore should be considered for severe applications.

4.3.2.3.2 Carbon equivalent

The maximum carbon equivalent (CE) is 0.43

- Concentrations of Alloy Elements

All elements which are deliberately added are to be reported such as calcium and rare earths for sulfide shape control, aluminium for deoxidization and elements which may be used in carbon equivalent calculations.

4.3.2.4 Tensile strength requirements

The carbon steel alloy grade that is selected should have the lowest possible tensile strength consistent with the actual application. Because of greater susceptibility to some forms of corrosion in a hydrogen environment, substituting a higher strength material is not an improvement. A maximum tensile strength of 800 MPa (116 ksi) is recommended.

4.3.2.5 Toughness requirement

As the hydrogen pressure increases, toughness is increasingly important. Steels and the mill forms identified with the footnote (1) in Appendix C have to meet impact test requirements in the applicable API, ASTM specifications. Generally, the mill forms which have to meet impact toughness requirements are made from killed steel per a fine grain practice.

It is recommended that toughness requirement be considered on certain steel mill forms to be used in hydrogen pipeline applications. Toughness requirements can be found in references (Mohitpour, Golshan, and Murray, p 594 and 595). It is especially important for applications at pressures of 50 bars and above.

4.3.3 Microalloyed steels

4.3.3.1 General

Microalloyed steels are described in more detail than other materials in this document to familiarize readers with this relatively new and promising technology. Large scale natural gas pipelines marked the first significant utilization of microalloyed line pipe in gas transmission applications. Since early 1990s, a significant amount of microalloyed line pipe in the API 5L X52 grade has been used to transmit hydrogen gas at pressure in excess of 7 MPa (1000 psi).

This section covers special requirements for the production of microalloyed ERW linepipe intended for high pressure hydrogen service. The application requires high toughness levels in the fabricated line pipe and relative insensitivity to welding problems as a consequence of possible embrittlement scenarios that can be encountered in service.

Note that none of the API 5L PSL 2 (or PSL 1) grades are listed as “microalloyed steel” in the standard. If microalloyed steel is preferred, the user should specify appropriate supplementary requirements, including added chemistry and property requirements, to attain the benefits of microalloyed steel. It is the responsibility of the user to determine the necessary supplemental requirements. The following sections provide guidance.

4.3.3.2 Codes, standard and grades

Pipe shall be manufactured in accordance with all the provisions of the latest edition of API Specification 5L or equivalent except as may be modified by the additional requirements noted in this document.

The specific API 5L grades allowed in microalloyed form for hydrogen pipelines are X42 and X52. The manufacturer shall not substitute steel intended for higher strength grades.

4.3.3.3 Process of manufacture and material

The material used in making the pipe shall be basic oxygen or electric furnace steel that is continuously cast. All steel used for hydrogen service shall be fully killed.

The weld seam and heat affected zone shall be heat treated so as to simulate a normalizing heat treatment. Low temperature stress relief of fabricated pipe prior to hydrotesting is permissible.

4.3.3.4 Chemistry

The sulfur content shall not exceed 0.01% (API 5L PSL 2 limit is 0.015%).

The phosphorus content shall not exceed 0.015% (API 5L PSL 2 limit is 0.025%).

The use of sulfide shape control agents such as calcium is permitted. However, all additions made for this purpose shall be reported.

The maximum carbon equivalent (CE) is 0.35 (API 5L PSL 2 limit is 0.43%)

The concentration of any intentionally added element such as rare earths, Ti, Nb, B, Al etc. shall be reported. Also to be reported are any elements which affect carbon equivalent determinations.

4.3.3.5 Metallographic and microscopic examination

The final ferrite grain size shall be ASTM 8 or finer. Samples of the seam weld will be cut from one pipe length of each one hundred lengths or fraction and examined to ensure that proper weld fusion has been obtained across the thickness of the weld. In addition, Rockwell hardness surveys shall be conducted across the weld-and- heat affected zone of the parent metal and test sections. Hardness shall not exceed 95HRB.

4.3.3.6 Mechanical properties

Actual yield and tensile strengths shall be less than the following maximum above the minimum specified for different API 5L grades:

X-52	24,000 psi (165 MPa)
X-42	25,000 psi (172 MPa)

The flattening acceptance test criterion for ERW pipe shall be increased to 1/2 of original OD without weld opening instead of that appearing in API 5L.

4.3.3.7 Impact tests

The test temperature will be 0 °C (32 °F). For each heat a set of three transverse and three longitudinal impact specimens will be impact tested. For small diameter pipes, only longitudinal specimens are required.

The following table lists minimum acceptable absorption energies for different sizes of Charpy V notch specimens.

Specimen Size	Absorbed Energy, transverse Ft-lb (J)		Absorbed Energy, Longitudinal Ft-lb (J)	
	Average	Minimum Single	Average	Minimum Single
Full Size	69 (94)	52 (71)	87 (118)	65 (88)
3/4	52 (71)	39 (53)	65 (88)	49 (67)
2/3	35 (48)	35 (48)	58 (78)	43 (58)
1/2	26 (35)	26 (35)	43 (58)	32 (43)
1/3	17 (23)	17 (23)	29 (39)	22 (30)
1/4	13 (18)	13 (18)	22 (30)	16 (22)

Full wall thickness specimens will be used in the testing. Energy absorption values for these specimens will be obtained via linear interpolation between "Standard Sizes".

The largest size Charpy specimen that is consistent with the available wall thickness of the pipe will be utilized for the fracture testing. Transverse specimens will be flattened if necessary to obtain specimens more representative of the full wall thickness. The flattening should be done mechanically with no application of heat e.g., torches.

Ductile shear percentage will be a minimum of 75% for an average of 3 specimens with no single value below 60%.

4.3.4 Carbon-molybdenum (C-Mo) and Carbon-molybdenum-chrome (C-Mo-Cr) Low alloy steels

Normally, these high temperature steels are not used in high pressure hydrogen gas transmission pipelines but for buffers, see 4.3.1.1. However, it is conceivable that these alloys might be welded to a gas transmission pipeline. Accordingly, some of the common ASTM C-Mo and C-Mo-Cr low alloy pipe standards and compositions are listed in Appendix C. It should be noted that the high Cr content grades can be more difficult to weld, subject to cracking and could have local hard spots in the weld HAZ. Consequently, preheating and post weld heat treatments are more often needed for these steels than for carbon steels.

4.3.5 Stainless steels

4.3.5.1 Austenitic stainless steels

Some of the materials listed in Appendix C might be used to transmit hydrogen gas, particularly, at pressures at the high end of the hydrogen pressure range cited in the specification. The excellent toughness and ease of welding, particularly in field locations, are important attributes.

These materials might also be used for hydrogen transmission at elevated pressures outside of the application range cited in this document. Typically, the presence of even mildly corrosive environments may require that the low carbon (304L, 316L) or stabilized grades (316Ti, 321 and 347) be used when welding is used. In hydrogen application, the most likely corrosion site can be on the outside of the pipe. For hydrogen service, stainless steels with high austenite stability are preferred (i.e. high austenite stability or high nickel equivalents).

Type 316L is preferred to 304L for hydrogen gas service because 316L has higher austenite stability and is less subject to hydrogen embrittlement.

Austenitic stainless steels with a positive austenitic stability factor according to a “modified Post and Eberly formula” (see reference Hydrogen and Materials) were found suitable for hydrogen service.

4.3.5.2 Other stainless steels

Other stainless steels such as ferritic, martensitic, duplex or precipitation hardened may be used in hydrogen pipeline components providing they are used at low stress. The toughness of these steels is generally not as good as the austenitic varieties. Strength levels should be minimal and consistent with the application. The fully annealed condition is preferred for the ferritic and duplex steels. Martensitic and precipitation hardening grades should be heat treated to develop strength levels at the low end of the available range.

4.3.6 Nickel alloys

Many nickel alloys are susceptible to hydrogen embrittlement. Nickel alloys should be avoided unless the user verifies the alloy is suitable for hydrogen gas service.

Monel® K-500 and Inconel® X-750 which are precipitation hardened alloys may be used with hardness limits in subcomponents where high strength is required. Again, modest strength levels and avoidance of high nickel levels are worth noting.

4.3.7 Copper and cobalt alloys

Copper alloys are subject to hydrogen damage when copper contains oxygen. Hydrogen can enter the metal and react with oxygen in solid solution or oxide inclusions to form water. At elevated temperatures, greater than 370°C (700°F), steam pressure is high enough to cause cracking. Most copper alloys are deoxidized, and these generally do not suffer hydrogen embrittlement and are suitable for use in hydrogen gas.

Certain cobalt alloys may be used where abrasion resistance or wear resistance is required. These usually are Stellite formulations. Cobalt alloys are considered acceptable for hydrogen gas service.

4.4 Compatibility with non-metallic materials

See also ISO 11114-2 for compatibility with non-metallic materials

4.4.1 Plastics

Plastics exhibit varying behaviour in the presence of hydrogen.

The temperatures at which the resistance of some plastics in the presence of hydrogen seems assured are given in the table below. In certain cases these values do not exclude the possibility of resistance at higher temperatures.

Material	Temperature (°C)
Plasticized cellulose	20
Cellulose diacetate	20
Formo-aniline	20
Formo-urea	20
Phenol-formaldehyde	20
Furaphenol	20
Polyamides	20
Polyfuran	110
Polychloroprene	100
Polyepoxydiphenylpropane	90
Polyethylene glycol terephthalate	20
Polyurethane	20
Polyurethylmethacrylate	20
Polyvinyl acetate	20
Polyvinyl chloride	60
Polytrifluorochlorethylene	180
Polytetrafluoroethylene	250
Polyethylene	60
Polyisobutylene	100
Polystyrene	20
Polyacrylonitrile	20
Polyvinyl-vinylidene chloride (20-80%)	60

In using other plastics, it is advisable to conduct suitable strength tests prior to use.

4.4.2 Elastomers

Most elastomers are compatible with hydrogen. Their chemical resistance is given in the table below:

Material	Compatibility
Natural rubber	B
Butyl rubber	A
Silicone rubber	B
Neoprene®	A
Buna S®	A
Hypalon®	A
Viton®	A
Buna N®	A

A: good

B: fair.

Permeation of hydrogen through elastomers at 25 °C
(multiply these values by 10^{-10} to obtain $\text{cm}^3 \text{ S.T.P.mm.sec.}^{-1}.\text{cm}^{-2} (\text{cmHg}^{-1})$)

Material	Permeation
Natural rubber	492
Butyl rubber	74
Buna S®	399
Perbunan® G	158
Neoprene® G	133
Hycar or 15®	74
Polybutadiene	424
Polymethylpentadiene	428
Perbunan 18®	251
Isoprene-methacryl-nitrile copolymer	138
Hycar or 25®	118
Polydimethylbutadiene	172
Vulcoprene A®	64
Isoprene-acrylonitrile copolymer	74
Thiokol S	16

4.5 Piping systems

4.5.1 Underground piping systems

Piping should be of all welded construction in accordance with a specification and inspection code such as API 1104 (see Appendix K). Underground piping shall be externally coated to an approved specification, to protect against soil corrosion. Reference to current, internationally accepted, coatings standards and specifications is recommended (see Appendix K)

Underground piping should be adequately buried to protect it from frost, casual surface construction, shifting due to unstable soil, back fill damage to the external surface of pipe or the coating, and above ground loads such as vehicles or equipment moving over the path of the pipeline. Pipe casings or load shields, if required by special agencies, should be installed at railroad or road crossings or where unusual above ground loading can occur. Casings or sleeves require careful consideration and special measures to avoid cathodic protection problems and arcing, which can be caused due to an electrical connection forming between the sleeve and carrier pipe due to settlement, etc. In general the use of metallic casings or sleeves is to be avoided wherever possible.

Underground hydrogen piping is vulnerable to damage by lightning strikes or ground fault conditions, which can rupture the pipe material. To reduce the likelihood of one of these occurring, electrical continuity between underground hydrogen piping and above ground piping, or other metal structures, should be avoided.

Due to the possibility of leaks it is preferable to have no flanged or other mechanical joints underground. If this cannot be avoided then the number should be limited and they should be installed in a way which provides access for inspection and maintenance e.g. in valve pits.

4.5.2 Above ground piping systems

Above ground hydrogen piping systems should follow good mechanical design practices as applied to any other above ground piping system. It should be noted that hydrogen is more prone to leakage problems than other gases, due to its small molecular size. The use of welded connections is recommended whenever this is possible. Above ground piping should be painted to an approved specification to protect against atmospheric corrosion.

Above ground portions of pipeline systems should connect to underground portions through an electrically insulated joint to isolate the underground cathodic protection system (see 5.5.4).

All above ground pipelines shall have electrical continuity across all connections, except insulating flanges, and shall be earthed at suitable intervals to protect against the effects of lightning and static electricity. The electrical resistance to earth of the installed pipeline should not exceed 10 ohms for personnel protection against electrical or high voltage shock.

Flange bolting will provide the necessary electrical bond provided the bolts are not coated with a dielectric material or paint and are well maintained to avoid rust.

In the case of short above ground sections, where insulating flanges are not used, the pipe should be insulated from the support structure by means of an isolating pad.

Hydrogen piping should not be exposed to external forces which can cause a failure or dangerous situation such as external impingement from hot gas or steam vents, vibration from external sources, leaking oil dripping onto the line, etc.

Above ground piping systems outside plant fence lines can be subject to deliberate or accidental damage. Consideration should be given to installing pipe and valves below ground, with extensions for above ground operators and instrumentation.

4.5.3 Pipeline markers

Overhead piping should be colour coded and/or identified. Underground piping should be identified with markers placed on the ground near the buried pipeline. Markers should be suitably spaced to indicate the route of the line.

4.5.4 Corrosion protection

4.5.4.1 Underground pipelines

Corrosion caused by galvanic action between the outside of the pipe and the soil is probably the most frequent cause of leaks except for mechanical damage. It is caused by the difference in electric potential between the pipe and the soil which sets up an electro-chemical cell. This electrolytic cell acts to continuously remove metal from the pipe and deposit it in the soil. If not prevented or sufficiently inhibited eventually a hole(s) is made in the pipe during its working life. Corrosion protection is achieved by cathodic protection, either by sacrificial anode or by impressed current, both in combination with electrical isolation by coating. To achieve a good cathodic protection in a given circumstance, it is necessary to understand the soil conditions and the anti-corrosion methods used by near-by pipelines. The advice of an expert in these matters is strongly recommended in known difficult corrosion areas and is a worthwhile precaution in any area. Cathodic protection may be done

according to recognized standards, such as NACE RP 177 or EN 12954. It is suggested that electrical isolation (pipeline coating) plus one other of the two methods listed below be employed on every underground pipeline.

- 1) **Electrical isolation** – this method acts to prevent corrosion by electrically isolating the pipeline from the soil. This is the most basic technique and, as a minimum should be practiced on every section of underground pipeline. The pipe is isolated from the soil directly by an external coating and indirectly by isolating flanges where it connects to above ground piping. The weakness is that even small flaws in the coating become sites for what is often very rapid rates of corrosion. These flaws can be present in the coating as supplied, come from damage during installation, occur as the coating loses its dielectric strength or after some time in service may be caused by bacterial activity. It should be assumed that a number of defects in the coating exist or will come to exist during the lifetime of the pipeline. This does not negate its value but does lead to the necessity of providing another means of protection together with electrical isolation.
- 2) **Sacrificial anode** – this method acts to prevent corrosion of the pipe by providing a source of material which is more electrolytically active (anodic) than the piping material. Corrosion takes place preferentially on this sacrificial anode and the pipeline is thereby spared – at least until the anode is used up. Sacrificial anodes are most effective when used together with electrical isolation since they are well suited to protecting against small areas of corrosion such as occur at flaws in the pipe coating. However, there is a limited distance in which a sacrificial anode is effective so that many of them are required at intervals along the pipeline.
- 3) **Impressed current** – To be free of the limited driving voltage associated with sacrificial anode systems, current from some outside source may be impressed on the pipeline by using an anode ground bed and a power source, the most common of which is a rectifier. The rectifier converts AC to DC, and is usually provided with means of varying the DC output voltage, in small increments, over a reasonably wide range. Most pipeline rectifiers operate in a wide range between 10 and 50 volts and can be obtained with maximum current outputs ranging from less than 10 amps to several hundred amps. The anodes employed in impressed current systems generally depend on electrochemical oxidation of water and other chemicals in the soil or electrolyte to exchange current with the environment. Specific materials used for anodes are: graphite (carbon), high silicon iron alloys, platinized titanium or niobium, and certain conductive mixed metal oxides applied to a titanium metal base. Most anodes used in an impressed current system, exhibit an electrical potential that is more noble than iron or steel. Therefore, the anodes themselves remain relatively inert and unaffected by the transfer of current. The source of electric current shall overcome this back potential as well as electrical resistance in the circuit before current will flow in the proper direction. Steel anodes, such as rails, are also commonly used, but they will exhibit a wear of 9 kg/Amp.year. They have to be replaced, when necessary.

Because of the complexity involved, it requires the most experienced and specialized knowledge to properly implement. It is strongly recommended that an expert be consulted.

Monitoring of the corrosion protection system at intervals over the lifetime of the pipeline is essential to achieving satisfactory results. In the case of sacrificial anodes and impressed current systems, this requires monitoring the electrical potential at the cathodic protection stations and at monitoring points in between stations.

4.5.4.2 Above ground pipelines

Because above ground pipelines can be visually inspected, corrosion can be more easily controlled. However, this is only the case if the inspections are frequent, methodical and all the discovered problems remediated.

Uninsulated above ground pipelines should be protected against environmental corrosion by an appropriate coating system, usually paint. The selection of the system will vary with the environment, but as a general rule a system suitable for a chemical plant environment should be used as a minimum.

Insulated above ground pipelines are also subject to environmentally caused corrosion which occurs underneath the insulation and is therefore not visible. This type of corrosion is quite common and is recognized as a significant problem in industry. Reference may be made to standards, such as NACE-RP 01/98. The pipe should be painted before insulating to provide surface protection. The pipeline should be regularly inspected for corrosion under the insulation by removing small sections of insulation at various places and visually checking. A positive indication is cause to remove further samples in the same area until the full extent of the corrosion has been identified. Remediation and re-insulation should then follow.

4.5.5 Leakage surveys

As hydrogen is more prone to leakage than other gases, it is particularly important to survey pipelines with a hydrogen detector periodically. Pipelines should be surveyed between 1 and 4 times per year, depending upon the population density in the area, and as defined by national regulations. Particular attention should be paid to flanged connections, valve stems, and compression fittings.

4.6 Hazard analysis and risk assessment

4.6.1 General

Some level of risk is inherent in all human activities and positive steps should be taken to reduce the risks to a reasonable level whenever this is possible. Every new transportation pipeline system shall be designed, constructed and operated in such a way that the additional risk to people, property and the environment is kept within acceptable limits.

To this end, a safety analysis should be performed on every new pipeline system or significant modification to an existing system. The safety analysis is a proven way to assess the risks of the pipeline system to the environment, the risks to the pipeline from its environment, as well as to define the measures, to be applied during design, construction and operation, to reduce the probability of occurrence and the consequences of abnormal events.

Normally, the level of detail of the safety analysis is based on the population density around the pipe route, the potential severity of an incident, and the likelihood an incident could occur.

The method typically used in a safety evaluation is to determine the individual risk and to show that it is within acceptable limits. It is not unusual to define individual risk, as the probability of a person remaining at a given open-air location at all times being fatally injured as a result of any abnormal event affecting the pipeline and to give an acceptable limit in terms of fatalities per number of years. Local regulations often provide guidelines on performing safety analysis and specify acceptable limits.

A typical example of a full risk assessment for densely populated areas might comprise the following steps

4.6.2 Identification of the hazards

The minimum list of hazards to be considered is:

- damage by third parties;
- use of non-compatible materials and equipment at all operating conditions;
- hydrogen embrittlement;
- external corrosion due to improper cathodic protection;
- leaks at valve packing, gaskets;
- over pressurisation of the pipeline;
- improper inerting procedure;
- improper operation and maintenance of the pipeline;
- abnormal loads due to land slide, floods, earthquakes, crossing of roads, railways;
- influence of other structures, such as high power electrical lines, electrical railways;

- damage due to an abnormal event on a parallel pipe;
- road accident or fire in the vicinity of above ground parts of the pipeline; and
- the radiation of a vent fire or a flare

4.6.3 Mitigating measures

For each hazard, mitigation measures shall be identified, such as:

- control of third party interference;
- increased thickness of the pipe;
- non-destructive test on welds;
- inerting of the pipe;
- pipeline marking;
- isolation valves;
- excess flow or low pressure shut down valves;
- leak detection by mass balance;
- deepen the pipeline;
- physical protections: concrete coating or encasement, concrete slabs;
- rerouting pipelines;
- reducing pipeline operating pressure; and
- operating procedures, including: inspection programs, corrosion control programs, emergency plan, personnel training, information of third parties, collaboration with local authorities.

4.6.4 Typical event scenarios

For ease of analysis, the events frequently considered are:

- the full bore rupture;
- the 50% full bore; and
- a small leak (5% of the full bore).

4.6.5 Consequences of these events

The minimum consequences of these typical events to be considered should be a release of hydrogen, which ignites immediately or spontaneously rises and disperses in the open air, possibly with delayed ignition.

4.6.6 Selection of a model to simulate the impact of an incident

As a minimum, the following items should be taken into account in order to configure a proper simulation:

- pressure drop due to the dynamic flow in the pipe;
- transient flow regime due to the decompression of the pipe; and
- velocity of the gas at the breach.

4.6.7 Criteria for the feared event

The Eisenberg method to define the hazard zone is to use the radiation dose approach. This considers that the effect of radiant heat on humans is a function of both radiation intensity and duration of exposure. Eisenberg et al. (reference listed in Appendix K) studied data on the lethality from thermal radiation and concluded that the dosage-response relationship for various probabilities of injury/fatality should be in the form,

$$D = t I^{4/3} \text{ in units of } (W/m^2)^{4/3} - \text{sec}$$

where:

$$D = \text{dosage for various probability of injury}$$

t	=	duration of the exposure, sec
I	=	thermal radiation intensity, W/m ²

Damage criteria for thermal radiation

Damage Levels	Thermal Dosage, D
Extreme Pain	1.1×10^6
Second Degree (blistering threshold)	2.4×10^6
Third Degree threshold	7.2×10^6
Second Degree under 9.3 oz/yd ² (FRT Cotton)	10.3×10^6
1% Fatality	10.6×10^6
Second Degree under 6.8 oz/yd ² (Nomex®)	13.1×10^6
50% Fatality	23.0×10^6
99% Fatality	65.7×10^6

Eisenberg's data is adapted for radiation durations less than 45 seconds. Usage of the damage criteria should be limited to short exposure durations.

For longer periods, the thermal radiation limits listed above, compared to the damage criteria of Eisenberg may be used:

- 3 kW/m²: for an exposure time of 120 seconds - limit of approach for the public. This is outside the limits of the Eisenberg correlation since the exposure time is greater than 45 seconds.
- 5 kW/m²: taken as the radiation level at which breakage of glass by thermal effect occurs and also at which 2nd degree burns on the skin of a non-protected person exposed for 30 seconds - limit of approach of the operators or other trained personnel. This corresponds to a dose of 2.6×10^6 , i.e. close to the blistering threshold
- 12,5 kW/m²: taken as the radiation level at which fire propagates on vessels sprayed with water and also the onset of pain on the skin of a non-protected person exposed for 6 seconds - limit of evacuation of housing and other normally occupied buildings. This corresponds to a dose of 1.7×10^6 which Eisenberg's equation would categorize as extreme pain.

With these criteria, it is possible to transform in distances around the pipe the results of the simulations, in order to identify the zones concerned by the occurrence of the major event. This risk evaluation method is a deterministic approach and is required in certain countries.

4.6.8 Definition of the zone to be studied around the pipe

Within the distances of concern found by the simulation, the zoning shall be studied for the whole length of the pipe, to identify points where compensatory measures should be considered.

Another widely used method to define the zone around the pipe that could be affected by a leak or rupture is using a potential impact radius. This method is documented in ASME B31.8S and is dependent on the MAOP and outside diameter of the pipeline.

4.6.9 Risk criteria

The risk criteria taken into account depend on the governing national or local regulations. The risk criteria of The Netherlands and of the United Kingdom are given in Appendix J for information

4.7 Siting

Siting of hydrogen systems shall be carefully studied, especially at points where venting to atmosphere can occur, for example valve stations, vents, drains, safety valves, etc.

The location of potential vent sites should be chosen with care and, in so far as is practical, to avoid the immediate proximity of vulnerable areas and equipment such as electrical equipment, flammable product storage tanks, public roads, public buildings, car parks and transfer stations.

Siting and safety distances should follow established practices and applicable regulations. Typical arrangements for siting of hydrogen stations in relation to other areas and equipment can be found in the table of Appendix E.

5 Piping, valves and equipment

5.1 General criteria

This chapter describes how the design philosophy presented in Chapter 4 can be applied in practice to piping, valves, specific piping components and equipment configurations.

5.2 Material selection criteria

Selection of material for pipes, valves, equipment, etc. shall be in accordance with Sections 5.4, 5.5 and 5.6.

Due to the hazardous nature of the gas, above ground pressure containing parts such as piping, valve bodies, strainer and filter housings, etc. shall be made of metallic materials only. The use of non-metallic materials shall be limited to services such as valve internals (inserts only), external coatings, etc. which do not provide primary mechanical strength.

One of the most important criteria is resistance to stress corrosion cracking and hydrogen embrittlement. The risk of these occurring is increased at higher temperatures and pressures and is mitigated by low stress levels. Therefore, material selection, fabrication processes, and material thicknesses should be chosen with a view towards achieving low residual stresses. Typical methods of lowering stresses once the operating temperature and pressure have been decided are closer pipe support spacing, thicker pipe walls, thermal relieving residual welding stresses.

There are no special velocity restrictions for piping in hydrogen service other than the underlying economics. However, the sonic velocity of hydrogen is approximately four times that of most flammable gases. Therefore, close attention should be paid to possible erosion and abrasion at such items as control valves and relief valves which usually will have sonic or near sonic velocities. Because of the high sonic velocity, it is quite possible that problems will arise at differential pressures which would not have caused a problem with most other gases.

5.3 Electrical hazardous area requirements

As hydrogen systems may pose a fire or explosion risk, electrical systems shall be in accordance with the applicable codes. These provide requirements and suggestions for determining the level of hazard (classification) and mitigating the risks involved. Typically used codes are:

- National Fire Protection Association (NFPA) 70
- IEC 79
- NFPA 496, 497
- American Petroleum Institute RP 500 A,B,C
- European directive ATEX 94/9

It is recommended that as a minimum either NFPA 70 or IEC 79 be used.

The type of electrical equipment which may be installed and the installation methods depend upon the level of hazard classification and are described in the prescriptive sections of the codes.

It is worth noting that the equipment and piping should be carefully bonded and grounded to drain static electricity and to carry electrical fault currents to earth ground, to prevent the release of electric sparks which could ignite hydrogen leaks in the area.

5.4 Piping

Welded connections are preferred and should be used wherever practical to minimize potential leak sources. Threaded connections which are seal welded are considered as welded connections for this purpose. Either seamless or longitudinally welded pipe and wrought or machined fittings shall be used except in exceptional circumstances e.g. absolute unavailability.

5.4.1 Venting

The flammability and auto ignition potential of hydrogen gas is a significant potential risk factor. Therefore, care shall be taken when venting. The discharge piping from all vent sources such as vent valves, safety relief valves, compressor packing vents, etc. shall be piped to a properly designed and sited disposal system which can be as simple as a single pipe or as complex as a manifolded collection header connected to a flare. The back pressure this creates shall be properly accounted for in the design, especially on safety relief valve discharges (API RP 520, 521 are often used reference documents for this). There are two types of systems which may be used – venting to atmosphere and destruction in a flare. The same materials as are used elsewhere in the pipe line should also be used for vent collection and disposal piping with one exception which is discussed below under venting to atmosphere.

5.4.1.1 Venting to atmosphere

When not prohibited by local regulation, very large flows of hydrogen gas may be vented directly to atmosphere at a safe outdoor location. When large quantities of hydrogen shall be vented to atmosphere, it is recommended to first perform a dispersion study to guide the vent design. Venting to atmosphere is most commonly used along the length of the pipe line since a flare is usually not available. However, where this presents advantages, it is also acceptable for use where a flare system is available.

The system shall collect and route the hydrogen either individually or in manifolded headers to a vent stack discharging outdoors in a location and direction that avoids impingement of escaping gas on adjacent equipment, structures, or personnel. The exit should allow the hydrogen to flow easily out to atmosphere, minimize water ingress from the environment, discourage creatures from entering, and provide quick dissipation of the hydrogen into the atmosphere. To minimize the possibility of auto ignition when the hydrogen leaves the stack, it is recommended that the piping immediately upstream of the exit be made either of stainless steel or a non-sparking metallic material.

There are varying opinions about the need for and efficacy of a flame arrestor to inhibit backward propagation of a fire into the vent pipe. Similarly, purging of the vent line with an inert gas such as nitrogen can help to prevent auto ignition, but there are numerous reported instances where a purge was ineffective. Therefore, this document makes no recommendation either way at this time other than to point out that flame arrestors and nitrogen purges do no harm.

5.4.1.2 Destruction in a flare

The design of a vent collection and flare system for flammable gases is a complex design task and should only be performed by persons familiar and experienced in this area. For a good reference and a layman's understanding API 521 a good source.

When attaching to an existing vent collection and / or flare system it is essential to understand the basis of the system's design so that the designer's intent is not inadvertently compromised. The performance of the new attachment affects the performance of the existing system, possibly negatively. Issues such as back pressure on devices, back flow, instantaneous volume, inert purge, materials of construction, etc. are typically involved. The owner of the existing vent / flare system is usually the best resource to ensure compatibility and it is greatly preferred that he be directly involved in reviewing the design and fabrication of the attachment and that his approval be obtained. If this is not possible, then an analysis of the existing system shall be performed from existing documents and inspection of the equipment and the results used to design the attachment.

5.4.2 Flanges and gaskets

Where welded connections are not practical, flanges are the next best choice. Leak resistant flange types such as raised face, tongue and groove, or ring joint flanges shall be used. Gasket materials shall be appropriate for the design pressures and temperatures, and be hydrogen compatible and leak resistant. In addition, consideration should be given to resistance to fire, due to the flammability of hydrogen. In general filled spiral wound steel gaskets are preferred with raised flanges, but composition gaskets which are graphite based are also used at lower pressures. Soft metallic rings are preferred with ring joint flanges. Overall then, a Teflon or graphite filled spiral wound gasket with a raised face flange or a copper ring with a ring joint flange are typical choices since they embody the desired features to a large extent. Since small leaks to atmosphere present a significant safety risk, flange covers should be considered.

5.4.3 Threaded connections

These shall be used only where welded (including seal welded threaded connections) and flanged connections are not practical. The sealant shall be hydrogen compatible and should be high temperature resistant to reduce the risk of leaks during a fire. Typical uses of threaded connections are to match equipment, especially instruments.

5.4.4 Instrument tubing

Instrument tubing shall be stainless steel with compression fittings. The use of continuous runs shall be maximized to reduce the number of fittings since these can be leak sources.

5.5 Valves

5.5.1 General

The major concern specific to pure hydrogen service is to prevent leakage either to the ambient or across the valve.

Leakage to ambient is most frequently caused by packing and bonnet leaks and to a lesser extent by leaking castings. To minimize the potential for leaks the following, or equivalent, is recommended:

- Double seals or packing
- Each casting to be hydraulically leak tested
- Soft seat in a metal retainer for in-line automatic valves and automatic vents; specify bubble tight shut off
- Metal to metal seat or soft seat in a retainer for in-line manual valves; these should be combined with a means of positive isolation if used to block flow before attempting maintenance or inspection inside the line.
- Metallic seat with valve outlet blocked. Typical arrangements used are double valves, blind flange, plug, or cap (threaded connections are acceptable).
- Preferably no through bolting, body flanges or threaded connections in assembly of the body of the valve.
- Mainline isolation valves should be of full port design, when pipeline pigging for inspection is foreseen

5.5.2 Valve functions

5.5.2.1 Isolation valves

Isolation valves with lock out capabilities are used to isolate portions of the pipe line in emergencies or for routine maintenance and inspection. These should be installed in an accessible location since they could need to be manually closed on an emergency basis.

For safe maintenance access it is necessary to have a means of positive isolation with a supporting lock out or tag out maintenance procedure. Typical accepted arrangements are double block and bleed valves, blind flange, double trunnion mounted ball valve equipped with a body vent or spool removal.

These are typically ball, plug, gate, or butterfly type valves.

5.5.2.2 Emergency isolation valves

Emergency Isolation Valves (EIV) are used to provide emergency blockage of the flow. They may be manual, automatic, or both. Although the number location and type of EIVs depend on the specifics of the inspection, maintenance and risk management strategies, as a minimum they shall be provided at the beginning of the pipeline and at each user.

EIV's shall be capable of being fully closed to ensure against gas leakage and in the case of automatic valves shall be designed to close on instrument air, signal, hydraulic and electrical failure. A typical arrangement would be spring return actuators which fail closed. Fail in place valves are not acceptable.

When automated, EIV's are typically ball or gate valves and are of fire safe construction. When manual valves these are typically gate valves. It is often advisable to install a means of positive isolation along with an EIV.

5.5.2.3 Control and pressure reducing valves and regulators

These are used for flow and pressure control functions. The use of hardened seats and plugs or other special design features should be considered when the pressure drop through the valve or regulator is greater than 10% of the upstream pressure because of the high sonic velocity of hydrogen. Erosion, abrasion, and excessive noise should be addressed in the design.

These are frequently globe valves, but notched ball valves are also used.

Regulators should not vent process gas to the ambient in an uncontrolled way. They should either vent internally or the vent should be treated as in Section 5.4.1.1.

5.5.2.4 Safety relief valves

The purpose of safety relief valves is to protect the system and its components from damage caused by pressures above the maximum allowable working pressure (MAWP). Pure hydrogen service does not in general require a more or less severe analysis than most other flammable gases except that special attention should be paid to the potential of hydrogen leaking through the valve when it is closed and the requirements of Section 5.4.1 for safe venting shall be followed. The number, location, type, sizing criteria, safe venting, and inspection intervals for pressure relief devices are governed by local regulatory authority and these requirements shall be strictly followed. Typically pressure vessels, for example large filter housings, will fall under the pressure vessel regulations and the balance will fall under the piping and / or pipe line regulations.

Some of the dos and don'ts as typically practiced.

- Safety valves should be located as close as possible to the item which they protect.
- Back pressure on the safety valve discharge caused by the vent collection system shall be considered.
- Consideration shall be given to the reaction forces when a safety valve discharges.
- API RP 520, 521 are often used reference documents on safety valve relief and vent system design methods.
- Although it is preferable not to, it is sometimes necessary to install block and / or by-pass valves together with safety relief valves to meet local inspection/testing regulations or when connecting to an existing vent or flare system. However, this presents inherent safety risks since the safety valve could be blocked. Therefore, a careful analysis of the entire system, its

components, and the supporting operational and maintenance procedures (e.g. lock out) by an experienced professional shall be performed.

5.5.2.5 Manual vent and drain valves

Typical practice is to provide positive sealing through the valve by redundancy. The most common arrangements used are double valves, blind flange, plug, or cap (plugs and caps should be threaded without seal welding since it is necessary to remove them for the vent valve to perform its function).

These are typically ball, plug, gate, or globe valves.

5.5.2.6 Excess flow valves (EFV)

These are usually designed similarly to emergency isolation valves (EIV').

5.5.2.7 Check valves (non-return valves)

Pure hydrogen does not present special concerns for check valves besides leakage. The concerns are similar to those for automatic valves and a soft seat in a metal retainer or specially lapped metal to metal seats are preferred, especially when small back leakage would present a significant risk. As with all check valves installation in the proper orientation can be crucial. Typically check valves are not considered fully reliable flow stoppers. Therefore, a check valves shall not be used as a substitute for an isolation valve.

5.5.3 Valve type summary

5.5.3.1 Ball and plug valves

Ball and plug valves are inherently quick opening and good sealing. They can be manually or automatically operated. They are frequently preferred as isolation, emergency isolation, excess flow, and vent and drain valves. They can also be used as control valves in certain circumstances although their control characteristics are generally less precise than globe valves or butterfly valves. Ball valves are usually full ported and shall be full ported if it is required to run a pipeline internal inspection device through them. Ball and plug valves are typically used in small sizes.

5.5.3.2 Butterfly valves

Eccentric disc wafer valves (high performance butterfly) may be used. They can be manually or automatically operated and can be used as a control valve when the pressure drop across the valve is not too large. The main disadvantage is that the valve seat is particularly exposed to particulate damage. If these are chosen, they shall be double eccentric and bubble tight shut off. Butterfly valves are not suitable to run a pipeline internal inspection device through since the disc and pin sit permanently in the flow path.

This document does not take a position on the use of these valves other than to acknowledge that there is difference of opinion about their use with some pipe line operators allowing them in certain circumstances and others not permitting them at all. However, as there are potential benefits in certain situations, a description of them was considered appropriate to include.

5.5.3.3 Gate valves

Gate valves are rugged proven valves which are typically used to block flows. Although they can be automated they are by far most often manually operated. The main disadvantage is that, except for certain special designs with soft sealing strips on the disc, they are not as tight sealing as ball, plug, butterfly, or globe valves. To mitigate this they should be specified with flexible wedges (gates). Gate valves are suitable to run a pipeline internal inspection device through them.

5.5.3.4 Globe valves

Globe valves are commonly used in control applications and where a tight shut off is a pre-eminent concern. They can be manually or automatically operated. They are widely used as control valves because of the precise nature of their control characteristics. They are also used as automated vent and isolation valves because of their tight shut off. They are more used at smaller sizes than larger sizes. The gas which flows through a globe valve is forced to change direction. This is how its precise control characteristic is created; however, it makes them susceptible to erosion and abrasion. For this reason the use of hardened plug and seat materials should be considered in applications which have a large pressure drop across the valve. The high sonic velocity of hydrogen means that this problem occurs at lower pressure drops than with most other gases.

5.5.3.5 Pressure relief valves

These are valves which are specifically designed to prevent over pressurization of an item or system by automatically and reliably stopping the increase of internal pressure by venting gas once a pre-set pressure has been reached. Pressure relief valves are self-contained in that they do not require operator or control system actuation to perform their function. There are several different types and styles of safety relief valves including direct acting, pilot operated, variable back pressure, etc. Direct acting spring actuated relief valves are acceptable. Internals should be of hydrogen compatible corrosion resistant materials. Both metal to metal and soft materials in a metal retainer are typically used as seats. The main difference between them is that metal to metal seats are less likely to be damaged when the safety valve lifts but they also tend to leak more easily when the safety valve is closed.

Pressure relief valves typically shall meet international, national, and local regulatory requirements which typically include design, materials of construction, testing, quality assurance, inspection in service, and often official sealing after the relief pressure has been set to guard against tampering.

Although many materials may be used for the valve body, it is preferable to use either carbon steel or stainless steel since these materials are economic and avoid some of the potential corrosion issues which could arise if impurities entered the pipe line.

5.5.3.6 Check valves (non-return valves)

These are valves which are specifically designed to permit flow in one direction and to stop it in the reverse direction. There are numerous types including swing, flapper, ball, poppet, spring loaded, gravity operated, hydraulic assisted, etc. Swing and flapper types are most often used in larger sizes and ball or poppets in very small sizes (<2"). To minimize back leakage when the valve is closed, a soft seat in a metal retainer or specially lapped metal to metal seats are preferred, especially when a small backwards flow would present a significant risk. As with all check valves installation in the proper orientation can be crucial. Typically check valves are not considered as reliable flow stoppers as isolation valves and, therefore, a check valves shall not be used a substitute for an isolation valve.

5.5.4 Miscellaneous valve issues

5.5.4.1 Packing

Positive sealing of packing glands is important in hydrogen service. Packing materials should be hydrogen compatible and suitable for high temperatures to better maintain their integrity in case of a fire. Graphite based compounds are typically used. Double packing should be used to mitigate the chance of leakage to atmosphere which can present a flammability risk.

5.5.4.2 Damage from particulates

To protect soft seats from possible damage from particulates carried with the gas, a strainer of 300 microns (50 mesh) or finer may be installed upstream of valves or valve clusters with soft seats which are normally open to flow during operation. Typically this excludes vents, drains, and pressure relief

valves (pressure relief valves should not have a strainer upstream of them in any case since a partially blocked strainer would reduce the relieving capacity).

5.6 Other equipment

5.6.1 Strainers and filters

Strainer and filter installation is recommended to avoid contamination, particularly upstream of pressure control and metering devices, as the sonic velocity of hydrogen is very high compared with most gases. The housing material should as a minimum be equivalent to the pipe and the internals should be of a corrosion resistant metal.

5.6.2 Flow measuring devices

Orifice plate, venturi and turbine meters are frequently used.

The selection of flow meter type is normally based on the accuracy requirements for the required range of gas flow to meet customer requirements. Instrumentation for converting the output from the volumetric primary device into a mass flow may use an Integrated Electronic System, which may comprise the following:

- pressure transmitter
- temperature transmitter
- differential pressure transmitter
- mass flow computer

5.6.3 Rupture discs

Safety relief valves are preferred to rupture discs because rupture discs are more prone to premature failure and once actuated they are not self-closing. Overall this means that it is more likely to have an accidental release of hydrogen and that the release will be large and will continue until the source of hydrogen is blocked. Therefore, rupture discs shall not be used unless a safety valve is not practical. In case a rupture disc is unavoidable, the requirements generally follow those for safety relief valves (see 5.5.2.4 and 5.5.3.6). Rupture discs shall be compatible with hydrogen and resistant to atmospheric corrosion.

5.6.4 Insulating joints

Insulating joints are essentially two pieces of pipe separated by a material with a high dielectric constant (insulator) so as to electrically isolate two systems or items. Typically this is done to create separate zones of possible corrosion for example between underground and aboveground segments of the pipe line. Although the design of these devices is well known, there is still a possibility that a spark could be created between the electrically isolated sections and that this spark might ignite a fire. Proper specification and installation of insulating joints is necessary to mitigate this risk. Therefore, a knowledgeable and experienced person should review the specification and installation of this item.

5.6.5 Flexible connections (hose, expansion joint, etc.)

When piping and equipment warms up it expands putting stress on the system as it changes shape to accommodate the now longer material. A flexible connection is a device to allow for this growth by its inherent flexibility; it expands so the piping does not have to. Unfortunately, flexible connections are significantly less robust in service as pipe, and this presents a significantly increased risk of failure, which would be dangerous with any flammable gas, and even more with hydrogen. The preferred solution is to design flexibility into the piping system by means of expansion loops (out of plane runs of pipe) and this shall be the design used unless there is no practical alternative. In case a flexible connection is unavoidable it shall be made of corrosion resistant metal, have a liner, and shall be inspected frequently in service to detect early signs of incipient failure. Expansion joints may be in accordance with existing standards, such as of the Expansion Joint Manufacturer's Association (EJMA). Proper specification and installation of flexible connections is necessary or they can fail

prematurely or even immediately. Therefore, a knowledgeable and experienced person should review the specification and installation of this item.

5.6.6 Miscellaneous equipment items

In general, the concern with most piping and equipment items in pure hydrogen service is no different than for any other flammable gas service except that leaks are more likely to occur. The design, installation, and inspection of these items should follow the principals and suggestions in this document as they apply to each item.

6 Cleaning

6.1 General requirements

6.1.1 Cleaning strategy

Cleaning of a hydrogen pipeline system is normally accomplished by a combination of building clean and final cleaning after construction. During construction, visual is performed on sections of pipe as they are assembled, making sure there is no gross contamination left in the pipe. In addition, fabrication techniques are used which do not introduce contamination to the pipe. This is followed by a thorough cleaning of the pipeline system after construction. It is both impractical and impossible to fully inspect a pipeline system for cleanliness after construction and final cleaning, so the methods used shall provide that security. It is therefore strongly recommended that a detailed written procedure, including the sequence for construction and cleaning, be well established and carefully followed throughout the project. The piping system design shall be compatible with cleaning, construction and pressure testing methods to be used.

6.1.2 Standard of cleanliness

A system is considered to be clean for hydrogen when internal particulate matter has been extensively removed. The cleaning process shall assure the removal of contaminants such as dirt, water, filings, scale, weld spatter, paints, or other foreign material from the interior of the pipeline system. This level of cleanliness is often referred to as "commercially clean". Contractual requirements or customer specifications may require a more stringent cleaning process.

6.1.3 Cleaning methods

The cleaning of hydrogen pipelines after construction may be accomplished by any one, or a combination of more than one, of the following methods:

- Pigging
- Mechanical scraping
- High velocity gas purge

Pigs are commonly used for internal cleaning of pipelines. The types of pigs available fall into the following broad categories:

Type	Application
Gauging	To ensure freedom from obstruction
Foam (or soft pig)	Dewatering
	Removal of fine, loose debris and dust
Rubber disc or cup	Dewatering
	Removal of loose debris
Wire brush	Removal of pipe scale
	Removal of adhered particles and rust
Scraper	Removal of pipe scale
	Removal of adhered particles and rust

In general, pigs will be fabricated from materials that would be compatible with hydrogen. For this reason, along with the level of cleanliness required, pigging is normally the primary choice for cleaning of hydrogen pipelines. The correct selection and use of pigs to suit the anticipated condition of the internal surface of the pipe at the various stages of cleaning will minimize the likelihood of damage to the pigs and lead to the desired level of cleanliness.

6.1.4 Pipeline components

Equipment such as tees, valves, check valves, insulation joints, regulators, meters, filters and other fittings will normally be purchased with cleaning levels acceptable for hydrogen service and installed after the completion of pipeline cleaning operations. Visual inspection of equipment items should be carried out just before installation to ensure that the required standard of cleanliness has been met. If items are identified as being deficient in meeting cleaning criteria they shall be cleaned at the site until the desired level of cleanliness has been achieved.

Branch lines and parallel lines shall be treated as separate systems for the purpose of cleaning, and the final tie-ins shall be made after cleaning is completed. This is necessary to be certain that the cleaning medium whether pig, high velocity gas, or scraper actually reaches all the pipe and that no branch has been short circuited.

6.1.5 Welding

The pipe sections shall be welded together using a recognized welding process. Ultimately, it is essential that the internal weld surfaces are smooth and substantially free of slag, beads or loose debris thereby preserving the internal cleanliness. It is recommended that the root pass of all butt welds be done with a welding technique which uses an inert gas purge since this minimizes the chance of slag deposits on the underside of the weld. Refer to Section 7.4 for further information on welding requirements.

6.1.6 Pressure testing

Pressure test should be performed in such a way that cleanliness of the pipe is not compromised (see Section 7.7.1 for further details).

6.1.7 Installation of pipeline equipment

On completion of final cleaning all aboveground connections can be installed, including pre-cleaned and pre-tested tees, valves, fittings, branch piping and other items. See 7.6.2 for non-destructive testing requirements.

6.2 Post-installation cleaning

6.2.1 General

All line pipes should be installed with sections of pipe that are generally in accordance with 5.3. Otherwise there are no other special requirements. It is important, however, to ascertain the likely condition of the piping (e.g. degree of mill scale) as delivered from the stockist or manufacturer's works to ensure that the proposed cleaning method is capable of achieving the desired specification of the pipeline owner.

Hydrogen Pipelines are normally cleaned using various types of pigs; wire, foam, scraper, dewatering, line-sized, and oversized. They are pushed through the pipeline using a pressurized system. Other methods of cleaning may be used, provided the desired standard of cleanliness can be achieved.

A pig launcher shall be used for injecting pigs into the pipeline. The pig launcher shall have a quick-opening closure, a full-pipe-size check valve, and adequate shutoff valves to permit rapid and frequent launching of the pigs.

A pig catcher shall be used to capture pigs exiting the pipeline. The pig catcher shall prevent the pigs from becoming airborne and endangering personnel. The pig catcher shall be designed to minimize any damage to the pigs so that they can be reused.

Before and during use, pig launchers and catchers should be kept clean.

Only new pigs or used ones which have shown to be in good repair shall be used at the start of cleaning. Pigs may be reused during cleaning until they become worn and cannot perform their intended function efficiently.

The velocity of the pigs should be controlled as indicated in this specification. This can be done by controlling the amount of the pig driving media flowing into the pipeline behind the pig(s). Back pressuring the pipeline to control the velocity of the pigs is also acceptable.

The cleaning operation is normally done after the hydrostatic or pneumatic pressure tests are complete, as this accomplishes dewatering as well. If necessary, the cleaning operation may precede a pneumatic pressure test.

Pipeline equipment such as tees, valves, check valves, insulation joints, regulators, meters, filters and other fittings should not be installed until the pipeline has been cleaned. This minimizes the chance of damage to the items or pigs and provides unambiguous flow paths during cleaning.

6.2.2 Propelling medium

When compressed air is used for propelling pigs through the pipeline, residues such as water, oil, and particulate should first be removed from the air stream. Generally, compressed air is passed through a drier, for example with dual and switchable beds of silica gel or activated alumina, an oil coalescer, and filter before entering the system being pigged. The dry, oil-free air shall have a dew point of -40°C (-40°F) or lower and a hydrocarbon content of less than 5 mg per cubic metre.

When dry, oil-free nitrogen from a liquid nitrogen pumper, gaseous nitrogen tube trailer or other source is used, precautions shall be taken to provide appropriate ventilation as an asphyxiating atmosphere may be created. Employees at the exit end of the pipeline are susceptible to large volumes of nitrogen. Workers shall be trained for the potential hazard of anoxia or asphyxiation.

6.2.3 Typical cleaning sequence

The following steps outline the cleaning sequence that begins after the hydraulic pressure test.

6.2.3.1 Dewatering

Dewatering shall be done after the pipeline has been hydrostatically pressure tested. Dewatering should be completed using dewatering pigs made of hard polyurethane foam with sealed, double-dished ends. Wire brushes or scrapers shall not be attached to nor included as part of these dewatering pigs.

The propelling media for the pigs shall be oil-free air or nitrogen as defined in 6.3.2.

The pigs shall effectively seal against the interior pipe wall to minimize water leakage past the pigs.

The pigs shall be run through the pipeline until no water is accumulated at the pig catcher. At a minimum, no less than three dewatering pigs shall be run through the pipe.

To avoid potential mechanical damage to the pipeline and also for safety reasons, the velocity of the initial dewatering pig should not exceed 5 km/h (3 mph) and the velocity of subsequent dewatering pigs should not exceed 16 km/h (10 mph).

6.2.3.2 Drying

After the line has been dewatered, the water adhering to the interior pipe wall shall be removed by running new, bare polyurethane drying pigs through the pipeline.

The propelling media for the drying pigs shall be dry, oil-free air or nitrogen as defined in Section 6.3.2.

For good results and also for safety reasons, the maximum velocity of the drying pigs should be around 6.5 km/h (4 mph).

These drying pigs shall be run through the pipeline until they do not absorb any more water. This can be determined by feeling the drying pig surface for dryness.

Drying pigs may be reused if they are not saturated with water and less than 70% of their surface area is discoloured.

This operation shall continue until the pipeline interior surface is completely dry. This will be considered to have been achieved when the interior dew point at the drying pig receiving end is measured at -20°C (-4°F) maximum.

6.2.3.3 Dry cleaning

After the line has been dried, the line shall be cleaned of rust and mill scale by using wire-brush and foam pigs.

The propelling media for the pigs shall be dry, oil-free air or nitrogen as defined in 6.3.2 . The dew point of the propelling media for final stages of wire brushing and foam pigging shall be controlled at or below -20°C (-4°F).

The wire brush pigs shall be made of hard polyurethane foam covered with flame-hardened steel bristles and shall be new and free of all oil and grease.

Pigs shall be launched one at a time, or in trains, at a frequency that will prevent pigs from gathering and lodging in the pipeline, or successive pigs or trains of pigs from arriving together at the pig catcher or terminus of the pipeline segment being cleaned.

For good results and also for safety reasons, the maximum pig velocity for this cleaning operation should be around 40 km/h (25 mph).

Wire-brush pigs shall be run until no dirt, dust, or any other debris is deposited at the end of the pipe, and the dew point at the receiving end is below -20°C (-4°F).

The wire-brush pigs may be reused if they have an interference fit with the pipeline interior, have over 90% of wire bristles available for cleaning, and have no accumulation of deposits in the bristles.

Wire-brush pigs may require up to 50% more driving media than foam pigs. This extra media requirement is necessary because of large amounts of flow bypassing the wire brush pigs because of the long wire bristles. The contractor may elect to run a foam pig directly behind the wire brush pigs to limit the bypass of the driving media around the wire brush pigs.

After wire-brush pigs have been run, foam pigs shall be run until the line is clean.

Following completion of cleaning, all pre-cleaned valves, tees, and meters shall be installed.

6.2.3.4 Final drying

Final drying is typically accomplished by the intermittent purging and bottling of the pipeline with dry nitrogen gas until the desired dew point level is achieved. At this point all pre-cleaned valves, tees, and meters shall be installed.

Vacuum drying can be utilized after executing the nitrogen purge drying sequence, if lower dew points are desired. Vacuum drying can achieve dew points in the range of -56°C (-70°F) to -76°C (-105°F).

6.2.4 Maintaining cleanliness

During the installation of the pipeline ingress of contaminants should be avoided as much as possible (e.g. oil, grease, soil, debris, and runoff water).

6.2.5 Inspection

After satisfactory completion of the construction, testing and cleaning processes, the pipeline shall be inspected at both the inlet and discharge ends and at all accessible points to assess the condition of the internal surface. A record of the inspections that is descriptive of the interior pipe surface shall be maintained as part of the pipeline quality control dossier.

6.2.6 Acceptance criteria

The pipeline is considered clean when no more dust leaves the pipeline and the foam pigs emerge with a light grey or light brown colour that has penetrated the pig's surface no more than 3 to 6 mm (1/8 to 1/4 in).

6.2.7 Sealing, inerting, leak testing and monitoring

Following the pipeline inspection and acceptance of the standard of cleanliness, the pipeline will be sealed at all open ends with either welded caps or blind flanges and purged with nitrogen. Once the oxygen content and dew point have reached the required levels, the pipeline system shall be sealed and pressurised with nitrogen to about 0,06 MPa (10 psig). The pressure shall be monitored on a regular basis to check the absence of leaks and maintained in this condition until the pipeline is required for service with the product gas. As nitrogen is used, warning panels against anoxia shall be affixed.

7 Construction

7.1 General criteria

The total installation of the pipeline, including testing and cleaning, should be undertaken by a reputable organisation with a proven record of experience in pipeline construction. The fabrication, testing and cleaning procedures shall have been reviewed and approved by the purchaser before work is begun. The detailed construction program, including the sequence of testing and cleaning procedures, shall be defined to suit specific project requirements. The design of the pipeline system shall have made provision for the cleaning and pressure testing methods to be used.

The construction of the piping systems should follow good engineering practice in accordance with recognised national or international piping and construction codes.

Systems of work shall be in place to ensure the safety of the construction personnel in the fabrication and erection areas and the general public in adjacent populated areas.

Appropriate efforts shall be made to ensure the quality and the operational safety of the piping being installed.

The piping system shall be fabricated and installed in accordance with the piping and construction codes as defined in the project specification.

Necessary precautions and measures should be taken to protect materials and piping from damage caused during off-loading, storing, installation, or other activities. Piping should be carefully stored and handled to prevent contamination of the interior of the pipe and to prevent damage to the exterior protective coating (if applied).

The line pipe shall be fabricated and/or installed in accordance with approved drawings. Installation of the line pipe shall include all manual valves, special piping items, control valves, relief valves, in-line items and pipe supports as required by the approved drawings.

If required, the piping system shall be constructed to accommodate the passage of instrumented internal inspection devices. This criteria does not apply to meter stations or regulator stations.

Procedures for any remedial work that might be required should be agreed with the purchaser prior to the work being performed.

7.2 Specification and manufacture of line pipe material

7.2.1 General requirements

All essential requirements for the specification and manufacture of the line pipe which have a direct bearing on the cleaning process should be formally submitted to the pipe supplier as part of the full technical specification for the purchase of the line pipe. The origin and quality control of the purchased line pipe shall be fully traceable and the relevant documentation submitted to the purchaser for retention.

7.2.2 Codes and standards

Generally, the manufacturing process, material, grade, and inspection requirements for the piping should be in accordance with standards, such as EN 10208-2 or API 5L specification or other codes as defined in the project specification as a result of purchasers requirements, national regulations, or other reasons. The material composition should generally be in accordance with the aforesaid codes and the manufacturers normal standard for line pipe.

7.2.3 Manufacturing process

Both seamless and welded pipes may be used. In the latter case, the line pipe shall be manufactured using either the High Frequency Induction (HFI) or Electric Resistance Welding (ERW) or Submerged Arc Welding (SAW) process. Line pipe manufactured by other processes should not be used without the prior approval of the purchaser.

7.2.4 Heat treatment

Heat treatment for either the longitudinal weld (normally carried out as part of the continuous HFI or ERW or SAW production process) or the pipe body should be such that the finished line pipe is essentially free of mill scale.

7.2.5 Hydrostatic test of line pipe

Regardless of the nature of the pressure test carried out in the field, the manufacturer of the line pipe shall, as part of the manufacturing and quality control process, carry out a hydrostatic test on each section of the finished pipe. The test should be in accordance with the requirements of the applicable national regulations or codes, such as EN 10208-2 or API 5L, unless dictated otherwise in the project specification as a result of the purchaser's requirements.

7.3 Construction plan

A formal construction plan should be developed which provides a comprehensive, logical progression of work including proper supervision, regular inspection, and verification.

7.4 Pipe fabrication and welding

7.4.1 General

To the greatest extent possible piping shall be assembled by welding. Where welded connections are not possible, flanged connections shall be used wherever practical. Threaded connections shall be kept to an absolute minimum.

To preserve the internal cleanliness of the piping, the internal weld surfaces shall be smooth and substantially free of slag, beads or loose debris. Gas Tungsten Arc Welding (GTAW) also known as Tungsten Inert Gas (TIG) is recommended for the root pass on these tie-in welds. Subsequent weld passes can be made using either the GTAW or other weld processes as preferred. This process will in itself produce the desired smooth finish on the internal weld surface. When using the Manual Metal Arc (MMA) welding technique, also known as the Shielded Metal Arc Welding (SMAW), followed by cleaning of the internal weld surfaces with wire brush or blade tool pigs to remove slag, beads and loose debris and thereby achieve the desired finish.

Gas Metal Arc Welding (GMAW) is an acceptable practice for shop pre-fabrication of piping

Inspection should be made of all pipe spools and components prior to assembly to ensure that flange or weld faces are clean and that there is no dirt or contamination inside the pipe. Any debris or foreign material inside the pipe shall be removed before pipe welds or flange connections are made.

As service pressure increases, greater attention to welding processes can be required, for example TIG root passes, post weld heat treatment, etc. Fracture mechanics analysis could be required.

7.4.2 Qualifications

All pipe welding shall be performed in accordance with welding procedures and by welders qualified to the procedures in accordance with the piping code as defined in the project specification and as required by local or national regulations.

7.4.3 Backing rings

Backing rings, which remain in place are not allowed as they will interfere with pipeline pigging operations and weld inspections.

7.4.4 Preparation for welding

All weld joints shall be prepared in accordance with the approved welding procedure and the relevant piping code. The longitudinal seams of welded pipe in adjoining pipe sections shall be staggered.

7.4.5 Welding requirements for materials

Use of low hydrogen welding rods is recommended. Keeping the weld rods dry during the construction period is very important. Inspection shall be performed according to Section 7.6.

The welding procedure should be selected so that the finished weld hardness is less than 22 Rockwell C, equivalent to 248 Vickers or 250 HB in the weld itself and the heat affected zone.

Post weld heat treatment should be considered to limit the maximum hardness or large variations of hardness in the heat affected zone, particularly in the case of pipeline materials with a carbon equivalent greater than or equal to 0,43.

In the case of austenitic stainless steel, the ferrite content in the welding zone should be limited to 7%. Too low ferrite content can lead to hot cracking.

7.5 Assembly and installation

7.5.1 Alignment

Before bolting up, the alignment deviation of the flange face and flange bolt holes shall not exceed the values defined in the project specification; all bolts shall pass easily through both flanges.

The tolerance on the termination of all piping other than flanged connections shall be as shown in the design drawings and specifications.

7.5.2 Flanged joints

Piping shall not be hung from flanges of compressors or other equipment without adequate supports.

Gaskets shall be installed in accordance with the design drawings. Gasket leaks are often a result of improper alignment and not following recommended tightening procedures. When gaskets containing non-metallic parts are used, non-metallic materials shall be chosen according to 4.4.2. The use of gasket types or materials other than those defined in the project specification shall be prohibited unless approved by the purchaser.

Bolting shall be pulled up gradually using a crossover sequence. The bolt type and size shall be matched to the flange and gasket material. If, in special circumstances, bolt loads are specified, the contractor should use bolt tensioning equipment to achieve the correct bolt loading. If torque values are specified, the contractor can use torque wrenches via the nuts to develop the necessary bolt load. The use of torque wrenches might dictate the use of a suitable lubricant on the bolt threads. If no bolt loads or torque values are specified, bolts shall be tightened sufficiently, in accordance with good engineering practice or vendor information, to ensure that the joint is capable of holding the tightness test without leakage.

The re-use of any gasket is prohibited; it is essential that new gaskets be inserted every time a flange is released. When a joint leaks on pressure test, the joint shall be re-made using new gaskets.

Gaskets, nuts and bolts shall be visually inspected to ensure that they are clean and in good condition. If so desired, a suitable lubricant, as defined in the project specification, can be applied to bolt threads and bearing faces of nuts and washers before bolts are inserted into flanges and tightened.

Alternatively, lubrication can be avoided by the use of appropriate, corrosion resistant materials for bolts, nuts and washers.

7.5.3 Insulating joints

Insulating joints for cathodic protection systems, particularly those of the monoblock type, are prone to damage and leakage if overstressed either laterally or longitudinally. Proper alignment of flanged isolation joints is also critical to proper installation of sleeves covering bolts for proper isolation after tightening. To reduce the likelihood of joint deformation beyond the acceptable limit, it is important that joints are adequately supported and correctly installed in accordance with design drawings and good construction practices. See also Sections 4.4.2 and 5.5.5. These joints shall be tested for electrical isolation prior to pipeline being placed in service.

7.5.4 Threaded joints

Any threaded joints should be kept to a minimum based on the products that this specification is covering. It is recommended that any threaded joints directly connected to the pipeline without a method of isolation shall be properly seal welded. All threaded end connections open to the atmosphere shall be sealed with a plug. Clean cut taper threads in accordance with the design requirements shall be used and shall be fully deburred.

7.5.5 Tubing

Stainless steel tubing is recommended for instrumentation. Copper tubing shall not be used for circuits which are exposed to the pipeline gas.

7.5.6 Valves

All valves shall be supplied with identification tags or plates and installed in the location defined by the design drawings. Identification tags or plates shall remain attached to each valve after installation. It is not permitted to interchange valves.

To minimise exposure to damage, valve top works, actuators and other associated equipment should be stored in a clean condition and installed as required after major construction work has been completed.

All valves shall be installed in accordance with the piping design drawings and handled in a way which maintains their cleanliness and prevents ingress of moisture, oil, dust, and other contaminants. Particular care should be taken with valves, whether manual, automated or pressure relief, to ensure that both the flow direction and orientation are correct.

The following precautions shall be observed with respect to the installation of pressure relief valves and other pressure relief devices:

- Apart from those required for construction and testing purposes, no pressure relief valves or other pressure relief devices shall be installed until all pressure testing, cleaning and blowout work have been completed.
- It is recommended that vent piping be fitted with protective devices that will prohibit restrictions to the proper functionality of the relief valve, like bird nests or ice.
- All relief valve vents shall be piped to a safe location.

Before welding any valve into a piping system, the valve shall be fully opened. The top works should be removed to prevent thermal distortion of the valve components. Soft seats and other components are usually vulnerable to damage by heat. After welding, soft seats and other vulnerable components should be checked. If excessive force is required to operate the valve, remedial action shall be taken.

7.5.7 Supports, guides and anchors

Supports, guides and anchors shall be positioned and secured before the installation of the piping. Additional temporary supports can be used during installation but they shall not be welded or bolted to any permanent structural members. Temporary supports, guides and anchors shall be removed before the pipeline is commissioned.

All welded connections, such as earth clamps or supports, attached directly to process piping or equipment intended for service at elevated pressures shall be made before pressure testing. Welding on pressure containing equipment after the successful completion of a pressure test is not permitted.

Any support for cathodically protected piping shall be electrically isolated so that the protection of the pipeline is not compromised.

7.6 Inspection and examination

During construction, regular on-site inspections should be made to ensure that correct procedures for installation are being observed. During and after construction, the pipeline should be inspected and tested in accordance with the relevant piping code and procedures as defined in the project specification. Such inspections should, as a minimum, include those to verify the following:

- Correct materials (as a minimum by stamped markings and / or accompanying paperwork. It is recommended that spot Positive Materials Identification be performed as well.)
- Pipe concentricity
- Specified wall thickness
- Internal cleanliness
- Protective coating integrity
- Electrical isolation
- Absence of mechanical damage e.g. gouges, dents etc.
- Joint preparation
- Welding fit-up
- Welding
- Absence of arc burns
- Review of radiographic or other examination

7.7 Non-destructive testing

7.7.1 Pressure testing

The pipeline shall be subject to either a pneumatic or a hydrostatic pressure test at the pressure required by the code to which the pipeline has been constructed. The preference is for a hydrostatic test. Whichever test method is selected, it shall be conducted at a convenient point in the overall pipeline construction to suit project requirements and to minimise the likelihood of costly rework.

The strength test should be completed by conducting a hydrostatic test using clean water. The test shall be carried out in accordance with the code to which the pipeline has been designed and constructed.

The filling and testing operations shall be planned as a continuous operation to ensure that water does not remain in the pipeline system for any longer than necessary, particularly if below freezing ambient temperatures are foreseen during the test period. Adequate safety precautions to minimise the potential consequences of a pressure release shall be taken while the test is in progress. If a pneumatic test is conducted and nitrogen is used as the test medium, the risk of exposure of personnel to oxygen deficient atmospheres shall be assessed and appropriate precautions taken.

Water for testing and any subsequent flushing should be clean and free from any suspended or dissolved substance which could be harmful for the pipe material or which could form deposits within the pipeline. For carbon steel pipelines, the pH should be between 5 and 8 and the chloride not more than 1000 mg/litre (50mg/litre for stainless steel). It is best practice to minimize the time the hydrotest water remains in the pipeline, as water promotes corrosion and biological activity. If the water stays more than 8 days in the pipeline, the pH should be limited between 6 and 7.5 and chloride concentration less than 500mg/litre (5 mg/litre for stainless steel). Special care is needed in dealing with water sources containing potentially harmful chemicals or bacteria.

After the completion of a hydrostatic test the water should be preferably removed immediately either by draining or pigging or a combination of the two. See Section 7.2.5. For reasons of practicality, in the case of pipe tie-ins or final closing welds it may be acceptable to waive the need for a pressure test provided that a prescribed alternative method of non-destructive testing is carried out and local regulations do not prohibit this.

7.7.2 Non-destructive examination

7.7.2.1 General

All NDE examinations shall be performed by a licensed qualified operator with the exception of dye penetrant and magnaflux examination which may be applied by a trained assistant and interpreted by a licensed operator. All NDE activities shall be fully traceable preferably with a weld map. A report shall be made identifying each weld which is examined and showing its location, the weld procedure used, the weld operator who made the weld, NDE procedure used, and results including repairs.

Longitudinal pipe seams, which exist as a result of the pipe manufacturing process, are exempt from on-site non-destructive testing (See Section 7.7).

7.7.2.2 Radiographic examination

All radiographs shall be of the entire length of the weld. It is required that 100% of the butt weld joints in the pipeline be fully radiographically examined as defined in the project specification. Final closing welds shall be fully radiographed.

In situations where the radiological hazards presented by X-rays (or Gamma rays) cannot be accommodated by reasonable means, 100% non-destructive examination by an equivalent method such as UT may be substituted.

7.7.2.3 Dye penetrant and magnaflux examination

Socket weld and fillet weld joints cannot be suitably radiographed but should be examined using dye penetrant or magnaflux examination. It is recommended that 100% of these joints be examined.

7.7.2.4 Micro hardness test

In order to control that the toughness of the pipe material is not affected by the welds, micro hardness tests may be performed as part of the weld procedure and weld operator testing and, by samples of production welds.

7.8 Documentation

The following documents relating to the construction and installation of the pipeline shall be retrieved and collected in a dossier that is retained for reference by the operator:

- Pressure test report
- Weld procedures, procedure qualifications, and qualification records for each welder.
- Weld joint NDE reports (including rejects/repairs, weld map, weld operator identification, welding technique used).
- Summary of all NDE procedures demonstrating that all code, regulatory, and project specific requirements have been met.
- Report of internal pipe cleaning and inspection.
- Inspection reports for all inspection activities
- As-built drawings.
- As-built data logs.
- Records of construction personnel qualifications.
- Material control certificates.
- Other reports and certificates required by local and/or national authorities, the relevant piping code and the project specification.
- Protective coating integrity test report (report on pinholes or defects in the external coating)
- Cathodic protection and electrical isolation report.

At the completion of the work, the fabricator should supply a written statement that all NDE requirements have been met which has been executed by the quality assurance supervisor or other qualified individual.

8 Design and construction of stations

8.1 Function

The function of a process control station is to control and meter gas in conjunction with a supply pipeline. Each process control station is designed and constructed for individual customer requirements and incorporates appropriate process control equipment. Typical arrangements are shown in Appendix A, Diagram 1.

The different functions may be:

- isolation for maintenance and/or for emergency;
- metering;
- pressure and/or flow regulation; and
- filtration.

This type of station is typically located at a customer's site.

Additionally regulatory requirements may require isolation stations at defined intervals along the pipeline.

8.2 Design brief

A design brief summarising the basic requirements (Process Definition and P & I Diagram) should be used as the basis for design.

The design brief should be developed by reference to the following:

- process pattern data supplied by customer;
- safety, e.g. inerting system for maintenance;
- environmental, customer, and other statutory requirements; and
- site requirements, including interaction with surrounding plant, e.g. vent collection system.

A Hazop study and/or Risk Assessment may need to be considered with the design brief.

An example of a complete process control station showing possible components is shown in Appendix A, Diagram 2.

The main elements are described below

8.2.1 Excess flow valves

Excess flow valves may be provided to afford protection against pipeline failures. The closure of the valves can be initiated manually or automatically from a central control room or by automatic signals derived from high flowrate, low pressure or rate of decay of line pressure.

8.2.2 Isolation valves

Due to the risk of ignition of an hydrogen leakage, maintenance shall be done after positive isolation of the concerned installation, followed by inerting. Positive isolation may be done by double block and bleed valves, blind flange, double trunnion mounted ball valve equipped with a body vent or equivalent.

8.2.3 Filters and strainers

Filters may be installed at the inlet to the process control station to protect control devices from particulate matter (originating from the upstream carbon steel pipeline or equipment/machinery) which may be entrained in the gas stream.

For high purity applications (e.g. electronics) more stringent filtration levels (typically less than 5 µm) may be specified.

8.2.4 Flow meters

The billing quality meter measures accurately the total quantity of gas passing through the process control station. The meter consists of a primary device and instrumentation to convert the process variables to a volumetric or mass flow value.

A bypass is recommended to facilitate removal for calibration and maintenance.

The selection of flow meter type is normally based on the accuracy requirements for the required range of gas flow to meet customer requirements. Instrumentation comprised of pressure, differential pressure and temperature transmitters measure and convert the process variables into signals that are typically input into a flow computer. The flow computer uses these inputs to calculate a flow rate which is integrated over a specific time period to calculate and record volumes.

8.2.5 Flow and pressure control

Flow control devices are typically provided to overcome erratic flow patterns to produce constant supply irrespective of customer demand, or to limit the flow available to the customer. Pressure

control systems regulate the variable pipeline pressure to deliver gas at constant pressure to the customer.

Installed block and manual by-pass valves are the recommended minimum scope to achieve reliable supply and provide for ease of maintenance. In some cases it may be preferable to consider a redundant control valve instead of the manual by-pass for even higher reliability.

8.2.6 Gas storage

Storage vessels or additional volume of piping may be required to provide buffer capacity to satisfy peaks in customer demand and to provide downstream capacity to facilitate efficient control valve operation. The materials of construction of these should, as a minimum, follow the pipeline requirements in intent and selection criteria. Vessels should be designed with sufficient parent metal and weld zone toughness for leak before break criterion and to withstand fatigue in service.

8.2.7 Pressure relief

In order of preference based on fail safe design, the following provisions are recommended:

- The entire station should be designed for the MAWP of the pipeline to avoid the need for pressure relief valves to protect the station from over pressure.
- Where this is not possible, then safety valves safely vented to atmosphere may be used if not prohibited by regulation.
- In order to avoid venting to the atmosphere, an automatic shutoff system, with two emergency shutoff valves, may be installed instead of a pressure relief valve. This device shall remain closed until manually reset.

The effects of the pipeline on the customer's system and vice versa shall be considered since the pipeline necessarily interacts with the customer's system. This should be discussed with the customer.

8.2.8 Instruments

Instruments are usually electric, electronic, pneumatic, or a combination of these types of systems. The instrument and control system should be designed to fail safe electrically and pneumatically unless the customer desires a fail in place system for higher reliability. The pipeline supplier should consider the advantages and risks to this less fail-safe but more reliable arrangement before agreeing. In any case it is recommended that written instructions be received from the customer before proceeding.

8.2.9 Electrical

See Section 5.3.

Part or all of the station is classified as a hazardous electrical area and the equipment and installation shall conform to the relevant code requirements.

The equipment and piping shall be electrically connected and grounded to drain static electricity and to carry electrical fault currents to earth ground, to prevent release of electric sparks which could ignite hydrogen leaks in the area.

8.3 Standards and design codes

Design, fabrication, inspection, examination and testing shall be in accordance with national or international standards, such as ASME B31.3 and B31.8.

Electrical and instrument installations shall be designed and installed in accordance with the relevant international or national standards for the electrical hazardous area classification.

8.4 Materials and fabrication

Fabrication shall be carried out by contractors approved in their particular discipline, i.e. mechanical, civil, electrical, instruments. Installation work shall be completed in accordance with the design drawings and specifications. The completed work should be inspected and approved by the relevant technical authority.

8.5 Access limitation

Each station should be enclosed within a clearly marked area with signs indicating the risk and the necessary emergency response.

When a station is located in a public area, a fence which does not inhibit free air flow should enclose the station to prevent unauthorized access. The enclosure should have at least 2 gates and be lockable. Exits should open outwards into areas that are free of obstructions.

When a station is located on a plant site, then a chain instead of a fence may be considered sufficient in some cases.

8.6 Location

It is preferable to locate a station outdoors. The design shall be such that natural ventilation is well provided and that hydrogen cannot accumulate at the top. There can be instances where a station shall be located in an enclosure or pit. This requires careful analysis of the installation to ensure that safe entry is provided for both in the design and in operating procedures. Monitoring the atmosphere in the enclosure and the design of ventilation systems are important topics to be included in the analysis. It is worth noting that locating a station indoors may, and locating one in a pit always, require more stringent hazardous electrical designs.

When selecting a location, it is preferable to have significant clear space around the enclosure. This may not always be practical. Some examples of good siting practice are given in Appendix E.

Hydrogen piping may be installed on a concrete slab and the station should be surrounded by a fence

The fence, of a height of at least 2 m, will be provided with at least two emergency escape doors in opposite sides.

Activities involving the use or production of flames, sparks or other ignition sources are forbidden within the enclosure or the distance requirements of the applicable codes, whichever is greater, except as authorised by a safety work permit.

An acceptable standard of lighting shall be provided to illuminate the station, when this is deemed necessary to ensure personnel safety. The lighting fixtures and installation shall conform to the code requirements for the hazardous electrical area.

8.7 Grounding

The resistance to earth (or ground) of the station pipework should not exceed 10 ohms at any point throughout the installation; tests shall be conducted from a known earth point. If necessary cross flange bonding may be required to achieve the stated minimum value. If cross bonding has been adopted, measures shall be taken to prevent corrosion of component parts.

Pipework systems should not be used as grounding rods. Each piece of equipment should be individually earthed.

All grounding should be to a common grounding grid to ensure that all items, including the pipe work, are brought to a common electrical potential.

Pipework systems together with all other common services shall be bonded at a common point.

All test results including reference earth point shall be recorded and periodic testing undertaken.

8.8 Installation

Installation shall be carried out by contractors approved in their particular discipline, i.e. Mechanical, Civil, Electrical, Instruments. Installation work shall be completed in accordance with the design drawings and specifications. The completed installation should be inspected and approved by the relevant technical authority.

8.9 Pressure and leak testing

Pressure testing to meet code requirements is required. Usually the station is tested separately from the pipeline. This may take place either at a fabricator or in the field. If hydrostatic testing is used, the piping shall be thoroughly drained, dried and cleaned after testing.

Pneumatic leak testing is also required. This may take place either at a fabricator or in the field or preferably both. Inerting the pipeline is sometimes combined with the leak test. As nitrogen is used as the test / inerting gas, precautions against asphyxiation shall be specified. Vent pipes should be fitted, where necessary, to ensure that gas is discharged to a safe area.

8.10 Commissioning

The preparation of a suitable commissioning procedure should be undertaken with details of the following accommodated:

- interaction with customer processes; and
- safety considerations

A knowledgeable and experienced person shall be appointed to control all aspects of the commissioning procedure.

8.10.1 Safety

Only authorised personnel should be allowed in the vicinity of the station during commissioning. The person responsible for the co-ordination and control of the commissioning shall ensure that the Customer and all personnel are properly briefed. Normally a commissioning programme and procedure will be prepared and discussed with all concerned before commissioning starts. All Gas Supplier and Customer standing orders and safety instructions shall be observed.

8.10.2 Pre-commissioning checks

The commissioning procedure should start after satisfactory completion of pressure testing and the issue of the relevant test certificates. The procedure should include the following pre-commissioning checks:

- P & I D is compared and verified with the new station equipment and piping;
- relevant material, cleaning, authenticated calibration and test certificates are available;
- warning notices and instruction plates are posted;
- filter elements are fitted, if and where specified;
- satisfactory operation and adjustment of:
 - o meters;
 - o flow Controllers;
 - o spill valves;
 - o pressure controllers;
 - o safety valves (if fitted);
 - o safety shut-off valves (if fitted);
 - o shut-off valves;
 - o safety devices, alarms and trips; and
 - o all automatic actions and responses.

- Verification of meter installation and calibration by a customer's representative is frequently required.

8.10.3 Inerting

Inerting of stations may be performed by the method of successive pressurizations and depressurizations (pressure pumping) since the stations invariably have undrained cavities (dead legs, hands). A minimum of three cycles of pressurization and depressurization shall be performed. Verifying that the inerting is complete by local analysis is suggested. Inerting may also be done including piping and stations by simply flowing nitrogen through the system, see Section 8.10.3.

During commissioning the filter differential pressure gauges should be monitored, especially in the first phases of commissioning, in order to detect when filter element changes are required. Such a monitoring exercise should also be carried out following maintenance / shutdown operations.

8.10.4 Pre-commissioning checks of the whole pipeline system

When pipeline and stations have been inerted, the oxygen content shall be measured to ensure that there is no more air or oxygen in the pipeline. Then hydrogen can be introduced into the pipeline system until all nitrogen has been displaced. Hydrogen pressure is increased step by step and checked to be at a stable level. During that process, flanges and mechanical joints, which could not be previously tested, are checked for leaks using for example an explosimeter.

8.11 Operation

Process control stations are normally automatic in operation once the controls have been set. The only manual operations required are:

- opening and closing of isolating valves to suit process and maintenance requirements;
- monitoring of gauges and other indicator displays to ensure the process control station or components are operating within limits;
- maintenance of a clean process control station area and particularly the exclusion of flammable products; and
- implementation of a maintenance program.

Personnel entrusted with the operation of the process control station shall have been trained in the operating techniques required, the potential hazards associated with hydrogen and in the emergency procedures.

8.11.1 Filters / screens

Initially on a new station, due to high velocity test and purge flowrates during commissioning, any filters can receive a considerable amount of foreign matter from the pipeline and can choke rapidly. Therefore, after a short time in operation, the filter / screen differential pressure should be checked and the filter / screen cleaned if necessary. Depending on the degree of cleanliness of the pipeline and station piping, it may be necessary to repeat this process.

9 Operation and monitoring

9.1 Operation and maintenance manual

An Operations and Maintenance Manual is required for the operation of all Hydrogen pipelines. The operator shall provide all information needed for safe operation of the pipeline in the form of rules, guidelines, and procedures within this document.

The pipeline system can be influenced by the reliability of the individual components and the experience and training of the operations personnel. In order to meet these performance standards the following precautions and provisions shall be considered:

- ensure safe operation of the pipeline system;
- monitor its condition;
- perform maintenance safely and effectively; and
- deal effectively and responsibly with incidents and emergencies.

9.2 Management systems

A management system shall be established and implemented with the objectives of ensuring the following:

- safe operation of the pipeline system;
- compliance with design;
- managing pipeline integrity;
- safe and effective execution of maintenance, modifications and abandonment; and
- dealing effectively with incidents and emergencies.

The management system should include the following:

- identification of personnel responsible for the management of the operation and maintenance of the pipeline and for key activities;
- an appropriate organization chart;
- a written plan covering operation and maintenance procedures;
- a written emergency response plan, covering failure of pipeline systems and other incidents;
- a written work permit system;
- a written management of change,(MOC), process;
- a written operator training and qualification program;
- a periodic review and update process; and
- an effective pipeline integrity management system.

9.3 General safety requirements

When performing work on a hydrogen system the following will be required:

- smoking and other sources of ignition are forbidden in stations and within a minimum distance of 5 metres;
- personal protective equipment including flame retardant clothing;
- use of non-sparking tools;
- work permit required when performing maintenance and/or repairs. It should request the presence of minimum two persons, when there is work which can involve a release of gas;
- positive isolation is required prior to performing maintenance and/or repairs;
- proper purging and inerting required prior to any welding or cutting;
- fire watch required when performing welding or cutting; and
- temporary grounding is recommended during maintenance and/or repair.

9.4 Personnel for operation and maintenance

As well as having the usual work safety knowledge, personnel who operate, maintain and repair hydrogen systems shall also have special knowledge of how to handle hydrogen and the potential hazards that are involved. They shall be well acquainted with the location of the pipelines, the stations and the control equipment. All the operating and safety procedures shall be available to the personnel.

All personnel including Sub-contractors shall be made aware of any abnormal operating conditions and have access to all the relevant safety information.

9.5 Welding and cutting

9.5.1 In service welding and cutting

Any welding on in-service hydrogen pipelines could cause localized heating and/or adversely affect the integrity of the piping system and therefore shall be avoided. The only exceptions are:

- drilling small openings in depressurised pipelines during connection work;
- welding on cathodic protection devices; and
- welding on hot tapping saddles, as described in Section 9.7.

The above work requires special equipment and procedures; it may only be carried out under the supervision of highly experienced and trained personnel. The process qualification should verify that the pipe metallurgy and properties are not adversely affected by the process. Although it is preferred that these processes be done when the hydrogen line is out of service, it is recognized that occasions may arise when this is not practical, but these should be minimized.

9.5.2 Out of Service welding and cutting

All maintenance welding of hydrogen pipelines shall be to the same standards and requirements called for in the construction section above.

A weld that cannot be repaired as outlined above may be repaired by installing a full encirclement welded split sleeve using circumferential fillet welds or cutting out and replacing that section of pipe. If a segment of a pipeline is repaired by cutting out the damaged portion of the pipe as a cylinder, the removed section should be cut at least two pipe diameters on each side of the defect or weld. The replacement pipe shall be of comparable strength and metallurgy and be suitable for the hydrogen service at the intended maximum allowable working pressure (MAWP). The replacement section of pipe shall be pre-tested to match the MAWP of the pipeline. All field girth butt welds not strength tested shall be radiographically examined after installation.

Cold cutting of pipelines for tie-in and repairs is preferred to reduce the possibility of ignition keeping in mind that this does not reduce any of the requirements for safe maintenance activities.

9.6 Shut down, repair and start-up of pipelines

A hazardous work permit is generally required for shut down, repair and start up and maintenance of pipelines. The personnel involved in the work, including contractors, shall be qualified and be informed of the abnormal operating conditions related to hydrogen and the tasks to be performed. A positive shut-off is required. This shut off can be carried out by:

- complete disconnection of the section concerned from the pipeline system;
- installing blind flanges; or
- closure and mechanical locking of two valves arranged in tandem with an open venting valve between them (if the valve has an electric drive, the power should also be disconnected) : or a double trunnion mounted ball valve equipped with a body vent.

A check valve cannot be used as a shut-off mechanism for maintenance work.

Inerting of the section of pipe to be repaired, which should include local analysis, shall be done prior to the start of any work.

Lock out and tag out procedures shall be used to indicate that the equipment has been placed in the shut off position and to reduce the risk of uncontrolled operation of the valves. Operations shall inform the maintenance team that the pipeline is ready for their work.

9.7 Hot tapping hydrogen pipelines

9.7.1 General

Hot-tapping is a process which involves an under pressure drilling/hole cutting machine cutting a hole in an operating pipeline. The process is completed without leakage or without interruption of flow. A typical hydrogen hot-tap application includes the use of a fitting designed to contain system pressure welded to the pipeline, a valve used to control the new branch connection, and the drilling/hole cutting machine to make the hot-tap.

A hydrogen hot-tap shall not be considered a routine procedure, but shall be used only when there is no other practical alternative. All other avenues of performing the tie-in to the pipeline shall be considered prior to making the decision to perform a hydrogen hot-tap.

9.7.2 Restrictions

Because of the risks involved with welding on a pipeline pressurized with hydrogen it is important to fully evaluate the process prior to executing the work. A hot-tap thermal analysis program shall be used to review, analyse, and provide the product flow and weld parameters during the hot-tap.

Hot-taps in hydrogen service shall not be performed on pipelines:

- with a pipe wall thickness less than 6.4 mm (0.250");
- with a specified minimum yield strength greater than 360 MPa (52,000 psi);
- where the operating temperature is 121°C (250°F) or greater;
- if ambient temperature is 0°C (32°F) or below;
- where the operating pressure is greater than 6.2 MPa (900 psi);
- if the hardness of the pipeline is measured greater than 225 BHN (Brinnell Hardness Number);
- within 46 cm (18") of a flange weld;
- where the hot-tap fitting will not have a clearance greater than 7.6 cm (3") from a girth weld;
- that have any type of internal lining or coating; and
- upstream of rotating or reciprocating equipment, unless the equipment is protected by a strainer or filter.

9.7.3 Hot tap procedure recommendations

The following is intended to be an illustrative guide based on industry experience.

Hot-tap holes 3.8 cm (1.5") and larger shall be cut using a drilling machine fitted with a hole saw and drill. The hot-tap hole coupon shall be removed as part of the hot-tap operation. The drill that is part of the hole saw shall be fitted with a device that will catch the coupon for removal when the hole saw is removed. Hole sizes less than 3.8 cm (1.5") shall be drilled.

It is important to verify the wall thickness and hardness of the pipeline before the installation of the hot-tap fitting. All pipe coating, paint, scale, rust, and any other dirt shall be removed to a bright metal finish. The cleaned area shall extend a minimum of 7.6 cm (3") beyond the extremities of the fitting to be installed. The wall thickness of the pipeline shall be examined at a minimum of 4 locations in the vicinity of weld attachment to the pipeline. The hardness of the pipeline shall be checked and verified to be less than 225 HB at a minimum of 4 locations in the vicinity of weld attachment to the pipeline.

Only two types of fittings shall be used for attachment to the pipeline. A Full encirclement, split fitting shall be used if the ratio of the branch diameter to the pipeline diameter is greater than 0.5. After attachment the hardness of the circumferential welds and the heat-affected zone shall be measured at a minimum of 2 locations in each weld area. A welded branch connection fitting (weldolet or equivalent) shall be used if the ratio of the pipeline diameter to the branch diameter is 0.5 or less. After attachment the hardness of the attachment weld and the heat-affected zone shall be measured at a minimum of 2 locations. In each case the hardness measurements should be less than 225 BHN

and the weld procedure for the attachments should be prepared to assure that this will be achieved. Also, it is very important that the root pass and the final weld for the attachment of the hot-tap fitting be visually and dye-penetrant inspected for cracks and other imperfections.

The hot-tap operation requires that the connection fitting be welded to the operating pipeline. The pressure in the hydrogen pipeline shall be reduced as much as possible while maintaining flow through the pipeline. Maintaining flow is very important in removing heat from the weld area. Pressure and flow shall be carefully regulated while the welding operation takes place. In addition to this it is prudent to require special flame retardant outfits and body harnesses with rescue lines to be worn by the welder and the person directly assisting the welder. There shall be no more than two persons (the welder and assistant) directly engaged in the welding operation. It is imperative to have hole watches assigned to each individual for rescue purposes. Appropriate safety equipment such as gas detectors, fire extinguishers, ladders, flame-resistant clothing shall be available before this operation is started. Because of the critical nature of the safety aspects of this operation it is recommended that a checklist is developed to assure that all aspects of proper preparation for the hot-tapping operation are verified before proceeding with the work.

Since the hot-tap fitting and any additional piping that is connected will become pressurized when during the drilling/cutting process it is important that the attached assembly is pressure tested prior to drilling/cutting after the weld attachment is completed. This pressure test should be conducted in accordance with local codes. It is important to note that the differential pressure between the pipeline operating pressure and the test pressure in the attached assembly shall be reviewed to assure that the test pressure will not buckle the operating pipeline. During this pressure test it is prudent to have the drilling/hole cutting machine attached to the assembly being tested. The test medium for the pressure test is normally nitrogen. Following the pressure test the assembly including the drilling/hole cutting machine shall be purged to remove any oxygen from the assembly. This purging is normally accomplished by pressure pumping the assembly a minimum of 5 times; however, depending on the length of the assembly more pressure pumping cycles may be required. An oxygen detection device shall be used to verify that all oxygen has been removed.

Only personnel specifically trained in the operation of hot-tap machinery shall complete the final aspect of the hot-tap connection, which is to make the cut into the operating pipeline. These personnel need to be informed of all the properties (pipe wall thickness, pipe material grade, properties of the hydrogen in the pipeline, etc.) before they begin the drilling/cutting operation. Again, it is imperative that the technician performing the drilling/cutting operation be outfitted with the proper safety equipment as required for the welder.

9.8 Venting and pressure relief

9.8.1 Venting:

Venting should be in accordance with Section 5.4.1.

9.8.2 Purging and inerting

Nitrogen or other inert gas shall be used to purge hydrogen from the pipeline before loosening or disconnecting flanges, instruments, etc. Dead ended legs of the pipeline system that cannot be swept by nitrogen shall be pressure purged. The number of pressure purging cycles shall be evaluated for each specific job.

A written purging plan should be prepared that insures all hydrogen is removed from the pipeline system to non-detectable levels.

When using nitrogen, it shall be ensured that unauthorised access to the outlet is prevented and that no-one can be endangered by oxygen deficient atmospheres.

9.9 Commissioning pipelines and stations

After the successful mechanical completion of the installation, repair or maintenance work, including all testing, cleaning and drying, the pipeline is ready for commissioning. The maintenance team

should inform operations of the completion of the work and that the system is ready for recommissioning.

The steps in commissioning the pipeline are:

- remove any blind flanges;
- flow and pressure purge the pipeline with nitrogen until all air is removed; verify by analysis;
- introduce hydrogen gas and vent;
- pressure purge any dead-ended legs with hydrogen gas;
- test for required purity of hydrogen gas;
- close off all vent and purge valves;
- pressurize system to operating pressure; and
- leak check all valves, flanges, and fittings.

When commissioning starts, the pipeline shall first be purged with hydrogen so that nitrogen that is already in the pipe is removed. The purging process is carried out using throttling and bypass valves, if present (depending on the nominal diameter of the pipeline) via the last valve under pressure. The hydrogen should be introduced in a specific direction in order to ensure hydrogen purity. All flow purging should be done at low pressure as a safety precaution.

The purity of the hydrogen should be measured at all outlets using analysis equipment. If the purity, as required by the customer specifications, is adequate at the outlet, the relevant valve can be closed.

When the pipeline has been purged and all the purging points have been closed, the pipeline can be pressurised, using a by-pass, a throttling valve or a control valve in order to slowly pressurise the pipe up to the operating pressure.

All mechanical connections, such as flanges, valve bonnets, threaded couplings should be checked for leaks at regular intervals during commissioning.

9.10 Operation and monitoring

Supplier's and manufacturer's instructions for the equipment and systems shall be followed as received from the supplier or as upgraded by an authorized person in the operating company. Pipeline and stations shall be kept in good working order from an operational and safety point of view. The operator shall follow a defined maintenance program, including all safety and technical monitoring measures. A detailed description of the work to be carried out should be documented by outlining specific tasks that are routinely used for pipeline maintenance.

An example of a preventive maintenance program can be seen in Appendix F, which illustrates the main tasks to be performed. The frequency at which inspections are performed will be dictated by national regulations and/ or established company practices.

9.11 Information to third parties, work adjacent to pipelines and update of documents

9.11.1 General

The maintenance of pipelines does not concern just technical and operational considerations. Statistics from pipeline companies show that more than two accidents out of three occurring on underground pipelines are due to external events.

To protect pipelines and ensure the reliability of supply, it is necessary that third parties be informed of the location of the pipelines, any work adjacent to the pipelines and information regarding the installation of new pipelines.

9.11.2 Flow of information

National regulations, when they exist, shall be followed.

These regulations typically require that:

- operators of underground structures (pipes, cables, etc.) submit a declaration to the local authorities concerned;
- contractors performing earthworks in the area of underground structures inform the operators of those underground structures, in the form of a declaration, about the nature of such work prior to starting any work;
- operators respond to the contractors in timely manner; and
- operators have a qualified inspector present during any third party earthworks over, adjacent to or under its underground structures at all times while the work is being performed.

In absence of national regulations, a similar plan for information flow should be adopted.

9.11.3 Summary of work

A summary of work carried out on pipelines or near pipelines and also of work not performed should be made by the pipeline operator.

When work is performed adjacent to pipelines, the summary should be formalised by the issue of a written document countersigned by the site manager.

9.11.4 Records

Records of the following should be made by the pipeline operator:

- requests from contractors;
- replies to those requests, with the transmitted documents, including preferably GPS coordinates of the work; and
- work supervision documentation.

9.11.5 Updating of pipeline drawings

Updating of pipeline documents, in particular pipe installation drawings or maps, should be carried out on existing pipelines to reflect deviations and modifications which occurred when work was performed.

9.12 Specialised surveys

In addition to the routine monitoring of cathodic protection system potentials, consideration should be given to investigating the integrity of the pipeline coating system and other faults, which can reduce the effectiveness of the cathodic protection (C.P) system. This can be achieved by the use of specialised survey techniques, such as:

- Pearson survey;
- current attenuation survey;
- close interval potential survey; and
- direct current voltage gradient.

These investigations can be undertaken at 5 to 10 year intervals, depending on the particular pipeline and the type of cathodic protection system applied. It is common practice to compare the results of such surveys with those obtained immediately following installation. For reference, see NACE RP0502.

9.13 Damage to the pipeline system

9.13.1 Leakage

It is essential that all leaks be quickly identified so that proper remediation can take place. If a leakage of product from the pipeline is suspected, and cannot be located through visual, audible or analytical evidence, it may be necessary to isolate the pipeline in sections and pressure test it to identify the source of the leak or prove that the pipeline is sound.

Another method of locating small leaks is to use sophisticated detection equipment that can identify minute amounts of inert substances known as tracer compounds that are injected into the pipeline.

9.13.1.1 Other defects

Other defects can be coating defects, dents, gouges, welding arc strikes, pits, cracks and corrosion damages to the pipe. These defects shall be evaluated to define the proper type of repair, replacement or reinforcement of the damaged piping and remediated as required.

Coating defects may not need to be repaired, if they do not compromise the efficiency of the cathodic protection.

It is important to capture the geographic coordinates of the damages to the pipe and trace the repairs.

9.13.2 Detection of defects

Various methods can be used to detect defects as caused by the many different types of threats to a pipeline. Some of the assessment methods include in-line inspection, pressure testing, and types of direct assessment. The process of determining and assessing defects is defined in ASME B31.8S, titled, "Managing System Integrity of Gas Pipelines".

9.13.3 Revalidation

Consideration should be given to revalidation (a detailed inspection, including a pressure test) to establish the pipeline's suitability for continued service after an incident occurs, which can call this into question. Typical of such incidents are leakage, fire or other significant incident, not attributable to third party interference. Similarly, a significant modification to the pipeline system can suggest comparable action.

10 General protective measures

10.1 Emergency response plan

An emergency procedure document enables all operating staff and others, who could be involved, including the public authorities, to be adequately informed of the actions to be taken in the event of an emergency. Procedures should be developed to meet the particular needs of each individual pipeline system. National laws or regulations can dictate the form and content of such a procedure, however, even if no regulation exists, it is strongly recommended that an emergency response plan be developed by the operator. The following is a typical list of subjects issued as a guide to be considered when compiling such procedures.

10.1.1 Liaison with public authorities and other Consultees

The effective handling of a pipeline incident will often require the co-operation of public authorities (e.g. Police, Fire, Public Utilities etc.). A list of emergency contacts should be established and copies of the relevant sections of the emergency procedure should be circulated to those authorities that could be involved.

10.1.2 Description of pipeline system

This should include all relevant technical data such as routing, length, diameter, pressure of the pipeline, location, drawings of control stations including location of isolating valves.

10.1.3 Control centres

It is recommended that a single designated group or individual be responsible to control activities during an emergency. The role and location of the control centre for dealing with an emergency should be established and communication media (e.g. telephone, radio, e-mail and/or fax) should be identified. To be effective, clear instructions for dealing with emergencies should be formally established and generally available.

10.1.4 Notification of an incident

The incident could be detected by operators at a pipeline control centre or be notified by a third party through the observation of some abnormal condition on site. The control centre should be responsible for identifying the precise location of the incident, recording all details and passing the information to the emergency response team without delay. Notification should include the appropriate authorities responsible for public safety such as fire, police and transportation authorities.

10.1.5 Alerting procedure

It is the responsibility of the control centre to alert the engineer and personnel on call. The emergency procedure should clearly identify the initial action to be taken by all personnel on receiving an emergency call. Any restrictions on entering land should be included. Provision shall be made for the mobilisation of a responsible person at the site together with staff capable of assessing and dealing with the scale of the operation.

The alerting procedure should include a clearly defined safety perimeter around the incident centre into which no unauthorized persons can enter.

The alerting procedure should also include requirements to inform all concerned when normal conditions are restored.

10.1.6 Shutting down a pipeline

A clear procedure and understanding with the public authorities regarding the isolation and shutdown of the pipeline in an emergency situation should be established. It is recommended that the pipeline control centre take charge of these events in the interests of the safety of all involved.

10.1.7 Emergency equipment

Equipment to deal with the emergency shall be kept in a state of readiness at an appropriate location. Typical examples are transportation for equipment and manpower, effective communication system between control centre and the incident location, analysis equipment, fire extinguishers, protective clothing and safety devices, lighting sets and power supply, repair materials and tools.

10.1.8 Remedial action

A detailed assessment of the action to be taken in dealing with the emergency can only be established following an initial assessment at the site.

However general guidelines on the approach to be taken in the more likely situations should be indicated in the procedure, e.g. steps to be taken in dealing with an incident.

Annual reviews of emergency response plans with local authorities is often a mandated requirement and is considered a good practice in any event.

10.1.9 Pipelines with cathodic protection

If a pipeline has been severed, the cathodic protection system should be isolated and temporary bonds established if required.

10.1.10 Incident report form

Details of the incident should be written down and maintained in the files of the operator. They should be compiled and recorded on the form required by the legislative requirements of the country concerned and/or the company reporting procedure. The geographic co-ordinates (GPS) of the incident may be also recorded.

10.1.11 Emergency drills

To ensure that the emergency procedure adequately covers the requirements of the pipeline system for which it is drawn up, and to provide practice situations for personnel, it is recommended that emergency drills be carried out periodically.

10.2 Accident and damage report

If a pipeline accident occurs a thorough investigation should take place and a clear and concise report issued. The report should contain an accurate description of the conditions which pertained during the last minutes before the accident, the material involved and the consequences of the accident, such as a secondary ignition, injury to people and damage to equipment or property. It is a recommended practice that for serious incidents, a Root Cause Analysis be conducted in order to determine what should be changed to prevent a similar occurrence.

10.3 Safety management system

Consideration should be given to establishing a specialised form of safety management system, commonly referred to as a Pipeline Integrity Management System (P.I.M.S.). Such a system enables formal control of key aspects of safety management to be established and demonstrated.

An effective system typically provides detailed information, specific to the particular pipeline to cover the following subject headings.

10.3.1 Notification to authorities and consultation on routing

These are normally stipulated in the prevailing legislation and rules applying to the country the pipeline is to be installed in.

10.3.2 Design and construction

Overall design and construction practice is dictated by the relevant design standards, codes of practice and specifications acknowledged in the country concerned. In addition to these, industry and/or company standards and specifications which relate to the particular product to be transmitted are applied

10.3.3 Shutdown systems

Shutdown may be manual or automatic. Shutdown devices (e.g. emergency shutoff valves) may be actuated by a leak detection system or by sensing high flow, low pressure, or rate of decay of line pressure.

10.3.4 Operations

A control strategy is devised to control the pipeline supply within safe operating parameters. Variables incorporated into the control strategy may include:

- Pressure: to ensure that the required delivery pressure from the pipeline is maintained. Protection against excess pressure is generally not an issue, since pipelines are normally designed to withstand pressures in excess of the maximum that can be developed by the production unit. A suitable pressure relief device may be required upstream of the pipeline to provide protection against overpressure beyond the design criteria.
- Temperature: to ensure that cryogenic liquids from the storage units do not enter the pipeline system.
- Flow: to match customer demand by product flow into the pipeline.
- Product purity: to ensure any product which does not meet specification does not enter the pipeline system.

Any product disposal needed to maintain the required pipeline conditions is preferably achieved through controlled venting on the production site.

10.3.5 Control of third party interference

Measures typically employed are:

- marker posts on the pipeline route;
- distribution of “as built” drawings and information on the pipeline route to landowners, local authority planners, and other interested parties;
- similar information is also distributed to “one call” systems, a single point of contact where information on all pipelines and services can be obtained - (where applicable); and
- scheduled patrols of the pipeline by foot or aerial survey to search for unauthorised interference and to identify abnormal conditions. (See also Section 10.3.5).

10.3.6 Maintenance and inspection

A planned maintenance and remediation system (including routine patrols of the pipeline) is recommended.

Examples of typical tasks included in such programmes listed for guidance, are:

- routine testing of cathodic protection system;
- visual leak check on above-ground flanges;
- visual check for signs of unauthorised interference with the pipeline system;
- visual check for signs of land subsidence;
- visual check for any accidental damage to the system;
- visual check for any development activities in the vicinity of the pipeline;
- check that all pipeline marking devices are in place;
- visual checks for dead or burned vegetation; and
- visual checks for bubbling.

10.3.7 Major accident prevention policies and safety management systems

A document detailing the organisation and personnel, hazard identification and evaluation, operational control, management of change, planning for emergencies, monitoring performance and audit/review may be prepared (dependent upon the perceived extent and nature of the major accident hazards presented by the pipeline and local regulations and practice).

10.3.8 Emergency planning

An emergency plan is prepared so that any incident can receive effective response. This plan is specific to the parent site(s), and defines the roles of local personnel in an emergency situation. It also identifies any emergency contacts, both internal and external to the operating company. The plan is structured to be locally self-sufficient.

Personnel who could be called on to deal with an incident shall receive training appropriate to their role in such an event. Any special protective clothing and equipment that might be required is kept readily accessible and is maintained in a fit condition for use.

10.3.9 Information to the public and interested parties

Plans and documentation illustrating the route of the pipeline should be sent to the local government authority planning department, landowners and other parties who could have an interest in the pipeline (e.g. railway, mining authorities, road authorities, fire and police departments.) Where appropriate, information is also provided to the public by means of marker posts along the route of the pipeline; see also Section 4.5.

10.3.10 Land use planning

The pipeline operator can exercise some control over the land area defined by his /easement agreement. Land outside the limits of this “right of way” is not however controlled by the pipeline operator. Although adjacent property is not controlled by the pipeline operator, this does not relieve him of the responsibility to attempt to become familiar with and if practical to monitor the activities and risks associated with the activities on and the uses of the abutting properties. In other words, the operator should be a concerned neighbour.

10.3.11 Accident reporting

This is normally included in the legislative requirements of individual Member States or local authorities.

Appendix A: Typical arrangements for pipelines systems

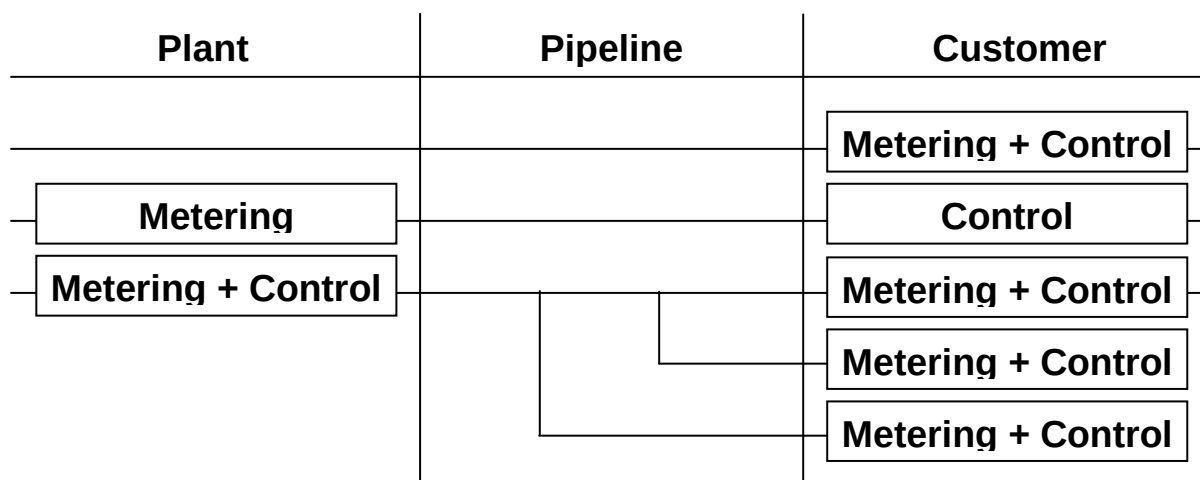


Diagram 1: Typical transmission and distribution piping systems

Note: the transmission pipeline system includes the metering/control station at the production plant, the pipeline itself and related equipment and the control/metering stations at customer site.

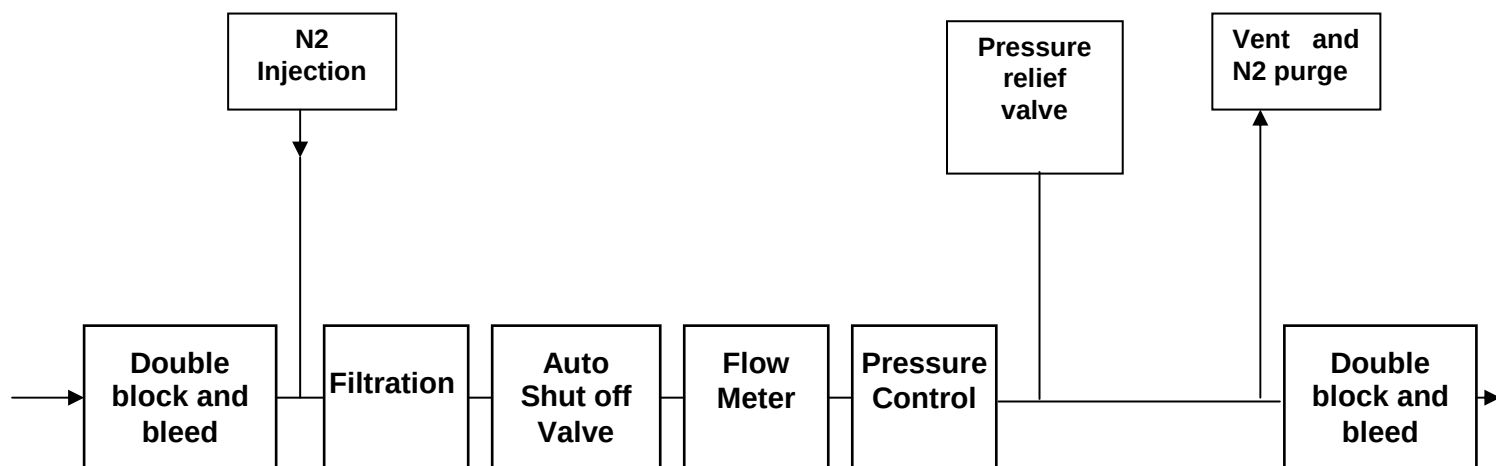


Diagram 2: Basic components of process control

Note: Items shown in Diagram 2 are not always used or required

Appendix B: Embrittlement and environmental damage mechanisms involving hydrogen and applicable test methods

B1. Introduction

There are a number of mechanisms involving hydrogen which have caused embrittlement or damage to engineering alloys. Some of these may be of concern in pipelines used for the transmission of hydrogen gas or hydrogen gas mixtures and the others are not. A brief description of the mechanisms which fall into the two categories follows. In addition, there is a brittle fracture mechanism known as stress corrosion cracking which is of concern to hydrogen pipelines but it does not necessarily involve hydrogen in the embrittlement process. A brief description of stress corrosion cracking also follows.

B2. Embrittlement or environmental damage mechanisms pertinent to hydrogen pipelines

B2.1 Hydrogen gas embrittlement

Hydrogen Gas Embrittlement (HGE) is the generic term which encompasses all of the detrimental effects which engineering alloys might experience in hydrogen gas at ambient temperatures. Some of the effects are more serious than others. Materials variables and actual service conditions will have an effect on the appearance of the various HGE modes.

A number of test methods are available to evaluate the suitability of material to resist hydrogen gas embrittlement (see ISO 11114-4 and B4 below); some make use of fracture mechanics specimens, others of tensile test or disk specimens.

In general, the degradation of the mechanical properties of materials is greatest when the strain rate is low and the hydrogen pressure and purity is high. Under the conditions most appropriate to the operation of a hydrogen gas transmission pipeline, it is generally believed to be true that the gas is dry. Fatigue is not supposed to be a problem and species which contribute to environmental aggressiveness are not supposed to be present. Nevertheless, the following have been selected as most likely to be of concern in hydrogen pipelines:

B2.1.1 Hydrogen stress cracking (HSC)

Hydrogen stress cracking describes a phenomenon which resembles stress corrosion cracking but occurs in hydrogen gas. In the presence of hydrogen gas (or another gas bearing hydrogen) a material can become brittle and may fail if the stress level is too high. This phenomenon is optimum around room temperature for usual metallic materials such as ferritic steels. It does not apply for steels above 150 °C but could then be replaced at high temperature by “hydrogen attack” (see reference Interaction of steels with Hydrogen in petroleum industry pressure vessel service, Paris 89). It also tends to be negligible at cryogenic temperature except for some unstable austenitic stainless steels.

If “pre-cracked” fracture toughness tests of selected materials are compared in an inert atmosphere vs an embrittling agent such as hydrogen, susceptible materials will show a reduction in the fracture toughness parameter in environments such as hydrogen. The extent of the property loss is a function of alloy and environmental factors. The major benefit of such tests and results is that analytical techniques exist for determining critical flaw sizes in engineering structures which can be detected via NDT techniques. For a given alloy and environment, a critical stress intensity (typically called K_H) can be determined below which hydrogen induced crack growth will not occur. Another benefit of such data is that it can be used to identify the conditions under which “leak before break” fracture will exist vs catastrophic running fractures. The other test methods define sometimes a maximum embrittlement index for the acceptance of materials.

Non-destructive inspection techniques can be used to determine if unacceptable flaws are present. Local imperfections can act as a stress raiser.

Susceptible materials may, in presence of tensile stresses either residual or directly applied, develop cracks in hydrogen gas environments. Material variables which affect the susceptibility of engineering alloys include alloy chemistry, microstructure, hardness and strength level. Hydrogen variables at ambient temperature which are significant include impurities and pressure.

Manufacturing or heat treatment procedures which eliminate residual tensile stresses, mitigate HSC. In the case of carbon or low alloy steels such treatments may soften weld heat affected zones and temper martensite which may be present in such areas. Prudent alloy selection including the specification of maximum strength levels or alloy heat treatment can be used to eliminate or mitigate the problem.

It should be noted that certain nickel alloys may be subject to this phenomenon.

Hydrogen stress cracking is characterized by the brittle fracture of a normally ductile alloy under sustained load in the presence of hydrogen. Most often, fracture occurs at sustained loads below the yield strength of the material. This cracking mechanism depends on the hydrogen fugacity, strength level of the material, heat treatment/microstructure, applied stress, and temperature. For many steels, a threshold stress exists below which hydrogen stress cracking does not occur. This threshold is a function of the strength level of the steel and the specific hydrogen-bearing environment. Therefore, threshold stress or stress intensity for hydrogen stress cracking is not considered a material property. Generally, the threshold stress decreases as the yield strength and tensile strength of an alloy increase. Hydrogen stress cracking is associated with absorption of hydrogen and a delayed time to failure (incubation time) during which hydrogen diffuses into regions of high triaxial stress. Hydrogen stress cracking may promote one mode of fracture in an alloy rather than another form normally observed in benign environments. Thus, all modes of cracking have been observed in most commercial alloy systems; however, hydrogen stress cracking usually produces sharp singular cracks in contrast to the extensive branching observed in HSC.

B2.1.2 Reduction of tensile ductility and notched tensile strength in hydrogen gas

Hydrogen gas will reduce the tensile strength/ductility and notched tensile strength of susceptible materials in high pressure environments. The effect can be determined by conducting tensile tests of candidate materials in dry air or inert gas comparing the results of similar tests conducted in a hydrogen environment. Premature failures of burst discs have been attributed to this phenomenon.

B2.1.3 Hydrogen assisted fatigue

Acceleration of fatigue crack growth and degradation in fatigue endurance limits have been observed in tests of susceptible materials via both pre-cracked specimens and smooth specimens in dry hydrogen gas environments. Carbon and low alloy steels show such degradation even at relatively low pressures in hydrogen gas. This is a mechanism which should be considered, preferably avoided if possible, in such applications. Since pipelines normally operate at near constant pressure, fatigue cracking is usually not a concern.

Tests have been conducted at pressures up to 45 MPa (7000 psig) under both static and dynamic conditions. Stable austenitic stainless steels generally show little environmental damage in such tests. However susceptible materials including metastable austenitic stainless steels, ferritic stainless steels, martensitic stainless steels and carbon/low alloy steels show some degradation in tensile strength ductility and notch tensile strength, this effect being dependent upon alloy strength level, heat treatment and hydrogen pressure.

Acceleration of fatigue crack growth and degradation in fatigue endurance limits have been observed in tests of susceptible materials via both pre-cracked specimens and smooth specimens in dry hydrogen gas environments. Carbon and low alloy steels show such degradation even at relatively low pressures in hydrogen gas. The accelerated fatigue crack growth is more pronounced at ambient temperatures and becomes less severe at elevated temperatures. The presence of hydrogen reduces the threshold cyclic stress intensity factor (ΔK_{th}) as well as fatigue life. The degradation of fatigue properties is attributed to the reduction in crack tip ductility in presence of hydrogen. Despite the supposed absence of fatigue conditions in pipelines, fatigue may be a problem in some cases.

B2.2 Stress corrosion cracking (SCC) of line pipe steel in underground environments

Stress cracking of carbon/low alloy steel line pipe in underground environments from both anodic stress corrosion and/or hydrogen stress cracking mechanisms has been reported. This is usually an external corrosion phenomenon and is not influenced by the hydrogen gas being transported. The presence of residual or directly applied tensile stresses, the presence of a susceptible environment and susceptible metals are required for the mechanism. Factors which contribute to stress cracking, in addition to the preceding, may be hard spots, untempered martensite in weld areas, coating defects, microbiological activity and inadequate or improper cathodic protection schemes. Careful alloy selection, controlled alloy chemistries and controls over manufacturing processes will help mitigate this problem.

Stress corrosion cracking is an electrochemical process with distinct anodic and cathodic reactions. Corrosion specialists generally recognize true stress corrosion cracking as a mechanism in which cracking is controlled by the anodic reaction and consider cracking which is controlled by the cathodic reaction as a form of hydrogen embrittlement. Poor cathodic protection practices could contribute to the embrittlement mechanism. Outside of the laboratory, it may be difficult to discern the differences between the two cracking mechanisms.

B3. Brittle fracture or damage mechanisms not pertinent to hydrogen pipelines

As a consequence of operating conditions such as elevated temperatures, specific contaminants not normally associated with hydrogen pipelines and the specificity of materials involved, there are brittle fracture or damage mechanisms which are not pertinent to hydrogen pipelines. A brief description of these follows:

B3.1 Elevated temperature environmental effects on ferrous alloys

Hydrogen attack is frequently used inappropriately to describe hydrogen embrittlement mechanisms in line pipe steels because it occurs far above normal service temperatures of a hydrogen linepipe and is strictly an elevated temperature degradation mechanism.

Hydrogen attack and decarburization are the two common damage mechanisms encountered by carbon or low alloy steels involving hydrogen at elevated temperatures. "Hydrogen attack" of a carbon steel or low alloy steel is a mode by which carbon reacts with hydrogen to form methane which results in crack formation. "Decarburization" of a carbon or low alloy steel may also occur in hydrogen atmospheres. Austenitic stainless steels are considered immune to decarburization and hydrogen attack.

The "Nelson Chart" shows operating limits for carbon and low alloy steels in hydrogen atmospheres at elevated temperature and pressures. It should be noted that the Nelson Chart is only pertinent to the two mechanisms previously cited and not to other damage mechanisms involving hydrogen (see for example reference API 941).

B3.2 Elevated temperature effects on cuprous alloys

Cuprous alloys are subject to a special form of hydrogen attack at elevated temperatures. If the alloy is not deoxidized, hydrogen will react with cuprous oxide to form water. Subsequently, grain boundaries will fissure. Properly deoxidized copper alloys are not susceptible.

B3.3 Hydrogen blistering

Hydrogen blistering is not pertinent because it requires the presence of acidic electrolyte in substantial amounts. In this mechanism, steels exposed to acid electrolyte absorb large quantities of hydrogen at local cathodes and subsequently fissure and blister.

B3.4 Sulfide stress cracking (SSC)

This is a subset of hydrogen embrittlement in which the cathodic reaction controls the cracking reaction. However, SSC occurs in water within certain ranges of hydrogen sulfide content. Certain oilfield environments and “sour” natural gas are associated with the cracking mechanism.

Consequently, if sour natural gases are mixed with hydrogen gas, this cracking mechanism would be of concern.

B3.5 Hydrogen induced cracking (HIC)

HIC is a degradation mode which generally occurs in sour wet gas service. In this mode of environmental damage, atomic hydrogen formed during the corrosion process is trapped in microscopic voids around nonmetallic inclusions. Usually, these are of the manganese sulfide type. High gas pressure trapped around the inclusion can generate highly localized stresses which may initiate crack nuclei parallel to the rolling direction of the material. As crack nuclei link up, stepwise cracks will develop and cause failure. HIC is sometimes referred to as “stepwise cracking”.

B3.6 Hydride formation

The degradation of mechanical properties and cracking is due to the precipitation of metal hydride phases. The most susceptible materials are titanium, magnesium and niobium alloys. The applied stress may promote the formation of hydride in some alloy systems.

B4 Pertinent test methods

Generally, two sources of hydrogen contribute to the embrittlement: environmental gaseous hydrogen and electrochemical reaction generated hydrogen. Experiments are designed according to the operating conditions to evaluate the susceptibility of hydrogen embrittlement. Hydrogen environments may affect every aspect of mechanical properties such as tensile strength, elongation, fatigue life, fatigue crack growth rate and fracture toughness. The attributes of the mechanical properties can be evaluated by conducting the pertinent experiments in the desired hydrogen environment or on hydrogen precharged specimens.

Several test methods were developed over the past years. Standard test methods appropriate for hydrogen embrittlement in gaseous hydrogen exist. Since hydrogen embrittlement and stress corrosion cracking share many common features, the tests to evaluate materials resistance to SCC can also be applied to study materials' behavior in hydrogen environment. Typical tests for hydrogen embrittlement are described as follows:

B4.1 Tensile and notched tensile properties

The susceptibility of metals to hydrogen embrittlement can be evaluated by conducting tensile tests on smooth or notched specimens in hydrogen environment at different pressures. The test method is described in ASTM G 142-98 “Standard Test Method for Determination of Susceptibility of Metals to Embrittlement in Hydrogen Containing Environments at High Pressure, High Temperature, or Both”.

B4.2 K_{IH} test

K_{IH} test is a fracture mechanics test to evaluate the threshold stress intensity factor for hydrogen stress cracking. In K_{IH} test, a pre-cracked specimen is loaded in tension and in gaseous hydrogen environment. The minimum applied stress intensity factor that can cause crack propagation (K_{IH}) can be used to evaluate the resistance to hydrogen assisted cracking. There are various ASTM or ISO test procedures that can be modified for these tests.

B4.3 Slow strain rate (SSR) test

Since the hydrogen attack is a time dependent process, a slow strain rate test can be employed to evaluate the strain rate sensitivity of the materials in hydrogen environment. In the slow strain rate test, the test is conducted at strain rates as low as 10^{-7} . The test can be done in hydrogen

environments or specimen can be pre-charged with hydrogen and subsequently tested in air or hydrogen. A general procedure of SSR tests is described in ASTM G129-00 "Standard Practice for Slow Strain Rate Testing to Evaluate the Susceptibility of Metallic Materials to Environmentally Assisted Cracking".

B4.4 Disk pressure test

Disk pressure test measures susceptibility to hydrogen embrittlement of metallic materials under high pressure hydrogen. A thin disk sample is placed as a membrane in a test cell is subject to high pressure helium and hydrogen. The ratio between the helium burst pressure and the hydrogen burst pressure indicates the susceptibility of the material to environmental hydrogen embrittlement. A standard test procedure has been established as ASTM F1459 "Standard Test Method for Determination of the Susceptibility of Metallic Materials to Gaseous Hydrogen Embrittlement".

Appendix C: Table of nominal alloy compositions and ranges

MATERIAL TYPE OR ALLOY	EN-MAT.NO. (7)	UNS NO. (8)	NOMINAL COMPOSITION RANGE
Carbon Steels, Pipe			
ASTM A53, Type S Grade A		K02504	C, Mn, Bal. Fe
ASTM A53, Type S Grade B		K03005	C, Mn, Bal. Fe
ASTM A106, Grade A		K02501	C, Mn, Bal. Fe
ASTM A106, Grade B		K03006	C, Mn, Bal. Fe
ASTM A333, Grade 1 ⁽¹⁾		K03008	C, Mn, Bal. Fe
ASTM A333, Grade 6 ⁽¹⁾		K03006	C, Mn, Bal. Fe
API 5L Grade A PSL1			C, Mn, Bal. Fe
API 5L Grade B PSL1 and PSL2 ⁽¹⁾			C, Mn, Bal. Fe
API 5L Grade X42 PSL1 and PSL2 ⁽¹⁾			C, Mn, Bal. Fe
API 5L Grade X46 PSL1 and PSL2 ⁽¹⁾			C, Mn, Bal. Fe
API 5L Grade X52 PSL1 and PSL2 ⁽¹⁾			C, Mn, Bal. Fe
NF A 49-211 TUE 220 b2			C, Mn, Bal. Fe
NF A 49-211 TUE 250 b2			C, Mn, Bal. Fe
NF A 49-400 TSE 220 cl. II			C, Mn, Bal. Fe
NF A 49-400 TUE 250 cl. II			C, Mn, Bal. Fe
L245 NB	1.0457		C, Mn, Bal. Fe
L245 MB	1.0418		C, Mn, Bal. Fe
L290 NB	1.0484		C, Mn, Bal. Fe
L290 MB	1.0429		C, Mn, Bal. Fe
L360 NB	1.0582		C, Mn, Bal. Fe
L360 MB	1.0572		C, Mn, Bal. Fe
P265 NL	1.0453		C, Mn, Bal. Fe
P275 NL1	1.0488		C, Mn, Bal. Fe
P355 NL1	1.0566		C, Mn, Bal. Fe
CSA Z245.1-98, 207 Categories. I, II ⁽¹⁾ , III ⁽¹⁾			C, Mn, Bal. Fe
CSA Z245.1-98, 241 Categories. I, II ⁽¹⁾ , III ⁽¹⁾			C, Mn, Bal. Fe
CSA Z245.1-98, 290 Categories. I, II ⁽¹⁾ , III ⁽¹⁾			C, Mn, Bal. Fe
CSA Z245.1-98, 317 Categories. I, II ⁽¹⁾ , III ⁽¹⁾			C, Mn, Bal. Fe
CSA Z245.1-98, 359 Categories. I, II ⁽¹⁾ , III ⁽¹⁾			C, Mn, Bal. Fe
Carbon Steels, Other Mill Forms			
ASTM A105 (Forging)		K03504	C, Mn, Bal. Fe
ASTM A234 Grade WPB (Fitting)		K03006	C, Mn, Bal. Fe
ASTM A334 Grade 1 (Tube) ⁽¹⁾		K03008	C, Mn, Bal. Fe
ASTM A334 Grade 6 (Tube) ⁽¹⁾		K03006	C, Mn, Bal. Fe
ASTM A350 Grade LF2 (Forging) ⁽¹⁾		K03003	C, Mn, Bal. Fe
ASTM A352 Grade LCB (Casting) ⁽¹⁾		K03011	C, Mn, Bal. Fe
ASTM A352 Grade LCL (Casting) ⁽¹⁾			C, Mn, Bal. Fe
ASTM A420 Grade WPL6 (Fitting) ⁽¹⁾			C, Mn, Bal. Fe
ASTM A516 Grade 55 (Plate) ⁽¹⁾		K01800	C, Mn, Bal. Fe
ASTM A516 Grade 60 (Plate) ⁽¹⁾		K02100	C, Mn, Bal. Fe
ASTM A516 Grade 65 (Plate) ⁽¹⁾		K02403	C, Mn, Bal. Fe
ASTM A516 Grade 70 (Plate) ⁽¹⁾		K02700	C, Mn, Bal. Fe

Appendix C: Table of nominal alloy compositions and ranges (Cont'd)

MATERIAL TYPE OR ALLOY	EN-MAT.NO.(7)	UNS NO.	NOMINAL COMPOSITION RANGE
Carbon Steels, Other Mill Forms (Cont'd)			
NF E 29-204 BF 42N			C, Mn, Bal. Fe
NF E 29-204 BF 48N			C, Mn, Bal. Fe
NF E 29-204 BF 48F			C, Mn, Bal. Fe
NF A 49-218 AE 220			C, Mn, Bal. Fe
NF A 49-218 AE 250			C, Mn, Bal. Fe
NF A 49-218 AE 275B			C, Mn, Bal. Fe
C22.8 (Forging)	1.0460		C, Mn, Bal. Fe
P355 NH (Forging)	1.0565		C, Mn, Bal. Fe
GP240 GH (Casting)	1.0619		C, Mn, Bal. Fe
GS-38 (Casting)	1.0420		C, Mn, Bal. Fe
GS-45 (Casting)	1.0446		C, Mn, Bal. Fe
G20Mn5 (Casting)	1.6220		C, Mn, Bal. Fe
P265 GH (Plate)	1.0425		C, Mn, Bal. Fe
P355 NH (Plate)	1.0565		C, Mn, Bal. Fe
P355 NL1 (Plate)	1.0566		C, Mn, Bal. Fe
Cobalt Alloys			
Stellite 6	Stellite 6	R30006	55.5Co, 29Cr, 4.5W, 3Ni, 1C, 7 (Fe, Si, Mn, Mo)
Stellite 6B	Stellite 6B	R30016	53Co, 30Cr, 4.5W, 3Ni, 1C, 8.5 (Fe, Si, Mn, Mo)
Copper and Copper Alloys			
Brass	2.0380	Various	55-85 Cu, 15-44 Zn, 1-3 (Sn, Pb, Fe, Al)
Copper	2.0090	C10100 C10200	99.9+Cu
Copper-Nickel Alloys	2.0882	C70600 C71500	67-87 Cu, 10-31 Ni, 1-2 (Fe, Mn, Zn)
Tin Bronzes	2.1080	Various	85-89Cu, 5-11Sn, 5-10 (Zn, Pb, Ni)
Ferrous Castings (Non- Stainless)			
Gray Cast Iron	0.6030	F12801	3C, 2Si, 0.8Mn, Bal. Fe
Nodular Cast Iron	0.7040	F32800	3.6C, 2.7Si, 0.4Mn, Bal. Fe
Ni Resist Type D2	0.7673	F43010	20Ni, 3C, 2Si, 2Cr, 1Mn, Bal. Fe
Ferrous Castings, (Stainless)			
CF-3 ⁽²⁾	1.4308	J92500	19.5Cr, 10Ni, 2Si, 1.5Mn, Bal. Fe
CF-8 ⁽²⁾	1.4308	J92600	19.5Cr, 10Ni, 2Si, 1.5Mn, Bal. Fe
CF-3M ⁽³⁾	1.4408	J92800	19Cr, 11Ni, 3Mo, 1.5Si, 1.5Mn, Bal. Fe
CF-8M ⁽³⁾	1.4408	J92900	19Cr, 11Ni, 3Mo, 1.5Si, 1.5Mn, Bal. Fe
CG-8M ⁽⁴⁾	1.4439	J93000	20Cr, 12Ni, 3Mo, 1.5Si, Bal. Fe
CN-7M ⁽⁵⁾		N08007	21Cr, 29Ni, 4Cu, 3Mo, 1.5Si, 1.5Mn, Bal. Fe
Low Alloy Steels, (C-Mo)&(C-Cr-Mo)			
ASTM A335, Grade P1		K11522	C, 0.5Mo, Bal. Fe
ASTM A335, Grade P2		K11547	C, 0.65Cr, 0.5Mo, Bal. Fe
ASTM A335, Grade P12		K11562	C, 1.0Cr, 0.5Mo, Bal. Fe
ASTM A335, Grade P11		K11597	C, 1.25Cr, 0.5Mo, Bal. Fe
ASTM A335, Grade P22		K21590	C, 2.25Cr, 1.0Mo, Bal. Fe

Appendix C : Table of nominal alloy compositions and ranges (Cont'd)

MATERIAL TYPE OR ALLOY	EN-MAT.NO.	UNS NO.	NOMINAL COMPOSITION RANGE
Nickel Alloys			
Monel K-500 ⁽⁶⁾	2.4375	N05500	66.5Ni, 30Cu, 3(Al, Ti)
Incoloy 800		N08800	33Ni, 21Cr, Bal. Fe
Incoloy 800H		N08810	33Ni, 21Cr, Bal. Fe
Incoloy 800HT		N08811	33Ni, 21Cr, Bal. Fe
Incoloy 825		N08825	42Ni, 21.5Cr, 3Mo, 1Ti, Bal. Fe
Hastelloy	2.4819	N10276	56Ni, 12Cr, 13.5Mo, 4Fe, 3W, 2.5Co
Inconel 600	2.4816	N06600	76Ni, 15Cr, 9Fe
Inconel 625	2.4856	N06625	60Ni, 22Cr, 9Mo, 5Fe, 4Nb
Inconel X-750 ⁽⁶⁾	2.4669	N07750	74Ni, 15.5Cr, 7Fe, 2.5Ti, 1Al
Stainless Steels, Wrought			
304	1.4301/1.4306	S30400	19Cr, 9Ni, 2Mn, 1Si, Bal. Fe
304L	1.4301/1.4306	S30403	19Cr, 9Ni, 2Mn, 1Si, Bal. Fe
316	1.4401/1.4404	S31600	17Cr, 12Ni, 2Mn, 3Mo, 1Si, Bal. Fe
316L	1.4401/1.4404	S31603	17Cr, 12Ni, 2Mn, 3Mo, 1Si, Bal. Fe
316Ti	1.4401/1.4404	S31635	17Cr, 12Ni, 2Mn, 3Mo, 1Si, Ti 5xC min., Bal. Fe
321	1.4541	S32100	18Cr, 11.5Ni, Ti 5XC min., Bal. Fe
347	1.4550	S34700	18Cr, 11.5Ni, Nb 8XC min., Bal. Fe
410	1.4006/1.4024	S41000	13Cr, 1Mn, 1Si, Bal. Fe
430	1.4016/1.4742	S43000	17Cr, 1Mn, 1Si, Bal. Fe
17- 4PH H1150/H1150M Tempers ⁽⁶⁾	1.4542/1.4548	S17400	17Cr, 4Ni, 4Cu, 1Si, Bal. Fe
X3 Ni Cr Mo 13-4	1.4313	S41500	13Cr, 4.5Ni, 1Mo, 1Si, Bal. Fe
Carpenter 20 Cb-3	2.4660	N08020	35Ni, 20Cr, 3.5Cu, 2.5Mo, Bal. Fe

Notes :

- (1) Toughness testing required by specification or PSL2 requirement
- (2) Cast Analogs of 304L/304 stainless steel
- (3) Cast Analogs of 316L/316 stainless steels
- (4) Cast Analog of 317 stainless steel
- (5) Alloy 20
- (6) Age Hardened Condition, lower strength temper or hardness limits imposed
- (7) EN-MAT.N°:the method to give a number for materials is given in the European standard EN 10027-2 "Designation systems for steel Part 2 Numerical system
- (8) UNS: Metals and Alloys in the UNIFIED NUMBERING SYSTEM, Society of Automotive Engineers, Warrendale, PA, 9th Edition, 2001.

Appendix D: Metallurgical factors affecting hydrogen toughness and brittle fracture mechanisms

D1. Introduction

It is generally acknowledged that engineering alloys used in the transmission of high pressure gas via pipelines shall have adequate toughness. In addition, it is also acknowledged that hydrogen gas may embrittle and adversely affect the toughness of many engineering alloys. Gas parameters that may affect toughness and related properties include factors such as hydrogen purity, gas composition, temperature and pressure. In addition, there are metallurgical factors which also play an important role. This section will briefly touch on the metallurgical factors which are considered significant in hydrogen embrittlement.

D2. Crystal structure

The major engineering alloys have crystal structures which are face centred cubic (FCC), body centred cubic (BCC) and hexagonal closed-packed (HCP). Under certain conditions such as rapid quenching and welding, suppressed allotropic transformation will result in the formation of martensite, a body centred tetragonal lattice. Strain induced martensite is also possible. Generally, the highest toughness is achieved with FCC structures followed by BCC and HCP. The most common used alloys for the transmission of high pressure gas are carbon steels which have a BCC structure. Also, while nickel alloys generally have FCC structure, some of them are subject to embrittlement in H₂.

D3. Key metallurgical controls

Key metallurgical controls or techniques which impact toughness and play a role in line pipe steels are as follows:

- controls on alloy chemistry;
- inclusion shape control additives;
- fine grained microstructures;
- use of killed steels;
- low or reduced carbon equivalents; and
- microalloying.

It should be noted that some of the above fall in more than one category and are related in terms of the effects on toughness.

D4. Controls on alloy chemistry

The effects of sulfur and phosphorus contents on the toughness of steel have been known for some time. Elements such as sulfur, phosphorus, antimony, tin and arsenic and their compounds also have been found to inhibit the hydrogen recombination reaction, thus increasing the charging of atomic hydrogen into the alloy.

Sulfur is usually present in the form of elongated sulfide inclusions. High concentrations of sulfide inclusions reduce toughness particularly in the transverse direction of pipes or plates. With modern steel making processes, maximum sulfur levels of 0.01% are feasible and desirable for high toughness wrought mill forms.

Phosphorus has a deleterious effect on toughness. It raises the impact transition temperature by as much as 8 °C (15 °F) for each increase of 0.01%P. A maximum level of 0.015% P is recommended.

Carbon and manganese levels are very important in carbon steels. A Mn:C ratio of at least 3:1 is desirable. Mn tends to reduce the impact transition temperature while C will raise it. However, high Mn:C ratios when carbon levels are high may cause problems with hardenability and weldability.

D5. Sulfide shape control

The detrimental effect of sulfide inclusions is primarily due to their shapes which are elongated with sharp ends and akin to cracks. Additions of species such as rare earth elements or calcium can modify the sulfide shape to produce sulfide inclusions with globular shapes which do not reduce toughness. Sulfide shape control technology can be used in conjunction with reduced maximum sulfur levels.

D6. Killed steels

Control of residual oxygen by utilizing “killing” agents or deoxidizers will improve toughness. Aluminium killing has the additional advantage of forming aluminium nitrides which contribute to forming fine grained microstructures. Silicon and reactive metals such as vanadium, titanium etc. may also be used to kill or deoxidize steels.

D7. Microstructure and effects of fine grained microstructure

Martensitic, normalized and hot formed microstructures are used in mill forms of carbon and low alloy steels. Quench and tempered martensite generally has the highest toughness and this is followed by fine grained normalized microstructure. In linepipe, quench and tempered martensite structures are relatively rare. Normalized and hot formed microstructures are commonly encountered. When high toughness is needed, normalizing is the most usual approach for linepipe. Normalizing produces a uniform fine grained microstructure when done properly. A change in the microstructure of one ASTM grain size can shift the ductile to brittle transition temperature by approximately 10-15°C.

Thermomechanical processing typically used in the manufacture of ERW microalloyed linepipe is another technique for obtaining fine grained microstructure. The toughness of such steels greatly exceeds that of linepipe steels produced by traditional carbon steel processing techniques.

D8. Control of carbon equivalent

Welding is a necessary consideration in the fabrication of high pressure industrial gas pipelines. In conventional carbon steel metallurgy, carbon and manganese are the major elements responsible for developing necessary strength properties but other elements such as Cr, Mo, Ni, Cu etc. will also contribute.

The major problem is that as the levels of alloying elements increase, the hardenability increases and so does the potential for forming hard and brittle untempered martensite after welding. The presence of brittle untempered martensite can lead to microcracks and increase susceptibility to failure mechanisms involving hydrogen.

One method of control is to place limitations on chemistry for pipelines or component steels by the carbon equivalent approach. There are various carbon equivalent formulas but the most common carbon equivalent (C.E.) formula in use today is:

$$CE = \%C + \frac{\%Mn}{6} + \frac{\%Cr + \%Mo + \%V}{5} + \frac{\%Ni + \%Cu}{15}$$

In older references, a carbon equivalent of 0.55 maximum was considered to be the limit for steels such as API 5L X52 in hydrogen service. More recently, a maximum carbon equivalent of 0.43 has been cited as the maximum allowable for pipelines, but special cases may require lower carbon equivalent levels.

With respect to the newer microalloyed steels with low carbon contents, alternative carbon equivalent formulas may be utilized. For steels with low carbon contents or carbon equivalents equal to or less

than 0.12%, the composition parameter P_{cm} , has been found to be a better indicator of crack susceptibility. This parameter developed by Ito-Bessyo is as follows:

$$P_{cm} = \%C + (\%Mn + \%Si + \%Cu + \%Co) / 20 + \%Ni / 60 + \%Mo / 15 + \%V / 10 + 5 \%B$$

The acceptable limit is 0.20% maximum.

D9. Weld heat affected zone (HAZ) Hardness

Controls over the weld and weld heat affected zone hardness can be improved to eliminate or minimize the presence of hard brittle untempered martensite. Both weld procedure and weld operator qualification can be controlled with respect to weld and HAZ hardness. The most common hardness limitation is a level of Rockwell C 22 which is equivalent to Vickers 248. Typically, mounted weld samples are tested using microhardness techniques. The hardness limitation has been applied to pipe parent metal in sour gas services and it is applicable to hydrogen service also.

D10. Pre and post weld stress relief

One option for controlling weld HAZ hardness when welding steels which may be susceptible to HAZ martensite formation is through modification of the welding process. Pre weld heat thermal treatment helps prevent martensite formation while post weld heat treatment will temper any martensite and stress relieve the HAZ simultaneously. Generally, pre and post weld heat treatments have added costs and the preferred approach is to place limitations on alloy chemistry.

In regard to an assessment of austenite stability and microstructural constituents, some familiarity with the following parameters may be needed:

- 1) Stability factor (Δ)
- 2) Austenite transformation factors (M_s , M_d30)
- 3) Chromium equivalent, C_{req}
- 4) Nickel Equivalent, N_{ieq}

The parameters are defined in an earlier section but Peckner and Bernstein's "Handbook of Stainless Steels"[?] is recommended as a reference for additional background.

D11. Metastable austenitic stainless steels

Austenitic stainless steels have excellent toughness and resistance to environmental damage for mechanisms involving hydrogen. In certain austenitic stainless steels such as 201, 301, 302, 304, 304L and 321, the austenite is metastable and may transform to martensite when strained, particularly, when temperature is reduced. The presence of strain induced martensite in excessive amount is detrimental; increases in magnetism in cold worked or strain hardened metastable austenitic steels may be due to the presence of strain induced martensite or delta ferrite.

The problems with metastable austenitic stainless steels are not likely to be severe at low hydrogen pressure but might be of concern at high pressures. A solution for high pressure is to select austenitic stainless steels with high austenite stability, e.g., 316 or 316L.

D12. Strength level

In low strength carbon steels, hydrogen damage occurs predominantly by loss in tensile ductility or blistering. Low strength steels usually fail in a ductile mode in hydrogen environment. Higher strength carbon steels are prone to hydrogen embrittlement and usually fracture in a brittle mode. At the same strength level, a quenched and tempered fine grain microstructure is more resistance to hydrogen cracking than the normalized microstructure.

The susceptibility of stainless steels to hydrogen embrittlement is also dependent on the strength level. Ferritic stainless steels are resistant to hydrogen embrittlement at low strength levels. Austenitic stainless steels are highly resistant or immune to hydrogen cracking in the annealed or lightly cold worked condition. Martensitic and precipitation hardening stainless steels are extremely susceptible to

hydrogen embrittlement with increasing yield strength. The lower strength tempers of precipitation hardening steels are preferred for hydrogen services.

D13. Microalloyed steels

A major development in the area of linepipe has been the introduction of microalloyed steels; particularly, in ERW pipe. Microalloying refers to the use of small amounts of alloying elements which produce an effect generally very significant and seemingly out of proportion to the amount added. Examples of microalloying agents include: Nb, V, Ti, rare earth elements and Ca.

The use of microalloyed steels coupled with the special thermal mechanical processing results in steels with very fine grained microstructures, exceptional toughness and weldability due to low carbon equivalent. The high strength and low carbon equivalent combinations are superior to conventional carbon steels with carbon and manganese as the major alloying elements.

The major microalloying element used in ERW linepipe is Nb. Ca addition may be made for sulfide shape control. V is usually the major microalloying agent in seamless weld pipe. Specification API 5L places controls on the total amount of major elements typically used in microalloyed steel linepipe.

It is very possible that many users of line pipes are using microalloyed steels and are unaware of this.

D14. Welding

There have been references to welding in previous portions of this section. Welding is extremely critical. The welding process should produce defect free welds and weld heat affected zones which match the mechanical and toughness properties of the linepipe being joined. It is important that hardness levels in the weld and weld heat affected zone be controlled to avoid hard spots. Weld filler metals, weld process qualification, weld operator qualification, mechanical tests, metallographic techniques and NDT techniques all play a role in ensuring that the fabricated pipeline has adequate toughness for hydrogen applications.

Appendix E: Table of typical safety distances for hydrogen control and isolating / metering Stations

Nature of exposure	All hydrogen stations
Above ground pipeline (flammable fluid, oxygen)	Minimum 3m*
Buried Tank (flammable fluid)	Minimum 3m*
Vent or fill openings of buried tank (flammable fluid)	8m
Pressure vessel, (non-flammable fluid) with $P \times V > 200 \text{ bar.m}^3$ water capacity ($P \times V > 100000 \text{ psi.ft}^3$)	Minimum 3m*
Flammable product storage (above ground)	Minimum 3m*
Liquid hydrogen storage, liquid oxygen storage	Minimum 3 m*
Compressor intakes	15m
Transformer station	15m
Administrative Building with openings or air conditioning intake owned by customer	15m
Public Building	8m (note 1)
Public road/railway/car park	5m (note 1)
Internal road/ railway	5m
High tension electric cable (above ground)	15m
Boundary of user's property	5m (note 1)
Internal car park	5m
Flame and/or spark producing activities	5m

* : The distance of 3m is a minimum, it may be increased depending on the size of the concerned vessel, storage and hydrogen station. The chosen value should take into account Note 1 below.

Notes:

1. The actual minimum safety distances to be observed shall be determined through a risk analysis taking into account the whole of the environmental parameters.
2. The safety distances given in this table may be reduced by using properly designed barriers in accordance with applicable codes
3. Hydrogen stations should not be beneath high tension cables without protection.
4. Avoid any roof on a hydrogen station or install adequate openings to ensure sufficient ventilation and prevent from gas accumulation.

APPENDIX F: Example of preventive maintenance program for hydrogen pipelines

Note: Intervals shown are only examples and do not reflect required or universal practice.

a. Pipeline systems

		Checking interval						
Underground pipelines		1 Month	3 Months	6 Months	1 Year	3 Year	5 Year	When required
	Pipeline patrol		X					
	Pipeline patrol in critical area	X						
	On-foot servicing inspection				X			
	Pipeline risers and casing inspection			X				
	Effect of mining (subsidence)					X		
Above ground pipelines								
	Pipeline patrol and servicing			X				
	Pipe bridges – inspection and painting				X			
	Supports and anchorages						X	
	Inner pipeline inspection							X

b. Cathodic protection

		Checking interval						
		1 Month	3 Months	6 Months	1 Year	3 Year	5 Year	When required
	Drainage stations	X						
	Impressed current stations	X						
	Protection devices against AC	X						
	Pipe/ground DC potential, on/off			X				
	Pipe/ground AC potential and current			X				
	Earths, anodes, connections fuses, spark gaps			X				
	Insulating joints			X				
	Overall CP effectiveness				X			
	Coating defect detection in sensitive areas						X	
	Comprehensive system audit							X

c. Checking of stations

		Checking interval						
		1 Month	3 Months	6 Months	1 Year	3 Year	5 Year	When required
	General tightness			X				
	Telecommunication system				X			
	Record measurements gas detector				X			
	Emergency shut-off valve				X			
	Valves, control valves, etc.				X			
	Cleaning filter				X			
	Safety valve					X		
	Cleaning and repainting piping					X		
	Calibration flow meters						X	

APPENDIX G: Composition criteria for hydrogen and hydrogen mixtures

This document specifically refers to carbon monoxide and syngas as defined below:

State: Gas

Components (molar):

Water: less than 20 PPM (dew point @ 1 atmosphere = -55°C(-67°F))

Inerts and / or methane (natural gas): balance

CO₂: less than 100 PPM

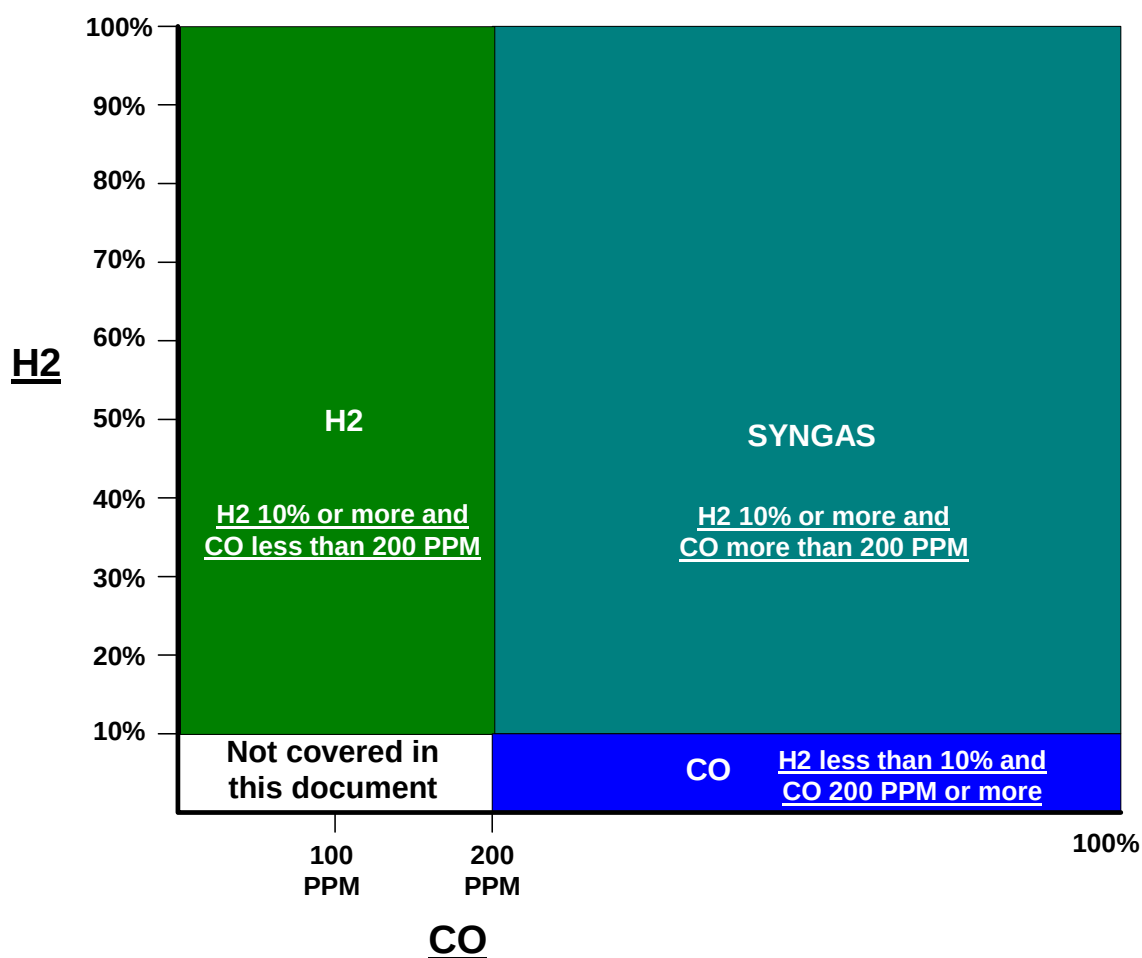
H₂ and CO per Classification of H₂ / CO Mixtures diagram

Other components: negligible

It is important to note that moisture is a critical contaminant in this context and this document should not be used for mixtures in which condensation of moisture may be expected to occur.

See the EIGA Doc 120 on Carbon monoxide and SYNGAS pipeline systems

Classification of Gas Mixtures Containing H₂ and / or CO



Appendix H: Requalification of existing pipelines for hydrogen service

The following illustrates some of the more important recommended procedures to be carried out in order to qualify an existing pipeline presently used in another fluid service. It is recommended that the procedures be carried out in the order shown. The cost of each step is progressively higher, and there may be a point at which it becomes clear that the attempt to qualify the pipeline for hydrogen service should be abandoned.

1. Review of technical documentation and history

Information regarding the operational history of the pipeline shall, to the extent available, be obtained from the owner's files, and by discussions with the owner's operating personnel. These should include all documents required for the construction (including hydrostatic test records, welding procedures and pipeline specifications) and the operating and maintenance manuals.

Fluid Service: It is important to know which fluids have been transported through the pipeline during its operational life. Some fluids are potentially corrosive; others leave deposits in the pipeline. The owner shall be requested to provide a list and analysis of the fluids that have been used in the pipeline since construction and the maximum allowable operating pressure of the pipeline.

Leaks and Repairs: The owner shall provide a record of incidents and repairs from the beginning of operation in the owner's possession, including the material specifications for the pipeline used in the repairs.

Cathodic Protection: The quality of the coating of a pipeline, and the protection of this coating by cathodic protection, are the principal factors that determine the useful life of the pipeline. The condition of coating and cathodic protection system shall be determined in order to establish the value of a pipeline being considered for lease or purchase, and the risk associated with the proposed operation in hydrogen service.

The owner should be requested to provide cathodic protection test records since construction, or at least for the last ten years, and a map showing the locations of test points.

This shall demonstrate that a minimum of negative 0.850 volts potential has been continuously maintained at all test points. If there has been significant failure to achieve this potential, or if the owner's cathodic protection records are missing or inadequate, an evaluation by instrumented internal inspection device shall be carried out.

Pipeline test data:

The owner shall provide a record of the hydrostatic test(s) carried out at the time of construction, and records of any subsequent hydrostatic test and instrumented internal inspection device evaluation, in the owner's possession.

Pipeline Material Data: The owner should be requested to provide all mill certificates for pipeline material (including repair material), that are in the owner's possession. These should show the chemical analysis, the yield strength, the ultimate tensile strength and the Charpy impact strength of the pipeline material. The welding procedure and the inspection file should be provided. If the required material data are not available, a material audit and inspection shall be carried out as detailed in 5. of Appendix B.

Drawings: The owner should be requested to provide copies of drawings in the owner's possession covering the pipeline to be purchased. They are necessary to locate the pipeline for operational purposes.

2. Legal documentation review

Easements: There shall be an easement agreement for each tract of land on the line list.

The owner of the pipeline shall provide copies of all easements and other agreements, including, but not limited to, road and rail permits in the owner's possession, together with a list of all owners. There shall be a legal review of the owner's title to each tract of land. If there are deficiencies in title, arrangements for remedy shall be made prior to purchase of the pipeline.

Some easement agreements specify the liquid or gas that can be carried in the pipeline. If this is the case, it will be necessary to negotiate a change in the products that may be transported with the owner.

There shall also be a permit for each crossing of a road, railroad and waterway.

Government Permit Review: The government permit will usually show the length, size, materials, wall thickness, test pressure, and operating pressure of the pipeline, as well as the fluid to be transported. The owner of the pipeline shall provide a copy of the government pipeline permit.

Government regulations usually require a change to the operating permit if there is a change in fluid transported.

The change of ownership shall be reported to the applicable government agency.

3. Visual inspection

Above ground piping: This shall be inspected to observe the condition of paint or coating, and the condition of valves, or other equipment, which are part of the pipeline to be acquired. The spacing between isolation valves shall comply with applicable government regulations.

Crossings: All points at which the pipeline crosses roads, railways, rivers, and creeks shall be examined. Erosion of the soil may have exposed the pipeline at some locations, requiring repair or replacement of the pipeline. There should be markers at all crossings, as these are locations most likely to be subject to excavation or drilling by others.

Route: The entire length of the pipeline shall be viewed, either by vehicle or walking the route.

Document the location and number of occupied buildings in the area of the pipeline, and also any other structures that exist on the right of way of the pipeline. Documentation should be made of the location of all markers and cathodic protection connections.

The list of landowners should be updated, with current addresses and telephone numbers. Easement agreements should be checked to ensure that they correspond to current ownership.

4. Physical inspection

Location: The pipeline location should be verified (depth and horizontal) and compared to the drawings every mile.

Depth of cover: pipelines are normally buried at sufficient depth to protect them from agricultural operations. Erosion of soil may eventually reduce this coverage to a point where the pipeline is in danger of being damaged by ploughing and other surface activities. If the depth of cover is less than that required by applicable government regulations, remedial work may be required.

pipeline markers and test points shall be checked against the drawings, and if missing, replacement cost shall be included in the cost of the project.

Government regulations may restrict the allowable pressure in the pipeline, if there has been an increase in population density in the immediate vicinity.

A survey shall be made to count the number of buildings intended for human occupancy located near the pipeline, as required by government regulation.

5. Material audit in case of unknown material properties

PMI: Positive Material Investigation shall be carried out at a sampling rate of one examination per mile of pipeline minimum. This may be done by removal of coupons for analysis, or by on- site radioisotope excited x-ray fluorescence equipment.

PMI results shall provide evidence of material conformity to pipe steels listed in appendix C.

Charpy impact testing of coupons from base material and welds. One examination of base and weld material per mile of pipeline minimum. Impact test results shall assure the piping transition temperature is at least 20F below the minimum expected temperature. See item G (below) for guidance.

Material analysis: One examination every 1.6 Km (or mile) of pipeline minimum.

Weld coupons shall be subject to laboratory analysis to determine metallurgical condition (martensite-perlite, hardness and UTS)

Compliance: Non-conformance with the above material audit requirements will require additional evaluation for the use of the pipeline for the intended service.

On a case by case basis, it may be deemed necessary to conduct a rigorous metallurgical investigation. Pipeline age, pipeline location, prior history and the projected operating conditions such as high pressures are factors in the decision and final test plan.

The recommended supplementary tests which may be used as circumstance warrants are as follows:

A) Radiographic inspection of selected welds per a sampling plan to verify weld quality and the presence of manufacturing or service related defects.

B) Analysis of pipeline internal residue via techniques such as Fourier Transformation Infra Red Spectroscopy (FTIR) and Energy Dispersive Spectroscopy (EDS). These analytical techniques may be needed to verify prior service potential degradation mechanisms and to develop pertinent cleaning procedures.

C) Complete chemical analysis of selected areas sufficient to allow compliance with past certifications, applicable pipeline materials specifications and calculation of carbon equivalents.

D) Metallographic examination of selected parent metal, seam weld and girth weld specimens to verify pipe quality, damage, weld quality and corrosion damage. The presence of brittle fracture mechanisms such as stress corrosion cracking, hydrogen embrittlement would be of concern.

E) Microhardness measurements in transverse through pipeline parent metal, weld metal, seam weld and weld heat affected zones. The presence of hard spots in excess of 22 HRC is of particular concern.

F) Tensile tests of parent metal, weld metal and seam weld specimens removed from selected areas per a sampling plan.

G) Impact tests of the following sample conditions from areas selected per a sampling plan: (1) parent metal in longitudinal and transverse directions, (2) seam weld, (3) girth weld metal and weld heat affected zone.

Impact specimens should be the largest size which can be removed from the wall. Flattening of transverse specimens is permitted but heat application to facilitate flattening is prohibited. Impact specimens can be tested at various temperatures to develop a full temperature transition curve or at least 20 F below the minimum expected temperature. Various pass-fail criteria based upon energy absorption, ductile fracture percentage or lateral expansion can be selected to ensure safe operation. However, a minimum pass-fail criteria of a ductile fracture percentage in excess of 50% in each of three impact specimens tested at a selected condition, e.g., parent metal, weld metal and the weld heat affected zone, is proposed as a "default" criteria.

H) Flattening and bending tests

Flattening and bending tests are used to evaluate the weld quality under severe deformation. Flattening and bending tests should be conducted at areas and quantities determined by a sampling plan. The acceptance criteria of the flattening and bending tests can be found in specifications such as API 5L.

6. Internal pipeline inspection

Internal pipeline inspection is suggested:

- if cathodic protection records are missing, or if they indicate that protection has been inadequate if the previous service history of the pipeline is unknown, or if it has carried fluids such as crude oil or wet natural gas which are known to increase the likelihood of internal corrosion

if original material data reports for the pipeline are missing, internal inspection is required to supplement data obtained from samples (see item 5.)

Internal pipeline inspection may be waived if an internal inspection has already been made within 5 years of the evaluation, assuming that satisfactory records are available.

The internal pipeline inspection device shall be capable of locating internal and external corrosion, buckles and dents, and actual wall thickness. . If corrosion is found either the areas of corrosion will be cut out and replaced with new pipeline or the working pressure will be limited to the values calculated according to the applicable design standard.

7. Valves and flanges

Flanged joints shall preferably be replaced by welded joints. Any flanged joints that are present in the system shall meet the requirements for new pipelines as given in Section 5.4.2. Any flange older than 20 years shall re-faced or replaced. All valves shall be refurbished and valve flanges shall be refaced. In the case of any re-commissioned pipeline, all flanged joints shall be tested for fugitive emissions

8. Cleaning

Unless the pipeline has previously been used for a clean, dry gas, and has been continuously inerted when out of service, a cleaning procedure should be carried out according Section 6 of this document.

9. Records

Records shall be kept, including all investigations, tests, repairs, replacements, and alterations made under the requirements of this document. The records shall be retained for the working life of the pipeline.

10. Risk assessment

A hazard evaluation and risk assessment should be carried out according to Section 4.6 of this document, using the data obtained from the above procedures, in order to determine the suitability of the pipeline for hydrogen conversion.

Subject to the risk evaluation procedure, the pipeline may be used at a lower pressure. Depending on the degree of non-compliance, pressure shall be sufficiently low to reduce the stress level in the pipeline material to below 30% of the minimum yield strength at any point in the pipeline. The yield strength may be determined by performing a hydrostatic pressure test to yield.

Appendix I: Ultra High Purity (UHP) hydrogen pipelines

I.1. Introduction

On an increasing basis, UHP hydrogen is being used in high technology applications such as semiconductors and electronics. The requirements of these applications necessitate almost total elimination of particulates and gaseous impurities. Controls over pipeline materials, surface condition, cleaning and welding , as well as special monitoring procedures to ensure product purity are required

I2. Purity

UHP hydrogen has a nominal purity of at least 99.995% hydrogen by volume. Allowable impurities may be specified by contract and, in addition to limits on gaseous species, controls may be imposed on amount, types and size ranges of particulates, depending on application requirements.

I3. Materials and welding

UHP hydrogen is usually transported in electropolished 316L stainless steel pipe. Carbon steel has been used for “less severe” UHP service which is defined by the application. Depending upon application requirements, carbon steel pipe that is adequately cleaned and maintained in a clean and dry condition which meets the requirements of this document may be considered for certain UHP hydrogen applications.

Orbital welding techniques are preferred for welding UHP gas systems.

I4. Surface condition

Electropolished surfaces on the hydrogen side are usually required. Surface roughness of the electropolished surfaces may be specified as well as other chemical characteristics of the electropolish, depending on user needs. Other types of surface treatments may be considered depending on the actual application requirements.

I5. Cleaning UHP Hydrogen systems

UHP hydrogen systems require special cleaning subcontractors capable of meeting contaminant levels not exceeding 1000 micrograms per square metre. Such vendors shall be rigorously qualified and subject to periodic audits, inspections and process reviews. Once cleaned, installed UHP hydrogen systems shall be monitored to ensure that gas purity and particulate levels meet and maintain operational requirements.

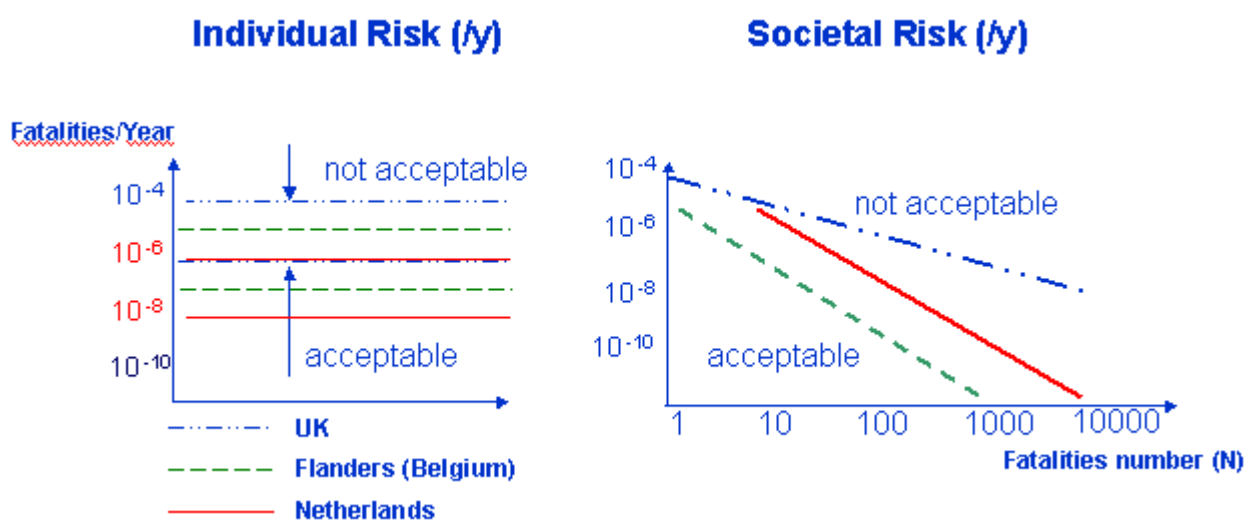
Despite efforts to maintain a pipeline in a clean and dry condition, some particles are usually present in the gas flow. Point of use filters are used to remove these particles.

Appendix J: Examples of risk criteria applicable in The Netherlands and in the United Kingdom

Reference is made to the article "An overview of quantitative risk measures for loss of life and economic damage", by S.N. Jonkman, P.H.A.J.M. van Gelder and J.K. Vrijling, published in the Journal of Hazardous Materials

The individual risk is defined as the probability for a person remaining at a given open air location at all times being fatally injured as a result of any abnormal event affecting the pipe.

The societal risk takes into account the number of fatalities, which may occur in the case of an abnormal event affecting the pipe. The required minimum probability of the abnormal event decreases with the number of fatalities



Appendix K: References

ASM

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ASM Handbook "Welding, Brazing and Soldering", Vol. 6, ASM International, Metals Park, OH

ASME

Pipeline Design and Construction published by ASME in 2000, pages 581-604

B31.3 : Pressure Piping for Refineries and Chemical Plants

B31.8 : Gas transmission and distribution piping systems

API

API-5L : Specification for line pipe

API-520 : Sizing, selection and installation of pressure-relieving devices in refineries

API-521 : Guide for pressure-relieving and depressuring systems

API-941: Recommended Practice for Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants

API-1104: Welding of pipelines and related facilities

API-RP500 A, B, C: Recommended practice for classification of locations for electrical installations at petroleum facilities

ASTM

G 142: Standard Test method for Determination of Susceptibility of Metals to Embrittlement in Hydrogen Containing Environment at High pressure, High Temperature or both

G 129: Standard Practice for Slow Strain Rate Testing to Evaluate the Susceptibility of Metallic Materials to Environmentally Assisted Cracking

F 1459: Standard test method for determination of the susceptibility of metallic materials to gaseous hydrogen embrittlement

ATEX

EU Directive 94/9/EC on equipment and protective systems intended for use in potentially explosive atmospheres (ATEX)

NASA

Safety Standard for Hydrogen and Hydrogen Systems: Guidelines for Hydrogen System Design, Materials Selection, Operations, Storage and Transportation

NACE

ANSI/NACE MR0175/ISO 15156, Petroleum and natural gas industries—Materials for use in H₂S-containing environments in oil and gas production

ANSI/NACE TM0284-2011, Evaluation of Pipeline and Pressure Vessel Steels for Resistance to Hydrogen-Induced Cracking

SP0177: Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems

SP0198-2010 Control of Corrosion under Thermal Insulation and Fireproofing

ANSI/NACE SP0502-2010, Pipeline External Corrosion Direct Assessment Methodology -

EIGA

- Doc 100: Hydrogen cylinders and transport vessels
- Doc 15: Gaseous hydrogen stations
- Doc 95: Recommendation for the avoidance of failure of CO and CO/CO₂ mixtures cylinders
- Doc 75: Determination of safety distances

CGA

- G 5.4: Standard for hydrogen piping systems at consumer locations
- G 5.5: Hydrogen vent systems

ISO

- ISO 13623: Petroleum and natural gas industries -- Pipeline transportation systems
- ISO 11114 Gas cylinders -- Compatibility of cylinder and valve materials with gas contents -- Part 1: Metallic materials
- ISO 11114 Gas cylinders -- Compatibility of cylinder and valve materials with gas contents -- Part 2: Non-metallic materials
- ISO 11114 Transportable gas cylinders -- Compatibility of cylinder and valve materials with gas contents -- Part 4: Test methods for selecting metallic materials resistant to hydrogen embrittlement
- ISO 9809: Gas cylinders -- Refillable seamless steel gas cylinders -- Design, construction and testing -- Part 1: Quenched and tempered steel cylinders with tensile strength less than 1 100 MPa
- ISO 11120: Gas cylinders -- Refillable seamless steel tubes for compressed gas transport, of water capacity between 150 l and 3000 l -- Design construction and testing
- ISO 21809-1 Petroleum and natural gas industries. External coatings for buried or submerged pipelines used in pipeline transportation systems Polyolefin coatings (3-layer PE and 3-layer PP)

European Standards

- EN1594: Gas supply systems - Pipelines for maximum operating pressure over 16 bar - Functional requirements
- EN 14161: Petroleum and natural gas industries - Pipeline transportation systems (ISO 13623:2009 modified)
- EN 10208-2: Steel pipes for pipelines for combustible fluids. Technical delivery conditions Pipes of requirement class B
- EN 12954: Cathodic protection of buried or immersed metallic structures - General principles and application for pipelines
- EN12732: Gas infrastructure. Welding steel pipework. Functional requirements
- EN 14161: Petroleum and natural gas industries. Pipeline transportation systems
- EN 60079-10: Electrical apparatus for explosive gas atmospheres- Part 10: Classification of hazardous Areas
- EN60079-14: Electrical apparatus for explosive gas atmospheres- Part 14: Electrical installations in Hazardous areas
- EN 61508: Functional safety of electrical/electronic/programmable electronic safety related systems

European Legislation

European Union Directive 97/23 Pressure Equipment Directive

NFPA

- NFPA 55: Compressed Gases and Cryogenic Fluids Code
- NFPA 70: National Electric Code
- NFPA 496: Standard for Purged and Pressurized Enclosures for Electrical Equipment

NFPA 497: Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapours and Of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas

IEC

IEC 60079-0: Explosive atmospheres - Part 0: Equipment - General requirements

BRITISH STANDARDS

BS PD 8010: Part 1, Pipelines on land: design, construction and installation

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